Horizontal Eccentric Towing and its Effects on Sprint Performance

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Abstract

The success of many team sports and track and field athletes can be in part linked with their sprint performance. Therefore, improving sprint performance has been the foci of researchers and practitioners alike. The most commonly used tools that deliver sprint-specific training stimuli are resisted towing devices (RST) (e.g. sleds). RST provides a predominantly concentric (CON) horizontal overload to the musculo-skeletal system, especially in the acceleration phase of the sprint. Perhaps an eccentric (ECC) horizontal overload may be beneficial given the benefits of ECC training; such as, injury prevention and rehabilitation, shift towards faster muscle phenotypes, hypertrophy, strength and power improvements. This resulted in the overarching research question, "Can a novel horizontal ECC towing device improve sprint performance?". The aim of this thesis was to develop a device that would provide a horizontal ECC stimulus, evaluate the biomechanics of the device and test its effects on sprint performance. A review of existing ECC training devices found limited devices overload in the horizontal plane and none eccentrically overload the musculo-skeletal system in a sprint-specific gait. Therefore, a movement termed horizontal ECC towing (HET) was developed which involves an athlete in a sprint stance trying to move forwards but is being pulled backwards. A device termed the HET device was then developed to automate this movement. The device was powered by a 10 kW electric motor that can tow athletes at velocities up to 3.58 m/s and can tolerate forces up to 2.8 kN. Two familiarisation sessions were found to achieve movement consistency during HET. Biomechanics analysis was conducted to further understand the movement which would help inform training programme development for coaches. Since HET is a novel movement, no research existed. Thus, ECC towing was compared to its opposite, the CON towing direction (CTD). Statistical Parametric Mapping (SPM) analysis of ground reaction force (GRF) profiles found that the two directions were significantly different ($p<0.05$) and were applying different movement strategies to produce force. This suggested that different lower limb joints were likely responsible for CON and ECC force production. Vertical and horizontal GRFs were lower in the ECC direction ($p<0.05$), which may be limited by the coefficient of friction and indicated that isokinetic horizontal towing does not follow the contractile-force-velocity relationship. Power

and work analysis of the lower limb joints showed that the ankle and hip joints are absorbing energy and likely dissipating it in the ECC towing direction (ETD). ETD has greater ankle and hip joint power absorption and much smaller power production. A four-week intervention of ECC and CON towing in elite female field hockey players (n=10) resulted in no improvements in split times. There is still an opportunity for practitioners and researchers to apply a unique ECC stimulus to their athletes. The intervention study had its limitations as it was based out of the lab in a practical setting. However, no tool provides a similar overload as the HET device. We recommend to those that are interested in overloading the power absorption phase of the ankle and hip joints should incorporate HET. Further research with the HET device involving a larger cohort of athletes could provide more conclusive evidence on the effects on sprint performance.

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Attestation of Authorship

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

Chapters 2 to 8 of this thesis represent separate papers that have either been published or have been submitted to peer-reviewed journals for consideration for publication or have been embargoed due to confidential information and have not been submitted to a journal. My contribution and the contribution by various co-authors to each of these papers are outlined at the beginning of each chapter. All co-authors have approved the inclusion of the joint work in this doctoral thesis.

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Farhan Akbari Tinwala

17 February 2020

Co-Authored Works

Table 1: Co-Authored Works

Chapter publication reference		Author %
Chapter 2.	Tinwala F, Cronin J, Haemmerle E, Ross A. Eccentric Strength Training: A Review of the Available Technology. *Published in Journal of Strength and Conditioning*. 2017:39(1):32-47	FT: 90% JC: 5% EH: 2.5% AR: 2.5%
Chapter 3.	Tinwala F, Cronin J, Haemmerle E, Ross A. Forces and Velocities Associated with Horizontal Eccentric Towing: A Pilot Study. *Sports Biomechanics. [in preparation]*	FT: 90% JC: 5% EH: 2.5% AR: 2.5%
Chapter 4.	Tinwala F, Haemmerle E, Cronin J, Ross. Construction of an Isokinetic Horizontal Eccentric Towing Device to Improve Sprinting Performance. *Submitted to Journal of Sports Engineering and Technology. [in review]*	FT: 90% EH: 5% JC: 2.5% AR: 2.5%
Chapter 5.	Tinwala F, Cronin J, Haemmerle E, Ross A. Movement Variability Associated with Horizontal Eccentric Towing. *Conference Presentation*. *Presented at ISBS 2018.*	FT: 90% JC: 5% EH: 2.5% AR: 2.5%
Chapter 6.	Tinwala F, Cronin J, Nagahara R, Brown S, Cross M, Haemmerle E, Ross A. Differences in Ground Reaction Forces between Concentric and Eccentric Isokinetic Horizontal Towing. *Journal of Sports Sciences. [in preparation]*	FT: 80% JC: 7.5% RN: 2.5% SB: 2.5% MC: 2.5% EH: 2.5% AR: 2.5%
Chapter 7.	Tinwala F, Cronin J, Nagahara R, Brown S, Cross M, Haemmerle E, Ross A. Differences in Lower Limb Joint Power and Work between Concentric and Eccentric Isokinetic Horizontal Towing. *Journal of Applied Biomechanics. [in preparation]*	FT: 80% JC: 7.5% RN: 2.5% SB: 2.5% MC: 2.5% EH: 2.5% AR: 2.5%
Chapter 8.	Tinwala F, Cronin J, Ross A, Haemmerle E. Effects of Isokinetic Horizontal Towing on Sprint Performance in Elite Female Field Hockey Players. *Journal of Strength and Conditioning Research. [in preparation]*	FT: 90% JC: 5% AR: 5% EH: 2.5%

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

Supervisors

Prof John Cronin	Prof Enrico Haemmerle	Dr Angus Ross
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Ch 6 and 7	Ch 6 and 7	Ch 6 and 7

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My journey began six years ago when I was approached by Professor Kean Aw who mentored me during my undergraduate degree. He told me that he had a PhD opportunity at Auckland University of Technology. He mentioned that it would probably involve technology and sports. Before he could tell me more, he asked me to fully commit to the PhD by quitting my job and signing a Non-Disclosure Agreement with an organisation called High Performance Sport New Zealand. It sounded quite farfetched at the time, but he convinced me that this was a once in a lifetime opportunity. I would like to thank Professor Kean Aw for convincing me to pursue this PhD opportunity and take a leap of faith. Without him I would probably still be pushing paper for a big corporation. Thanks KC.

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Ethics Approval

Ethics approval for this thesis research was granted by the Auckland University of Technology Ethics Committee (AUTEC) on 6th November 2015 for a period of three years:

- 15/375 – Determining the variability of eccentric force and power during horizontal eccentric towing.

Nomenclature

α	Angular Acceleration
ω	Angular Velocity
BM	Body Mass
CV	Coefficient of Variation
CON	Concentric Muscle Contraction
CTD	Concentric Towing Direction
CI	Confidence Intervals
CT	Contact Time
ECC	Eccentric Muscle Contraction
ETD	Eccentric Towing Direction
ES	Effect Size
FT	Flight Time
HET	Horizontal Eccentric Towing
F_h	Horizontal Force
IL	Inertial Load Cycle Ergometer
IHT	Isokinetic Horizontal Towing
V_{max}	Maximum Velocity
μ	Mean
I	Moment of Inertia
SWC	Smallest Worthwhile Change
SD / σ	Standard Deviation
SF	Step Frequency
SL	Step Length
SSC	Stretch-Shortening Cycle
τ	Torque
F_V	Vertical Force

Chapter 1: Introduction

1.1 Rationale of the Thesis

The 100 m race has been the pinnacle event in athletics during the Olympics and World Championships for many decades. Becoming the fastest person in the world is considered one of the greatest accolades one can achieve for many athletes and coaches. However, sprinting is not exclusive to athletics, it is vital within team sports as well [1]. In rugby and soccer, players that can sprint faster and outrun their opponents are likely to score more points / goals or prevent the other team from scoring [2, 3]. This theme is shared in various other team sports irrespective of where they are played. Whether it is field hockey on artificial turf or netball on court, the sprinting abilities of team sport athletes, specifically their ability to accelerate, often contributes to their teams' success [4, 5]. Thus, improving athletes' sprint performance has been of interest to many practitioners and researchers and provides the focus for this thesis.

A typical sprint can be categorised into four phases: starting block; acceleration; constant velocity; and deceleration [6]. Each phase has its own unique requirements that differ in terms of mechanics and physiology. Coaches often must optimise these to improve their athlete's performance. The most commonly used method to improve sprint performance through physiological adaptations is resistance training. Resistance training has been shown to improve sprint performance in a range of athletes [7-11]. More specifically, a resistance training method called resisted towing has had an impact on sprint performance of athletes [12]. One of the reasons resisted towing has proven to be effective may be because it provides a sprint-specific stimulus, that is, athletes usually tow a sled whilst sprinting. Sprinting is a movement that occurs in the horizontal plane and resisted towing provides coaches a method to improve performance in this plane. Producing greater horizontal force is proven to improve sprint acceleration performance, whereas directing braking forces to be vertical and propulsive to be horizontal optimises the constant velocity phase of a sprint [13]. Thus methods such as sled towing have been used to target horizontal force production and accelerative sprint ability [14].

The resistance sled produces an overload through the friction force between the sled and the surface it is being towed over. The magnitude of loading is often expressed as a percentage of body mass of the participant [15, 16]. Other tools such as parachutes and weighted vests also provide a sprint-specific stimulus that share similarities with sled towing. The similarity between such tools is that they predominantly overload the musculo-skeletal system in a concentric (CON) manner as athletes produce force and power to accelerate their limbs. It must be noted that the overload is targeted to the CON actions of a sprint, and the work during a sprint is the coupling of both eccentric (ECC) and concentric muscle actions. However, it may be that an ECC towing stimulus could better overload the musculo-skeletal system.

ECC muscle contractions occur when an active muscle lengthens under tension where the external load is greater than the load produced by the muscle [17]. ECC muscle contractions are unique in that they allow for supramaximal forces (1.4 – 1.8 times higher than the maximum voluntary isometric contraction (MVIC)) as evidenced in the force-velocity relationship of muscles [18, 19]. The force-velocity relationship of muscles shows that ECC supramaximal forces can be generated at both slow and fast contraction velocities. This allows for a training stimulus that can incorporate high forces at high velocities [19]. This has created an opportunity for practitioners and researchers to further investigate the role of the ECC muscle contraction.

ECC strength training has become immensely popular amongst strength and conditioning coaches as research has now shown its unique benefits. Forms of ECC resistance training have been used for injury rehabilitation [20-24], injury prevention [23-25] and to increase strength and hypertrophy [26]. Researchers have also shown that ECC training at higher velocities may induce muscle phenotype changes towards faster twitch fibres [27-31]. A faster muscle phenotype could be of great benefit to sprint athletes as producing large amounts of force in the least amount of time spend on the ground may improve their sprint performance [32, 33].

The ability of resisted sled towing to overload power production is beneficial in sprint performance. However, overloading power absorption may also be beneficial to sprint performance. The stretch-shortening cycle (SSC) function, which is crucial for sprint athletes during the constant velocity phase of the sprint, is dependent on energy absorption and subsequent rapid energy production [34]. Targeting power absorption in a sprint-specific movement to optimise SSC function has not been previously researched. To the best of our knowledge, no current technologies or tools provide a sprint-specific horizontal ECC overload. Given the many benefits of ECC training and the importance of sprint performance, a novel method that delivers such a stimulus may improve sprint performance. Therefore, the purpose of this thesis was threefold. First, to develop a novel horizontal ECC towing (HET) device; second, to understand the stimulus; and third, to investigate its effects on sprint performance.

1.2 Research Questions

The overarching research question of this thesis was; ***"Can a novel horizontal ECC towing device improve sprint performance?"***. To answer this question, the following research objectives were identified:

1. Review ECC training technology and research what current tools and technologies are being used to administer ECC training stimuli, and to identify the gap in technology and in research. (Section 1: Chapter 2)
2. Design, development and construction of the HET device. (Section 2: Chapter 3 and 4)
3. Understand the biomechanics of the HET movement. Investigate the variability of the movement, its force and power production and absorption characteristics. (Section 3: Chapter 5, 6 and 7).
4. Test the effects of HET on sprint performance in an ecologically valid setting. (Section 4: Chapter 8)

1.3 Thesis Structure

This thesis was conducted using quantitative research methodology to answer the overarching research question and comprises a series of chapters each written in the format of a published scientific journal article. As such, repetition of some information (e.g. introductions, research methods and other points of discussion) inevitably occurs. Chapters 2-8 are divided into four thematic sections outlined in Figure 1.

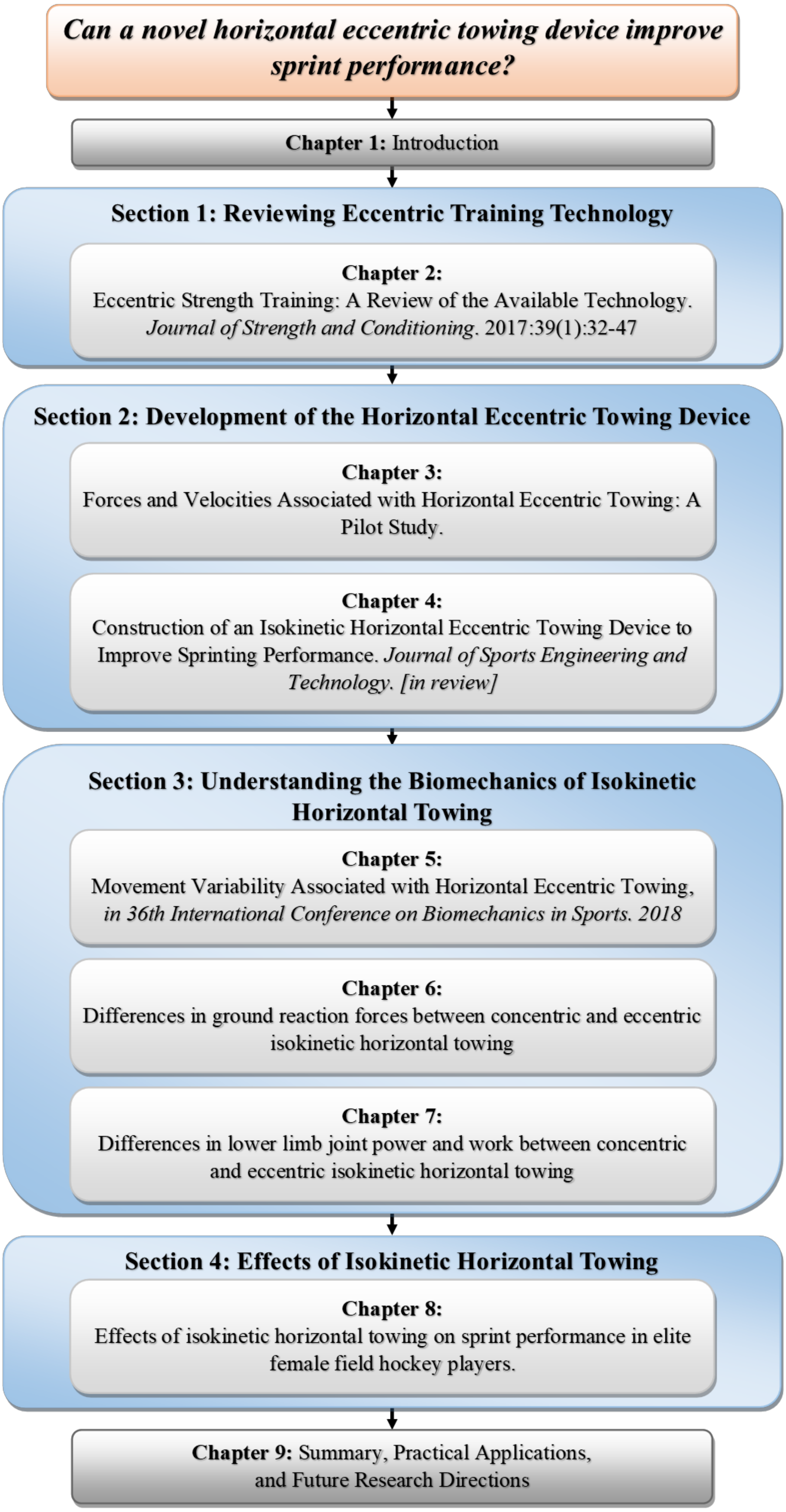

Figure 1: Thesis structure

Chapters 3-8 each begin with a Prelude that briefly describes the findings of the previous chapter and explains how the direction taken in the subsequent chapter will build upon these findings. The Prelude links the successive chapters together to ensure that the thesis is a cohesive whole.

Section 1 begins with an equipment review of the current available technology that administers ECC strength training (Chapter 2). The advantages and disadvantages of each device is discussed to clarify the gap in technology and to help form a list of requirements for the development of a new device.

Section 2 first investigates the forces and velocities involved with horizontal ECC towing in order to build on the list of specifications for the development of a new device (Chapter 3). The design, development and construction of the isokinetic horizontal ECC towing (HET) device is then discussed (Chapter 4).

Section 3 involves understanding the biomechanics of the isokinetic horizontal towing movement. The movement variability and reliability of force measures were investigated to determine the familiarisation requirements (Chapter 5). Since isokinetic horizontal ECC towing is novel movement it was important to understand the familiarisation protocol before athletes could use it in training. Finally, the ground reaction forces, power and work variables during isokinetic horizontal towing were measured to understand the role of force and power production and absorption across various towing velocities (Chapter 6 and 7). This would then help inform a training programme to use during the intervention study.

Section 4 determines the effects of a four-week isokinetic horizontal towing intervention on sprint performance in elite female field-hockey players (Chapter 8). Finally, key findings from the thesis and guidelines around implementing the HET device in a practical setting are discussed. Future research of HET is also discussed (Chapter 9).

Section 1: Reviewing Eccentric Training Technology

Chapter 2: Eccentric Strength Training: A Review of the Available Technology

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

Reference:

Tinwala F, Cronin J, Haemmerle E, Ross A. *Eccentric Strength Training: A Review of the Available Technology.* Strength and Conditioning Journal, 2017. 39(1): p. 32-47.

Supplemental digital content 1, http://links.lww.com/SCJ/A198.

2.1 Introduction

Muscular contractions are typically classified as; concentric (CON - active muscle shortens); isometric (active muscle is neither shortening nor lengthening); and eccentric (ECC - active muscle lengthens under tension). CON contractions occur when the total tension developed in a muscle is sufficient to overcome any resistance to shortening. ECC contractions occur when the tension developed in the muscle is less than the external resistance and the muscle is therefore lengthened [35]. When ECC and CON contractions are coupled this is termed the stretch-shortening cycle (SSC) [36]. Developing ECC strength is thought to be beneficial to sporting performance [26, 31, 37-39], rehabilitation [20-24] and injury prevention [23-25], and provides the focus of this article.

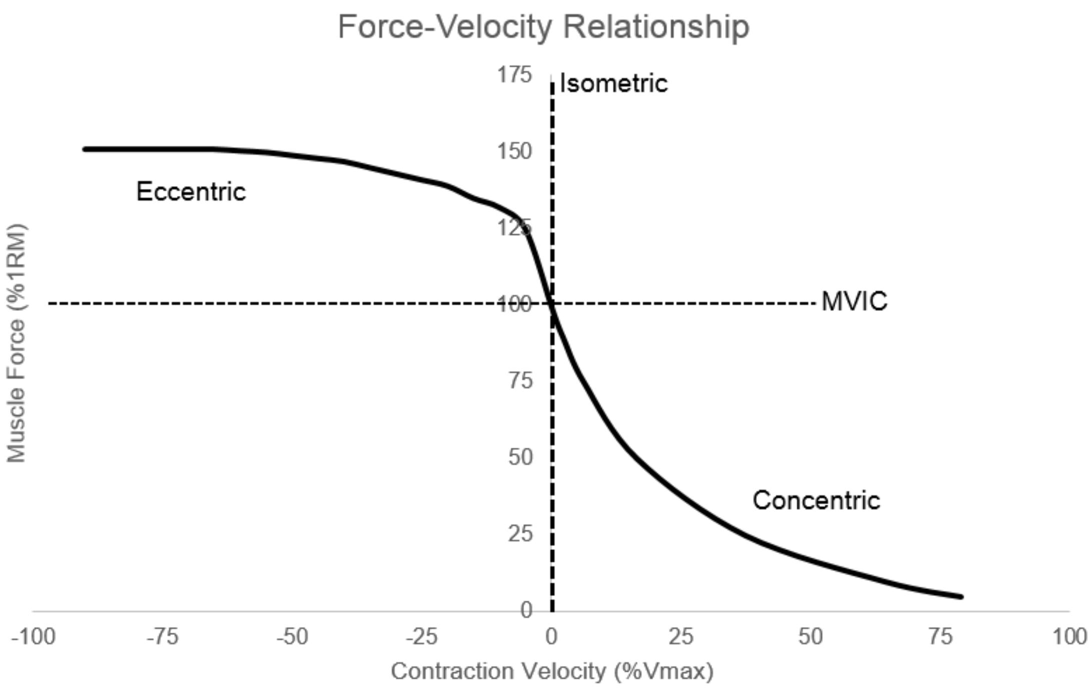

Figure 2: Force-Velocity relationship (adapted from Lieber [19])

ECC contractions are unique in a number of ways as evidenced in the force-velocity relationship of muscle (see Figure 2). During a CON contraction, the force generated is always lower than the maximum voluntary isometric contraction (MVIC). As the load the muscle is required to lift decreases, contraction velocity increases. This occurs until the muscle reaches its maximum contraction velocity V_{max}. The force-velocity relationship for a CON muscle contraction is defined as a steep rectangular hyperbola. When the contraction velocity is negative (the muscle is lengthening), the muscle is contracting eccentrically. The force-velocity relationship for an ECC muscle contraction is significantly different to a CON contraction. Supra-maximal forces can be generated at both slow and fast contraction velocities. This creates a method of training with high forces at high velocities, which is impossible to produce with CON contractions according to the CON force-velocity relationship [19].

Cowell et al. (2012) [26] discussed how the stress (force/load), strain (length or amplitude of movement), and velocity during the ECC phase, could be used to impose a variety of mechanical stimuli that have different adaptational and functional effects. Specifically, they mentioned that different forms of ECC resistance training could be used for: (a) tendon injury rehabilitation via tendinous remodelling; (b) muscle injury prevention via shift in the optimum length of muscle; (c) supramaximal and/or accentuated ECC loading (i.e. loads exceeding the 1 repetition maximum (1RM) and/or greater than the CON load) for strength, performance, and hypertrophy; and, (d) high velocity eccentrics for improved sports performance via SSC optimization.

Given the publicized benefits of ECC training, researchers and practitioners have been interested in designing and developing equipment that can improve the ECC strength of the client/athlete. The aim of this article is to review the technologies available for the development of ECC strength. First the device is described in order to understand the nature of the mechanical ECC stimulus. Thereafter the advantages and disadvantages of each device are discussed. It is hoped that such a treatise of the technology affords the reader a greater understanding of the options available for the training of eccentrics in relation to specific athlete or program needs.

2.2 X-Force™

2.2.1 Overview

X-Force™ (Stockholm, Sweden – bit.ly/30NH8eB) offer a range of training devices that focus on delivering ECC overload to the user. The devices achieve ECC overload by tilting the entire weight stack 45° during the CON phase and rotating the stack back to the vertical during the ECC phase (please see following link to observe these devices – bit.ly/2N6L7uF). X-Force™ claim that their devices can achieve 40% higher forces during the ECC phase using this technology. The company offers 14 training devices and each of them eccentrically train a specific movement or muscle group. For example, the conventional leg press machine can be replaced by the X-Force™ ECC Leg Press. This allows their users to train using familiar movements without having to learn and adapt to new equipment.

Figure 3: X-Force™ seated pec press

2.2.2 ECC Mechanism

The underlying principle behind all X-Force™ products is to tilt the weight stack by 45° to reduce the load during the CON phase and increase the load during the ECC phase. The free body diagram below explains this concept in more detail:

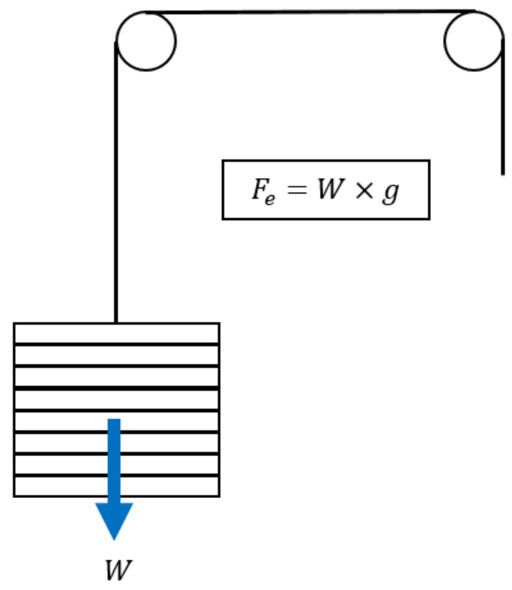

Figure 4: X-Force™ ECC mechanism

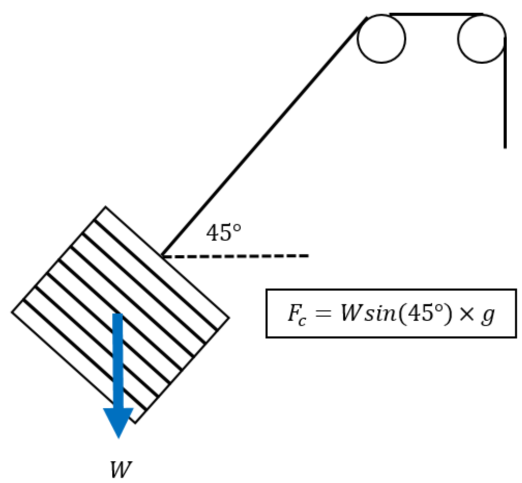

Figure 5: X-Force™ CON mechanism

Figure 4 depicts that the force during the ECC phase will be the total weight of the stack. For example, if the stack weighs 100 kg then the ECC force will be 981 N ($F_e = 100 \times 9.81 = 981\ N$). Figure 5 depicts the CON phase force. The CON force will now be a component of the total gravitational force on the stack, because it has been tilted by 45°. The CON force for a 100 kg weight stack rotated 45° will be 694 N ($F_c = 100sin(45°)\ \times\ 9.81 = 694$ N). In essence, the ECC force is approximately 40% ($\left(\frac{981}{694} - 1\right) \times 100\% = 41.4\%$) larger than the CON force. Thus, providing ECC overload.

In order to use the X-Force™ device for a training session, the user would set their CON load on the weight stack as per their requirement. They simply move the locking pin to the desired weight, as is the same in most conventional weight stack equipment. At this point the weight stack is already tilted by 45° as the user starts the CON phase. There is a start button on the device which the user engages to initiate the exercise. As the user moves in the positive direction (CON) the weight stack remains tilted. As the user reaches the maximum point in their range of motion (ROM) and starts to move in the negative direction (ECC), the device tilts the weight stack to the vertical position which overloads the movement by an additional 40%. The device tilts the stack every time the user transitions between CON and ECC phases. This is an isoinertial device, which means the inertia of the load is constant and the speed of movement is controlled by the user (i.e. free weights).

2.2.3 Technology

To tilt the weight stack, X-Force™ devices use an electric servomotor. Apart from this, X-Force™ does not reveal any technical details about the technology it is using. The size, weight, and colour of the devices are the only other technical specifications X-Force™ shares with the public.

2.2.4 Advantages vs Disadvantages

Table 2: Advantages and disadvantages of the X-Force™ devices

Advantages	Disadvantages
Simplicity – The X-Force™ devices use a very simple concept to achieve the ever so complex goal to overload eccentrically without the need for a second person or spotter. The rotation of the entire weight stack overloads 40% more eccentrically and it does it automatically. The devices are simple and easy to use. They are based on the conventional weighted stack machines found in most gyms. Therefore, users can train with this technology straight away. The smart programming of the machine removes the need for users to enter or manually set their range of motion. The machine detects when the user is at the positive apex and tilts the stack for the negative/ECC muscle action.	**Power, size and weight** – A conventional weight stack in a leg press machine would weigh approximately 100kgs. This equates to a very large moment of inertia ($I \approx 100kg.m^2$ (for a simple pendulum approximation at r=1m) and requires a large torque ($\tau = I\alpha,\ \alpha = angular\ acceleration$) to tilt the weight stack assembly. This means the size of the motor and the power it requires would be large. Having all 14 of the devices operating in the gym would increase the overall power consumption. Alterations may have to be made on the switch board (separate circuit breakers, higher rated fuses, etc.) before any of the devices are installed. The devices are also similarly sized to conventional weighted stack gym equipment. This means they are not portable and cannot be moved easily.
CON and ECC coupled training – X-Force™ incorporates both CON and ECC motions rather than an ECC only motion. There is evidence that suggests a coupled CON and ECC overload training method will yield improvements in power (increase in CON force, contractile velocity and muscle cross-sectional area) [37, 40].	**Synergetic muscle activation** – Since the devices X-Force™ provide are based on conventional gym equipment, they have a limited number of degrees of freedom (DOF). They focus on a particular movement or muscle group and limit the contribution from fixators and synergistic muscles (i.e. the seated chest press focuses primarily on the pectoral muscle group and does not engage the core to provide stability).
Safety – Safety features on these devices are identical to the safety features found on conventional weighted stack gym equipment (i.e. safety pins and range of motion limits). Hence, users will be familiar of the safety risks and hazards.	**Non-adjustable ECC overload –** The ECC overload is set and cannot be changed (40%). Users may want a higher or lower ECC overload depending on their training requirements or training status. Ideally, a device that can allow users to alter the ECC overload would be the most beneficial.

2.2.5 Validation

The X-Force™ website (bit.ly/2YEjxdG) alludes to the benefits of negative or ECC training, however, there is no mention as to whether their devices have been used in any empirically validated research at this point in time. Furthermore, the magnitude of the loading associated with the technology is estimated via free body calculations. The validation of the actual loading provided by this technology is not readily observed from the website. For example, a stack load of 100 kg could be vastly different depending on the design/inertia of the system.

2.3 REACT ECC Trainer

2.3.1 Overview

The ECC trainer (Atlanta, USA – bit.ly/3fulmk5) is a device that provides isokinetic ECC overloading for the lower body. The user is on a rotating platform and he/she absorbs the force generated with their knees (please see the following links to observe this device – bit.ly/2TlVNdu, bit.ly/2uDR2kX). The name REACT stands for Rapid Eccentric Anaerobic Core Trainer.

Figure 6: REACT ECC trainer

2.3.2 ECC Mechanism

This is an isokinetic device which means it is moving at a constant speed. In this case the platform is rotating at a constant rpm, which can be adjusted by the user before and during the workout. The device has a touch screen panel to set the speed and a safety tag that clips on the user's clothes (similar to a treadmill). The device has two rotating drums that are joined together with a platform. This creates an elliptical path for the platform (see Figure 7).

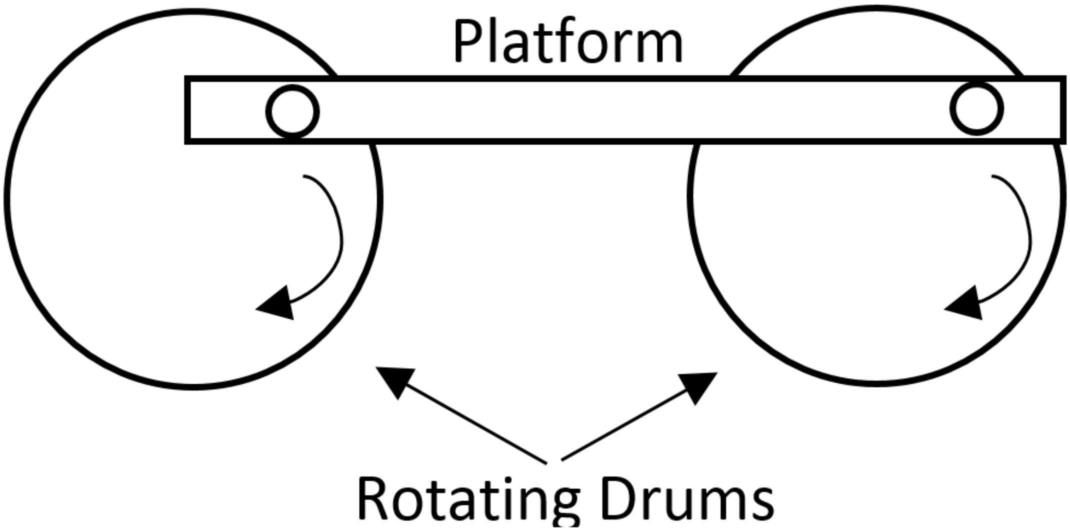

Figure 7: REACT ECC trainer mechanism

Since this is an isokinetic device, the ECC overload or resistance is entirely dependent on the user. The user can simply ride the device, but in order to benefit eccentrically from the exercise the user must absorb the rotation by bending their knees and engaging the lower body muscles. The faster and deeper the user does this, determines the magnitude of the ECC overload. The user can hold on to the rail or let go, which engages the core musculature to a greater extent as the user tries to stay balanced. The user stands on the platform and begins to exercise by pressing the start button on the touch screen. They can stand either facing forwards, sideways, left or right on the device to perform various exercises.

2.3.3 Technology

REACT provide a list of technical specifications on their website (bit.ly/2FIW7uK). The rotating speed ranges from 30-70rpm. The features of this device are similar to a conventional treadmill. It has the same safety tag feature with an emergency stop on either side. It also has a touch screen control panel which is becoming more common amongst recreational fitness equipment.

2.3.4 Advantages vs Disadvantages

Table 3: Advantages and disadvantages of the REACT ECC Trainer

Advantages	Disadvantages
Synergetic muscle activation – By absorbing the rotation and keeping your hips level, this compound ECC squat recruits more synergistic contribution than devices such as the X-Force™ leg press. The exercise can be made more difficult by simply letting go and holding your hands over your head. This engages the core muscles as well.	**Simplicity –** The general population of users such as athletes and patients will not be familiar with this technology and familiarization with the exercise and the permutations will take some time. This will be especially so when the individual starts to let go of the railing and engage their core.
Adjustable ECC load and velocity – The ECC overload can be adjusted by the user and depends on how hard they resist the rotation of the platform. The RPM of the platform can also be adjusted by the user. This allows coaches and practitioners the ability to train with a large number of permutations. The ability to change the velocity of the exercise is an important factor, allowing users to train to various goals. For example, athletes can train at higher velocities to increase the volume of work and also increase power. Rehabilitation patients can train at a lower velocity in order to slowly strengthen without exposing them to further injury risk.	**CON and ECC coupled training –** The device overloads the ECC contraction only. As the platform rotates from the bottom most position to the top, the lower body is absorbing the resistance and the muscles are working eccentrically. As the platform rotates from the topmost position to the bottom, the resistance is removed and the muscles are relaxed. This cycle continues throughout. As mentioned earlier, a coupled CON and ECC overload training method can be more beneficial.
Safety – There is a safety tag similar to those found on conventional treadmills. The device also has two large emergency stop buttons and infrared light beams that stop the device when broken These safety features reduce the risk of injury by immediately stopping the rotating platform in the event of an emergency.	**Power, size and weight –** The REACT device weighs 280kg and is 2300mm x 1090mm x 1420mm (LxWxH). The size and weight of this device are similar to a conventional treadmill and hence will not be portable and easy to move. It runs on single phase 120V-140V power. For countries that operate with 230V power, an additional voltage transformer will have to be purchased in order to operate the device. There is no indication of current or power rating. This must be accounted for before installation in the switchboard as most domestic limit single-phase current to 10A only. This is equivalent to 2400W of electrical power.

2.3.5 Validation

This rotating platform concept, also termed ‘quadmill’, first originated from skiing. It was developed for skiers to simulate the absorbing motion of the lower body when skiers navigate moguls in the snow. REACT have tried to introduce this to the recreational gym-goer. In order to state its reliability and validity, REACT reference the various benefits of ECC training. However, there is no mention as to whether this device has been used in any empirically validated research at this point in time.

2.4 BTE Eccentron™

2.4.1 Overview

BTE™ is a company based in Maryland, USA (bit.ly/2CbSOO1) and their ECC training device is called the Eccentron™. The Eccentron™ is an isokinetic device that simulates downhill walking. It can be described as an ECC recumbent cycle (please see the following link to observe this device – bit.ly/3d8XhxJ). The device provides adjustable resistance of up to 3300 N at speeds between 12-48 reps/min. It has a touch screen where the user can see their workout progress, and remote to control the speed.

2.4.2 ECC Mechanism

The Eccentron™ aims to bring the benefits of downhill running ECCs to the user. As stated earlier, the device is the ECC version of a conventional CON recumbent cycle. The pedals of the Eccentron™ push towards the user and the user must resist this push to perform the ECC exercise. The user initiates the exercise by simply pressing the start button on the remote. This remote also controls the speed of the exercise allowing users to go faster or slower depending on the training requirement.

2.4.3 Technology

BTE™ states that the Eccentron™ is capable of producing forces up to 3300 N on each leg and an operating speed of 12-48 reps/min (bit.ly/3elHygt). BTE™ does not reveal anything else about the technology inside the device.

2.4.4 Advantages vs Disadvantages

Table 4: Advantages and disadvantages of the BTE Eccentron™

Advantages	Disadvantages
Simplicity – The simplicity of the machine wins it some credibility amongst recreational users and physical therapists working with patients. The gait pattern associated with recumbent cycling is somewhat natural to humans. To elaborate, the user does not need a long learning session to familiarise themselves with the exercise.	**Power, size and weight** – This device weighs 325kgs and is 2490mm x 710mm x 1500mm (LxWxH). It operates on single phase universal voltage (100-250V). There is no indication of current or power rating.
Adjustable ECC load and velocity – Similar to the REACT trainer, the ECC load depends on how hard the user resists the push of the pedals. The speed is also controlled by the user. This is achieved via a remote near the hand grip. This allows the speed to be adjusted during a session.	**Synergetic muscle activation** – The Eccentron focuses solely on lower body muscle groups. During the exercise no other fixator or synergetic muscles are activated to aid the exercise such as core muscles.
Safety – Since this device is a recumbent bike, safety is not a big issue. The likelihood of harm to the user is minimal. The user can 'ride' the bike without exerting any force and there is an emergency stop in the remote controller next to the user.	**CON and ECC coupled training** – The Eccentron does not enable overloading of the CON contraction.

2.4.5 Validation

Similar to the other device manufacturers, BTE™ states the various benefits of ECC training for different types of patients. They provide a list of references on their website citing the benefits of ECC training in order to validate the device (bit.ly/37Doh7i). At this point in time no empirically validated research has directly investigated the benefits or the technology of the BTE Eccentron™. Furthermore, the validation of the specifications stated by BTE™ is not readily observed from the website.

2.5 Exentrix by SmartCoach™

2.5.1 Overview

Exentrix by SmartCoach™ (Stockholm, Sweden – bit.ly/2N6WxPf) is a multi-exercise cable pulley training device that is based on the conventional weight stack cable pulley. However, instead of a weight stack the Exentrix has an electric motor that controls the load. The device is wall mounted and has a 4 m cable drum. Since it is a cable pulley device, it allows users to train many modes and exercises, just as a conventional cable pulley device would. The device allows users to manually change the level of eccentric overload, as well as train in isoinertial and isokinetic modes. It has a smart touch screen user interface that controls the device. Please follow this link to see a video of this device being used – bit.ly/2N1oIz7.

Figure 8: Exentrix squat

2.5.2 ECC Mechanism

The device uses an electric servomotor to provide resistance and the ECC overload. For example, if the user wishes to perform an isokinetic squat (the speed of the movement is constant), they would first wear a harness that connects to the end of the cable from the device (as shown in Figure 8). The coach then configures the exercise settings (ROM, repetitions and velocity) on the touchscreen panel. During the CON phase of the squat, the electric servomotor unwinds the cable at a constant velocity and during the ECC phase, the cable is wound back in at a constant velocity. In isokinetic mode, the resistance is controlled by the user. This mechanism is similar to other isokinetic modes found on devices such as the BTE Eccentron™ and the REACT ECC Trainer.

2.5.3 Technology

SmartCoach™ provides a detailed list of technical specifications for the Exentrix device on their website (bit.ly/3fsNkNl). The two most important specifications are the maximum force of 800 N (1600 N with pulley) and the maximum velocity of 3.8 m/s (1.9 m/s with pulley). Exentrix uses an electric servomotor to control the force and the velocity of the exercise. The electric servomotor is connected to a cable drum which either winds the cable in (ECC) or resists the unwinding of the cable (CON). Electric servomotors are uniquely versatile as their position, velocity, acceleration and torque/force can be accurately controlled by software. This allows the Exentrix device to operate with various training modes such as; isotonic (resistance is a constant force); isoinertial (creates an inertial load proportional to acceleration); and, isokinetic (velocity is constant regardless of force).

2.5.4 Advantages vs Disadvantages

Table 5: Advantages and disadvantages of the Exentrix by SmartCoach™

Advantages	Disadvantages
Power, size and weight – The device is relatively small. It is comprised of a motor and cable drum that is then mounted on the wall for stability. The exact dimensions are not given but looking at the images and videos it is a lot smaller compared to the other eccentric devices. It runs on single phase power and has a current rating of 5A. It is electrically protected and there is no need for modifications on the switchboard.	**Simplicity** – Having multiple DOF and the ability to choose specific training modes can confuse the user. Although, having more variable parameters creates a versatile design, it also adds complexity to the interface. A user cannot simply start an exercise on this device without familiarising themselves with the equipment first. Thorough instruction manuals and video tutorials are needed. It is unclear if SmartCoach™ provide this upon purchase of the device.
Synergetic muscle activation – Since the concept of this device is based on a conventional cable pulley, there are a large number of exercises that can be performed by the user. The device also has a larger number of DOF than other ECC devices and therefore greater potential use of synergistic and fixator muscle groups.	
CON and ECC coupled training – The device can overload both the ECC and CON contractions. The user can also choose between ECC only or CON only.	
Safety – The device has an emergency stop switch/pedal, a safety class BF logic controller, and an electronically controlled range of motion. The risk of injury to the user is mitigated through these features by stopping the motor and removing the load.	
Adjustable ECC load and velocity – The ability to change contraction modes shows that it is a complex system with multiple adjustable parameters. Coaches and practitioners can optimise the parameters (velocity, force and contraction mode) depending on the user.	

2.5.5 Validation

Exentrix by SmartCoach™ does not appear to have any evidence of validation on their website (bit.ly/2N6WxPf). The website also does not reference any literature regarding ECC training. It is unclear whether the device has been used in any studies or literature. The validity of their products relies heavily on the credibility of the co-founder, Per Tesch, Professor of Muscle Physiology at Karolinska Institute of Stockholm.

2.6 Exerbotics

2.6.1 Overview

Exerbotics (Oklahoma, USA – bit.ly/2BjhT9d) provide a range of isokinetic devices. Similar to X-Force™, these devices are based on conventional weighted stack devices, such as; chest press; shoulder press; leg press; leg extension / curl; squat machine. Each device is powered by a linear actuator that delivers the load and controls the speed. There is a load cell that displays the CON and ECC force on a touch screen for the user.

Figure 9: Exerbotics squat machine

2.6.2 ECC Mechanism

Exerbotics label their technology as 'iso-velocity' i.e. isokinetic. They are implying that the speed is constant during both CON and ECC phase. The display outputs a detailed strength curve for both phases, which is graphed in real time as the exercise is executed.

To perform the exercise, the user has to first set their desired ROM. They do this by moving the machine with the software to the desired start and end positions. Each exercise can be customised in terms of number of repetitions. The device starts with the CON phase first. It carries on until the number of reps have been completed. During both the CON and ECC phase, the device moves at a constant speed. The speed is independent of the force the user produces.

2.6.3 Technology

All the Exerbotics devices share the same linear actuator technology. This linear actuator provides a single DOF of motion. The linear actuator uses a roller screw and a brushless servo motor. A maximum force of 6220 N is produced by the Exerbotics squat machine at a speed of 0.341 m/s as reported on their website. There is a load cell which is mounted directly on the shaft of the actuator. This load cell provides the data for the strength curve.

2.6.4 Advantages vs Disadvantages

Table 6: Advantages and disadvantages of the Exerbotics

Advantages	Disadvantages
Simplicity – The Exerbotics devices, just like the X-Force™ devices, are based on conventional weighted stack equipment. This makes it easier for the user to learn and start using the device. From personal experience, the software is also very simple and easy to use. The software is operated on a touch screen. It is a minimalistic design with large buttons, texts and a real-time strength curve.	**Power, size and weight –** The Exerbotics devices are slightly larger and heavier than conventional weighted stack gym equipment. The specifications for individual devices are listed on their website. They also require 110V single-phase power. This means countries that operate on 230V power supply have to buy a special voltage converter to change the voltage to 110V @ 60Hz.
CON and ECC coupled training – The Exerbotics devices overload both CON and ECC muscle actions.	**Non-adjustable contraction velocity** – The speed of the exercise is set and cannot be changed by the user. For the squat machine it is set to 0.341m/s. The default speed varies with different machines.
Safety – The Exerbotics has software configured ROM limits and an emergency stop in short reach of the user to stop the linear actuator and bring the moving platform to a halt. The user can also "ride" the device by exerting no force. This is an advantage for all isokinetic devices.	**Synergetic muscle activation –** Similar to the X-Force™ devices, the Exerbotics devices only have a single DOF. For example, chest press or squat. These exercises limit the number of synergetic muscles activated.
Adjustable ECC and CON load – Since this is an isokinetic device, the load is dependent on how hard the users resist during the ECC phase and push/pull during the CON phase.	

2.6.5 Validation

Again, similar to the other devices, Exerbotics states the benefits of ECC overload training. A reliability study was undertaken using the Exerbotics Squat device and found moderate-to-high reliability for the peak and mean force values obtained from the device [41]. At this point in time there seems to be no other empirically validated research that have used the Exerbotic devices.

2.7 nHANCE™ Flywheel Yo-Yo

2.7.1 Overview

nHANCE™ (Stockholm, Sweden – bit.ly/30SGHzJ) is a company that provides flywheel or inertial ECC training devices. They offer five different training devices (squat, knee extension, leg curl, leg press, and multi gym). These devices are all based on the same flywheel principle. A flywheel uses the concept of inertia and the conservation of energy to provide ECC overload, similar to a yo-yo. To see the device being used for a squat follow this link – bit.ly/37AZa55.

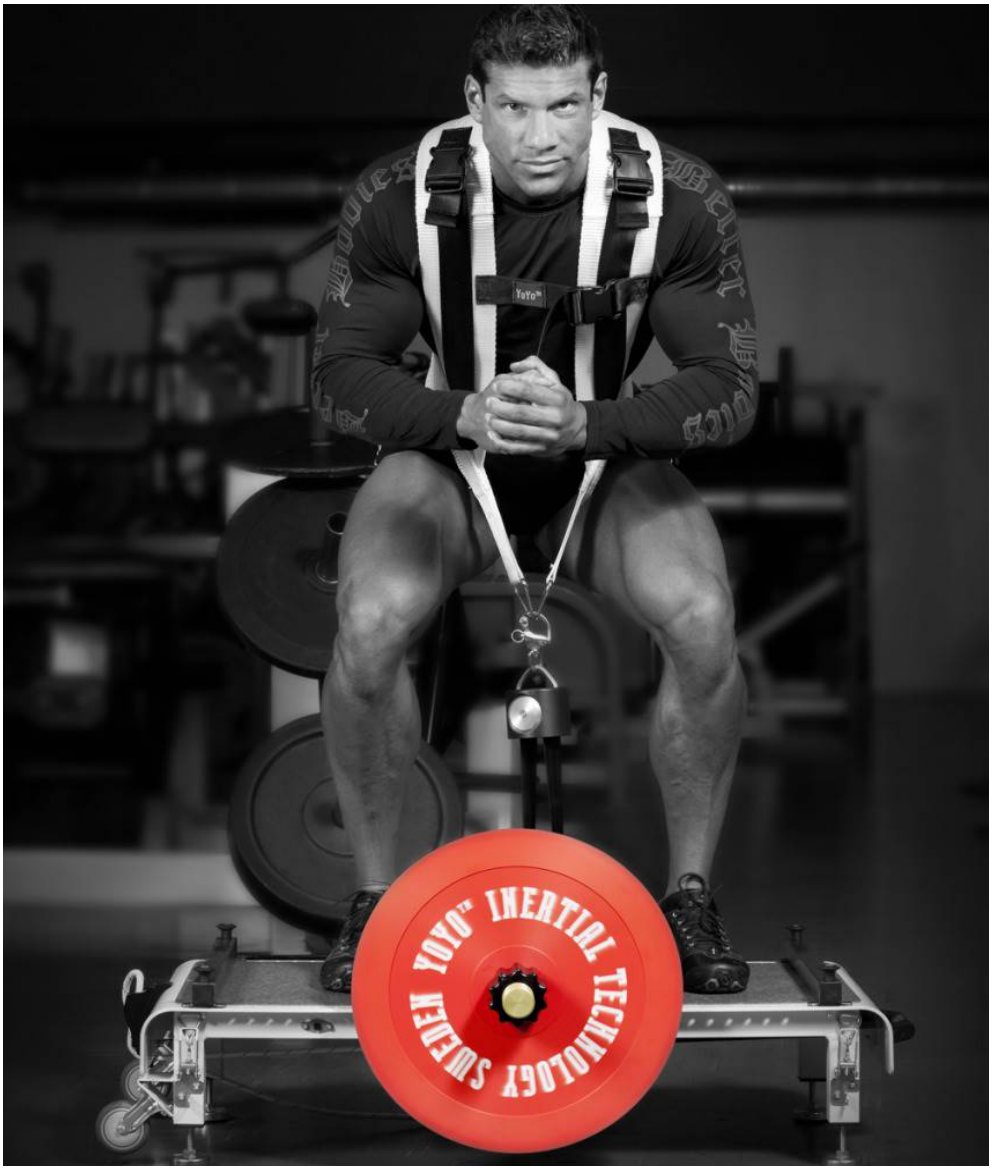

Figure 10: nHANCE™ flywheel yo-yo

2.7.2 ECC Mechanism

The flywheel is the component that provides the ECC overload. It does this by releasing the energy stored during the CON phase. For example, as the user pushes up during the CON phase, energy is being stored into the flywheel. As the user reaches the end of the CON phase and starts to move in the other direction, the flywheel releases all the stored energy in the form of a large torque. This torque is greater than the torque applied during the CON phase. This is because the flywheel wants to return to its original state as fast as it can. Therefore, there is a large angular acceleration in the opposite direction which equals to a large torque. This large torque generates a large force on the subject and hence the ECC overload is achieved (see Equation [1]).

$$\boldsymbol{\tau = I\alpha} \qquad [1]$$

$$where\ \tau = Torque, \qquad I = Moment\ of\ Inertia, \qquad \alpha = angular\ acceleration$$

The reason a flywheel behaves this way is because of the first law of thermodynamics, (conservation of energy) and Newton's laws of motion (an object at rest stays at rest and an object in motion stays in motion with the same speed and in the same direction unless acted upon by an unbalanced force. Also, known as conservation of angular momentum). The flywheel has an inertia I. When a subject rotates the flywheel at an angular velocity ω, the energy the flywheel absorbs is governed by the following equation:

$$\boldsymbol{E_k = \frac{1}{2}I\omega^2} \qquad [2]$$

This means that the faster the subject performs the CON phase the greater the energy stored in the flywheel and a greater ECC overload results. A point to note is that the energy exerted by the athlete during the CON phase is the same during the ECC phase (neglecting heat loss and vibrations), even though the ECC phase creates a greater force. The difference between the two phases is the velocity of the movement. During the ECC phase, the initial angular acceleration of the flywheel is large, but the angular velocity is small.

2.7.3 Technology

nHANCE™ state that they use an aluminium flywheel with an inertia of up to 0.05 kgm^2. Since this design is purely mechanical, there is no electronic control or interface software.

2.7.4 Advantages vs Disadvantages

Table 7: Advantages and disadvantages of the nHANCE™ Flywheel Yo-Yo

Advantages	Disadvantages
CON and ECC coupled training – The nHANCE™ flywheel devices deliver both CON and ECC training stimuli. An added benefit of the flywheel device is that it encourages users to be explosive during the CON phase and this will generate an even greater force during the ECC phase. A larger volume of work can be achieved with fewer repetitions.	**Non-adjustable ECC load and velocity** – The flywheel device works on the principle of conservation of energy. This means the more energy the user puts in the CON phase the more the device will exert during the ECC phase. The force and speed are solely based on the user. None of the parameters can be monitored by a coach or practitioner. The force and velocity cannot be measured without adding external sensors and data acquisition hardware. This limits performance analysis significantly as there is no feedback for the coach or practitioner.
Power, size and weight – These devices are small, lightweight and portable. They do not require any power source. This allows them to be used in any environment.	
Synergetic muscle activation – On each of the nHANCE™ devices, the user can perform multiple exercises. For example, the squat machine can perform squats, dead lifts, and vertical row. The user is tethered to the flywheel via a flat band. This increases the DOF allowing the activation of synergetic and fixator muscles.	
Simplicity – No doubt this device has to be the simplest design of all the ECC training devices. It uses the laws of physics to effectively achieve ECC overload. The device itself seems straight forward and simple to use. Users will take little time to get familiarised with it.	
Safety – Due to the devices' simplicity, the risk of injury is very low. Therefore, it does not require additional safety features.	

2.7.5 Validation

The flywheel device, compared to the other devices reviewed, has been thoroughly validated through published studies. There are hundreds of studies that have used the flywheel devices to administer ECC overload. Some of these studies prove that the ECC overload administered by this machine increases performance [20, 42-44]. Per Tesch is a major contributor to the studies around the flywheel devices and its validation.

2.8 Lifter by Intelligent Motion

2.8.1 Overview

Intelligent Motion (Linz, Austria – bit.ly/3d3OCMZ) has developed an ECC training device called the Lifter. This device uses moving support arms that spot the athlete during the CON phase. This reduces the CON load and allows users to train with heavier ECC loads. A conventional barbell is used which allows for a variety of exercises. The device can perform simulated loads with a fixed bar. The device also has an isokinetic measurement feature similar to the Exerbotics device. The device can be seen in operation at this site – bit.ly/2YKm4Dh.

2.8.2 ECC Mechanism

The ECC overload is achieved by reducing the CON load during the exercise. The device uses two moving support arms. During the ECC phase, there are optical sensors in the support arms that track the position of the barbell. The support arms are then lowered at the speed the user lowers the barbell during the ECC phase. Once the user has reached their lower ROM limit, the support bars drive the barbell up, reducing the CON load. A touch screen user interface allows the user to programme their ROM and choose their CON assist.

This mechanism of ECC overload is isoinertial, where the contraction velocity is determined by the user. However, this device is also capable of isokinetic ECC and CON loading. Intelligent Motion have called this, "simulated forces". In the support arms, there is a slot for a bar to be placed. The support bars then 'simulate force' by moving at a constant speed and the user resists. This mechanism is the same mechanism the Exerbotics devices use. The support bars can also be used for isometric loading and force measurement.

2.8.3 Technology

The moving support arms are the source of the ECC mechanism. Intelligent Motion has not disclosed the technology used to drive the support arms. However, an assumption can be made with the size and power requirements of the device. The structure of the device is tall rather than wide, suggesting linear actuators are used, similar to the Exerbotics devices. The three-phase power requirement suggests the likelihood of AC servomotors driving the linear actuators in a roller-screw arrangement, similar to the Exerbotics device. The support arms can produce a maximum simulated force of 250 kgs and can withstand maximum free barbell load of 400 kgs. The speed of the support arms is limited to a maximum of 1.4 m/s.

2.8.4 Advantages vs Disadvantages

Table 8: Advantages and disadvantages of the Lifter by Intelligent Motion

Advantages	Disadvantages
Simplicity – This device can be compared very closely to the Exerbotics device. It shares the same isokinetic mechanism and a software that is user friendly and easy-to-use. A brief look through their instruction manual and users can operate the software with little difficulty. The isoinertial mechanism also aides in the devices simplicity as it allows users to train with a barbell. Users can train with familiar exercises such as squats, bench press etc. without needing to go through a long familiarisation session.	**Power, size and weight –** The device requires three phase 400V electrical power and it consumes 15A current. In order to install this, an electrician will have to route power from the mains board and install protection circuitry. The device weighs 650kgs and stands 2650mm tall. In order to install this equipment, it will need to be forklifted and hoisted into its place and it cannot be moved once installed.
CON and ECC coupled training – The assist during the CON phase allows users to train with both CON and ECC loads. The isokinetic mode also allows users to train with both CON and ECC loads.	
Synergetic muscle activation – The isoinertial mode uses a free-weight barbell and hence increases the DOF of the device. This not only increases the number of exercises that can be trained but also increases the use of synergistic and fixator muscle groups.	
Safety – The moving support arms enable users to train with high ECC loads without increasing the risk of injury. In an emergency, the arms can be used as safety bars to dump the weight.	
Adjustable ECC load and speed – During the isoinertial mode, the CON load assist can be adjusted. Hence varying the CON to ECC load ratio. During the isokinetic mode, the speed can be increased to 1.4m/s for high speed ECC training.	

2.8.5 Validation

Intelligent Motion do not provide any evidence of validation through published research. They state the benefits of ECC training and discuss the involvement of academics in the development of the Lifter but do not reference their claims.

2.9 Cyclus 2 Eccentric

2.9.1 Overview

The Cyclus 2 Eccentric (Leipzig, Germany – bit.ly/2zCYobk) is an eccentric cycling ergometer. ECC cycling is a concept that has been around since the 1950s ever since Abbott et al [18] made the first ever ECC cycle. Instead of pedalling the crank forwards (CON), the cycle pushes back and the user must resist the push, driving the crank backwards (ECC). ECC cycles have since been developed and used for research and training purposes [45]. However, now there is a commercially available technology that can be purchased by coaches and practitioners. The user attaches their own bike onto the device (12T sprocket 1/2 x 1/8 inch). It can be driven in isokinetic (constant cadence, rpm) or isotonic (constant torque - Nm, or constant power - Watt) mode. It has a maximum power of 900 W. Please follow this link to see the device in use – bit.ly/2N6yXSO.

Figure 11: Cyclus 2 Eccentric

2.9.2 ECC Mechanism

When the force the user exerts on the pedals is large enough to rotate the crank, the motion is termed CON. If the force the pedal exerts on the user is larger than the resisting force exerted by the user, the pedals will drive the user's feet backwards. This is termed an ECC motion. As the pedals move toward the user, the user resists by applying force to the pedals. Because the magnitude of the force produced by the electric motor on the device exceeds that produced by the user, leg extensors actively lengthen (ECC muscle action).

The ECC force is difficult to produce through the entire revolution of the crank. The bike also has a tendency to oscillate left to right. When resisting at maximal loading, the crank drives the user out of the seat. It is difficult to stay seated whilst resisting maximally.

2.9.3 Technology

The Cyclus 2 Eccentric uses an electric motor to drive the pedals of the bike. The maximum power the system can produce is 900 W. There is no other technical information that can be gathered from their website. There is no indication of the range of speed (rpm) the device can produce. However, it can be assumed that it will not exceed 120 rpm and the range will be within normal operating speeds (approximately 30 rpm – 100 rpm).

2.9.4 Advantages vs Disadvantages

Table 9: Advantages and disadvantages of the Cyclus 2 Eccentric

Advantages	Disadvantages
Simplicity – The device is very simple and easy to use. The user interface is simple to operate and a real time measure of the power shows the user how hard they are resisting the push.	**CON and ECC only coupled training** – This device only performs ECC loading.
Adjustable ECC load and speed – The device can be controlled in three modes; isokinetic (cadence), power controlled (Watt) and torque controlled (Nm). The speed and load can both be changed. The load, speed and power are measured as real time feedback for the user and the coach or practitioner. The software allows the data to be exported for further analysis.	**Synergetic muscle activation** – The device has one DOF and does not activate synergetic or fixator muscle groups.
Safety – Similar to the other isokinetic device, the user can "ride" the device in order to reduce the ECC load. There is an emergency stop that the coach can operate to stop the motor. It is essential to have a coach or practitioner to operate the device for the user.	
Power, size and weight – The device is small, lightweight and portable. The user connects his or her bike which removes the need of having to change the height of the seat and other settings for different users. The device uses single phase power and does not require any additional circuit protection. The device can be easily moved from one training environment to another.	

2.9.5 Validation

This device has not been empirically validated through research. However, similar ECC cycles have been validated. Elmer et al. (2012) proved that ECC cycling is an effective method for improving leg spring stiffness and maximum power during multi-joint tasks that include stretch-shortening cycles.

2.10 ARX Fit

2.10.1 Overview

ARX Fit (Chicago, USA – bit.ly/30Na5Hx) offer two isokinetic training devices (ARX Omni, ARX Alpha). These devices are similar to the Exentrix device. They are based on conventional cable pulley weight stack equipment. An electric motor replaces the weight stack to provide the resistance. The name ARX stands for Adaptive Resistance Exercise.

2.10.2 ECC Mechanism

The ECC mechanism of the ARX devices is identical to the Exentrix devices. They both use electric servomotors to achieve ECC overload. However, ARX devices operate in isokinetic training mode only. Please see the following video links to see demos of the device - bit.ly/2AADF8K, bit.ly/3hvUC4R.

2.10.3 Technology

The ARX devices use an electric servomotor and a drive belt system. The drive belt is attached to a load cell which measures the force. The software is displayed on a standard monitor and is controlled by wireless controllers in the handles. An additional wireless controller can be used by the coach/practitioner. ARX does not reveal any other technical information regarding the maximum force output of the motor. ARX state on their website the fastest movement velocity permitted is between 3-5 second during each CON and ECC phase. The slowest speed permitted is approximately 1 minute during each CON and ECC phase. Since, ARX have stated the movement velocities in units of time (s) rather than velocity (m/s), the actual movement velocity will vary depending on the ROM.

2.10.4 Advantages vs Disadvantages

Table 10: Advantages and disadvantages of the ARX Fit

Advantages	Disadvantages
Synergetic muscle activation – Similar to the Exentrix device, this device is based on a conventional cable pulley and are a large number of exercises that can be performed by the user. The device also has a larger number of DOF than other ECC devices and therefore greater potential use of synergistic and fixator muscle groups.	**Power, size and weight –** The Omni is 3353mm x 762mm x 2438mm (LxWxH). The Alpha is 2438mm x 762mm x 1524mm (LxWxH). They both weigh approximately 227kgs and 120V power supply to operate. This means countries that operate on 230V power supply have to buy a special voltage converter to change the voltage to 110 V @ 60 Hz. There is also no current or power rating provided. These devices are large and heavy.
Simplicity – The ARX devices are based on conventional cable pulley machines found in most gyms. Therefore, users can train with this technology straight away.	
CON and ECC coupled training – The device can overload both the ECC and CON contractions.	
Safety – Similar to the other isokinetic device, the user can "ride" the device in order to reduce the ECC load. There is an emergency stop that the coach or user can operate to stop the motor.	
Adjustable ECC and CON load and velocity – Since this is an isokinetic device, the load is dependent on how hard the users resist during the ECC phase and push/pull during the CON phase. The movement velocity is also adjustable.	

2.10.5 Validation

ARX do not provide any evidence of validation through published research. They focus on their 'adaptive resistance exercise' mechanism by comparing it to conventional weight stack equipment. They state that their device matches the force produced by the user, whereas in a weight stack machine the force is constant. They are essentially comparing isokinetic with isoinertial training modes. They claim that isokinetic training is better without stating any particular training adaptations or referencing empirically validated research.

2.11 Conclusions

ECC training has proven benefits, however, over time the challenge has always been to find a training tool that coaches and practitioners can use to safely and efficiently administer an ECC training stimulus. More and more ECC training devices are being developed to try and resolve this issue and this review aimed to provide a better understanding of commercially available ECC training devices, the technology used, and the advantages and disadvantages.

In summary, devices were either isoinertial (X-Force™, and nHANCE™ YoYo), isokinetic (REACT©, Eccentron™, Exerbotics, and ARX), or both (Exentrix, Lifter, and Cyclus 2 Eccentric). Devices that enable both isokinetic and isoinertial, and allowed coaches or practitioners to switch between modes, may better optimise the training of the athlete and/or client. The ability to adjust the load and the speed on a device is another advantage to the coach or practitioner in terms of program design. Devices such as the X-Force™ and the nHANCE™ YoYo do not have the capability to adjust these parameters and are hence at a disadvantage to the rest of the training devices reviewed. CON and ECC coupled training has proven to be a better training method than ECC only [37, 40]. Hence, devices such as the BTE Eccentron™, REACT and Cyclus 2 Eccentric are disadvantaged in this respect i.e. they offer only one contraction mode. Safety of the user is extremely important when performing ECC training, as ECC overload can involve supramaximal loads and faster speeds, which increases the risk of injury. All devices acknowledged and mitigated this risk. The number of degrees of freedom (DOF) in terms of movement associated with a device can limit the utility and applicability to activities of daily living and sporting performance. Devices such as the Lifter, Exentrix, REACT©, ARX and nHANCE™ YoYo provide larger number of DOF and hence have the ability to provide better activation of synergetic and fixator muscles. The simplicity of a device determines how easily the device can be set up and used and also how long users take to become familiarised with the device. The Exentrix device comes with a large number of options and settings that it may confuse the user. The REACT device uses an ECC mechanism and technique that most users will take some time to familiarise themselves with. All devices, except the nHANCE™ YoYo and Cyclus 2 Eccentric, are large, heavy and immovable once installed. The nHANCE™ YoYo is also the only device that does not require a power source. Power, size and weight may not be significant factors for most coaches and practitioners, but they still need to be considered nonetheless.

Please note that the authors have only had first-hand experience with the Exerbotics, the nHANCE™ Yo-Yo, and the Cyclus 2 devices and most of the information for this review has been derived from website information, the veracity of which is unknown. The reader needs to be cognizant of this limitation and that the detail provided by manufacturers is sometimes inadequate for a full understanding of the devices. If the reader is interested in a particular device, we advise they contact the manufacturer directly and request a trial of the device to experience the eccentric overload it provides.

From the devices reviewed it can be concluded that there is no one device that will benefit all needs of the coach and the practitioner. The user must be cognizant of the strengths and limitations of each of the devices and clearly understand the nature of the adaptation required before investing in ECC technology. It is the belief of these authors that the ideal ECC training device should include the following features:

- Incorporate multiple training modes such as, isoinertial, isotonic and isokinetic.
- Train with CON and ECC coupled modes and with CON or ECC only.
- Adjustable speed during isokinetic and load during isoinertial for both CON and ECC phases.
- Large number of DOF so exercises can be performed in both horizontal and vertical planes.
- Easy to use interface. Simple set of instructions and use a simple ECC mechanism to decrease familiarisation time.
- Hardware and software safety protocols to minimise risk of injury to athlete.
- Software real time feedback and easy data download capability.
- Can be installed in a training area without the need of modifications to the room or the power distribution.

Finally, what is apparent is that most of the devices load the musculo-skeletal system in the vertical plane, or in a rotating plane (BTE Eccentron™ and Cyclus 2 Eccentric). The Exentrix and ARX devices are the only devices that load in the horizontal plane while using the cable pulley system found in most gyms. Most research has investigated the effects of ECC training in the vertical plane or in one dimension and consequently the preponderance of vertical ECC loading technology. Horizontal ECC training has not been explored to the knowledge of these authors, the design of and loading/training with such equipment should be the focus of future research.

Section 2: Development of the Horizontal Eccentric Towing Device

Chapter 3: Forces and Velocities Associated with Horizontal Eccentric Towing: A Pilot Study

This chapter comprises of the following paper entitled "*Forces and Velocities associated with Horizontal Eccentric Towing: A Pilot Study"* that has been completed but not submitted.

3.1 Prelude

The advantages and disadvantages of nine ECC training devices were reviewed in the previous chapter. It was found that most of the devices loaded the musculo-skeletal system in the vertical plane or in a rotating plane and only two devices loaded in multiple planes. It was evident that limited technology provided horizontal ECC loading and thus a list of potential features was proposed for a device that could be of benefit to practitioners and researchers. The main features discussed were: 1) incorporate multiple training modes such as, isoinertial, isotonic and isokinetic; 2) the ability to overload in ECC and CON modes; 3) have adjustable speed during isokinetic and load during isotonic movements; and, 4) have a large number of degrees of freedom so the movement can occur in multiple planes. Before any development of a horizontal ECC device could occur, detailed requirements such as force and velocity needed to be identified. Therefore, the purpose of the following chapter was to determine the forces and velocities associated with a horizontal ECC towing. This would then inform the type of technology (e.g. electric motor or pneumatics) that would be required to provide the horizontal ECC overload. The following chapter was conducted as a pilot study with two elite power athletes to determine the upper threshold of forces and velocities.

3.2 Introduction

Many different training methods and modalities are used in training the speed of athletes. One such method is the utilisation of resisted sled towing devices [46-48]. Typically, these devices are designed to work the muscles concentrically whilst the athlete is moving forward and are used by strength and conditioning coaches in addition to gym based resisted training. However, it may be that an eccentric towing motion provides a better form of overload for the athlete given that: 1) a shift in fibre type towards fast twitch type IIb where fast eccentric training can yield improvements in high speed concentric power [30]; 2) an increase in leg spring stiffness from eccentric training can yield improvements in higher stride frequency due to a decreased ground contact time [49]; and, 3) a high frequency eccentric leg press has been shown to improve both jump height and sprint time [27].

Horizontal eccentric towing is a novel concept that allows athletes to overload eccentrically in the horizontal plane through running forwards while being pulled backwards. The majority of research in the field of eccentric training has been focused on modalities that only overload the athlete in the vertical plane and are centred around exercises such as squats, dead-lifts, bench press, etc. However, no research has been published on horizontal eccentric towing focused around running or sprinting. The purpose of this study, therefore, was to quantify the magnitude of the forces and velocities generated by athletes undergoing horizontal eccentric towing. Understanding these variables will assist in the design and development of equipment to eccentrically overload the horizontal force capability of athletes. Furthermore, given that the concept of horizontal eccentric towing is relatively new, the methods described in this paper can provide practitioners with a relatively simple procedure for horizontally eccentrically overloading athletes.

3.3 Methods

3.3.1 Experimental Approach to the Problem

A total of twelve trials by two elite athletes were conducted to determine the horizontal eccentric forces and velocities. Two running modalities, forward and backward running, were tested. The peak force and velocity from each trial were the key parameters collected. The eccentric force was measured by a load cell which was connected via a tether between the waist belt of the athlete and the towing device. The velocity was measured by a radar gun placed in-line with the athlete.

3.3.2 Subjects

Two elite male throwers (age 26 and 29; 1.78 and 2.01m tall; 118 kg and 122 kg) volunteered to participate in this study. These two athletes were chosen as it was thought these power athletes would produce maximum eccentric forces and velocities and hence representing upper limits as well as providing insight into the design parameters for eccentric towing equipment.

3.3.3 Equipment

The horizontal eccentric force was measured by a 2.5 kN S-Beam load cell from Applied Measurement, Australia connected to a waist belt on the athlete. The belt was connected via a tether to the towing sled (see Figure 12). This measured the tensile force between the resistance towing device and the athlete (how much the athlete resisted the pull). The load cell was connected to a National Instruments Data Acquisition Module (NI-9219 24-Bit Analog Input Module). The high resolution of the analog-to-digital converter allowed for accurate data and a high signal-to-noise ratio. The data acquisition module was configured to send the data over a wireless network (2.4GHz Wi-Fi). This was important as the athlete and load were in motion and the risk of obstructing wires was mitigated. The module was also battery powered which eliminated the need for extra wires or cables. The Stalker ATS Pro II radar gun from Stalker Sport Radar, USA was used to measure the velocity of the athlete. Radar guns have been previously used extensively in sprint research and have been thoroughly validated [50]. The gun was placed behind and in-line with the athlete. The radar gun was interfaced directly to a computer using the software provided by Stalker, USA. The load cell was interfaced with a custom-designed LabView (National Instruments, USA) software program that collected the wireless data from the Data Acquisition module. The equipment was configured to output data in SI units (N or $kgms^{-2}$ from the load cell and ms^{-1} from the radar gun).

Figure 12: The experimental setup to measure force and velocity – 1. The athlete has a waist belt which is connected to one end of the load cell. 2. The load cell measures the eccentric force the athlete produces. 3. Assistant provided the resistance by pushing the towing sled to the left in figure 4. Towing sled that pulls the athlete to the left in figure.

3.3.4 Procedure

After a standardised warm-up and a familiarisation session two motions were tested: backwards running motion, where the athlete faced the towing sled and tried to run backwards while being pulled forwards (see Figure 13A); and, forwards running motion, where the athlete faced away from the towing sled and tried to run forwards while being pulled backwards (see Figure 13B). A total of twelve trials over 5 metres were performed, with an equal number of forward and backward runs. Both subjects performed three trials of each running motion.

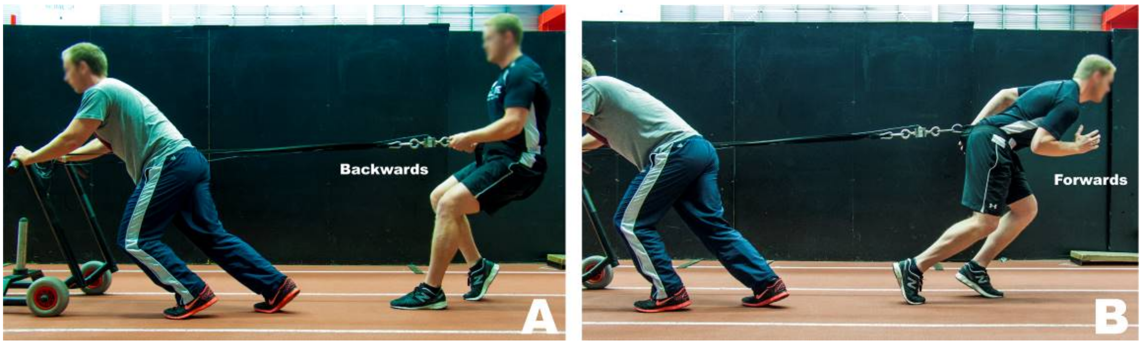

Figure 13: Backward (left) vs forward running motion (right)

Before testing began, the load cell and radar gun were calibrated. The load cell was zeroed to account for the weight of the tether. At the beginning of each trial, the athlete lined himself up with the track. For the backwards run, the athlete used the tether to support their hands. However, they were told not to pull on the tether using their hands as this would compromise the data. A countdown initiated the trial and two assistants immediately pushed the towing device as hard and fast as they could whilst the athlete tried to resist this pull. The two assistants would push the towing device for approximately 5 m and stop. The athletes were told to perform at maximum effort. There was a two-minute rest period between each trial while the data was stored and the equipment reset.

3.3.5 Data Analysis

Custom-designed LabView software collected and stored the data from the load cell. As the load cell and the data acquisition module had a high noise rejection ratio (65dB at 50-60Hz), the raw unfiltered data was used for the calculations. The Stalker ATS 5.0 software was used to collect and store the data from the radar gun. The software applied a low-pass filter called a medium-dig acceleration filter. This filter was automatically chosen by the software based on the raw data collected.

3.3.6 Statistical Analysis

The two variables, force and velocity, were exported to Microsoft Excel. The peaks of each variable during each trial were calculated. The means and standard deviations of the peak force and velocity were calculated for the two running motions (forwards and backwards) and also for all of the twelve trials.

3.4 Results

Representative signals from the load cell and radar can be observed in Figure 14. The force and speed curves have a distinct sinusoidal feature, representing ground contact of the left and right limbs.

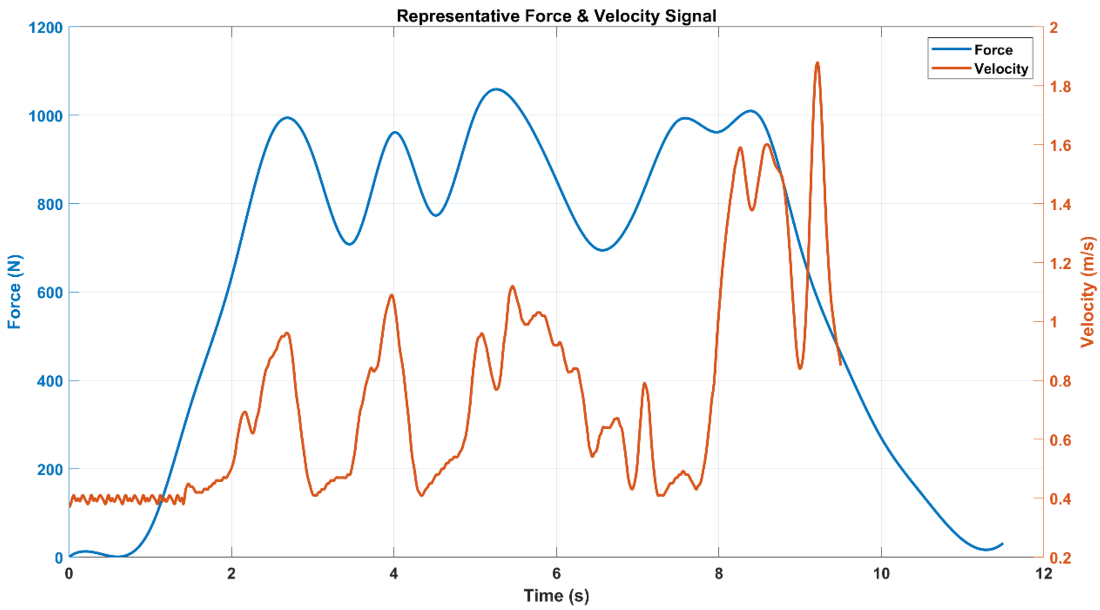

Figure 14: Force and velocity curves for a representative trial

The summary of force and velocity results are detailed in Table 11. The peak forces from both the running motions over the twelve trials ranged from 561 N to 1120 N. A greater average peak force (938 N forwards; 844 N backwards) was noted during forward running as compared to backward running (11.2% higher). The variance in performance (SD) was also smaller moving forwards (21.3% smaller). The overall peak velocities in both running motions ranged from 1.87 m/s – 2.9 m/s, forward motion average peak velocity was 8.6% higher than the backwards motion.

Table 11: Summary table of results

	Backwards	Forwards	Overall
Variables	*μ ± σ* *(Min - Max)*	*μ ± σ* *(Min - Max)*	*μ ± σ* *(Min - Max)*
Peak Force (N)	**844 ± 156** (561 – 1030)	**938 ± 123** (801 – 1120)	**883 ± 145** (561 – 1120)
Peak Velocity (m/s)	**2.43 ± 0.27** (1.87 – 2.7)	**2.64 ± 0.31** (2.1 – 2.9)	**2.52 ± 0.29** (1.87 – 2.9)

3.5 Discussion

Not much is known about the forces and velocities associated with eccentric towing. When the horizontal eccentric forces found in this study (average peak force, 883 N) are compared with horizontal concentric forces (~320-350 N) obtained from studies using similar strain gauge arrangements on non-motorised treadmills, it can be observed that the eccentric forces are much higher. For example, researchers found that seventy-eight physically active men and women (22.9 ± 2.7 years; 73.0 ± 14.7 kg; 170.7 ± 10.4 cm) that performed a 30-second maximal sprint on a non-motorized treadmill could generate 283 ± 38 N (183–352) [51]. Another study testing sprinting performance of injured vs non-injured 22 Australian Rules Football players reported horizontal concentric forces of 324 ± 44 N [52]. The higher eccentric force is expected as studies have proven that humans are much stronger eccentrically [53] and certainly, the two elite throwers in this study would have greater force capability, both eccentric and concentric compared to the cohorts mentioned previously.

It was noticed that the forward motion produced higher average peak forces than the backward motion (11.2% higher). The average peak velocities achieved during the forward motion were also higher than the backward motion (8.65% higher). This can be most likely explained by forward motion being more natural to humans than moving backwards. A study comparing the forwards and backwards running joint compression forces also found that forward running generated larger forces than the backwards running [54]. The smaller standard deviation of the forwards running gait also supports this hypothesis. For future studies, it is proposed that a longer familiarisation session for the backwards running motion be conducted before testing, in order to reduce movement variability and possibly get a more accurate quantification of the forces and velocities associated with this type of motion.

The average peak velocity over the 12 trials was calculated to be 2.5 m/s. However, this would seem a design limit of this study. One can imagine that if an athlete were towed faster, then a higher eccentric velocity could be achieved. Currently, the towing device is a trolley, which has to be manually pushed resulting in the eccentric velocity dependent on the force-velocity capability of the assistants. If the velocity of the athlete being towed could be controlled remotely, a much more reliable set of force and velocity data could be obtained. Furthermore, an accurate horizontal eccentric force versus towing velocity relationship could be established. Acknowledging these limitations and understanding the indicative forces and velocities, however, is the first step in the design process for such a device.

3.6 Practical Applications

In conclusion, a gait specific horizontal eccentric towing modality can be developed using the maximum force and velocity parameters found in this study. Eccentric towing equipment that can administer high forces (~1120 N) and at high speeds (~2.9 m/s) will most likely be beneficial to increase aspects of sports performance due to the proven benefits of eccentric training. In the interim, the study has outlined methods that can be used by the practitioner to deliver a horizontal eccentric training stimulus, without large capital investment. Given the novelty of this type of overloading, careful consideration needs to be given to the progressive and systematic loading of athletes using such motion. Initially, slow eccentric towing is recommended until athletes are adequately familiar with this motion and have mastered their technique as reflected in low movement variability in the variables of interest.

Chapter 4: Construction of an Isokinetic Horizontal Eccentric Towing Device to Improve Sprinting Performance

This chapter comprises of the following paper entitled *"Construction of an Isokinetic Horizontal Eccentric Towing Device to Improve Sprinting Performance"* that has been prepared as a technical note and submitted to the *Journal of Sports Engineering and Technology*.

4.1 Prelude

The previous chapter determined the forces and velocities associated with horizontal ECC towing. Two different towing movements were investigated (forwards and backwards). It was found that the forwards ECC towing movement displayed greater forces (+11.2 %) and velocities (+8.65 %) than the backwards ECC towing direction. The main finding from the previous chapter was that a custom-built horizontal ECC towing device must be able to administer forces up to 1120 N and at velocities up to 2.9 m/s. This information coupled with the list of features from Chapter 2 formed a complete list of specifications for the development of a horizontal ECC towing device. The following chapter discusses the methodology and decisions made on the construction of such a device. It is written as a technical note that will give readers the opportunity to follow the document as a guide to constructing a horizontal ECC towing device.

4.2 Introduction

Sprinting performance is one of the most important aspects for athletes and coaches in not only athletics but a variety of other field-based team sports. There are many different training methods and modalities used to improve sprinting performance. One such method is the utilisation of resisted towing devices [46-49]. Typically, these devices concentrically overload the musculo-skeletal system and are used by strength and conditioning coaches as an adjunct to gym-based resistance training. However, it may be that eccentric towing devices provide a better form of overload for the athlete given that: 1) a shift in fibre type towards fast twitch type IIb with eccentric training can yield improvements in high speed concentric power [28, 37, 55]; 2) an increase in leg spring stiffness from eccentric training can yield improvements in higher stride frequency due to a decreased ground contact time [49]; and, 3) an eccentric leg press motion has been shown to improve both jump height and sprint time [27]. We analysed currently available devices that provide eccentric stimuli [56]. The review discussed the advantages and disadvantages of a number of devices and found there were few devices that applied an eccentric stimulus in the horizontal plane. There was no such device that targeted a sprinting-specific movement pattern to eccentrically overload the musculature, similar to an eccentric cycling ergometer that targets cycling performance and concluded that there was a gap in knowledge and technology that we wished to investigate [18, 45, 57]. The novel horizontal eccentric stimulus that we developed requires the athlete to move forward whilst being pulled backwards by a rope or tether (see Figure 15). Similar to a winch retracting an anchor on a boat, the Horizontal Eccentric Towing (HET) device pulls an athlete inwards at a pre-determined velocity (Figure 15). During the movement, the athlete's objective is to resist this motion in a maximal manner. Irrespective of the amount of force the athlete produces, the HET device will continue to pull them inwards and maintain a constant towing velocity, providing an isokinetic training stimulus. The development of this HET device is described in this technical note (see Figure 16). A demonstration of the HET device can be found at bit.ly/37FkeHJ.

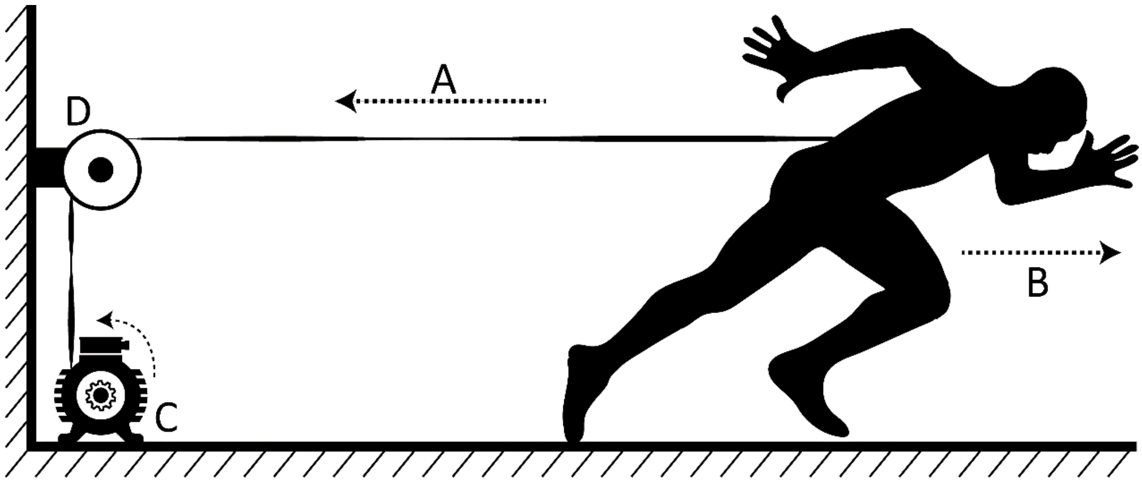

Figure 15: Conceptual drawing of the winch towing system. A=The direction the athlete moves due to the winding in of the motor, B=The direction of the force the athlete produces and tries to resist the motion, C=The motor winding in the tether/cable, D=A pulley that guides the tether/cable.

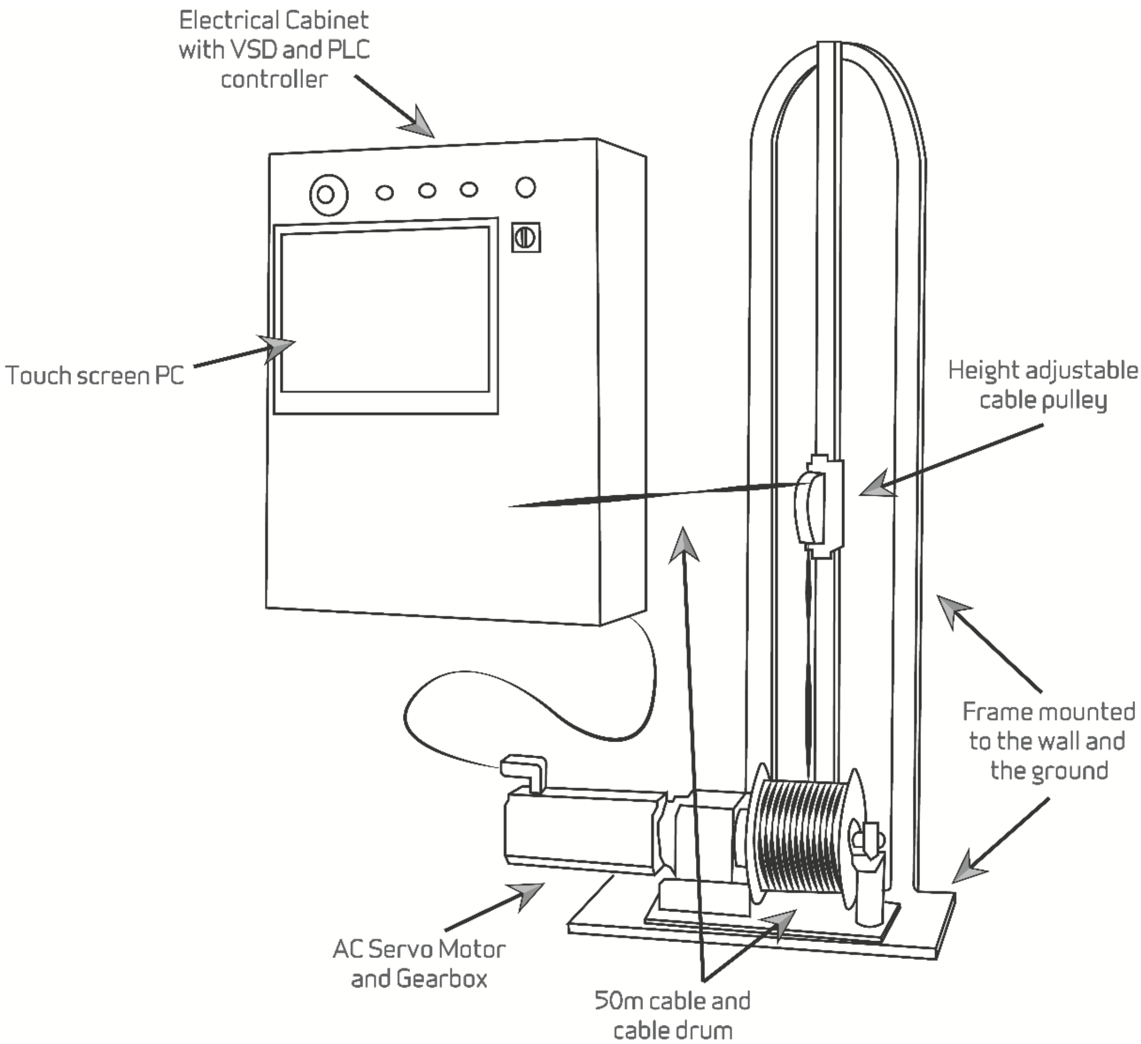

Figure 16: Diagram of the horizontal eccentric towing (HET) device and its components

4.3 Methods

4.3.1 Concept and Pilot Study

The concept envisaged was an athlete trying to move forwards in a sprint stance whilst being pulled backwards (Figure 15). The athlete must resist this motion and the system must always overload the force so the athlete is consistently being pulled backwards; similar to a supramaximal eccentric muscle contraction, where the external force is greater than the force produced by the muscle, causing the muscle to lengthen under tension [17]. We decided to call this an eccentric towing modality. Progressing this concept meant automating the horizontal eccentric stimulus using an electric motor-driven winch (Figure 16). Key design specifications were investigated, most importantly the size of the motor, its torque (or force) and speed output, which determined the power (kW) rating. For this, two male elite throwers (age 26 and 29 years; 1.78 and 2.01m tall; 118 and 122 kg) participated in trials to determine the required upper limits of the system. The two athletes performed six HET trials whilst tethered to a trolley. The trolley was pushed by two people to provide the overload stimulus. A load-cell (Applied Measurement, Australia) positioned in line with the tether measured the tensile forces (eccentric overload forces) generated by the athlete, with a radar gun (Sport Radar, USA) quantifying the towing velocity. The maximum force and maximum velocity measured were 1120 N and 2.90 m/s respectively (Chapter 3). Consequently the device was designed with these specifications as upper thresholds – of being able to produce at least 1500 N (based on a safety factor of 1.33) at towing velocities up to 3.00 m/s. Actual values however, must be able to be set by the coach or user and the device must maintain that velocity independent of the force produced i.e. isokinetic mode.

4.3.2 Motor and Gearbox

The decision to use an electric motor was discussed with engineers and contractors from High Performance Sport New Zealand (Auckland, New Zealand). This confirmed that an electric motor, with accurate speed and position control, would be ideal for a winch-like system. Pneumatics, hydraulics and other methods would be unable to provide accurate speed and position control. Furthermore, the complexity of the design with an electric motor-based system is lower than that of hydraulics or pneumatics-based systems. There are many commercially available winch systems that use electric motors, and many companies that specialise in electric motor solutions. The selected motor and gearbox solution, an R57 CMP100M AC synchronous servo motor, was provided by SEW-Eurodrive (Auckland, New Zealand). AC motors are the convention in most industrial applications. They do not require a transformer and can be connected to single-phase or poly-phase power supplies. Synchronous servo motors have accurate speed and position control, which is a requirement for this device [58]. The R57 CMP100M met all the requirements and produced a maximum output force of 2.80 kN at ground velocities of up to 3.58 m/s. This allowed for a large safety factor and a greater operating range. The low inertia of the motor and gearbox ($26.3 + 4.3 = 30.6 \times 10^{-4} kgm^2$) allowed for a faster acceleration and hence better speed control. 0 to 3000 rpm was achieved in 7 ms.

4.3.3 Variable Speed Controller (VSD) and Programmable Logic Controller (PLC)

A variable speed drive (VSD) was used to control the speed and torque of the motor by adjusting the amplitude and the frequency of the voltage applied to the motor. The VSD MOVIDRIVE B MDX61B0055-5A3-4-0T was provided by SEW-Eurodrive and has a maximum power output of 11kW. The VSD was programmable through the MOVI-TOOLS software which is also provided by SEW-Eurodrive. A programmable logic controller (PLC) was used to interface a touchscreen PC with the VSD. The PLC was where the logic systems and state control was programmed. The MOVI-PLC provided by SEW-Eurodrive connected directly to the VSD using proprietary communication protocols. User commands were entered via the touch screen PC and transferred to the PLC using a RS485 communication protocol. The PLC allowed for a higher-level motion control, computing parameters to send to the VSD. The VSD delivered the correct voltage and frequency to the motor, controlling the position, speed and torque (Figure 17).

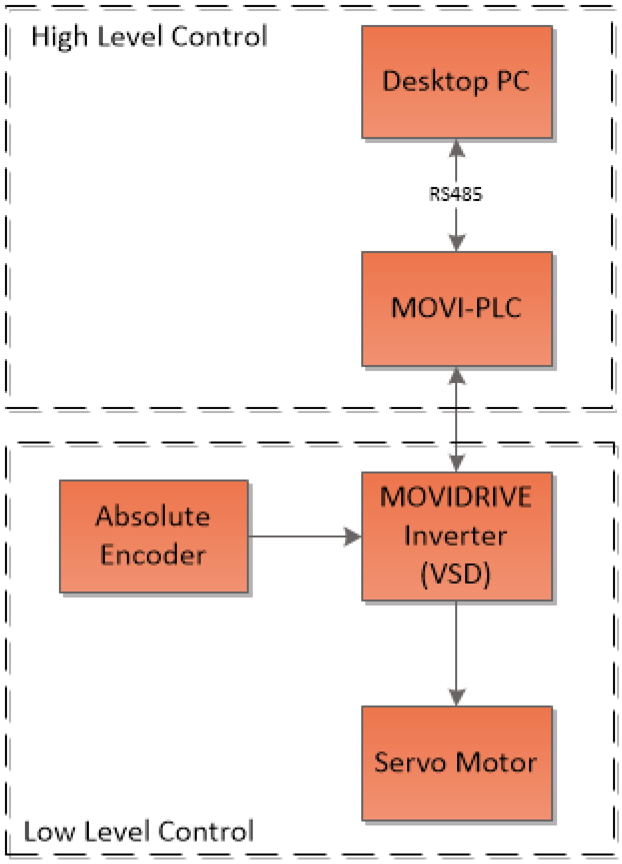

Figure 17: Block diagram of the links between components of the HET device

4.3.4 Safety System

An electromechanical brake system was placed in the motor housing that enabled an emergency stop. The emergency stop was a crucial safety factor for the device. To ensure the athlete's safety, this emergency stop feature must be reliable and fail-safe. The brake used 24V DC and is an electromagnetic brake with springs. When the magnet is energised, the brake is released. When the magnet is turned off, the brake is engaged. In the case of a power outage, the brake will engage. The brake torque is rated at 47 Nm and is controlled by a separate safety rated PLC (UCS10B – SEW-Eurodrive, New Zealand), rated in accordance with IEC 61800-5-2 and EN ISO 13849-1 safety standards. There were two emergency-stop buttons (E-STOP), which were wired directly to the safety PLC. If any one of the E-STOP buttons were pressed, the safety PLC sent a signal to the variable speed drive (VSD), which in turn engaged the brake and disabled power to the motor.

4.3.5 Operating Modes

The desired operating mode was isokinetic or constant velocity. It was envisaged that whatever the force produced by the athlete, the motor would overload it by maintaining a constant velocity. This is similar to an escalator, where the motor drives the stairs and operates it at a constant velocity irrespective of how many people get on and off the escalator [59]. From the literature it seems that an isokinetic eccentric stimulus may be more beneficial to increase power capabilities compared to isoinertial or isotonic eccentric stimuli [31, 60, 61]. Developing power capability is thought to be essential to sprinting performance [51]. However, there are possibilities to add isotonic and isoinertial modes to the HET device, as well as a 'concentric' modality (similar to resisted towing), by programming the PLC.

4.3.6 User Interface

The user interface is a software application that runs on the touchscreen PC. The application was developed in HMI-Builder.Pro which is SEW-Eurodrive's propriety Integrated Development Environment (IDE). The coach/operator is first prompted to enter the athlete's name into the application. This is used to log and track athlete data over time. The coach/operator then selects the distance they want the athlete to travel during the exercise. Then they enter a desired towing velocity and click start to begin the movement. The athlete is towed back the desired distance and the velocity is ramped up and ramped down at the beginning and end of the trial, respectively. This ensures that the acceleration does not jerk the athlete at the start and their momentum is limited towards the end of the trial.

4.3.7 Force and Velocity Measurement

The motor has an absolute encoder (AK1H, 1024 steps/rev resolution) located on the rotor. This was also supplied by SEW-Eurodrive and interfaced directly with the VSD to provide an accurate measurement of position and speed. The absolute encoder had non-volatile memory, which allowed it to store the position data even when power to the system was removed. This was an important safety feature because the motor would not accidently move to an arbitrary position in case power was returned to the system after being lost or disabled.

The VSD had sensors built in that allowed it to measure the current delivered to the motor in Amps (A). Motor torque (τ_m) is linearly proportional to motor current (I_m) ($\tau_m \propto I_m$)[20]. The VSD had an internal calculation that returned the instantaneous motor torque based on the current drawn by the motor. This was then converted to a tangential force (F) on the cable based on the radius (r) of the cable drum ($F = \frac{\tau_m}{r}$).

Both the force and velocity measures were logged at a sample rate of 100 Hz and displayed on the user interface. Specific measures, such as average force and peak force were also displayed on the user interface for real-time feedback to the coach and the athlete. A typical force and velocity curve during a single HET trial can be observed in Figure 18. The velocity ramp up and ramp down were clearly indicated at the beginning and end of the trial. The set velocity for this trial was 1.1 m/s and the oscillation of velocity about the set velocity shows that the system maintains a constant velocity irrespective of the external force on the motor.

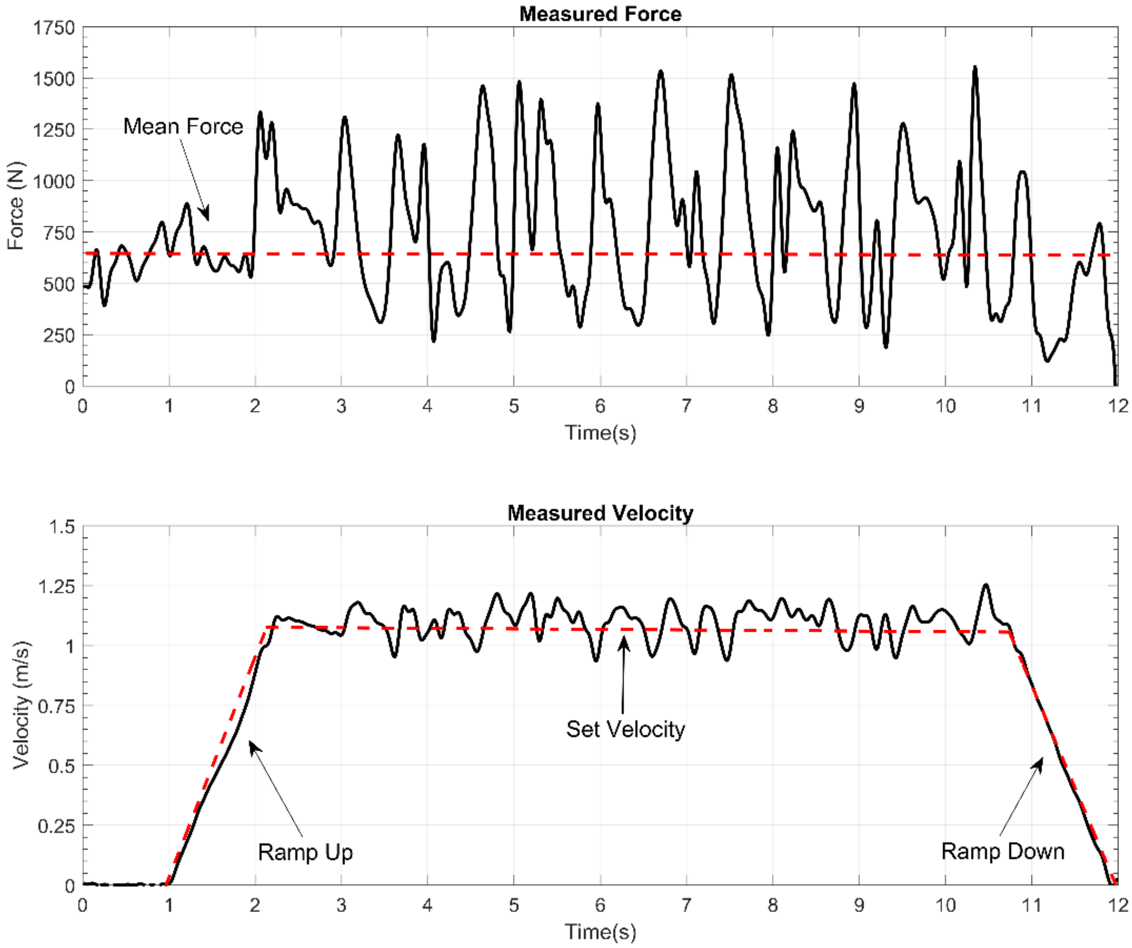

Figure 18: Graph of force and velocity measured from the HET during a single trial

4.4 Results

A HET device was successfully developed using an electric servo motor attached to a cable drum, and controlled by a VSD and PLC. The HET device tows users at speeds up to 3.58 m/s and can produce forces up to 2.8 kN.

4.5 Discussion

This technical note discussed the components used in the development of a novel eccentric device that provides a unique horizontal eccentric sprinting-specific stimulus. Safety checks and basic testing took place to ensure all systems were working correctly. A weighted sled was attached to the end of the cable and the device was used to tow the sled in. Numerous trials were performed at a range of speeds and weights. The E-Stops worked without fail, with the motor stopping immediately, even at the fastest speed of 3.58 m/s. The user interface and data logging also worked without problems. Initial pilot testing has confirmed that the motor and gearbox were the correct specifications. The two male elite hammer throwers that participated in the manual pilot study (see 'Concept and Pilot Study') tested the device. Piloting began at 0.5 m/s with a towing distance of 10 m in the position shown in Figure 15. From observations, it appears that the actual movement is quite challenging for the subjects initially, but fluidity of movement improves significantly over successive trials i.e. the first trials were jerky and un-coordinated as the tether oscillated between steps as the subject tried to resist during ground contact. As such a learning effect is associated with use of the device and a few sessions of familiarisation have been found important before the device is used for research purposes. To the authors' knowledge, a HET device has not been developed anywhere else in the world, the concept of HET is novel and original. It is envisaged that the device will be used for training and research purposes, initially investigating the effects of HET loading and training on sprint performance.

Section 3: Understanding the Biomechanics of Isokinetic Horizontal Towing

Chapter 5: Movement Variability Associated with Horizontal Eccentric Towing

This chapter comprises of the following paper presented at the *36th International Conference on Biomechanics in Sports.*

Reference:

Tinwala, F., et al., *Movement Variability Associated with Horizontal Eccentric Towing*, in *36th International Conference on Biomechanics in Sports*. 2018: Auckland, New Zealand.

5.1 Prelude

The previous chapter discussed the development of a custom-built horizontal ECC towing (HET) device. The device has the ability to pull athletes inwards (similar to a winch) at a constant towing velocity (isokinetic). The device is powered by an electric motor that can tow athletes in isokinetic mode up to 3.58 m/s and can tolerate forces up to 2.8 kN. However, the ECC towing movement has not been previously researched and understanding the biomechanics of the movement is the focus of Section 3. Specifically, to understand the time required for athletes to familiarise themselves before training with the HET device can begin. Therefore, the purpose of the following chapter was to determine the movement variability associated with the use of the HET device. In order to achieve this, the force between the athlete and the device was measured using a load cell in line with the tether and the harness. The variables of interest were the impulse, peak and mean horizontal eccentric force. Reliability was measured by calculating the coefficient of variation (CV) and intraclass correlation coefficients (ICC).

5.2 Introduction

Many different training methods and modalities are used in training the speed of athletes. One such method is the utilisation of resisted towing devices [46-48]. Typically, these devices concentrically overload the musculo-skeletal system and are used by strength and conditioning coaches as an adjunct to gym based resisted training. However, it may be that eccentric towing devices provide a better form of overload for the athlete given that: 1) a shift in fibre type towards fast twitch type IIb with fast eccentric training can yield improvements in high speed concentric power [30]; 2) an increase in leg spring stiffness from eccentric training can yield improvements in higher stride frequency due to a decreased ground contact time [49]; and, 3) high frequency eccentric leg press motion has been shown to improve both jump height and sprint time [27]. However, typically the eccentric overload is administered in the vertical plane, and to the knowledge of the authors no researchers have developed a device to eccentrically overload an athlete in the horizontal plane e.g. an athlete trying to move forwards but is being pulled backwards (Figure 19). This concept has provided the impetus to design and construct such a device, aptly named a horizontal eccentric towing (HET) device (Figure 19). Similar to a winch retracting an anchor on a boat, the HET device pulls an athlete inwards at a pre-determined velocity (Figure 15). During the movement, the athlete's objective is to resist this motion in a maximal manner. Irrespective of the amount of force the athlete produces, the HET device will continue to pull them inwards and maintain a constant towing velocity, providing an isokinetic training stimulus (see Chapter 4 for more information on the HET device). Follow this link to see a video of the device being used – bit.ly/37FkeHJ. Prior to studying the acute and longitudinal adaptation associated with such a training device, it is important to understand the movement variability associated with the HET, hence the purpose of this study.

Figure 19: Horizontal eccentric towing device being used. The user is trying to move forward but is being pulled back into the wall by a custom-built electric winch called the horizontal eccentric towing (HET) device

5.3 Methods

5.3.1 Subjects

Ten elite female field hockey players (mean ± SD age = 22.2 ± 2.7 years, height = 168 ± 6.92 cm, body mass = 66.1 ± 6.49 kgs) participated in this study. All the subjects were undergoing resistance and strength training as per their regular training schedule and had two or more years of strength training experience. They had been screened for current and past injuries within the last six months. The team coach and physiotherapist were also consulted before testing. The testing procedures for this study were approved by the Auckland University of Technology Ethics Committee (15/375 – see Appendix I, II and III for more details). The subjects were given information sheets and were asked to sign consent forms.

5.3.2 Testing Procedure

Testing was conducted over four sessions that were separated by seven days. The testing sessions were scheduled during their regular training sessions in the gym. The subjects performed a prescribed warm-up as programmed by their coaches. Each testing session was conducted on the same day of the week and at the same time of day. In the first session, the subjects were shown the HET device and the exercise they were going to perform. Their body mass and height were measured before harness placement on their body. They were then asked to perform a one sub-maximal effort trial (70%) and three maximal effort trials. During the following three sessions the subjects performed three maximal effort trials. The rest period between trials was sixty seconds. The movement velocity of the HET was set at 0.8 m/s for a distance of 10 m for all testing sessions.

Since the exercise is novel, safety of the subjects had to be taken into consideration. The person operating the HET device had their hand over an emergency stop button, which would engage a braking mechanism to stop the exercise within 100 ms. The subjects were told to resist as hard as they could but at the same time provide constant resistance throughout the exercise. The HET device has a display which outputs metrics such as the peak force, mean force, and a real time force time curve. These metrics were calculated from the point at which the exercise started to when the subject had travelled 10 metres.

5.3.3 Equipment

The HET device is custom built and uses an electric servomotor and gearbox (SEW-Eurodrive, Germany). The motor is mounted to a cable drum and is controlled by a variable speed drive and programmable logic controller (SEW-Eurodrive, Germany). The device is operated with a touch screen monitor (shown on the top left of Figure 19). In addition to the HET device, a load cell (500 kg S-Beam load cell, Millennium Mechatronics, Auckland, New Zealand) was used to measure the tensile force between the subject and the tether (Figure 20). The load cell was connected to a wireless data acquisition data module (WLS-9163 NI-9219, National Instruments, Austin, Texas, USA). Data was sampled at 100 Hz at 18-bit resolution and collected using a laptop computer running custom LabVIEW 2014 (National Instruments, Austin, Texas, USA) software. Analysis was performed using MATLAB R2014a (MathWorks, Natick, Massachusetts, USA). High speed video was recorded at 240 frames per second (GoPro Hero 4 Black, 720p @ 240fps, San Mateo, California, USA).

Figure 20: The harness which holds an S-beam load cell to measure the tensile force between the subject and the tether which is in turn connected to a wireless data acquisition data module

5.3.4 Data Analysis

During each trial the peak horizontal eccentric force (PHEF), mean horizontal eccentric force (MHEF), and impulse was calculated. The raw data from the load cell for each trial was read into MATLAB. Figure 21 shows the data points used in the analysis (indicated in red). The initiation of the exercise was defined at the point of a sharp decrease in force following a steady increase in force indicating the slack in the cable was taken up and the first step was taken. The end of the exercise was defined at the point of the last sharp decrease in force indicating the penultimate step. The impulse was determined by calculating the area under the force-time curve. An inbuilt MATLAB numerical integration function was used to calculate the impulse. The raw data was used for all the analysis without the need of a filter.

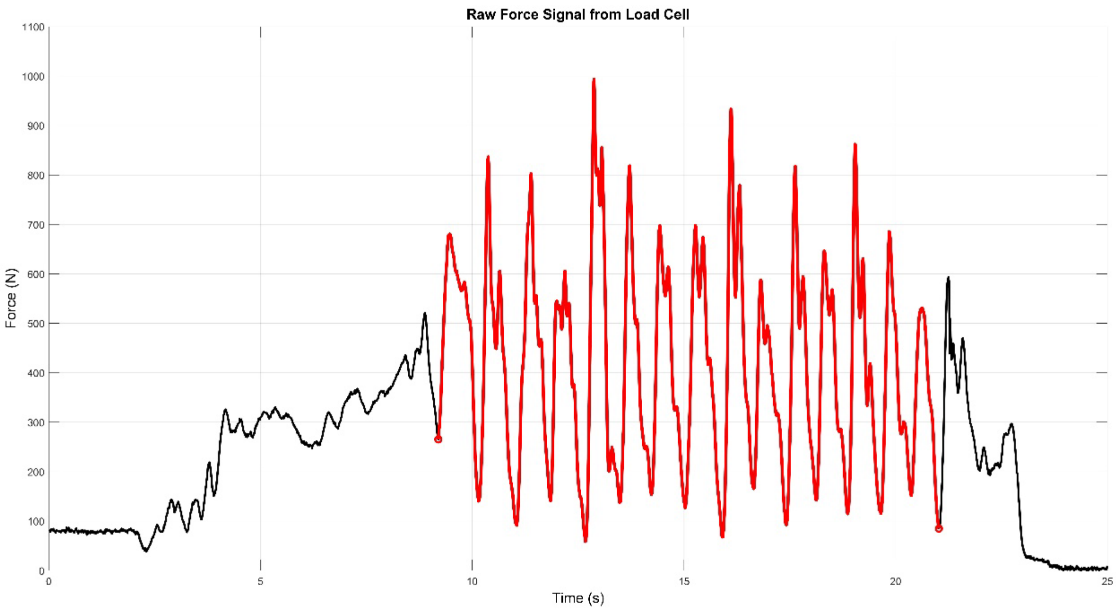

Figure 21: Sample raw force signal measured from the load cell

5.3.5 Statistical Analysis

The mean and standard deviation was calculated for the three trials within a session for each subject. This was then normalised by the subject's body weight. Change in the mean (CM), typical error of measurement expressed as a coefficient of variation (CV), intraclass correlation coefficients (ICC), and 90% confidence limits were used to determine the variability of the PHEF, MHEF, and impulse. The CV was used to quantify the absolute variability or within-subject variation of the different variables [62]. Percent change in the mean was reported to indicate the extent to which the average performance got better or worse over testing sessions because of systematic effects (e.g. learning effect) and random effect (e.g. noise) . Relative consistency was quantified via the ICC and refers to the consistency of the rank or position of a subject in relation to others. All measures were computed using a customised Microsoft Excel® spreadsheet [63].

Table 12: Mean, SD and reliability of the horizontal eccentric towing variables

Variables	Mean ± Standard Deviation			
	T1	T2	T3	T4
PHEF (N/kg)	12.7 ± 2.83	13.6 ± 2.15	13.7 ± 1.70	13.9 ± 2.36
MHEF (N/kg)	4.22 ± 1.11	4.97 ± 0.93	5.20 ± 1.04	5.48 ± 1.10
Impulse (N.s/kg)	56.8 ± 15.1	67.4 ± 13.2	70.1 ± 14.9	74.4 ± 15.2

Variables	% Change in Mean CM (90% CI)		
	T2-T1	T3-T2	T4-T3
PHEF (N/kg)	8.51 (0.25 - 17.5)	1.41 (-8.19 - 12.0)	1.94 (-2.8 - 6.92)
MHEF (N/kg)	19.8 (9.04 - 31.6)	4.35 (-0.97 - 9.94)	7.84 (1.46 - 14.6)
Impulse (N.s/kg)	20.5 (10.5 - 31.5)	3.79 (-1.15 - 8.98)	8.47 (1.00 - 16.5)

Variables	Coefficient of Variation CV (90% CI)		
	T2-T1	T3-T2	T4-T3
PHEF (N/kg)	10.1 (7.30 - 17.2)	12.9 (9.24 - 22.1)	5.59 (3.98 - 9.76)
MHEF (N/kg)	12.2 (8.73 - 20.8)	6.58 (4.76 - 11.1)	7.21 (5.13 - 12.7)
Impulse (N.s/kg)	11.2 (8.08 - 19.2)	6.13 (4.44 - 10.3)	8.49 (6.03 – 15.0)

Variables	Intraclass Correlation Coefficient ICC (90% CI)		
	T2-T1	T3-T2	T4-T3
PHEF (N/kg)	0.81 (0.50 - 0.94)	0.32 (-0.24 - 0.72)	0.90 (0.69 - 0.97)
MHEF (N/kg)	0.79 (0.47 - 0.93)	0.91 (0.74 - 0.97)	0.90 (0.71 - 0.97)
Impulse (N.s/kg)	0.83 (0.54 - 0.94)	0.93 (0.79 - 0.98)	0.87 (0.63 - 0.96)

5.4 Results

The means and standard deviations for the three variables of interest can be observed in Table 12. There is a systematic increase in all variables over the four testing occasions, the largest change in the mean between sessions T2-T1 (8.51% to 20.5%), which is reduced over subsequent sessions (1.41% to 8.47%). The greatest change in the means was noted for impulse whereas the least was PHEF.

The between sessions CVs for all three variables across the four testing occasions ranged from 5.59% to 12.9%, the greatest variability associated with the first testing occasions (10.1% to 12.2%) and the least variability noted with the latter T4-T3 testing (5.59% to 8.49%). PHEF had the greatest average variability across all testing occasions (CV = 9.53%), whereas MHEF and impulse were less variable and the variation quite similar in magnitude (CV = ~8.6%).

The ICC is a measure of relative consistency and of the nine comparisons only one ICC was less than 0.70 (T3-T2) and by the T4-T3 comparison all ICCs were greater than 0.85. Were it not for the ICC=0.32, the rank order between testing occasions would seem very consistent and trending upwards.

5.5 Discussion

It is important to understand the reproducibility of movement associated with any new training device, this contention providing the purpose of this paper. Horizontal eccentric towing is a novel movement pattern and certainly was performed on a novel custom-built device and therefore a high degree of movement variability was expected. In summary, it would seem that for the most part the reliability statistics improved over the trials suggesting a learning effect and more time is needed to be spent in familiarisation. By the fourth testing occasion the reliability statistics were more than acceptable, with percentage change in the means and CVs less than 10% and ICCs greater than 0.85.

Large CMs were observed for all three variables between T2-T1, which can likely be explained as a learning effect. This learning effect is a systematic change in performance and these changes are probably due to the exposure and experience of the previous trials [62]. A similar learning effect was also shown when Brughelli and Leemputte [64] studied the variability associated with a novel eccentric sprint cycling task. They reported significant increases in mean and peak power (% or ES) on their second testing occasion. It would seem that at least 1-2 familiarisation sessions are needed to reduce the movement variability associated with horizontal eccentric towing.

In terms of absolute consistency, the greatest CVs were associated with the first testing occasions (10.1% to 12.2%) and the least variability noted with the latter T4-T3 testing (5.59% to 8.49%). The within-subject variation or CV consists of technological variation (variation arising from measurement equipment) and biological variation (variation arising from subject-related factors) [62]. It can be assumed that technological variation would be minimal over the testing sessions as the equipment and testing conditions were constant, hence the reduction in variation is more likely associated in a reduction in biological variation. Attempting to resist (eccentric) being towed backwards was a novel and therefore challenging movement task for most subjects. The subjects were instructed to find a balance between resisting as hard as they could and holding that resistance throughout the exercise. This was important because, subjects can generate very high forces during initial ground strike but cannot hold this force with muscle shortening in between steps (follow link to see slow motion footage of this phenomenon – bit.ly/3e9GyvH). So initially backward motion was typified by a high degree of 'jerkiness'. As the subjects familiarised themselves with the technique in subsequent sessions, a more constant force was applied and hence the reduction in the CV, particularly evident in the MHEF and impulse.

The movement variability of this study was similar to Stock and Luera [41] who reported CVs of 10.6% and 9.6% for peak and mean ECC force respectively, as measured on a novel isokinetic eccentric squat machine. Although, the squat exercise was not novel, the device being used to administer the exercise was. Brughelli and Leemputte [64] found large CVs between T2-T1 (10.9% - 37.9%) and showed decreases in CVs in T4-T3 (4.7% - 16.2%). The findings of both these studies quantifying the variability associated with novel eccentric training devices were similar to the trends of this study. Finally, PHEF had the greatest average variability across all testing occasions. This is most likely explained by the peak relating to one point in the force time curve, whereas the MHEF and impulse variables are an average or integral of the complete signal (shown in red in Figure 21). This inherently causes the PHEF to have greater variation compared to MHEF and impulse.

ICCs are used as a measure of relative consistency and relate to the reproducibility of the rank order of subjects on the retest. Of the nine comparisons only one ICC was less than 0.70 (T3-T2) and by the T4-T3 comparison all ICCs were greater than 0.85. Were it not for the one outlier (ICC=0.32) which is difficult to explain, the rank order between testing occasions would seem very consistent and trending upwards. Brughelli and Leemputte [64] also found similar improving ICCs by T4-T3 (0.82-0.96).

5.6 Practical Applications

There are many ECC training devices available but none overload the musculo-skeletal system eccentrically in the horizontal plane in a gait-specific modality. This novel stimulus and training tool could have potential impacts on sprinting-specific performance given the benefits of ECC training as described earlier. The results of this study suggest that MHEF and impulse can be reliably measured after two familiarisation sessions. This allows for further research into the training adaptions of the HET device to be conducted.

Chapter 6: Differences in Ground Reaction Forces between Concentric and Eccentric Isokinetic Horizontal Towing

This chapter comprises of the following paper entitled *"Differences in Ground Reaction Forces between Concentric and Eccentric Isokinetic Horizontal Towing"* that has been prepared but not yet submitted.

6.1 Prelude

The previous chapter showed that two familiarisation sessions were required for athletes to achieve movement consistency during horizontal ECC towing. Additionally, mean horizontal ECC force and impulse were deemed to be reliable after two sessions. Most of the ICCs measured were above 0.85 and CVs were less than 10 %. Based on the findings from the previous chapter, all future research and training conducted with HET device will require athletes to undergo a minimum of two familiarisation sessions. However, as mentioned before, horizontal ECC towing is a novel movement that has not been researched previously. Therefore, it is important to understand this towing movement and how it may be implemented in training to improve sprint performance. Thus, the purpose of the following chapter was to investigate the ground reaction forces during the HET movement. To further understand the mechanics of movement it was compared to a similar movement but in the opposite direction. If ECC towing pulls an athlete inwards at a constant velocity, the opposite direction was termed CON towing, where the athlete moves out at a constant velocity. The ground reaction forces were measured at three towing velocities (0.75, 1.00, 1.25 m/s) in two towing directions (CON and ECC). It was deemed important to analyse not only the discrete variables but the shape of the profiles to give further insight into the effects of each direction and velocity on ground reaction force.

6.2 Introduction

Sprint performance is vital to the success of not only track and field athletes but a multitude of team sport athletes [1-3, 65]. For many decades improving sprint performance has been the topic of interest for researchers, coaches and athletes. Ground reaction forces (GRFs) are important kinetic determinants of sprint performance, and have been essential in our understanding of the biomechanics of sprint running [6, 33, 66, 67]. Horizontal GRF production plays a significant role during the acceleration phase of sprint running, and producing force in the horizontal plane has been directly related to sprint performance [32, 46, 49, 68, 69]. As a result, there are numerous tools and modalities available that deliver training stimuli in the aim of improving horizontal force production capabilities; one of the most commonly used tools are resisted towing devices (e.g. sleds) [12, 14]. The reason why this training modality is popular is because it overloads the running action and provides a horizontal stimulus. However, these tools predominantly provide a concentric (CON) overload to the musculo-skeletal system and perhaps a horizontal eccentric (ECC) overload might be a better form of overload given that ECC stimuli can yield positive performance adaptations in power and stretch-shorten cycle function [70], both of which are crucial in sprint performance [66, 71].

A review of commercially available devices that provide ECC overload showed that most devices provide an overload in the vertical plane and none provided a horizontal overload in a sprint-specific manner, similar to a resisted towing device [56]. Therefore, we developed a novel device that provided a horizontal ECC overload called the Horizontal Eccentric Towing (HET) device. Similar to a winch retracting an anchor on a boat, the HET device pulls an athlete inwards at a pre-determined velocity (Figure 15). During the movement, the athlete's objective is to resist this motion in a maximal manner. Irrespective of the amount of force the athlete produces, the HET device will continue to pull them inwards and maintain a constant towing velocity, providing an isokinetic training stimulus (see Chapter 4 for more information on the HET device). The device can tow athletes at various velocities and can also be used for CON towing exercises, like a sled. Instead of being pulled inwards, the athlete would move outwards, either with a constant resistance/load (isotonic) or at a constant velocity (isokinetic). This unique movement is currently unexplored in the literature. The purpose of this study was to understand the differences in GRFs between isokinetic horizontal CON towing direction (CTD) and ECC towing direction (ETD). Determining the ground reaction forces at various towing velocities will help in understanding the mechanical differences between CON and ECC isokinetic horizontal towing, which in turn will inform programme development for improving sprint performance using the HET.

6.3 Methods

6.3.1 Subjects

Eight national representative sprint-trained athletes (five males and three females) were recruited to participate in this study (mean ± SD: age, 24.5 ± 4.66 years; stature, 1.77 ± 0.06 m; body mass, 74.6 ± 8.20 kg). The participants comprised of two male pole vaulters; one female heptathlete; one male 400 m sprinter; one female 100 and 200 m sprinter; one female and two male beach flag sprinters. All participants were free from any lower-limb injury for at least six months prior, had represented their country in international competitions in their respective events, and were resistance trained with substantial sprint specific training. Informed consent was completed by all the participants. The testing procedures in this study were approved by the Auckland University of Technology Ethics Committee (15/375 – see Appendix I, IV, and V for more details).

6.3.2 Procedure

Participants were asked to attend four sessions separated by seven days each. The first two were familiarisation sessions to achieve movement consistency [72], during which the participants performed twelve 10 m trials interceded with three-minutes rest. Six trials at each towing direction (CTD and ETD) were performed, comprising of two trials at three towing velocities (0.75, 1.00, 1.25 m/s). The three velocities were chosen based on pilot studies with the HET device, which suggested that the pre-determined velocities would be appropriate representations of slow, medium and fast towing velocities. Ten metres was chosen to allow athletes enough distance to perform multiple steps without the risk of fatigue, as participants were asked to perform twelve max effort trials in one session. The participants were given verbal cues to apply the maximum amount of force while applying consistent tension into the tether and the harness. This was to minimise the tether oscillation that might disrupt the gait cycle of the athlete. To standardise the coefficient of friction between the participant and the track surface athletes wore a selection of standardised footwear throughout the testing procedures, supplied in their respective sizing (Asics, Kobe, Japan).

During the third and fourth sessions the participants performed the same twelve trials over a custom 10 metre elevated platform (Figure 22) which had two embedded AMTI Accupower force plates (AMTI, Watertown, Massachusetts, United States of America) to capture GRF data. The two force plates were positioned inline to capture multiple left foot contact phases. During a pilot testing session, it was found that during a slower ECC trial, the participant would miss one plate altogether. The force plates were positioned to capture the left foot because of the limited physical space where the HET device was located. The HET device was immovable and was placed on the last track in an indoor track facility (AUT Millennium, Auckland, New Zealand). Two dummy plates, which could not collect any data, were positioned to create a continuous surface for the participant. Each participant performed a standardised 15-minute dynamic sprint warmup. Their respective height and weight values were recorded. The subjects then performed the twelve trials, in randomised order. The data was recorded using the Vicon Sync Box and the Nexus 2.2 software at 1000 Hz (Vicon, Oxford, United Kingdom).

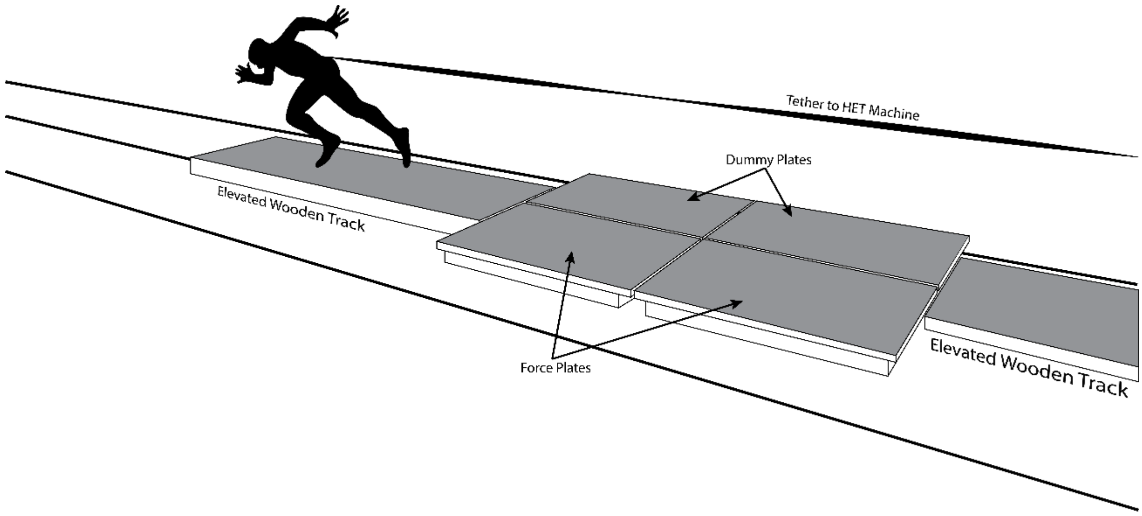

Figure 22: Experimental set-up of force plates and platform

6.3.3 Data Analysis

Force-time data were processed using a fourth-order low pass Butterworth filter with a cut-off frequency of 12 Hz (selected via residual analysis) [73]. For each trial, individual steps were determined by manually identifying the sudden onset and offset of force above zero (Figure 23). The number of steps successfully captured varied between 1-3 steps for each trial, due to varying cycle lengths and strategies for each trial condition. The individual steps were then time normalised from 0-100% of stance and GRFs were made relative to the body weight of each participant. The force plate data measured both horizontal and vertical components of the GRF. The CON towing movement produced only propulsive force whereas ECC towing produced only braking force. For the sake of comparison, the horizontal GRF was calculated as positive values for both towing directions. The discrete variables calculated were peak force, percentage of stance where peak force occurred, mean force, impulse and contact time. All the data was analysed using MATLAB 2019a (MathWorks, Natick, Massachusetts, United States of America).

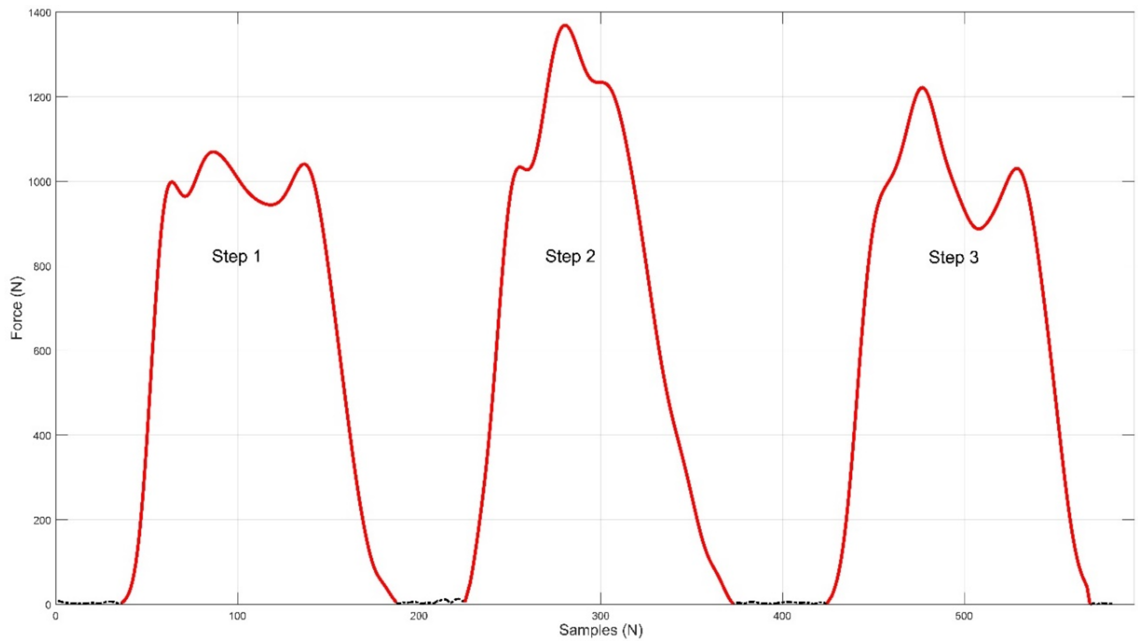

Figure 23: Identification of individual steps during a trial based on resultant force

6.3.4 Statistical Analysis

Statistical Parametric Mapping One Dimension (SPM1D) and One-Way ANOVA were performed on the continuous force-time data using the open-source software available from www.spm1d.org. The critical threshold was set to 5% (α=0.05) using random field theory [74-76]. SPM1D allows analysis of entire waveforms for time-domain data, which provides further insight of the shape of the waveform, when compared to discrete measures such as peaks and means. However, it must be noted that normalising force curves to percentage of stance can skew SPM1D results. By including the additional analysis of peaks and means, any artificial results are minimised. The discrete variables shown in Table 13 were calculated as the cumulative mean and standard deviation of each individual step (e.g. the maximum value from the vertical force data column was extracted from each step and then averaged across all steps in the particular condition, which resulted in peak vertical force). Figure 24 and Figure 25 show the mean (black solid line) and standard deviation (grey shaded area) of the averaged time-normalised waveforms (e.g. the data columns of the stance-normalised vertical force were averaged at each point in stance which resulted in a single waveform). This was done to avoid calculating averages of averages and to keep the discrete variables measured as accurate as possible. It must be noted that the values in

Table 13 may not coincide with the waveforms shown in Figure 24 and Figure 25 because of this reason. The purpose of averaging the waveforms into a single waveform for each condition was to compare the shape and characteristics of the curve using SPM1D, which is difficult with discrete variables alone. One-Way ANOVA was performed on the discrete variables using IBM SPSS Statistics 24 (IBM, Armonk, New York, United States of America). One-Way ANOVA was calculated to compare the differences in towing velocities in ETD only, and the differences between CTD and ETD, irrespective of towing velocity. Significant interactions and main effects were subsequently analysed using a Tukey post hoc test. Significance was set to $p<0.05$. Effect sizes were calculated using Cohen's d [77]. Threshold values for ES were set as: ≤0.19 trivial, 0.2 – 0.59 small, 0.6 – 1.19 moderate, 1.2 – 1.99 large, 2.00 – 3.99 very large, and >4.00 extremely large.

Table 13: Mean and standard deviation of variables

Variables	CTD				ETD			
	0.75 m/s $\mu \pm \sigma$ n = 52	**1.00 m/s** $\mu \pm \sigma$ n = 43	**1.25 m/s** $\mu \pm \sigma$ n = 45	**Total** $\mu \pm \sigma$ n = 140	**0.75 m/s** $\mu \pm \sigma$ n = 42	**1.0 m/s** $\mu \pm \sigma$ n = 36	**1.25 m/s** $\mu \pm \sigma$ n = 30	**Total** $\mu \pm \sigma$ n = 108
Peak Vertical GRF (N/kg)	11.3 ± 1.11	11.9 ± 1.08	13.1 ± 2.18	**12.1 ± 1.71**	11.7 ± 1.57	11.8 ± 1.18	12.4 ± 1.34	**11.9 ± 1.4**
Peak Vertical GRF Stance (%)	40 ± 11.5	41.4 ± 10.8	45.0 ± 12.5	**42.0 ± 11.8**	42.6 ± 17.3	42 ± 19.1	35.2 ± 13.9	**40.3 ± 17.2**
Mean Vertical GRF (N/kg)	7.17 ± 0.59	7.57 ± 0.67	8.06 ± 0.75	**7.58 ± 0.76**	6.66 ± 0.62	7.16 ± 0.81	7.36 ± 0.90	**7.02 ± 0.82**
Vertical Impulse (N.s/kg)	5.85 ± 1.14	4.78 ± 0.88	4.59 ± 0.72	**5.12 ± 1.1**	6.13 ± 2.26	5.41 ± 1.17	4.80 ± 1.28	**5.52 ± 1.77**
Peak Horizontal GRF (N/kg)	7.82 ± 1.37	8.22 ± 1.23	8.8 ± 2.33	**8.26 ± 1.74**	8.18 ± 1.73	7.92 ± 1.56	8.39 ± 2.19	**8.15 ± 1.81**
Peak Horizontal GRF Stance (%)	48.3 ± 22.4	46.9 ± 19.5	53.6 ± 15.2	**49.6 ± 19.5**	34.0 ± 18.7	28.7 ± 15.3	26.5 ± 13.4	**30.2 ± 16.4**
Mean Horizontal GRF (N/kg)	4.77 ± 0.85	4.95 ± 0.76	5.01 ± 1.03	**4.9 ± 0.89**	4.11 ± 0.72	4.18 ± 0.91	4.17 ± 0.83	**4.15 ± 0.81**
Horizontal Impulse (N.s/kg)	3.94 ± 1.11	3.11 ± 0.59	2.82 ± 0.53	**3.33 ± 0.94**	3.78 ± 1.42	3.16 ± 0.92	2.78 ± 1.06	**3.3 ± 1.24**
Contact Time (s)	0.82 ± 0.17	0.64 ± 0.13	0.58 ± 0.12	**0.69 ± 0.18**	0.92 ± 0.31	0.76 ± 0.16	0.66 ± 0.16	**0.8 ± 0.25**

n = number of steps analysed for each condition

Table 14: Percentages changes of means with One-Way ANOVA results

Variables	**% Change between CTD and ETD**	**% Change between towing velocities only in ETD**		
	Overall	**1.00 m/s – 0.75 m/s**	**1.25 m/s – 1.00 m/s**	**1.25 m/s – 0.75 m/s**
Peak Vertical GRF (N/kg)	-1.41 %	1.10 %	4.83 %	5.98 %
Peak Vertical GRF Stance (%)	-4.08 %	-1.29 %	-16.2 %	-17.3 %
Mean Vertical GRF (N/kg)	-7.36 % ♦ *(0.69)*	7.48 % ♦ *(0.64)*	2.86 %	10.6 % ♦ *(0.95)*
Vertical Impulse (N.s/kg)	7.89 % ♦ *(0.28)*	-11.8 %	-11.2 %	-21.7 % ♦ *(0.68)*
Peak Horizontal GRF (N/kg)	-1.26 %	-3.09 %	5.88 %	2.6 %
Peak Horizontal GRF Stance (%)	-39.1 % ♦ *(1.07)*	-15.4 %	-7.72 %	-21.9 %
Mean Horizontal GRF (N/kg)	-15.4 % ♦ *(0.87)*	1.68 %	-0.31 %	1.37 %
Horizontal Impulse (N.s/kg)	-0.88 %	-16.5 %	-12.1 %	-26.6 % ♦ *(0.74)*
Contact Time (s)	15.3 % ♦ *(0.48)*	-17.5 % ♦ *(0.61)*	-13.8 %	-28.9 % ♦ *(1.01)*

♦ = significant difference ($p<0.05$)
() = Cohen's d Effect Size

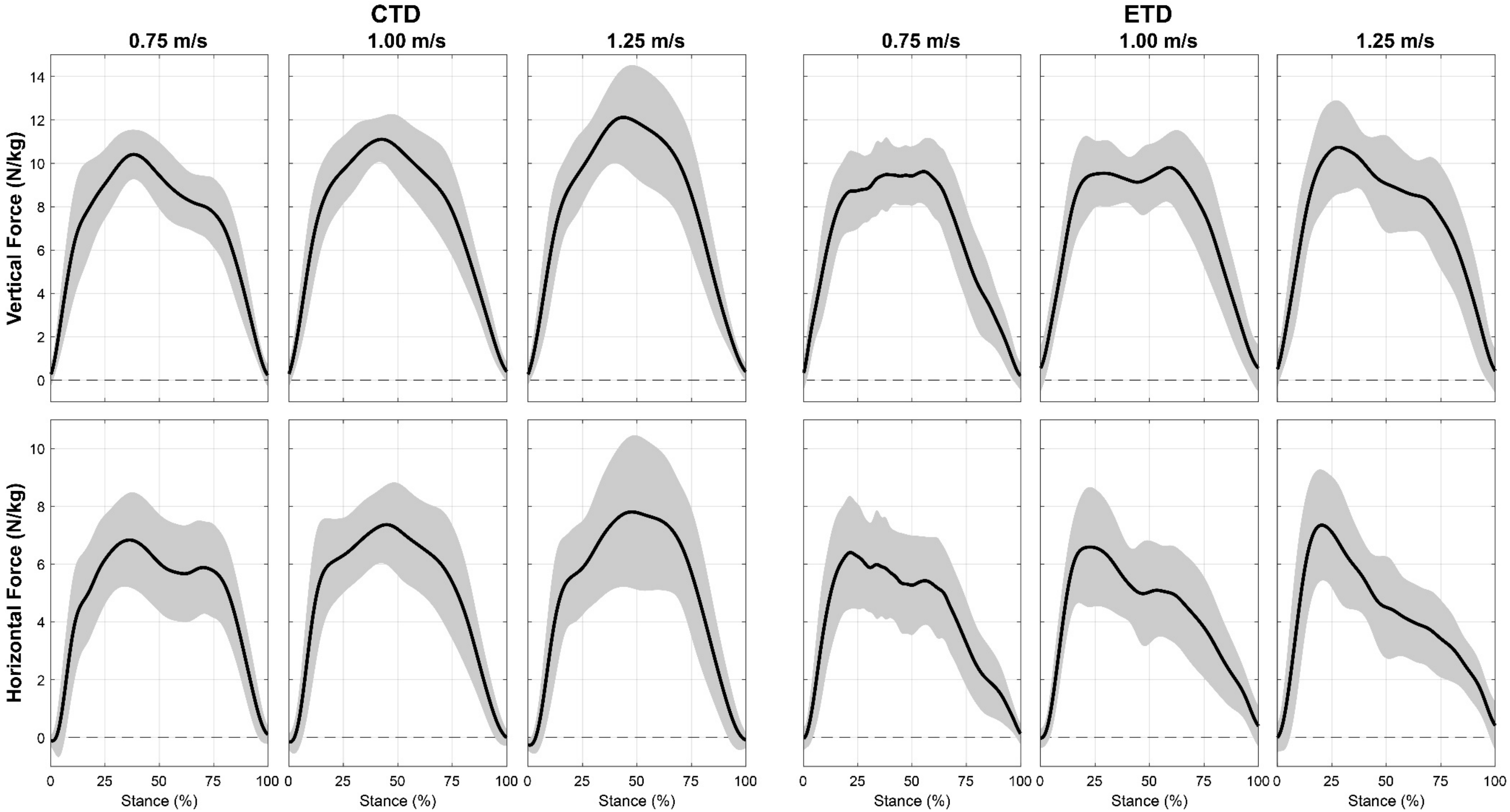

Figure 24: Averaged and stance normalised GRF curves (mean ± standard deviation)

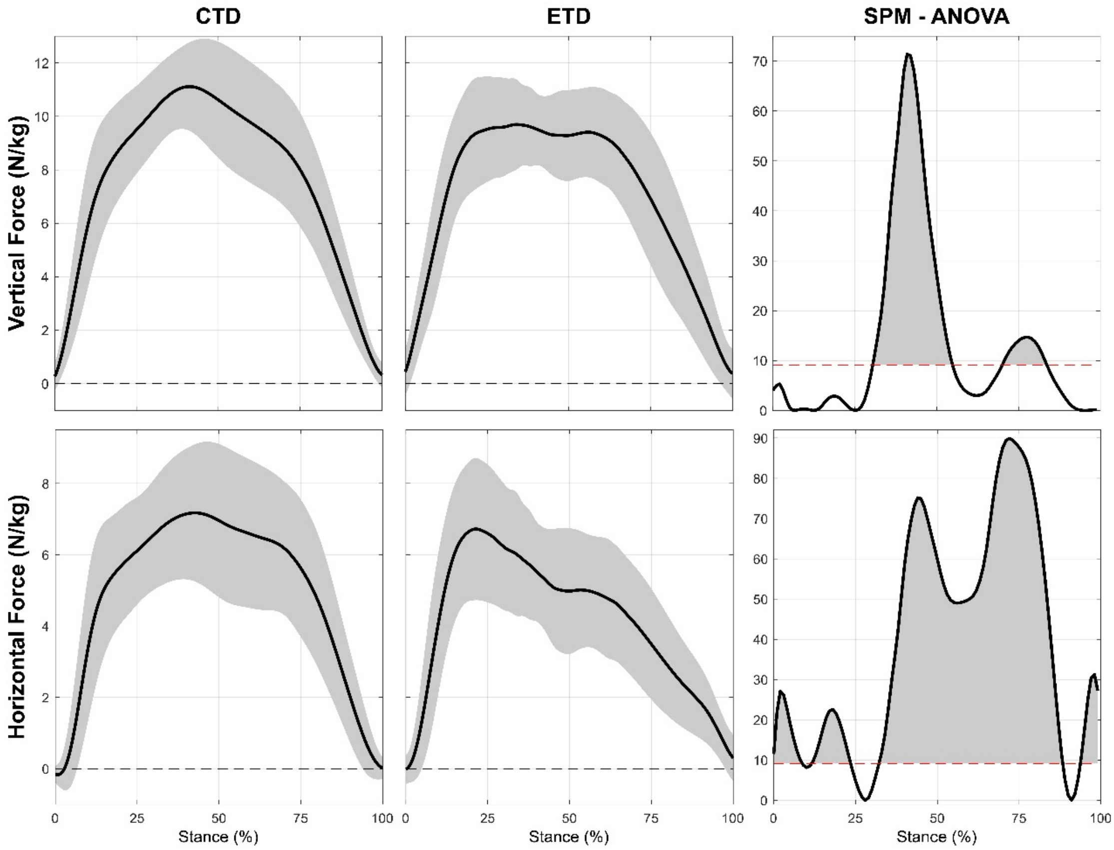

Figure 25: One-Way ANOVA and SPM of GRF data

6.4 Results

6.4.1 Towing Direction

The mean and standard deviations for all variables as well as the percentage changes can be observed in Table 13 and Table 14. The results discussed below are statistically significant ($p<0.05$), unless otherwise stated. From Table 13 it was observed that both CTD and ETD had similar peak vertical and horizontal GRFs. However, the percentage of stance where peak horizontal GRFs occurred were significantly earlier in the ETD (39.1 % earlier; ES = 1.07). Mean vertical GRFs were 7.36 % (ES = 0.69) lower and mean horizontal GRFs were 15.4% lower in the ETD. Vertical impulse was 7.89 % (ES = 0.28) larger in the ETD. However, horizontal impulse remained unchanged between towing directions. Contact times were 15.3 % (ES = 0.48) longer in the ETD.

6.4.2 Towing Velocity

Mean vertical GRF increased by 10.6 % (ES = 0.95) in the ETD between 1.25 m/s and 0.75 m/s, and by 7.48 % (ES = 0.64) between 1.00 m/s and 0.75 m/s. In both towing directions, vertical and horizontal impulse decreased with increasing towing velocity (6.13 to 4.59 N.s/kg, 3.94 to 2.78 N.s/kg). This was expected as contact times also decreased with increasing towing velocity (0.82 to 0.58 s CTD, 0.92 to 0.66 s ETD), since impulse is a product of contact time.

6.4.3 Force-Time Curve and SPM Analysis

Averaged and stance normalised GRF curves and the SPM One-Way ANOVA analysis of the GRF data can be observed in Figure 24 and Figure 25, respectively. Figure 24 shows that all curves increased in amplitude with towing velocity and vertical GRFs were larger than horizontal GRF for all towing velocities. Vertical and horizontal GRF peaks in the ETD became more prominent at early-stance (~25 % of stance) with increasing towing velocity and the GRF curves started to decrease more so after mid-stance with increasing towing velocity. Vertical and horizontal GRF curves in the CTD increased in amplitude at mid-stance (~50 % of stance) with increasing towing velocity. Figure 25 shows a distinct difference in the shape of GRF curves between CTD and ETD for all towing velocities. SPM results show that there was a significant difference in vertical GRF between towing directions at mid-stance (31 – 54 % of stance) and late-stance (71 – 83 % of stance). Horizontal GRF was significantly different at almost the entire stance phase (0 – 8, 12 – 23, 33 – 88, 94 – 100 % of stance).

6.5 Discussion

The novelty of the HET device and the lack of research surrounding isokinetic horizontal towing made understanding the GRFs and the influence of towing direction and towing velocity the focus of this research. The main findings were; 1) CTD and ETD have very different GRF profiles and this could be due to different movement strategies contributing to force absorption and production. 2) Peak vertical and horizontal GRFs differed according to the contractile-force-velocity relationship where force during the ECC contraction increased with contractile velocity and force during the CON contraction decreased with movement velocity. 3) Peak horizontal GRFs were similar regardless of towing direction. 4) The longer contact times were associated with the ETD.

The purpose of the ECC horizontal isokinetic towing movement was to administer a unique ECC stimulus in the horizontal plane that is similar to the CON horizontal stimulus from traditional resisted towing devices. To the authors knowledge this is the first study to show the force-velocity relationship during CON-ECC horizontal isokinetic towing. It was envisaged that ECC towing would produce a similar but larger GRF profile to CON towing, given that ECC muscle contractions can generate much larger forces than CON muscle contractions [17, 18]. The results found show that the GRF profiles are significantly different at almost the entire stance phase. This suggests that the two towing directions require different movement strategies to produce and absorb force. One of the key differences in GRF profiles between the two towing directions was the point in stance at which the peak GRFs occurred. Whilst CON GRF peaks occurred just before or at mid-stance, ECC GRF peaks occurred at early stance (Figure 25: One-Way ANOVA and SPM of GRF data). It is speculated that in the ETD, as the foot touched the ground, the ankle joint would be the first joint in the kinetic chain to absorb the force, which would then be propagated to the knee and hip joints. The onset of force later in stance during CON towing indicates that a movement strategy involving larger muscles groups around knee and hip joints are likely to be the ones contributing to force production. The GRFs in the ETD show a sharp decrease after mid-stance indicating that as the athlete's centre of mass moved closer to the foot's point of contact, it became more difficult to absorb the forces in the horizontal rather than vertical direction. This was probably due to the force vector changing to more vertical direction. This is similar to the role of the ankle during the braking phase of sprint running [78]. In the CTD, the braking phase was almost non-existent when compared to the rest of the stance phase, indicating that the role of the ankle was probably less compared to the ETD.

It is commonly known that force production decreases with increasing CON contractile velocity but increases with increasing ECC contractile velocity, with ECC forces being much larger than CON forces [18, 19]. It was hypothesised that this characteristic would also occur in isokinetic horizontal towing at a macro level. However, peak GRFs remained similar between CTD and ETD. This is probably due to the contractile force-velocity relationship and the ability to hold or increase ECC force with increasing contractile velocity. Greater CON and ECC muscle forces at higher contractile velocities is the ideal performance gain for most athletes. The ability to produce higher forces at higher velocities with a lower physiological cost is useful in training [18]. ECC isokinetic horizontal towing may provide this high force / high velocity overload which could be beneficial in sprint-training.

It was expected that ECC GRFs would be larger than CON GRFs given the contractile force-velocity relationship. The similarity in peak horizontal GRF between the towing directions suggests that perhaps the GRF is limited by the coefficient of friction (μ_s) rather than the athlete's individual force generation capabilities. The production and absorption of horizontal GRF (F_h) is a product of the static friction coefficient (μ_s) between the surface of the force plate and the sole of the shoe, and the vertical GRF (F_v) [79]. If the athletes were to wear to spikes or if the surface of the track had higher coefficient of friction while performing isokinetic horizontal towing, then it is envisaged that the ECC GRFs would be larger than the CON GRFs. However, this is speculative and further research would be needed to support such a contention.

Contact times decreased as towing velocities increased, which is a common phenomenon also observed in sprint running; as contact times decrease with running velocity [80]. Contact times were larger in the ETD because the athletes took a smaller number of steps over the same towing distance. Athletes were encouraged to keep a constant but high tension on the tether, and it was noticed that in order to achieve a high constant tension and minimise the oscillation of the tether, they increased their step time in the ETD. This correlates with the higher vertical impulse measures in the ETD.

6.6 Conclusion

Isokinetic CON and ECC horizontal towing directions have significantly different force profiles. The characteristic of increasing eccentric force during ECC towing with increasing towing velocities in a pseudo-gait-specific position might be of interest to practitioners as this stimulus, which to best of the authors' knowledge, is not available with conventional training modalities. Greater ECC GRFs and overload could be achieved by increasing the friction between the footwear and the surface. The differing movement strategies between each towing direction needs to be investigated further as applying eccentric stimulus to specific joints may be beneficial to overall sprinting performance, especially at the higher towing velocities that could possibly translate better to sprinting specific movements.

Chapter 7: Differences in Lower Limb Joint Power and Work during Concentric and Eccentric Isokinetic Horizontal Towing

This chapter comprises of the following paper entitled *"Differences in Lower Limb Joint Power and Work during Concentric and Eccentric Isokinetic Horizontal Towing"* that has been prepared but not yet submitted.

7.1 Prelude

The key finding from the previous chapter was that the GRF profiles were significantly different between isokinetic CON and ECC horizontal towing directions. This suggest that different movement strategies are being implemented to apply and absorb force. The shape of the GRF showed that peak horizontal force in the ECC towing direction was occurring at early-stance (~25 % of stance) and at mid-stance (~50 % of stance) in the CON towing direction. This suggested that different lower limb joints were likely responsible for CON and ECC force production. This was further investigated in the following chapter. Understanding the biomechanics of isokinetic horizontal towing was the focus of this section in particular investigating the power absorption and production of the lower limb joints was the purpose of the following chapter. It is important to note that the data from the previous and the following chapter was collected simultaneously with the same subject cohort. Therefore, parts of the methodology were identical.

7.2 Introduction

The success of many team sports and track and field athletes can be in part linked with their sprint performance [1-3, 65]. Therefore, improving sprint performance has been the foci of researchers and practitioners alike. The tools and modalities that deliver sprint-specific training stimuli are many, one of the most commonly used tools being resisted towing devices (e.g. sleds) [12, 14]. It appears that resisted sled towing (RST) can improve horizontal force production, which is linked with enhanced sprint performance, especially during the acceleration phase of the sprint [14, 32, 66]. Furthermore, it may be that RST offers a predominantly concentric (CON) horizontal overload to the musculo-skeletal system, especially in the early phases of the sprint and or with heavy loads [12, 14]. However, the authors believe that sprint athletes may benefit from an eccentric (ECC) horizontal overload given that ECC stimuli can yield positive performance adaptations in power and stretch-shorten cycle (SSC) function [70], both of which are crucial in sprint performance [66, 71]. Therefore, an isokinetic horizontal ECC towing (HET) device was developed. This device pulls an athlete inwards at a pre-determined velocity whilst the athlete resists this motion attempting to produce force in a forward direction (see Figure 15 and refer to Chapter 4 for more information on the HET device).

SSC function is comprised of an energy absorption phase (ECC) followed by an energy production phase (CON) [81]. SSC is best optimised when energy is recovered from the initial phase of absorption and then rapidly applied to the production phase [34]. The greater the energy recovered, the greater the efficiency of the movement. The time between the absorption and production phase is known as coupling time. A shorter time coupling time is associated with more energy recovered in the production phase from the absorption phase. A long coupling time may result in the elastic energy absorbed during the stretch of the musculotendon complex being dissipated. The coupling time may be determined by the limb's elastic characteristics and its ability to absorb and produce energy [82]. It was envisaged that isokinetic horizontal towing may have an effect on the lower limbs' elastic characteristics which would result in different phases of energy absorption and production being overloaded. This would have an impact on SSC function which would then have an impact on sprint performance as SSC function and sprint performance are linked [66, 71]. Therefore, understanding the role of energy absorption and production by measuring power and work of the lower limb joints during isokinetic horizontal towing was the focus of this study.

In terms of the biomechanics of sprinting, there is a great deal of research that show the ankle, knee and hip joints play significant roles is all phases of sprint performance [6, 83-88]. Joint power and work are important biomechanical parameters when analysing performance of human gait, as they describe the energy that initiates or controls the movement of each limb. Energy is usually defined as the capability for doing work. The generation of power at the hip, knee and ankle joints occurs in a proximal-to-distal temporal sequence, referred to as the kinetic chain [89]. Producing greater power along the kinetic chain has often been the goal for researchers and practitioners to improve sprint performance. RST is one of the tools used to overload the joints in a sprint specific manner to improve joint power. However, limited research has been conducted that investigate the lower limb joint power and work during RST [90, 91]. Certainly, no research has investigated the effects of HET across the hip, knee and ankle joints. It may be that both the CON towing direction (CTD) and the ECC towing direction (ETD) overload the kinetic chain differentially, and therefore could be used for different purposes given an athlete’s needs. However, such contentions are speculative and the purpose of this study therefore is to understand whether differences in lower limb joint power and work exist when isokinetic horizontal CON and ECC towing modalities are utilised.

7.3 Methods

7.3.1 Subjects

Eight national representative sprint trained athletes (five males and three females) were recruited to participate in this study (mean ± SD: age, 24.5 ± 4.66 years; stature, 177 ± 6 cm; body mass, 74.6 ± 8.2 kg). The participants comprised of two male pole vaulters; one female heptathlete; one male 400 m sprinter; one female 100 and 200 m sprinter; one female and two male beach flag sprinters. All participants were free from any lower-limb injury for at least six months prior, had represented their country in international competitions in their respective events, and were resistance trained with substantial sprint specific training. Informed consent was completed by all the participants. The testing procedures in this study were approved by the Auckland University of Technology Ethics Committee (15/375 – see Appendix I, IV, and V for more details).

7.3.2 Procedure

Participants were asked to attend four sessions separated by seven days each. The first two were familiarisation sessions to achieve movement consistency [72], during which the participants performed twelve 10 m trials interceded with three-minutes rest. Six trials at each towing direction (CON and ECC) were performed, comprising of two trials at three towing velocities (TV1 = 0.75 m/s, TV2 = 1.00 m/s, TV3 = 1.25 m/s). The three towing velocities were chosen based on pilot studies with the HET device, which suggested that the pre-determined velocities would be appropriate representations of slow, medium and fast towing velocities. 10 m was chosen to allow athletes enough distance to perform multiple steps without the risk of fatigue, as participants were asked to perform twelve max effort trials in one session. The participants were given verbal cues to apply the maximum amount of force while applying consistent tension into the tether and the harness. This was to minimise the tether oscillation that might disrupt the gait cycle of the athlete. To standardise the coefficient of friction between the participant and the track surface, athletes wore a selection of standardised footwear throughout the testing procedures, supplied in their respective sizing (Asics, Kobe, Japan).

During the third and fourth sessions the participants performed the same twelve trials over a custom 10 m elevated platform which had two embedded AMTI Accupower force plates (AMTI, Watertown, Massachusetts, United States of America) to capture GRF data, and four Vicon T10S cameras (Vicon Motion Systems Ltd., Oxford, UK) to record the position of 8 retro-reflective markers placed on the subject (Figure 22). The markers were placed on the following anatomical locations: the seventh cervical vertebra (C7), acromion process (SHO), greater trochanter (HIP), lateral epicondyle of the femur (KNE), lateral malleolus (ANK), base of the fifth metatarsal (MT5), lateral arch of foot directly below the lateral malleolus (ARC) and posterior calcaneus (HEE) (Figure 27) [92]. Markers HEE, ARC and C7 were used as redundancy markers. The markers were placed to create 4 rigid body segments (foot, shank, thigh and torso) and 3 joints (ankle, knee and hip) (Figure 28). An International Society for the Advancement of Kinanthropometry Level 3 qualified anthropometrist placed the markers on all subjects.

The two force plates were positioned inline to capture multiple left foot contact phases (Figure 22). The force plates and the cameras were positioned to capture the left foot strikes because of the limited physical space where the HET device was located. As a result, the subject had markers placed only on the left side of their body. The HET device was immovable and was placed on the last track in an indoor track facility (AUT Millennium, Auckland, New Zealand). Two dummy plates, which could not collect any data, were positioned to create a continuous surface for the participant (Figure 22). Each participant performed a standardised 15-minute dynamic sprint warmup. Their respective height and weight values were recorded. A static calibration trial was collected for each session. The subjects then performed the twelve trials, in randomised order. The force plate data was recorded at 1000 Hz and the marker data was recorded at 200 Hz using the Vicon Sync Box and the Nexus 2.2 software (Vicon, Oxford, United Kingdom). Both streams of data were time synchronised.

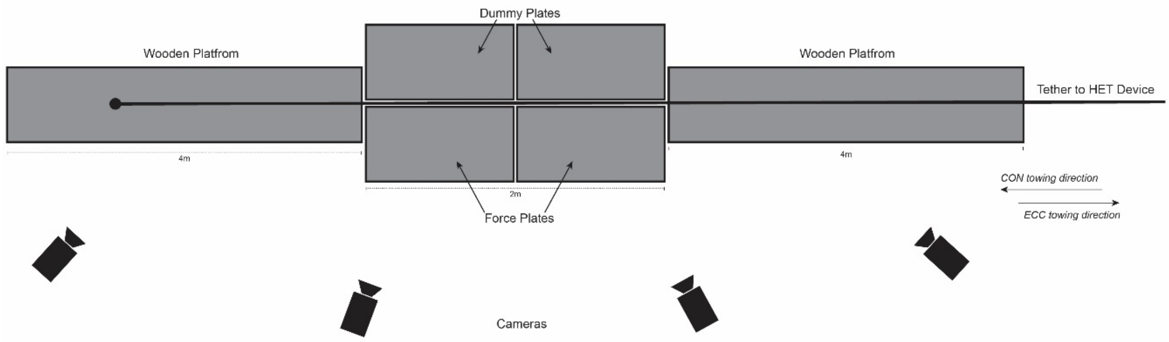

Figure 26: Experimental set-up of force plates, cameras and platform

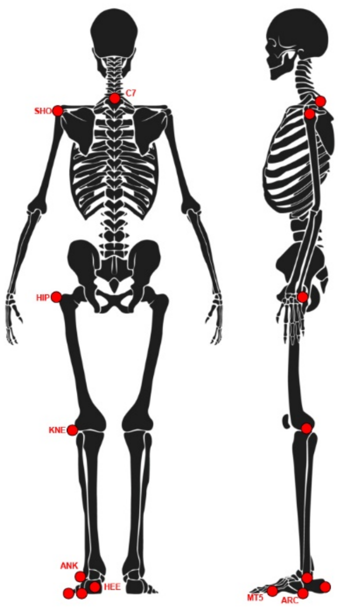

Figure 27: Reflective marker locations

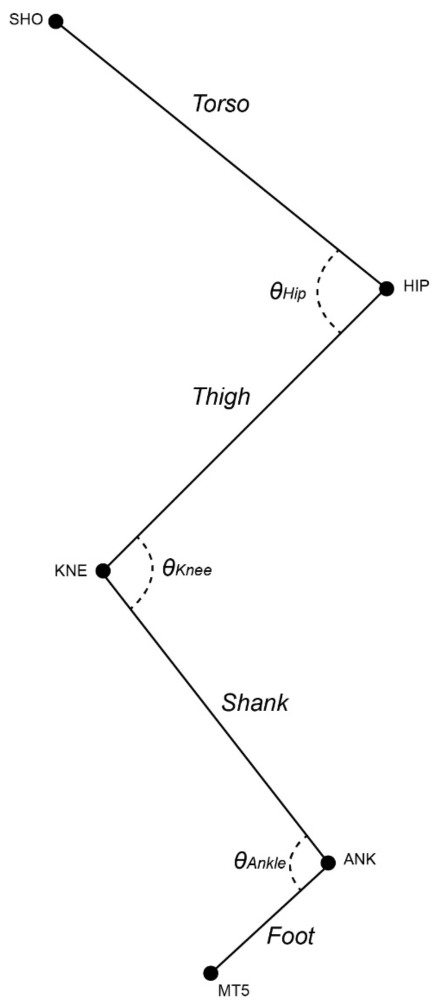

Figure 28: Rigid body segments and joint angles

7.3.3 Data Analysis

Marker data was pre-processed in Nexus 2.2 software (Vicon, Oxford, United Kingdom). Markers were labelled and gaps were filled using the 'spline' gap filling tool. All further data was analysed using MATLAB 2019a (MathWorks, Natick, Massachusetts, United States of America). Force-time and marker data were filtered using a fourth-order low pass Butterworth filter with a cut-off frequency of 12 Hz. Residual analysis was used and resulted in a 12 Hz cut-off frequency for both streams of data [73]. For each trial, individual steps were determined by manually identifying the sudden onset and offset of force from zero from the force plate data. The number of steps successfully captured varied between 1-3 steps for each trial, due to varying cycle lengths and strategies for each trial condition. The variables from all steps were averaged and time-normalised to 0-100 % of stance. The subjects' body segment parameters were calculated from the static calibration file using published cadaver data [93]. The mass of the shoe was added to the foot segment (0.25 kg). Joint angles were calculated as relative to the corresponding segments (ankle angle = angle between foot and shank segment). The standard inverse dynamics model was used to calculate the joint moments (calculations and free-body diagrams can be found in Appendix VIII) [93]. Power was calculated as the product of the joint moment and the angular velocity of the corresponding segment's centre of mass (ankle joint power = ankle moment x foot COM angular velocity). Power and work variables were scaled to body-mass. Positive and negative work was calculated as the time integral of the power production (positive) and absorption (negative) phases of the power curve. Joint kinematics data was used in conjunction with the force plate data to compute joint kinetics data.

7.3.4 Statistical Analysis

Statistical Parametric Mapping One Dimension (SPM1D) and One-Way ANOVA were performed using the open-source software available from www.spm1d.org. The critical threshold was set to 5% (α=0.05) using random field theory [74, 75]. SPM1D allows analysis of entire waveforms for time-domain data, which provides further insight into the shape of the waveform, when compared to discrete measures such as peaks and means. However, it must be noted that normalising time-domain data to percentage of stance can skew SPM1D results. By including the additional analysis of peaks and means, any artificial results are minimised. The discrete variables shown in Table 15 were calculated as the cumulative mean and standard deviation of each individual step (e.g. the maximum value from the ankle joint power data column was extracted from each step and then averaged across all steps in the particular condition, which resulted in peak ankle joint power production). Figure 29 shows the mean (black solid line) and standard deviation (grey shaded area) of the averaged time-normalised waveforms (e.g. the data columns of the stance-normalised ankle joint power were averaged at each point in stance which resulted in a single waveform). This was done to avoid calculating averages of averages and to keep the calculations as accurate as possible. It must be noted that the values in Table 15 may not coincide with the waveforms shown in Figure 29 because of this reason. The purpose of averaging the waveforms from all towing velocities into a single waveform for each towing direction was to compare the shape and characteristics of the curve using SPM1D, which is difficult to accomplish with discrete variables alone. One-Way ANOVA was performed on the discrete variables using IBM SPSS Statistics 24 (IBM, Armonk, New York, United States of America). One-Way ANOVA was calculated to compare the differences in towing velocities in the ETD only, and the differences between CTD and ETD, irrespective of towing velocities. Due to the novelty of ECC isokinetic towing, it was decided that comparing towing velocities in the ETD only would narrow the focus of this study and allow for in-depth analysis of ECC isokinetic towing. Significant interactions and main effects were subsequently analysed using a Tukey post hoc test. Significance was set $p<0.05$. Effect sizes were calculated using Cohen's d [77]. Threshold values for ES were set as: ≤0.19 trivial, 0.2 – 0.59 small, 0.6 – 1.19 moderate, 1.2 – 1.99 large, 2.00 – 3.99 very large, and >4.00 extremely large.

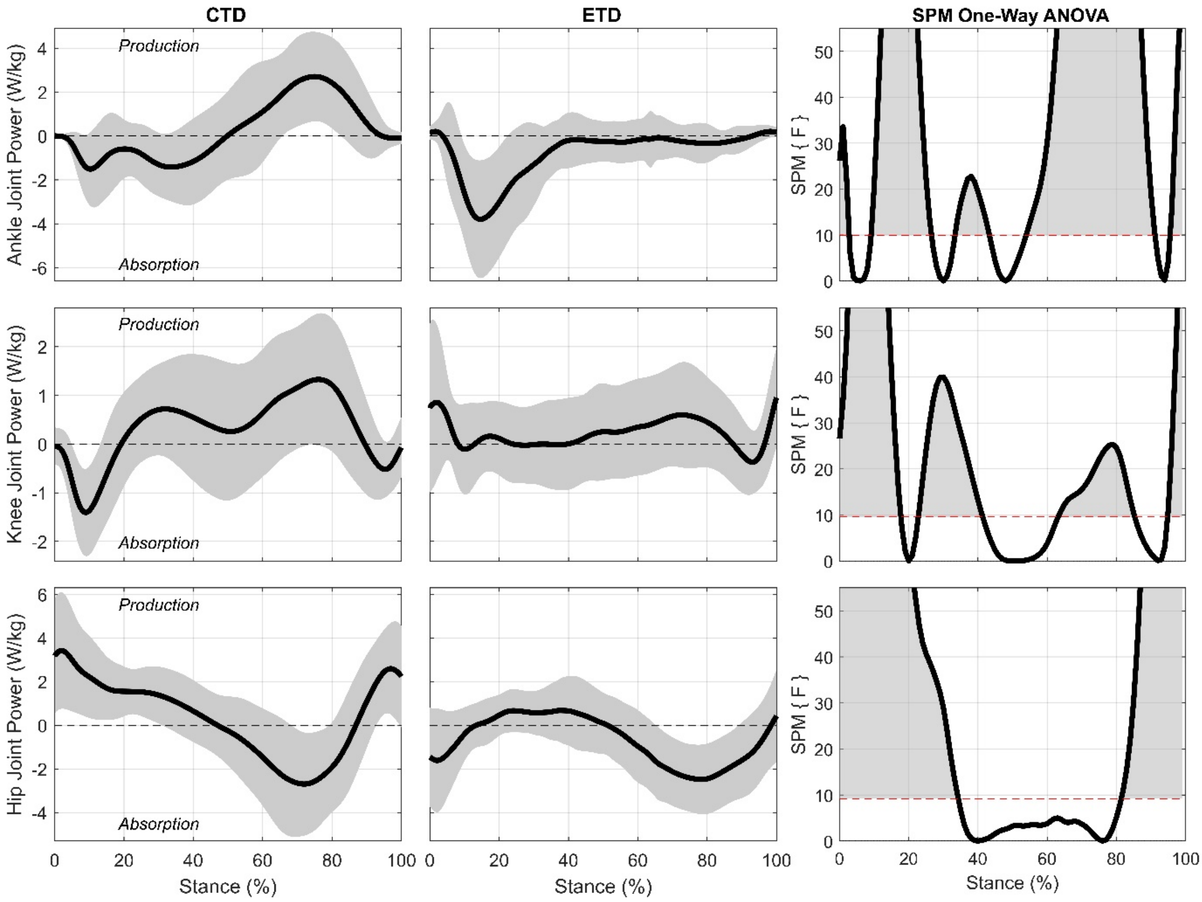

Figure 29: SPM One-Way ANOVA of joint power between towing directions

Table 15: Means and standard deviations of the power and work variables

Variables	CTD 0.75 m/s $\mu \pm \sigma$ n = 52	CTD 1.00 m/s $\mu \pm \sigma$ n = 43	CTD 1.25 m/s $\mu \pm \sigma$ n = 45	CTD Total $\mu \pm \sigma$ n = 140	ETD 0.75 m/s $\mu \pm \sigma$ n = 52	ETD 1.00 m/s $\mu \pm \sigma$ n = 43	ETD 1.25 m/s $\mu \pm \sigma$ n = 45	ETD Total $\mu \pm \sigma$ n = 140
Ankle Joint								
Peak power production (W/kg)	3.48 ± 1.4	3.81 ± 1.4	5.27 ± 3.44	**4.16 ± 2.38**	1.49 ± 1.02	1.63 ± 0.98	1.42 ± 1.18	**1.52 ± 1.05**
Peak power absorption (W/kg)	-2.84 ± 1.49	-3.75 ± 2.31	-3.29 ± 1.81	**-3.27 ± 1.9**	-4.21 ± 2.41	-4.98 ± 1.95	-7 ± 3.61	**-5.24 ± 2.88**
Mean power production (W/kg)	1.5 ± 0.62	1.72 ± 0.74	2.25 ± 1.64	**1.81 ± 1.12**	0.46 ± 0.29	0.55 ± 0.27	0.63 ± 0.57	**0.53 ± 0.38**
Mean power absorption (W/kg)	-1.07 ± 0.57	-1.41 ± 0.89	-1.25 ± 0.73	**-1.23 ± 0.74**	-1.13 ± 0.4	-1.46 ± 0.45	-2.05 ± 1.04	**-1.5 ± 0.75**
Positive work (J/kg)	0.57 ± 0.21	0.53 ± 0.18	0.57 ± 0.15	**0.56 ± 0.18**	0.16 ± 0.12	0.15 ± 0.11	0.12 ± 0.11	**0.15 ± 0.11**
Negative work (J/kg)	-0.44 ± 0.238	-0.43 ± 0.31	-0.33 ± 0.21	**-0.4 ± 0.26**	-0.65 ± 0.43	-0.73 ± 0.28	-0.87 ± 0.42	**-0.74 ± 0.39**
Knee Joint								
Peak power production (W/kg)	2.52 ± 1.07	2.65 ± 1.18	2.82 ± 1.39	**2.65 ± 1.21**	1.91 ± 1.4	2.34 ± 1.57	2.64 ± 1.93	**2.26 ± 1.63**
Peak power absorption (W/kg)	-1.98 ± 0.89	-2.01 ± 0.73	-2.06 ± 0.82	**-2.01 ± 0.82**	-1.29 ± 0.76	-1.58 ± 0.76	-1.52 ± 0.83	**-1.45 ± 0.78**
Mean power production (W/kg)	1.1 ± 0.44	1.18 ± 0.46	1.22 ± 0.61	**1.16 ± 0.5**	0.57 ± 0.31	0.77 ± 0.4	0.93 ± 0.56	**0.74 ± 0.44**
Mean power absorption (W/kg)	-0.72 ± 0.3	-0.82 ± 0.26	-0.85 ± 0.33	**-0.79 ± 0.3**	-0.48 ± 0.27	-0.6 ± 0.3	-0.64 ± 0.31	**-0.56 ± 0.3**
Positive work (J/kg)	0.49 ± 0.18	0.43 ± 0.17	0.37 ± 0.19	**0.43 ± 0.18**	0.3 ± 0.19	0.36 ± 0.25	0.36 ± 0.23	**0.34 ± 0.22**
Negative work (J/kg)	-0.25 ± 0.13	-0.22 ± 0.14	-0.24 ± 0.16	**-0.24 ± 0.14**	-0.2 ± 0.16	-0.2 ± 0.16	-0.19 ± 0.15	**-0.2 ± 0.16**
Hip Joint								
Peak power production (W/kg)	3.65 ± 1.31	5.36 ± 2.04	6.44 ± 2.28	**5.07 ± 2.22**	1.75 ± 1.72	2.02 ± 1.44	2.07 ± 1.54	**1.93 ± 1.57**
Peak power absorption (W/kg)	-2.81 ± 1.59	-4.17 ± 2.48	-5.41 ± 2.72	**-4.06 ± 2.51**	-3.64 ± 1.9	-4.33 ± 2.01	-5.7 ± 1.88	**-4.44 ± 2.09**
Mean power production (W/kg)	1.35 ± 0.45	2 ± 0.57	2.36 ± 0.87	**1.88 ± 0.77**	0.68 ± 0.64	0.8 ± 0.59	1.02 ± 0.77	**0.82 ± 0.67**
Mean power absorption (W/kg)	-1.37 ± 0.75	-1.99 ± 1	-2.61 ± 1.07	**-1.96 ± 1.07**	-1.21 ± 0.46	-1.73 ± 0.67	-2.3 ± 0.65	**-1.68 ± 0.73**
Positive work (J/kg)	0.68 ± 0.38	0.77 ± 0.38	0.87 ± 0.35	**0.77 ± 0.38**	0.28 ± 0.37	0.3 ± 0.36	0.3 ± 0.34	**0.29 ± 0.36**
Negative work (J/kg)	-0.52 ± 0.39	-0.56 ± 0.43	-0.564± 0.4	**-0.54 ± 0.4**	-0.78 ± 0.69	-0.77 ± 0.35	-0.92 ± 0.37	**-0.82 ± 0.51**
Total Work								
Total positive work (J/kg)	1.74 ± 0.54	1.74 ± 0.52	1.81 ± 0.44	**1.76 ± 0.5**	0.74 ± 0.56	0.81 ± 0.58	0.79 ± 0.52	**0.78 ± 0.55**
Total negative work (J/kg)	-1.2 ± 0.37	-1.21 ± 0.44	-1.14 ± 0.48	**-1.18 ± 0.43**	-1.63 ± 1.15	-1.7 ± 0.56	-1.98 ± 0.78	**-1.75 ± 0.89**

Table 16: Percentage changes and ANOVA results of the power and work variables

Variables	% Change between ETD and CTD	% Change between towing velocities only in ETD		
		1.00 m/s – 0.75 m/s	1.25 m/s – 1.00 m/s	1.25 m/s – 0.75 m/s
Ankle Joint	**Overall**	**TV2 – TV1**	**TV3 – TV2**	**TV3 – TV1**
Peak power production (W/kg)	-63.5 % ♦ *(1.38)*	8.9 %	-12.4 %	-4.6 %
Peak power absorption (W/kg)	60.6 % ♦ *(0.83)*	18.4 %	40.5 % ♦ *(0.71)*	66.3 % ♦ *(0.94)*
Mean power production (W/kg)	-70.5 % ♦ *(1.45)*	21 %	13.5 %	37.3 %
Mean power absorption (W/kg)	21.6 % ♦ *(0.36)*	28.5 % ♦ *(0.76)*	40.3 % ♦ *(0.76)*	80.3 % ♦ *(1.24)*
Positive work (J/kg)	-74 % ♦ *(2.66)*	-6.77 %	-16.5 %	-22.2 %
Negative work (J/kg)	84.5 % ♦ *(1.05)*	12.2 %	19.3 %	33.9 % ♦ *(0.52)*
Knee Joint				
Peak power production (W/kg)	-15 % ♦ *(0.28)*	22.6 %	12.5 %	37.9 %
Peak power absorption (W/kg)	-28 % ♦ *(0.71)*	22.4 %	-3.45 %	18.2 %
Mean power production (W/kg)	-36.5 % ♦ *(0.89)*	34.8 %	20.3 %	62.2 % ♦ *(0.83)*
Mean power absorption (W/kg)	-28.8 % ♦ *(0.76)*	26.4 %	5.89 %	33.8 %
Positive work (J/kg)	-22.1 % ♦ *(0.47)*	21.3 %	0.398 %	21.8 %
Negative work (J/kg)	-17.6 % ♦ *(0.28)*	0.0277 %	-7.83 %	-7.81 %
Hip Joint				
Peak power production (W/kg)	-62 % ♦ *(1.6)*	15.5 %	2.68 %	18.6 %
Peak power absorption (W/kg)	9.37 %	19.1 %	31.5 %	56.7 % ♦ *(1.09)*
Mean power production (W/kg)	-56.6 % ♦ *(1.46)*	17 %	27.9 %	49.7 %
Mean power absorption (W/kg)	-14 % ♦ *(0.29)*	42.4 % ♦ *(0.91)*	33.1 % ♦ *(0.86)*	89.5 % ♦ *(1.99)*
Positive work (J/kg)	-61.8 % ♦ *(1.29)*	7.61 %	0.348 %	7.98 %
Negative work (J/kg)	50 % ♦ *(0.6)*	-1.32 %	19.6 %	18 %
Total Work				
Total positive work (J/kg)	-55.9 % ♦ *(1.88)*	10.1 %	-2.72 %	7.07 %
Total negative work (J/kg)	48.1 % ♦ *(0.85)*	4.23 %	16.3 %	21.2 %

♦ *= significant difference between CTD and ECC (p<0.05)*
() = Cohen's d Effect Size

7.4 Results

The mean and standard deviations for the ankle, knee and hip joint power and work can be observed in Table 15. The total columns show averages of the all the steps across all the towing velocities in each towing direction. The percentage changes between the CTD and the ETD, and towing velocities in the ETD only can be observed in Table 16. Figure 29 shows the SPM1D One-Way ANOVA results of the comparisons between the CTD and the ETD and their respective power profiles for the ankle, knee and hip joints. It must be noted that when joint power profiles show periods of insignificance between CTD and ETD, their respective joint velocities and moments may be different. This could have a potential cancelling effect which would be masked by the power profiles. The focus of this study was on joint power and work and discussing the joint velocity and moment profiles was deemed inappropriate. However, the Tables and Figures containing joint kinematic and kinetic results can be found in Appendix IX. All the results discussed below are statistically significant ($p < 0.05$).

7.4.1 Ankle Joint

The SPM1D results show that ankle joint power was significantly different at various points during early-to-mid stance (0-2 %, 10-26 %, 34-43 %) and mid-to-late stance (55-91 %, 96-100 %). In both the CTD and the ETD there was a power absorption phase between early-to-mid stance (0~50 % of stance). However, the power absorption phase in the ETD was greater in amplitude when compared to the CTD, which may have contributed to the differences found in the SPM1D results. A power production phase was observed just after mid stance in the CTD (50~90 % of stance). In the ETD, no power was produced or absorbed after mid stance (~50 % of stance), attributing to the significant differences found in the SPM1D results after mid stance.

The comparison between the towing directions resulted in 63.5 % (ES = 1.38) and 70.5 % (ES = 1.45) higher peak and mean power production in the CTD. In the ETD, peak power absorption was 60.6 % (ES = 0.83) higher than the CTD. However, mean power absorption was only 21.6 %

(ES = 0.36) higher. Positive work was 74 % (ES = 2.66) lower whilst negative work was 84.5 % (ES = 1.05) higher in the ETD.

In the ETD, peak power absorption at the fastest towing velocity of 1.25 m/s (TV3) was 40.5 % (ES = 0.71) higher than at 1.00 m/s (TV2) and 66.3 % (ES = 0.94) higher at than at 0.75 m/s (TV1). Mean power absorption increased with towing velocity and was 28.5 %, 40.3 % and 80.3 % (ES = 0.76 to 1.24) higher between the comparisons (TV2-TV1, TV3-TV2, TV3-TV1). Negative work was 33.9 % (ES = 0.52) higher between the fastest and slowest towing velocities (TV3-TV1).

7.4.2 Knee Joint

The SPM1D results show that knee joint power was significantly different during early-to-mid stance (0-17 %, 23-41 %) and late stance (64-85 %, 95-100 %). In the CTD, there was a rapid power absorption phase just after toe-on between 0~20 % of stance. This was followed by a period of power production until ~90 % of stance, where a short phase of power absorption occurred just before toe-off. In the ETD, a similar short phase of power production occurred just before toe-off. An initial power production phase occurred (up to ~10 % of stance), which may have attributed to the differences found at early stance. This was followed by a period of no power production or absorption (up to ~40 % of stance). Power production occurred between 40~80 % of stance, which was much smaller in amplitude than in the CTD.

The comparison between the towing directions resulted in both power production and generation being lower in the ETD than in the CTD. Peak and mean power production was 15 % (ES = 0.28) and 36.5 % (ES = 0.89) lower. Peak and mean power absorption was 28 % (ES = 0.71) and 28.8 % (ES = 0.76) lower. Positive and negative work were 22.1 % (ES = 0.47) and 17.6 % (ES = 0.28) lower in the ETD.

Mean power generation increased by 62.2 % (ES = 0.93) between the fastest and slowest towing velocities in the ETD (TV3-TV1). No other significant findings were observed between the towing velocities in the ETD.

7.4.3 Hip Joint

The SPM1D results show that hip joint power was significantly different during early stance (0-32 %) and late stance (82-100 %). The difference during early stance can likely be attributed to a period of power production in the CTD compared to the ETD where the power produced was negligible. A similar phenomenon occurred at late stance, where a period of power production was observed in the CTD just before toe-off, whilst no power was produced in the ETD.

The comparison between the towing directions showed that peak and mean power production were 62 % (ES = 1.60) and 56.6 % (ES = 1.46) higher in the CTD. There was no significant difference found in peak power absorption. However, a small effect (ES = 0.29) was observed as mean power absorption was 14 % higher in the ETD. Positive work was 61.8 % (ES = 1.29) lower whilst negative work was 50 % (ES = 0.60) higher in the ETD.

The comparison between the towing velocities in the ETD resulted in peak power absorption being 56.7 % (ES = 1.09) larger in the fastest towing velocity compared to the slowest (TV3-TV1). Mean power absorption increased substantially with towing velocity and was 42.4 %, 33.1 % and 89.5 % (ES = 0.86 to 1.99) between the comparisons (TV2-TV1, TV3-TV2, TV3-TV1), respectively.

7.4.4 Total Work

Total positive work was 55.9 % (ES = 1.89) lower and total negative work was 48.1 % (ES = 0.85) higher in the ETD. No significant differences in total positive and negative work were found when comparing between towing velocities in the ETD.

7.5 Discussion

To the best of the authors' knowledge this is the first study to investigate joint power and work in isokinetic horizontal towing which is a novel gait unseen in previous research. As such, integrating previous unrelated research was seen as problematic. Hence, we compared the results found in ETD to CTD to further understand the differences found between each gait and how they could be further used by researchers and practitioners. Understanding the role of the ankle, knee and hip joint power was the focus of this research. The main findings were: 1) The ankle joint absorbed greater power in ETD at early-stance which increased in magnitude with ECC towing velocity and did not generate any power after mid-stance; 2) The knee joint did considerably less work than the ankle and hip joints in ETD and showed substantially less power production and absorption compared to the CTD; 3) During mid stance both CTD and ETD show a power absorption phase. However, similar to the ankle joint the hip joint showed minimal power production; and, 4) Total positive work was lower and total negative work was higher in the ETD.

Ankle joint power production was significantly higher in the CTD (peak: 63.5 %, ES = 1.38 & mean: 70.5 %, ES = 1.45, $p<0.05$) and power absorption was significantly higher in the ETD (peak: 60.6 %, ES = 0.83 & mean: 21.6 %, ES = 0.36, $p<0.05$). This supports previously found evidence that the two towing directions have fundamentally different movement strategies to produce and absorb force and power (Chapter 6). In the ETD, there was only power absorption at early stance and no power generation for the rest of the stance phase. This is supported by the significant differences found in the SPM1D results at early-to-mid stance (0-2 %, 10-26 %, 34-43 %, $p<0.05$) and mid-to-late stance (55-91 %, 96-100 %, $p<0.05$). In the CTD, there was more positive work done (0.56 J/kg) than negative work (-0.4 J/kg), which resulted in an energy surplus. The much greater negative work (-0.74 J/kg) compared to the negligible positive work (0.15 J/kg) done by the ankle joint in the ETD resulted in a substantially large energy deficit. This large energy deficit according to the work-energy theorem supports the finding that the ankle joint was likely dissipating the power absorbed as heat or energy was being leaked through the joints, either at the ankle or further along the kinetic chain. This also suggests that the ETD does not optimise ankle joint SSC function. Previous research (Chapter 6) showed that contact times were significantly larger during isokinetic horizontal towing (ETD = 0.8 s, CTD = 0.69 s) compared to conventional fast SSC movements such as drop jumps and sprinting [94]. This longer contact time coupled with the lack of a power production phase is further evidence that SSC was not being optimised and the energy absorbed was being dissipated at the ankle joint.

Figure 29 shows a large spike in power absorption just after toe-on. In the ETD, as the toe impacts the ground the ankle joint rapidly dorsiflexes absorbing large ECC forces. This is due to the athlete trying to prevent the ankle from dorsiflexing further and the heel touching the ground over the stance cycle. It was envisaged that maintaining a stiff ankle joint during the initial impact would allow athletes to absorb larger ECC forces in the ETD. As the towing velocities increased in the ETD, the ankle joint power absorption also increased significantly. Peak and mean power absorption were the highest at the fastest towing velocity (1.25 m/s – TV3) (peak: -7, mean: -2.05 W/kg) compared to the slowest towing velocity (0.75 m/s – TV1) (peak: -4.21, mean: -1.13 W/kg). It was previously reported that as the towing velocity increased the ground reaction forces increased upon impact (Chapter 6). It was speculated that as a result of the larger impact forces, the ankle joint absorbed more power as the towing velocity increased.

Figure 29 shows that in the CTD, a period of knee joint power production occurred until ~90 % of stance, where a short phase of power absorption occurred just before toe-off. In the ETD, power production and absorption were negligible compared to the CTD. The reason why both power profiles are vastly different to each other is unclear. Peak and mean power production and generation was lower in the ETD, and the knee joint did considerably less positive and negative work, in not only the ETD but also when compared to the ankle and hip joints. This is further supported by the shape of the power curve in Figure 29. This suggest that the knee joint power was not being overloaded during ECC isokinetic towing. It was envisaged that the CTD would be a more knee dominant movement given that the ability to extend the knee during early acceleration is associated with higher levels of sprint performance [95]. However, it was interesting to find that power production and absorption were lower than in the ankle and hip joints. Johnson and Buckley (2001) and Bezodis et al. (2008) also found that at mid-acceleration and maximum velocity phases of a sprint, the knee joint had lower power measures compared to the ankle and hip [85, 88]. This suggest that the role of the knee may simply be trying to maintain the body's centre of mass height instead of producing/absorbing force over the stance phase in both the CTD and the ETD, as suggested by Johnson and Buckley (2001). Furthermore, it can be speculated that the knee joint power may not be being overloaded during both the CTD and the ETD.

The hip joint power profiles showed a similar power absorption phase during mid-to-late stance between the towing directions (Figure 29). This may be attributed to the non-significant differences found by the SPM1D analysis between 35-81% of stance in both directions. Similar to the ankle joint, the hip joint showed minimal power production over the entire stance phase in the ETD. Much greater negative work (-0.82 J/kg) compared to positive work (0.29 J/kg) was also observed. This suggests energy leakage was occurring at the hip joint and both ankle and hip joints were overloading the power absorption or eccentric phase in the ETD. However, the power absorption phases occurred at different points in the stance between the two joints. The power absorption phase at the hip occurred at mid-to-late stance (~75 %) whereas the power absorption phase at the ankle joint occurred at early stance (~15 %). This intuitively makes sense as power is absorbed distal-to-proximal during the ECC or landing phase of sprinting. However, the power profile of the knee shows no power absorption through mid-stance, which suggests that a different strategy of power absorption was taking place instead of the kinetic chain mechanism. It is well established that during the CON phase power production in sprint running is transferred in a proximal-to-distal temporal sequence via the hip, knee and ankle joints [89]. This was clearly evident in the CTD as power was produced at the hip joint at early stance followed by the knee joint at mid-stance and then at the ankle joint at mid-to-late stance (Figure 29).

Total positive work was 55.9 % lower and total negative work was 48.1 % higher in the ETD, further supporting the contention that these two forms of towing offer different overloads and physiological stresses to the tissues involved in force transmission. CON isokinetic towing would seem of utility in that it emphasises normal SSC function, by programming set isokinetic towing velocities whilst specifically absorbing and producing power in a sprint specific manner. However, it is unclear the effect the larger contact times during the CTD (0.69 s, Chapter 6) would have on SSC optimisation, given that larger coupling times result in less energy recovery and greater energy leakage. ECC isokinetic towing on the other hand may offer a unique method to overload the tissues associated with ankle and hip joint power absorption without emphasising power production. As mentioned earlier, optimising SSC function is beneficial to sprint performance and it may be that overloading the eccentric or power absorption phase can preferentially target tissues influential in storing elastic energy. Targeting the ECC capabilities in such a manner may be of interest to researchers and practitioners, which to the best of the author's knowledge is difficult to replicate with conventional sprint training modalities.

Absorbing and producing greater joint power may be useful in improving sprint performance [86], as absorbing and then producing power can be characterised as SSC function [81], which was found to be a phenomenon that occurred in the CTD. Recovering larger amounts of energy absorbed in the production phase is known as optimising SSC function as the movement becomes more efficient. The importance of SSC function and optimising it in sprint performance has been well established [94]. However, it is unclear the effect the larger contact times during the CTD (0.69 s, Chapter 6) would have on SSC optimisation, given that larger coupling times result in less energy recovered [34].

Although comparing the power and work profiles found in this study to what has previously been reported in various phases of sprint may not be a valid comparison, it was however interesting to find that ankle joint power profiles in the CTD were similar during the early acceleration phase of the sprint. Charalambous et al. (2012), Bezodis et al (2014), and Brazil et al. (2017) found that the ankle joint power was in a period of power absorption up to mid stance followed by production during the first stance phase of a sprint [83, 84, 86]. Power production was substantially larger than power absorption (1.27 times larger) in the CTD, which is contrary to what Bezodis et at. (2008) and Johnson and Buckley (2001) reported during the maximum velocity phase and mid-acceleration of sprint running where the power absorption phase was larger than power production phase [85, 88]. Knee joint power profiles in the CTD differed to what has previously been reported during the early acceleration phase of the sprint [83, 84, 86]. However, in the CTD power was absorbed just after toe-on and was similar to what has previously been reported by Bezodis et al.

(2008) during the maximal velocity phase of sprint running [85]. Hip joint kinetic profiles in the CTD were similar to what has previously been reported during the early acceleration phase of the sprint. Charalambous et al. (2012), Bezodis et al (2014), and Brazil et al. (2017) found that the hip joint produced power up to mid stance followed by power absorption [83, 84, 86]. These comparisons may be of use to practitioners and researchers by giving them further insights into the movement of the two towing directions and which one may be better suited for the adaptations they are after.

7.6 Conclusion

In conclusion, CON and ECC isokinetic horizontal towing have significantly different power profiles. ETD has greater ankle and hip joint power absorption and much smaller power production when compared to CTD. ETD could be of use to researchers and practitioners that are interested in applying a unique power absorption overload stimulus to the hip and ankle tissues without producing power and without overloading the knee joint. Furthermore, training at higher ECC towing velocities could administer greater absorptive overload at the ankle and hip joints. Both CTD and ETD offer unique sprint-specific stimuli that are not achieved with conventional sprint training methods. Researchers and practitioners could incorporate CON and ECC isokinetic horizontal towing into their training, which could potentially have a substantial impact on the performance of the hip and especially the ankle joint that could lead to improved sprint performance. However, further longitudinal research needs to be conducted to determine the efficacy of CON and ECC isokinetic horizontal towing and its effects on sprinting performance.

Section 4: Effects of Isokinetic Horizontal Towing

Chapter 8: Effects of Isokinetic Horizontal Towing on Sprint Performance in Elite Female Field Hockey Players

This chapter comprises of the following paper entitled *"Effects of Isokinetic Horizontal Towing on Sprint Performance in Elite Female Field Hockey Players"* that has been prepared but not yet submitted.

8.1 Prelude

The chapters in Section 3 were conducted to inform the scope of the following chapter, which is the capstone training study. First, the variability of the ECC towing movement suggested that two familiarisation sessions were required to achieve consistency. Second, the ground reaction forces were analysed, which suggested that the two towing directions apply and produce force using different movement strategies. Third, the power and work analysis showed that the ankle and hip joints are absorbing energy and likely dissipating it in the ECC towing direction. This overload of the ankle and hip joints in a sprint-specific movement is unique and not seen with conventional resistance towing methods. Thus, the purpose of the following chapter was to determine the effects of CON and ECC towing on sprint performance. Specifically, to compare the effects within and between the two groups to determine if one or the other towing stimulus was better for improving sprint performance. The isokinetic horizontal towing periodized protocol was informed by the previous two chapters. Both chapters suggested that progressively increasing the towing velocity increases GRFs and power production/absorption.

8.2 Introduction

Team sports such as soccer, rugby and hockey often rely on their athletes' sprinting ability [1-3, 96]. Elite field hockey in particular requires athletes to perform repeated maximal effort sprints throughout a game [5, 96, 97]. Therefore, improving their sprint performance has often been a focus for practitioners and researchers. Resistance and strength training continue to be the most commonly used methods to improve sprint performance [98]. Resisted sprinting tools (e.g. sled towing) in particular are incorporated within training programmes due to their specificity to sprinting [12, 48, 49]. Resisted towing as a sprint training tool provides the focus of this study.

Typically resisted towing involves the athlete attaching a harness to themselves and a sled and thereafter puling a variety of loads over a variety of distances, depending on the sought adaptation. Of interest to these authors was whether a novel resistance training method called isokinetic horizontal towing provided a sprint-specific stimulus. Isokinetic horizontal towing is achieved by using a custom built horizontal eccentric towing device (HET) (for more information on this device, refer to Chapter 4). Isokinetic horizontal towing provides two different overload stimuli in a sprint-specific modality, a concentric (CON) and an eccentric (ECC) overload to the musculo-skeletal system (for a detailed explanation of the two movements, refer to Chapter 6). In the CON towing direction (CTD), the athlete would aim to move forward in a sprint stance whilst connected to the HET with a tether and a harness. However, their speed would be held constant regardless of their force input. In the ECC towing direction (ETD), the athlete would also aim to move forward in a sprint stance but would be pulled back in by the HET at a constant speed (Figure 15).

It has been established that there was a significant biomechanical difference between the two towing directions (Chapters 6 and 7). The ground reaction force profiles suggest different movement strategies were being implemented to produce and absorb force (Chapter 6). Joint power and work analysis of the two directions showed that in the ETD ankle and hip joint power absorption was overloaded and the amount of energy stored was dissipated due to slow coupling times i.e. energy leakage (Chapter 7). One of the speculated benefits of ECC isokinetic horizontal towing was that by overloading the energy absorption of the ankle and hip joints, adaptations in tissues would result in changes of elastic characteristics of the lower limb. Thus, resulting in changes in stretch-shortening cycle (SSC) function. Given the importance of SSC function in sprint performance [66, 71], it was hypothesised that ECC isokinetic horizontal towing would improve stiffness qualities which would translate into improved SCC function resulting in faster sprint times.

Another potential benefit of eccentric towing is that the ETD may elicit improvements in fast muscle phenotypic properties and power more so than the CTD, given that there is evidence to suggest the implementation of faster ECC contractions leads to changes in faster muscle phenotypes [27, 28, 30, 31]. Paddon-Jones et al. (2001) showed that applying an isokinetic ECC stimulus to joints at speeds of >180 °/s, would elicit a shift toward faster muscle phenotypes [30]. Although not reported in Chapter 7, peak joint velocities were calculated and were found to be greater than 180 °/s for the ankle, knee and hip joints. Peak ankle dorsiflexion velocities were 338 °/s in the CTD and 449 °/s in the ETD (Appendix IX). However, whether these phenotypic changes occur needs further investigation.

Incorporating CON and ECC isokinetic horizontal towing into the training sessions of athletes may have unique effects on sprint performance, however, no research has been conducted to determine its efficacy in an ecologically valid setting. Given the prior information, the purpose of this study was to determine the effects of concentric and eccentric towing on sprint performance of elite female field hockey players. First, it was hypothesised that both the ETD and the CTD would elicit improvements in sprint times over a four-week intervention period. Isokinetic horizontal towing provided the ability to overload force production and absorption in the horizontal plane that is specific to sprinting and was envisaged that it would improve the athlete's sprint performance by improving their horizontal force production capabilities. Second, the ETD would affect vertical and leg stiffness qualities, leg stiffness affected more so than vertical stiffness as isokinetic horizontal towing is overloading the horizontal plane more so than the vertical plane [99]. Third, it was hypothesised that the eccentric training would result in phenotypic changes observed as a change in optimal cadence results from an inertial load cycle ergometer which can be a proxy measure and correlate well with fast twitch muscle fibres in the lower limbs [100].

8.3 Methods

8.3.1 Experimental Approach to the Problem

Elite players from the New Zealand women's national field hockey team participated in this study, which aimed to determine the effects of CON and ECC isokinetic horizontal towing on sprint performance; specifically changes to their sprint profiles and kinematics and inertial load cycle ergometer performance and after a four-week intervention of two sessions per week. The subjects were randomly allocated into either the CON towing direction (CTD) group or the ECC towing direction (ETD) group. Both groups were given identical strength and conditioning programmes and participated in similar field- or turf-based training as a team. The difference between the two groups was the towing direction. The number of reps, towing velocity and towing distance were progressively increased and kept consistent between groups. Two familiarisation sessions were conducted to achieve movement consistency, as previously reported [72]. Pre- and post-testing consisted of 3 x 50 m sprints and 3 x inertial load cycle ergometer trials to calculate the following dependent variables: peak velocity, sprint times, sprint kinematics, stiffness properties, peak power and optimal cadence. The effects of CON and ECC isokinetic horizontal towing were determined through the calculation of change scores of the dependent variables within and between groups. Effect size (ES) statistics and qualitative inferences were used to determine the magnitude and likelihood of observed effects.

8.3.2 Subjects

Initially eighteen elite female field hockey players volunteered to participate in this study (except goal keepers). After attrition due to injury (unrelated to IHT), illness and unforeseen circumstances ($n = 8$), a final of ten subjects (Mean ± SD: age = 22.5 ± 2.07 years, height = 170 ± 5.82 cm, weight = 67.7 ± 6.05 kg) were retained. The subjects had at least one year of supervised training experience and were free from any lower limb injury for at least six months prior to the start of this study. The subjects were provided with an overview of all the procedures in this study prior to completing informed consent forms. This study had the full support of the coaching and support staff. The testing procedures in this study were approved by the Auckland University of Technology Ethics Committee (15/375 – see Appendix I, VI, VII for more details).

8.3.3 Procedures

The subjects had participated in an international competition and were coming off a two-week detraining period. This was followed by a six-week resistance training block prior to travelling to another international competition. This study was conducted during the six-week resistance training period. Pre- and post-testing were conducted during the first and last week of the six-week block resulting in a four-week intervention of CON and ECC isokinetic horizontal towing. During all testing sessions, the subjects completed a 15-minute standardised dynamic warmup which included dynamic stretching, sprint drills, jogging and submaximal sprint efforts. The subjects' heights and weights were measured at the start of each testing session. Pre- and post-testing consisted of 3 maximum effort 50 m sprints and 3 maximum effort trials on an inertial load cycle ergometer. The sprints were conducted on Mondays and the erg tests were conducted on Wednesdays (Table 17) during the pre- and post-testing weeks. The testing protocols and time of day for all tests were kept consistent between pre- and post-testing weeks.

8.3.3.1 Sprint Profiling

Sprint testing was performed in an indoor Mondotrack (Mondo, Alba, Italy track at AUT Millennium (Auckland, New Zealand). Subject's footwear was consistent for both pre- and post-testing. The testing sessions were conducted at the start of their Monday gym sessions (Table 18). After the subjects finished their standardised warmup, they were instructed to start the sprint from a split stance without a countermovement and to accelerate maximally without decelerating before the 50 m mark. Three trials were recorded with an inter-trial rest period of 5 minutes. The sprints were recorded using a radar device (Stalker ATS II, Applied Concepts, Dallas, TX, USA). The radar device was set two metres behind the subject and one metre high (approximate height of the subjects' centre of mass). The data from the radar device was sampled at 46.9 Hz and was interfaced using a portable laptop, which ran proprietary software supplied by the manufacture (Stalker ATS 5.0, Applied Concepts, Dallas, TX, USA). The data was pre-processed in this software. The start of the sprint was determined by any deviations above 0.5 m/s in the trace. The data was then exported to MATLAB (MathWorks, Natick, MA, USA) for further analysis. Radar data was then modelled to fit the inverse exponential function of the velocity-time relationship using the least squares method [101]:

$$v(t) = v_{max}. \left(1 - e^{-\frac{t}{\tau}}\right) \quad [3]$$

This equation was then integrated to calculate the distance-time curve [102]:

$$x(t) = v_{max}. \left(t + \tau. e^{-\frac{t}{\tau}}\right) - v_{max}. \tau \quad [4]$$

$\boldsymbol{v}$ = velocity (m/s), $\boldsymbol{x}$ = distance (m), $\boldsymbol{t}$ = time in seconds (s), $\boldsymbol{v_{max}}$ = maximum velocity (m/s), $\boldsymbol{\tau}$ = acceleration time constant

Peak velocity and split times at 10 m, 20 m, and 40 m were determined using the modelled velocity and distance time data and then averaged from the three trials. The sprint kinematic variables were measured using an OptoJump (MicroGate, Bolzano, Italy) light system placed between 35-50 m to record data during the maximum or constant velocity phase of the sprint. The OptoJump system consisted of a light transmitting bar and a receiving bar that contained 96 light-emitting diodes per meter. Fifteen of these bars were placed end to end and in parallel to either side of the sprint lane. The system recorded ground strike data as the foot broke the beam of light between the bars upon impact. Proprietary software provided by MicroGate (OptoJump Next) calculated the desired sprint variables. Flight time (FT), contact time (CT), step frequency (SF) and step length (SL) were calculated for each step during the maximum or constant velocity phase of the sprint. The sprint kinematic variables were then averaged across all steps between 35-50 m. Vertical stiffness (K_{vert}) and leg stiffness (K_{leg}) were calculated using the equations below described by Morin et al (2005) [103]:

$$k_{vert} = F_{max}.\Delta {y_c}^{-1} \qquad [5]$$

$$F_{max} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c}+1\right) \qquad [6]$$

$\boldsymbol{m}$ *= body mass (kg),* $\boldsymbol{t_f}$ *= flight time (s),* $\boldsymbol{t_c}$*= contact time (s)*

$$\Delta y_c = \frac{F_{max}{t_c}^2}{m\pi^2} + g\frac{{t_c}^2}{8} \qquad [7]$$

$$k_{leg} = F_{max}.\Delta L^{-1} \qquad [8]$$

$$\Delta L = L - \sqrt{L^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta y_c \qquad [9]$$

$\boldsymbol{L = 0.53h}$ *where* $\boldsymbol{h}$ *= height of the participant (m)*

8.3.3.2 Inertial Load Cycle Ergometer

A custom-built inertial load cycle ergometer (High Performance Sport New Zealand, Auckland, New Zealand) was used to assess peak power output and the pedalling rate at peak power (optimal cadence) during a maximal effort cycling sprint. After a standardised warmup, the subjects performed 3 maximal effort cycle sprints on the ergometer, each separated by a 5-minute rest period. Each trial required the subjects to remain seated on the bike and complete 8 crank revolutions (4-6 seconds) from a stationary position pedalling as fast as they could. The start position was held consistent at a 50° crank angle from the vertical of the right crank for all subjects. Seat and handlebar position were adjusted for each participant and remained consistent between pre- and post-testing. The inertial load cycle ergometer calculated the torque-velocity relationship by measuring the angular acceleration of the flywheel and multiplying it by its moment of inertia [104]. The ergometer had a large flywheel moment of inertia (I) of 1.08 kgm^2 and a high gear ratio (G) of 4.77 (62:13) which meant that the torque-velocity relationship was derived from a wide range of torques and angular velocities. The ergometer consisted of an optical encoder system fitted on a stationary flywheel-resistance bike (Element, Body Bike, Frederikshavn, Denmark). This was used to measure the angular velocity (ω) of the flywheel every 10° of flywheel rotation and every 2.1° of crank rotation. Custom LabView software and a data acquisition module (National Instruments, Austin, TX, USA) were used to capture the data and a custom spreadsheet was used to process the data. Angular acceleration (α) was calculated as the discrete time derivative of angular velocity results. The torque (T) and power (P) data were then calculated from the following equations:

$$T = I\alpha \times G \qquad [10]$$

$$P = I\alpha\omega \qquad [11]$$

The custom spreadsheet produced a parabolic power-velocity and a linear torque-velocity relationship. Peak power (W/kg) and the cadence at which peak power occurred (rpm) were calculated [104]. Inertial load cycle ergometer validity and reliability has been previously established [104-106]. The subjects in this study had previously used the ergometer and were already familiar with its use prior to the start of this study.

8.3.3.3 Isokinetic Horizontal Towing Protocol

After pre-testing, the subjects were randomly allocated into either the CTD or the ETD group. Independent t-tests were carried out for all the pre-testing variables which showed no significant difference between the two groups ($p<0.05$). During the six-week resistance training block, the strength and conditioning coach of the squad had a pre-programmed strength and power block that all the subjects followed (e.g. squats, bench pulls, power cleans). The training sessions for both groups were conducted on Mondays and Wednesdays for the four-week period. The sessions were incorporated within their gym sessions. The subjects had scheduled field-based sessions and played club games during the six-week period (Table 18). Two familiarisation sessions were conducted during the pre-testing week to achieve movement consistency [72]. The first familiarisation session was conducted on Wednesday after their cycle ergometer tests, and the second session was conducted on Friday prior to the start of their scheduled gym session.

The isokinetic horizontal towing training load was progressively increased for both groups over the four-week period. The towing velocity was increased from 0.75 m/s towing velocity to 1.25 m/s. Chapter 7 showed that power production and absorption increased in magnitude with towing velocity, specifically in the ETD. This suggested that testing the effects of an increasing towing velocity in this study may be beneficial. The repetitions and the distance travelled during a tow was also progressively increased. The isokinetic horizontal towing protocol and external training volume was kept consistent between both groups to improve the accuracy of between groups comparisons (Table 17). The ten subjects completed 100% of the isokinetic horizontal towing protocol.

Table 17: Six-week training programme

Phase	Week	Day	Reps x Towing Velocity (m/s) x Distance (m)
Testing	Week 1	Pre-Test	3x 50 m Sprints
		Pre-Test	3 x Trials - OC Bike
Familiarisation		Day -1	1 x 0.5 x 10
		Day 0	2 x 0.75 x 10
Intervention	Week 2	Day 1	3 x 0.75 x 12.5
		Day 2	3 x 0.75 x 12.5
	Week 3	Day 3	4 x 1 x 12.5
		Day 4	4 x 1 x 12.5
	Week 4	Day 5	4 x 1.25 x 15
		Day 6	4 x 1.25 x 15
	Week 5	Day 7	5 x 1.25 x 15
		Day 8	5 x 1.25 x 15
Testing	Week 6	Post-Test	3x 50m Sprints
		Post-Test	3 x Trials - OC Bike

Table 18: Weekly schedule of the Women's Black Sticks team

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
AM	Gym Session		Gym Session		Gym Session	Club Game	Rest
PM	Field Session	Field Session		Field Session			

8.3.4 Statistical Analysis

The data is presented as means and standard deviations ($\mu \pm \sigma$) with percentage change between pre- and post-testing for each group. Effect sizes (ES) with 90% confidence intervals were calculated based on Cohen's effect size statistics [77]. A statistical spreadsheet was used to determine the magnitude of change within and between groups [107]. Threshold values for ES were set as: ≤0.19 trivial, 0.2 – 0.59 small, 0.6 – 1.19 moderate, 1.2 – 1.99 large, 2.00 – 3.99 very large, and >4.00 extremely large. Probabilities were calculated to establish whether the true differences were lower, similar, or higher than the smallest worthwhile change of 0.2 or difference. Quantitative chances of higher or lower differences were qualitatively evaluated as follows: ≤0.99% almost certainly not, 1 – 4.9% very unlikely, 5 – 24.9% unlikely, 25 – 74.9% possible, 75 – 94.9% likely, 95 – 98.9% very likely, and >99% almost certain. If the chance of higher or lower differences was >5%, the true difference was deemed to be unclear [108].

Table 19: Performance data from the pre- and post-testing of both the CTD and ETD groups

Variables	ETD					CTD				
	Pre μ ± σ	Post μ ± σ	% Change	ES ± 90% CI	Qualitative Inference	Pre μ ± σ	Post μ ± σ	% Change	ES ± 90% CI	Qualitative Inference
Sprint Profiling										
Peak Velocity (m/s)	7.89 ± 0.3	7.76 ± 0.32	-1.6%	-0.29 ± 0.23	Likely Lower	7.58 ± 0.24	7.56 ± 0.33	-0.23%	-0.04 ± 0.32	Unclear
0-10m Time (s)	2.26 ± 0.09	2.28 ± 0.05	0.84%	0.19 ± 0.64	Unclear	2.27 ± 0.05	2.29 ± 0.09	1.19%	0.26 ± 0.51	Unclear
0-20m Time (s)	3.63 ± 0.13	3.67 ± 0.09	1.06%	0.25 ± 0.4	Possibly Higher	3.67 ± 0.07	3.71 ± 0.1	0.99%	0.27 ± 0.47	Possibly Higher
0-40m Time (s)	6.2 ± 0.22	6.28 ± 0.18	1.25%	0.28 ± 0.18	Likely Higher	6.33 ± 0.14	6.37 ± 0.19	0.74%	0.2 ± 0.36	Possibly Higher
Sprint Kinematics										
Flight Time (s)	0.111 ± 0.007	0.113 ± 0.01	1.62%	0.15 ± 0.33	Possibly Trivial	0.117 ± 0.005	0.108 ± 0.006	-0.91%	0.12 ± 0.42	Unclear
Contact Time (s)	0.129 ± 0.01	0.13 ± 0.011	0.79%	0.07 ± 0.25	Likely Trivial	0.133 ± 0.005	0.134 ± 0.007	0.14%	0.02 ± 0.44	Unclear
Step Frequency (Hz)	4.17 ± 0.1	4.12 ± 0.1	-1.18%	-0.35 ± 0.33	Likely Lower	4.17 ± 0.09	4.15 ± 0.16	-0.38%	-0.09 ± 0.46	Unclear
Step Length (cm)	190 ± 6.83	189 ± 8.92	-0.56%	-0.1 ± 0.24	Likely Trivial	182 ± 6.31	182 ± 5.91	-0.26%	-0.05 ± 0.19	Likely Trivial
Vertical Stiffness (kN/m)	97.9 ± 18.5	97.6 ± 21.2	-0.26%	-0.01 ± 0.25	Unclear	85.3 ± 8.45	85 ± 7.01	-0.27%	-0.02 ± 0.5	Unclear
Leg Stiffness (kN/m)	14.1 ± 2.26	14.7 ± 3.13	4.03%	0.15 ± 0.3	Possibly Trivial	13 ± 2.12	13 ± 1.87	0.45%	0.02 ± 0.18	Likely Trivial
Inertial Load Cycle Ergometer										
Peak Power (W/kg)	13 ± 0.77	14 ± 0.69	7.85%	0.98 ± 0.24	Most Likely Higher	12.9 ± 0.65	13.5 ± 0.97	4.74%	0.53 ± 0.55	Likely Higher
Optimal Cadence (rpm)	119 ± 9.34	117 ± 6.13	-1.21%	-0.13 ± 0.7	Unclear	117 ± 4.65	117 ± 6.14	0.36%	0.05 ± 0.47	Unclear

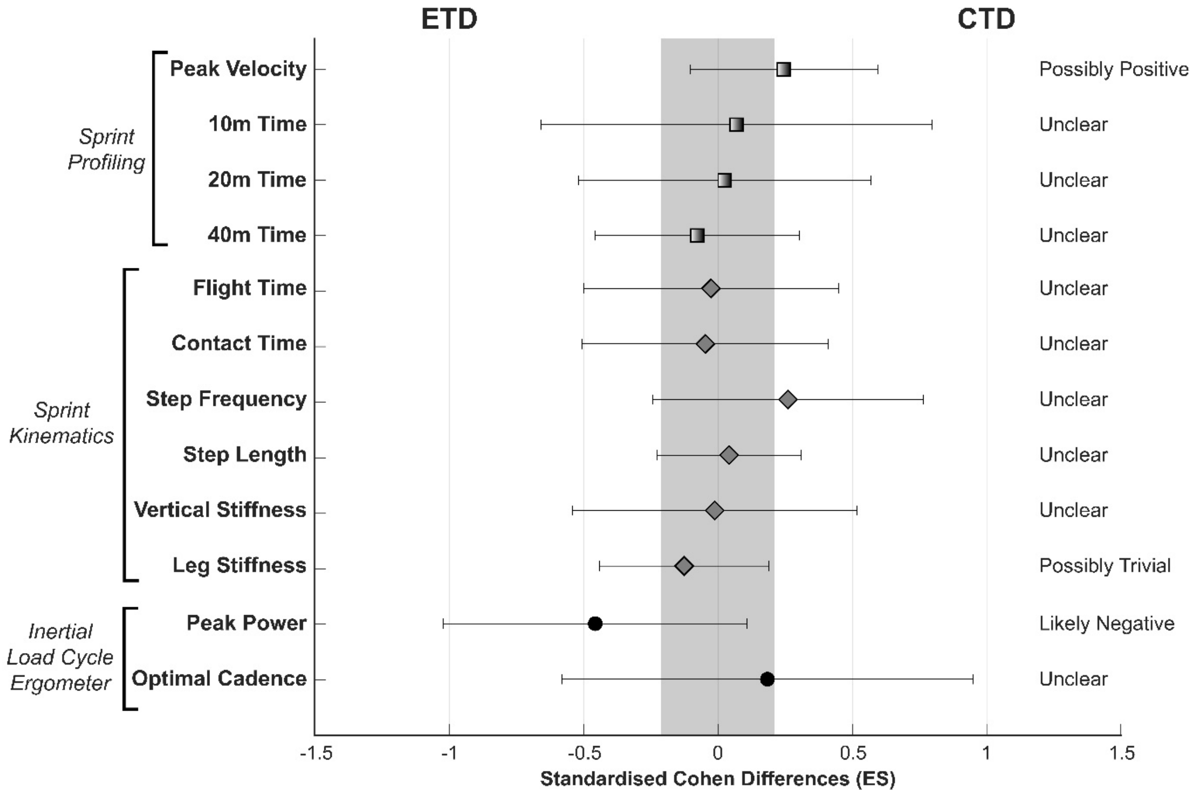

Figure 30: The standardised Cohen differences between the ETD and the CTD. Differences are for the change in selected performance variables. Negative values indicate a larger effect in the ETD, and positive values indicate a larger effect in the CTD. Qualitative inferences indicate the likelihood of the effect between ETD and CTD. Error bars indicate uncertainty in the true mean changes with 90% confidence intervals. The shaded area represents the smallest worthwhile change.

8.4 Results

8.4.1 Sprint Profiling

The means, standard deviations, percent change scores, effect sizes and qualitative inferences for all within group results can be observed in Table 3. The between group comparisons can be observed in Figure 30. A likely decrease in peak velocity was observed in the ETD group (~-0.13 m/s; ES ± CI: -0.29 ± 0.23). However, the effects were unclear in the CTD group which resulted in a possibly positive effect in favour of the CTD compared to the ETD (ES ± CI: 0.24 ± 0.35). The effects of isokinetic horizontal towing on the 10 m split times were unclear in both groups, whereas the 20 m split times were possibly higher in both the ETD and CTD groups (~+0.04 s; ES = 0.25 to 0.27). The 40 m split time was likely higher in the ETD group (~+0.08 s; ES ± CI: 0.28 ± 0.18) and possibly higher in the CTD group (~+0.04 s; ES ± CI: 0.2 ± 0.36). The effects of the training between the two groups on the three split times (10 m, 20 m and 40 m) were unclear.

8.4.2 Sprint Kinematics

Only one within group small training effect (ES = 0.35) was observed, the ETD resulting in step frequency becoming slower (~1.2%) All other comparisons were either trivial or unclear.

8.4.3 Inertial Load Cycle Ergometer

Peak power measured from the inertial load cycle ergometer tests most likely increased with ETD training (+1.0 W/kg; ES ± CI: 0.98 ± 0.24) and CTD training (+0.6 W/kg; ES ± CI: 0.53 ± 0.55). This resulted in a likely negative effect in favour of the ETD compared to the CTD (ES ± CI: -0.46 ± 0.57), indicating that ETD training had a greater effect on peak power than CTD training. Optimal cadence results were unclear within and between both training groups.

8.5 Discussion

This study sought to understand the effects of CON and ECC isokinetic horizontal towing on sprint performance. The main findings were: 1) Isokinetic horizontal towing in both towing directions did not improve sprint times after a four-week intervention. Forty metre time likely increased in the ETD group and possibly increased in the CTD group. 2) Peak velocity and step frequency likely decreased in the ETD group and other sprint kinematic changes were unclear or the effects in both groups were likely trivial. 3) Peak power from the inertial load cycle ergometer tests increased in both groups, with the greatest effects noted after ETD training.

Our hypothesis of improvements in sprint times with isokinetic horizontal towing was unsupported by our findings. The effects of ETD and CTD training had a slight negative impact on sprint performance as sprint times increased after the four-week intervention, which was contrary to what was hypothesised. Although 40 m sprint times increased in both groups (+0.04 s), the ETD increase was greater (+1.25%; ES = 0.28 ± 0.18) compared to CTD training (+0.74%; ES = 0.20 ± 0.36). This was likely due to the greater decrease in step frequency (-1.18%; ES = -0.35 ± 0.33) in the ETD group as compared to the CTD group (-0.38%; ES = -0.09 ± 0.46), as step frequency and step length contribute to sprint times. This is further supported by the greater decrease (-1.6%; ES = -0.29 ± 0.23) in peak velocity due to ETD training in comparison to CTD training (-0.23%; ES = -0.04 ± 0.32). It was interesting to note that step length was unaffected in both groups. These findings contradict our initial hypothesis as it was thought that the ETD training would increase stiffness qualities and therefore step frequency due to shorter contact times. An athlete's stiffness qualities contribute to the energy absorption and production of their lower limb musculature [34]. Furthermore, as ETD loading has been shown to overload energy absorption at the ankle and the hip (Chapter 7), it was thought that a chronic adaptation to this loading may provide better storage and utilisation of elastic energy, resulting in better sprint performance. However, this was not the case as contact times were unchanged. The decrease in step frequency likely suggests a detriment in stretch-shortening cycle function. It is however difficult to state that this phenomenon also occurred in the CTD as trivial or unclear effects were reported for the sprint kinematic variables.

It was further hypothesised that the ETD group would elicit changes to fast muscle phenotypic properties and power more so than the CTD. This was partly supported by the results found from the inertial load cycle ergometer tests. Peak power showed a 7.85% (ES = 0.98 ± 0.24) and a 4.74% (ES = 0.53 ± 0.55) increase in the ETD group and the CTD group respectively. However, optimal cadence results were relatively unchanged and were deemed unclear from the qualitative inference. It was envisaged that the ETD group would elicit a higher optimal cadence which is generally believed to reflect a larger proportion of fast-twitch muscle fibres comprising the lower limb musculature [100]. This was not the case; the optimal cadence results suggest that it was inconclusive to determine any muscle phenotype changes. The increases in peak power may be associated with the general resistance and strength training that occurred in both groups. It is unclear as to why peak power was greater in the ETD.

8.6 Limitations

- It is important to note the difficulty of conducting research outside the lab. However, this is the context in which athletes train and therefore the intervention ecologically valid. The training workload of elite athletes is substantial in order to gain a competitive edge. The strength and conditioning programme and their field-based training was progressively increased during the four-week intervention as the team prepared for an international competition series. This was not controlled by the researcher of this study and therefore their workload outside of the intervention may have been a contributing factor in the decreased sprint performance.
- As the team were preparing for a competition series, the intervention time-frame was limited to four weeks. This combined with two intervention sessions per week may not have been long enough to induce changes in performance. Perhaps a longer and a more frequent isokinetic horizontal towing intervention may be beneficial.
- The elite athletes that participated in this study were already very strong, powerful and fast as they need to be in order to play field hockey at the highest level. Therefore, large improvements in performance are unlikely to begin with, especially in between pinnacle competitions as was the case in this study.
- A control group was not included because the limited number of subjects (n=10) restricted the study design to only two intervention groups. It was also believed that balancing the workload between the control and the intervention groups may be challenging as there is currently no research around the workload of isokinetic horizontal towing. By not adding any additional training to the control group, the comparisons between groups may have been compromised. It was difficult to ascertain any equivalent training to add to the control group and thus the reason the control group was omitted from this study.
- A single post-testing session was conducted. Multiple post-testing sessions may have provided further insights into the chronic adaptations of ECC towing. Leong et al (2013) found that performance was depressed after an ECC strength training block which was followed by delayed performance improvement up to 8 weeks post intervention [57].

8.7 Conclusion

To conclude, isokinetic horizontal towing in the eccentric and the concentric towing directions did not improve sprint performance amongst elite female field hockey players. Split times were possibly slower after a four-week intervention. However, isokinetic horizontal towing does provide a unique stimulus and practitioners may look to incorporate it into a broader physical preparation programme. The effects found in this study apply to a small homogenous group (n=10) of elite female field hockey players and should not deter practitioners and researchers from incorporating isokinetic horizontal towing. It may be that different effects may be observed for a different group of athletes, especially ones that may not be at the elite level. Further research or training studies may involve a larger sample size to reduce the uncertainty of the results. Multiple post testing sessions would provide further insight into the long-term adaptations of isokinetic horizontal towing, specifically in the eccentric towing direction.

Chapter 9: Summary, Practical Applications and Future Research Directions

9.1 Summary

The overarching question of this thesis was: "***Can a novel horizontal ECC towing device improve sprint performance?***". Four research objectives were addressed in four separate inter-related sections of the thesis. The key conclusions from each section are summarised below. Ultimately, the aim of the research was to develop a horizontal ECC towing device and provide guidelines on how it could be used in training to potentially improve sprint performance. These guidelines are detailed in the Practical Applications section. Finally, the limitations associated with this thesis are discussed and suggestions for future research directions are detailed.

9.2 Key Findings

9.2.1 Section 1: Reviewing Eccentric Training Technology

Of the nine commercially available ECC training devices reviewed, seven exclusively overload either the vertical or rotational plane. The remaining two devices provided an overload in multiple planes. The advantages and disadvantages of each device was critiqued which resulted in a list of features that would be ideal for an ECC training tool. Whilst the list covered multiple important points, the key feature that was found to be missing across all the devices reviewed was that no device administered an ECC overload in the horizontal plane in a sprint-specific movement. This proved that a gap in the technology existed and thus formed the focus of this thesis. Furthermore, limited research in the field of horizontal ECC training exists providing another gap in the literature and focus for research.

9.2.2 Section 2: Development of the Horizontal Eccentric Towing Device

Due to the lack of horizontal ECC training technology found in the previous section, we suggested that a horizontal ECC towing movement that could be controlled through the use of technology may be of utility as a training tool. The novel horizontal ECC stimulus that we developed requires the athlete to move forward whilst being pulled backwards by a rope or tether (Figure 15). This novel ECC towing movement was then investigated to determine the forces and velocities involved. Two ECC towing movements were investigated (forwards and backwards) using elite power athletes to determine the upper limits of the force and velocity requirements. It was found that the forwards ECC towing movement displayed greater forces (+11.2 %) and velocities (+8.65 %) than the backwards ECC towing direction. The main finding from Chapter 3 was that a custom built horizontal ECC towing device must be able to administer forces up to 1124 N and at velocities up to 2.9 m/s. This information coupled with the list of features from Chapter 2 formed a complete list of specifications for the development of a horizontal ECC towing device. The HET device was constructed using a 10 kW AC synchronous servo gearmotor to act as a winch system. The motor is controlled by a variable speed drive and a programmable logic controller, which allows for accurate speed, position and torque control. A touchscreen PC runs the user interface displaying real-time force and speed measures. The HET device can produce a maximum towing force of 2.80 kN at ground velocities of up to 3.58 m/s. A separate safety logic controller that triggers a safety-rated brake system when the E-stop buttons are pushed to ensures the system can be stopped immediately to protect the athlete in case of an emergency. This section concludes with the successful development of the HET device.

9.2.3 Section 3: Understanding the Biomechanics of Isokinetic Horizontal Towing

Before the HET device could be used in training, we needed to understand the stimulus better, so as future training programme could be better informed. Thus, the purpose of this section was to understand the biomechanics of isokinetic horizontal ECC and CON towing. Chapter 5 found that two familiarisation sessions were needed to achieve movement consistency. This was then implemented in the methodology of Chapter 6, 7 and 8. Chapter 6 found that CON and ECC towing directions have vastly different GRF profiles and this could be due to different movement strategies contributing to force absorption and production. SPM1D analysis showed that there was a significant difference in vertical GRF between towing directions at mid-stance (31 – 54 % of stance) and late-stance (71 – 83 % of stance), and horizontal GRF was significantly different at almost the entire stance phase (0 – 8, 12 – 23, 33 – 88, 94 – 100 % of stance). Chapter 7 investigated the power and work profiles of the two towing directions and found that the ankle and hip joints absorbed greater power in the ETD which increased in magnitude with ECC towing velocity. Overloading the power absorption phase may have an impact of the elastic characteristics of the joint which would affect SSC function and hence sprint performance, a contention that needed investigation.

9.2.4 Section 4: Effects of Isokinetic Horizontal Towing

The four-week intervention of ECC and CON isokinetic horizontal towing yielded no improvements in sprint performance amongst elite female field hockey players. Split times were possibly slower in both towing directions and step frequency was lower in the ETD (~1.2%; ES = 0.35). Peak power on the inertial load cycle ergometer increased in both groups but this cannot be exclusively linked to the intervention as the athletes were also undergoing a strength and conditioning programme.

9.3 Practical Applications

The key objective of this thesis was to build a novel training tool that would have an impact on athletes' sprint performance. Specifically, to provide HPSNZ practitioners working with highly trained athletes' guidelines on the utility of the HET device. However, the practical applications listed below can give practitioners and researchers, working with all levels of athletes, new insight into the concept of horizontal ECC towing:

- The Exentrix and the ARX Fit devices were the only two commercially available ECC training devices reviewed that had the ability to provide a horizontal ECC stimuli. Both devices resembled a traditional cable pulley machine that could be used for various exercises. They used electric motors to control the force and velocity of each movement which gives them greater versatility.
- A horizontal ECC towing movement can be implemented without the need of a custom device. In Chapter 3, we used a trolley that was tethered to the athlete, the trolley was then pushed by one or two persons to tow the athlete whist they resisted maximally (Figure 13). This method does not control the towing velocity but can still be provide a horizontal ECC stimulus in a sprint-specific gait.
- If required, a custom horizontal ECC towing device can be built by following the technical note in Chapter 4.
- At least two familiarisation sessions of horizontal ECC towing are required before it is incorporated within a training programme.
- Although no improvements in sprint performance were found with horizontal ECC towing, there is still an opportunity for practitioners and researchers to apply a unique ECC stimulus to their athletes. The intervention had its limitations as it was based out of the lab in a practical setting. However, to the best of our knowledge, no tool provides a similar overload as the HET device. We recommend practitioners and researchers that are interested in overloading the power absorption phase of the ankle and hip joints should incorporate HET. Since, sprint performance relies on the joints ability to rapidly absorb and produce power, overloading the absorption phase in a sprint-specific manner could

be of use. Targeting the ankle joint's ECC capabilities alone may be of great importance to coaches. The ability of ECC towing to overload the ankle joint could affect joint stiffness. Towing at the faster velocity of 1.25 m/s may also be of use as it could induce a shift towards fast twitch muscle fibres. A progressive protocol is recommended. Faster towing velocities may be incorporated if shorter contact times are required.

9.4 Limitations

The following were the limitations of the thesis:

- The HET device was installed in a gym that is exclusive to New Zealand's elite athletes. The HET device was placed on 20 m indoor track that was surrounded by gym equipment. This limited the space where testing could occur. A custom wooden platform could only incorporate two force plates to capture a few foot strikes. Motion capture cameras could also be placed on one side which meant only a 2D kinematics and kinetics assessment could occur.
- The ECC overload during HET may be limited by the coefficient of friction between the athlete's footwear and the surface of the track. This could perhaps explain the lower ECC GRFs observed in Chapter 6.
- All the studies in this thesis were carried out with elite athletes that had substantial sprint training. It is important to note that although this was useful in Chapters 3, 5, 6, and 7, it is difficult to produce physiological improvement in such well-trained athletes. Greater effects may have been observed in cohorts that are perhaps not elite athletes but still require the tissue adaptations that could improve their sprint ability.
- The difficulty of conducting research outside the lab has often been a limitation. However, this is the context in which athletes train and therefore the intervention had to be incorporated within their existing training schedule. The training workload of elite athletes is substantial in order to gain a competitive edge. Therefore, it was impractical

to program an intervention that would disrupt their needs to perform. The HET intervention was supplemented to their existing strength and conditioning protocol which was not controlled by the researcher of the training study (Chapter 8) and therefore their workload outside of the intervention may have been a contributing factor in the decreased sprint performance.

- The intervention time-frame was limited to four weeks due to external commitments. This coupled with two sessions of ECC/CON towing per week may not have been long enough to induce changes in performance. A single post-testing session was conducted as the athletes had to depart for an international competition.
- There was no control group assigned in the training study (Chapter 8) as there was a limited number of subjects (n=10). This restricted the study design to only two intervention groups (ECC/CON towing). It was also believed that balancing the workload between the control and the intervention groups may be challenging as there is currently no research around the workload of isokinetic horizontal towing. By not adding any additional training to the control group, the comparisons between groups may have been compromised. It was difficult to ascertain any equivalent training to add to the control group and thus the reason the control group was omitted from this study.

9.5 Future Research Directions

Future research should build on the limitations described in the previous section. The HET currently cannot be moved but perhaps further hardware development could allow it to be placed at other facilities. Measuring the foot strikes throughout the entire towing distance along with 3D motion capture would allow for further analysis into the biomechanics of the movement. Further investigation needs to be carried out on the limited ECC GRFs during HET. It may be that footwear with spikes could increase the coefficient of friction between athletes and the surface of the track to increase the amount of ECC force during HET. However, further research needs to be conducted to determine whether the limited ECC GRFs are due to the coefficient of friction or by a different mechanism. It is suggested that a more comprehensive training study be conducted that involves a larger cohort of athletes. This would produce convincing evidence of the effects of training with the HET device. The intervention time frame and number of sessions per week should also be increased with multiple post-testing sessions. Chronic adaptations to the intervention require performance data to be captured over multiple instances. Future studies should include a control group and also compare between CON and ECC towing directions. It was also observed that both the CON and ECC towing directions put the athlete in a similar body position to what is seen during the acceleration phase of the sprint. Similar to how a sled can affect acceleration performance by loading the joints in specific angles, isokinetic horizontal towing could also affect the athlete's acceleration mechanics. Future research should study the acute and perhaps chronic changes in acceleration mechanics.

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Appendices

Appendix I – Ethics Approval Form for Chapters 5-8

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

6 November 2015

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **15/375 Determining the variability of eccentric force and power during horizontal eccentric towing.**

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

Your ethics application has been approved for three years until 6 November 2018.

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

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 6 November 2018;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 6 November 2018 or on completion of the project.

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

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

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

All the very best with your research,

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

Cc: Farhan Tinwala farhan.tinwala@gmail.com, Enrico Haemmerle

Appendix II – Participant Information Sheet for Chapter 5

Participant Information Sheet

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Date Information Sheet Produced:

20 October 2015

Project Title

Determining the variability of eccentric force and power during horizontal eccentric towing

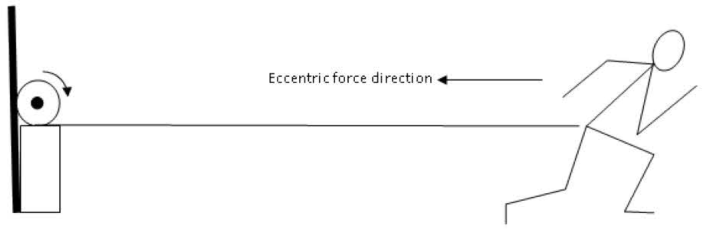
An Invitation

Hi, my name is Farhan Tinwala - I am a PhD student at AUT University. On behalf of my supervisors Professor John Cronin, Professor Enrico Haemmerle and Dr Angus Ross, I would like to personally invite you to participate in our project that aims to determine the variability of eccentric force and power during horizontal eccentric towing.

It is entirely your choice as to whether you participate in the project or not. If you decide you no longer want to participate you are free to withdraw yourself or any information that you have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Your consent to participate in this research will be indicated by you signing and dating the consent form. Signing the consent form indicates that you have read and understood this information sheet, freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT or HPSNZ.

What is the purpose of this research?

We have developed a new device that performs a novel type of exercise called horizontal eccentric towing. It is an eccentric exercise that is designed to focus on sprinting performance. Sprinting performance is related to lower limb stiffness and research shows that eccentric strength training increases stiffness. The device works by towing an athlete at a constant speed whilst the athlete tries to resist the pull. This is depicted in the diagram below:



We are looking to validate this device and prove that it improves sprinting performance. The first step towards validation is understanding how long do participants take to familiarise themselves with the technique and the movement. This study will track the participant's eccentric force and power to see how it changes over 5 weeks using a 15 min testing session each week separated by seven days.

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

You are eligible if you are between the ages of 18 and 35 years old; if you are a part of the men's or women's national hockey squad or the development squad; if you are currently injury free and have consent from the team physiotherapist and the strength and conditioning coaches.

What will happen in this research?

If you agree to participate in the research, you will be asked to complete a 15 min testing session each week at the HPSNZ carded athlete gym at AUT Millennium over a period of 5 weeks. The procedure will be as follows:

Initially your height and weight will be measured. You will be asked to a undergo 5-10 min standardized warm-up routine. We will then explain to you the concept and do a live demonstration of the device. For the first test you will get one trial to get a feel for the device and the technique. Following that there will be three testing trials. All trials will be over a distance of 10 m and at a constant speed of 0.75 m/s. There will be a 2 min rest in between each trial. The initial testing session will take 20-30 min. The following four testing sessions will take 10-15 min. All testing will be scheduled during your regular training time at the HPSNZ carded athlete gym. We will be liaising with your strength and conditioning coaches.

We will be using a high speed video camera to record the testing session. This is to document the session and to analyse your technique. This will provide you with better feedback in the following sessions. The video data will not be published without prior consent from the participant.

What are the discomforts and risks?

Since this is a new concept, there is a level of discomfort with being towed back whilst resisting. We will help you understand the technique and coach you throughout. We will be asking you to perform sub-maximal (moderate intensity) and maximal (very heavy intensity) exercises. You may experience fatigue and minor discomfort associate with high intensity exercises. You may experience transient muscle soreness 12-48 hours after the testing sessions. The pain is expected to decrease over consecutive testing sessions. There is also a risk or falling or tripping during the exercise. The device is equipped with a safety system which will stop device immediately in case of an emergency.

How will these discomforts and risks be alleviated?

Being trained athletes who regularly train at high intensity and are familiar with the risks associated with high intensity training, this eccentric exercise should be similar to what you are used to or have experienced during regular strength and conditioning sessions. If excessive discomfort is felt at any stage during the testing you are encouraged to inform the researcher with you at the time so that they can best address the problem. If you have any questions regarding risk or comfort that you anticipate, please feel free to address these concerns to the researcher so that you feel comfortable at all times throughout the process.

What are the benefits?

The participants get to be one of the first in the world to train using this novel concept on the custom built horizontal eccentric training device. You will help validate the device so that it can be used in everyday training. The researchers will also benefit by gaining new knowledge on this novel concept. The information gained from this study will help the researchers understand how long subjects take to familiarize a novel multi degree of freedom training method. The results from this study will allow HPSNZ to periodize training for high performing athletes and add horizontal ECC towing into their training programmes. This may have a potential impact on the world stage for these athletes. The results of this research are intended for publication, will contribute to part of my PhD thesis and will also be submitted to peer-reviewed journals for publication.

What compensation is available for injury or negligence?

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

How will my privacy be protected?

Testing procedures and subsequent data collection may occur in small groups, therefore confidentiality during this period will be limited between those performing sprinting within the same session. No results will be supplied during the testing occasion, your individual data will be protected and anonymous from other participants in your testing group. Outside of the testing occasion, your privacy will be protected by data being de-identified (an athlete code instead of name; e.g. 100m_A1), and the researcher will not disclose anyone's participation in this study. All participant data will be averaged and represented as group means. No names or pictures will be used in reporting (unless the participant gives explicit additional written consent for media purposes following AUT protocols and organised via the AUT university relations team). During the project, only the applicant and named investigators will have access to the data collected. The results of the study may be used for further analysis and submission to peer-reviewed journals or submitted at conferences. To maintain confidentiality, in all publications resulting from this research participants' data will be averaged and represented as group means.

All data will be stored on password protected computers or in locked files. Following completion of data analysis your data will be stored by the AUT University SPRINZ research office in the AUT University SPRINZ secure Ethics and Data facility at AUT Millennium campus. Given the progressive nature of research in this field, data will be kept indefinitely for the purposes of reanalysis (should future analysis methods arise) for purposes similar to that collected; however (as per above) all forms of data will be de-identified and kept secure for the entirety of the data's storage lifetime.

What are the costs of participating in this research?

Other than your time and effort, there will be no financial cost for you being involved with this study. The first session will take approximately 20-30 min. The following sessions will take approximately 10-15 min.

What opportunity do I have to consider this invitation?

We would appreciate it if you could let us or your strength and conditioning coach know within a week whether you would be available to take part in the study or not. After consideration you may withdraw your participation at any time.

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to your strength and conditioning coach, or Dr Angus Ross or the primary researcher Farhan Tinwala.

Will I receive feedback on the results of this research?

Yes, over the course of 5 weeks you will be given feedback based on your technique. Upon completion each participant will be sent a link of the analysed results.

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, Professor John Cronin, john.cronin@aut.ac.nz, + 64 9 921 921 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* , +64 9 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:

Farhan Tinwala, farhan.tinwala@gmail.com, +64 21 188 0494

Dr Angus Ross, angus.ross@hpsnz.org.nz, +64 21 271 0595

Project Supervisor Contact Details:

John Cronin, john.cronin@aut.ac.nz, + 64 9 921 921 ext 7523.

Approved by the Auckland University of Technology Ethics Committee on 6th November 2015, AUTEC Reference number 15/375.

Appendix III – Consent Form for Chapter 5

AUT
TE WĀNANGA ARONUI
O TĀMAKI MAKAU RAU

Consent Form

Project title: ***Determining the variability of eccentric force and power during horizontal eccentric towing***

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

Researcher: ***Farhan Tinwala***

- O I have read and understood the information provided about this research project in the Information Sheet dated 20th October 2015.
- O I have had an opportunity to ask questions and to have them answered.
- O 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.
- O I am **not** currently suffering from any sporting injury that may impair my physical performance.
- O I have previously undertaken resistance sled towing as a part of my training programme (please tick one): YesO NoO
- O I agree to answer questions and provide physical effort to the best of my ability throughout testing.
- O I agree to take part in this research.
- O I wish to receive a copy of the report from the research (please tick one): YesO NoO

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 6th November 2015 AUTEC Reference number 15/375.

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

2 July 2015 page 1 of 1 This version was last edited in July 2015

Appendix IV – Participant Information Sheet for Chapters 6 and 7

Participant Information Sheet

Date Information Sheet Produced:

01 November 2016

Project Title

The effects of towing velocity on the 2D single leg kinematics and kinetics during horizontal eccentric towing

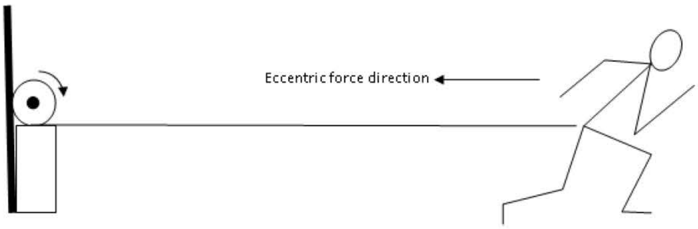
An Invitation

Hi, my name is Farhan Tinwala - I am a PhD student at AUT University. On behalf of my supervisors Professor John Cronin, Professor Enrico Haemmerle and Dr Angus Ross, I would like to personally invite you to participate in our project that aims to understand the kinematics and kinetics during horizontal eccentric towing.

It is entirely your choice as to whether you participate in the project or not. If you decide you no longer want to participate you are free to withdraw yourself or any information that you have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Your consent to participate in this research will be indicated by you signing and dating the consent form. Signing the consent form indicates that you have read and understood this information sheet, freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT or HPSNZ.

What is the purpose of this research?

We have developed a new device that performs a novel type of exercise called horizontal eccentric towing. It is an eccentric exercise that is designed to focus on sprinting performance. Sprinting performance is related to lower limb stiffness and research shows that eccentric strength training increases stiffness. The lean angle and horizontal force production is shown to have a high correlation with faster acceleration during sprinting. Horizontal eccentric towing may improve the acceleration phase performance by increasing horizontal force production and improving the lean angle. The device works by towing an athlete at a constant speed whilst the athlete tries to resist the pull. This is depicted in the diagram below:



We are looking to validate this device and prove that it improves sprinting performance. The first step towards validation is understanding the motion of the movement and quantifying it. This study will measure the angular velocities and moments of your knee, hip and ankle during horizontal eccentric towing.

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

You are eligible if you are between the ages of 18 and 35 years old; if you are currently injury free and have been injury free for the last six months.

What will happen in this research?

If you agree to participate in the research, you will be asked to complete two 30-minute familiarisation sessions and two 45-minute testing sessions over at the HPSNZ carded athlete gym at AUT Millennium over a period of 2 weeks. The procedure will be as follows:

Initially your height and weight will be measured. You will be asked to undergo 5-10 min standardized warm-up routine. We will then explain to you the concept and do a live demonstration of the device. Then you will go through a familiarisation session. This will involve multiple trials of horizontal eccentric towing. During the same week, you will be asked to go through another familiarisation session. Since, this is a very unique concept it takes two sessions to get familiarised with the technique and the movement.

The following week will be the testing sessions. During the first session, you will undergo the same standardized warm-up. We will then place reflective markers on your body. You will then be asked to perform a total of twelve maximum effort trials (6 concentric and 6 eccentric). You will be given a rest period of 2-minutes between each trial. The same will apply for the second testing session which will also be during the same week.

We will be using infrared cameras to track the markers on your body, force plates and a high speed video camera to record and document the sessions. The video data will not be published without prior consent from the participant.

What are the discomforts and risks?

Since this is a new concept, there is a level of discomfort with being towed back whilst resisting. We will help you understand the technique and coach you throughout. We will be asking you to perform sub-maximal (moderate intensity) and maximal (very heavy intensity) exercises. You may experience fatigue and minor discomfort associate with high intensity exercises. You may experience transient muscle soreness 12-48 hours after the testing sessions. The pain is expected to decrease over consecutive testing sessions. There is also a risk or falling or tripping during the exercise. The device is equipped with a safety system which will stop device immediately in case of an emergency.

How will these discomforts and risks be alleviated?

Being active and strength trained individuals who regularly train at moderate to high intensity and are familiar with the risks associated with this type of training, this eccentric exercise should be similar to what you are used to or have experienced during regular strength and conditioning sessions. If excessive discomfort is felt at any stage during the testing, you are encouraged to inform the researcher with you at the time so that they can best address the problem. If you have any questions regarding risk or comfort that you anticipate, please feel free to address these concerns to the researcher so that you feel comfortable at all times throughout the process.

What are the benefits?

The participants get to be one of the first in the world to train using this novel concept on the custom built horizontal eccentric training device. You will help validate the device so that it can be used in everyday training. The researchers will also benefit by gaining new knowledge on this novel concept. You will also receive metrics such as your isometric, eccentric and concentric horizontal force production at varying towing speeds. The information gained from this study will help the researchers understand the kinematics and kinetics of a novel multi degree of freedom training method. The results from this study will allow HPSNZ to periodize training for high performing athletes and add horizontal eccentric towing into their training programmes. This may have a potential impact on the world stage for these athletes. The results of this research are intended for publication, will contribute to part of my PhD thesis and will also be submitted to peer-reviewed journals for publication.

What compensation is available for injury or negligence?

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

How will my privacy be protected?

Testing procedures and subsequent data collection may occur in small groups, therefore confidentiality during this period will be limited between those within the same session. No results will be supplied during the testing occasion, your individual data will be protected and anonymous from other participants in your testing group. Outside of the testing occasion, your privacy will be protected by data being de-identified (an athlete code instead of name; e.g. 100m_A1), and the researcher will not disclose anyone's participation in this study. All participant data will be averaged and represented as group means. No names or pictures will be used in reporting (unless the participant gives explicit additional written consent for media purposes following AUT protocols and organised via the AUT university relations team). During the project, only the applicant and named investigators will have access to the data collected. The results of the study may be used for further analysis and submission to peer-reviewed journals or submitted at conferences. To maintain confidentiality, in all publications resulting from this research participants' data will be averaged and represented as group means.

All data will be stored on password protected computers or in locked files. Following completion of data analysis your data will be stored by the AUT University SPRINZ research office in the AUT University SPRINZ secure Ethics and Data facility at AUT Millennium campus. Given the progressive nature of research in this field, data will be kept indefinitely for the purposes of reanalysis (should future analysis methods arise) for purposes similar to that collected; however, (as per above) all forms of data will be de-identified and kept secure for the entirety of the data's storage lifetime.

What are the costs of participating in this research?

Other than your time and effort, there will be no financial cost for you being involved with this study. The first two familiarisation sessions will take approximately 30-minutes each. The following two testing sessions will take approximately 45-minutes each.

What opportunity do I have to consider this invitation?

We would appreciate it if you could let us know within a week whether you would be available to take part in the study or not. After consideration you may withdraw your participation at any time.

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to Dr Angus Ross or the primary researcher, Farhan Tinwala.

Will I receive feedback on the results of this research?

Yes, you will be given feedback based on your technique. Upon completion each participant will be sent a link of the analysed results.

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, Professor John Cronin, john.cronin@aut.ac.nz, + 64 9 921 921 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* , +64 9 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:

Farhan Tinwala, farhan.tinwala@gmail.com, +64 21 188 0494

Dr Angus Ross, angus.ross@hpsnz.org.nz, +64 21 271 0595

Project Supervisor Contact Details:

John Cronin, john.cronin@aut.ac.nz, + 64 9 921 921 ext 7523.

Approved by the Auckland University of Technology Ethics Committee on 6th November 2015, AUTEC Reference number 15/375.

Appendix V – Consent Form for Chapters 6 and 7

TE WĀNANGA ARONUI
O TĀMAKI MAKAU RAU

Consent Form

Project title:	***The effects of towing velocity on the 2D single leg kinematics and kinetics during horizontal eccentric towing***
Project Supervisor:	***Professor John Cronin***
Researcher:	***Farhan Tinwala***

- O I have read and understood the information provided about this research project in the Information Sheet dated 1 November 2016.
- O I have had an opportunity to ask questions and to have them answered.
- O 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.
- O I am **not** currently suffering from any sporting injury that may impair my physical performance.
- O I have previously undertaken resistance sled towing as a part of my training programme (please tick one): YesO NoO
- O I agree to answer questions and provide physical effort to the best of my ability throughout testing.
- O I agree to take part in this research.
- O I wish to receive a copy of the report from the research (please tick one): YesO NoO

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on 6th November 2015 AUTEC Reference number 15/375.

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

Appendix VI – Participant Information Sheet for Chapter 8

Participant Information Sheet

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Date Information Sheet Produced:

14 July 2017

Project Title

The effects of horizontal eccentric towing on sprinting performance in elite female field hockey players.

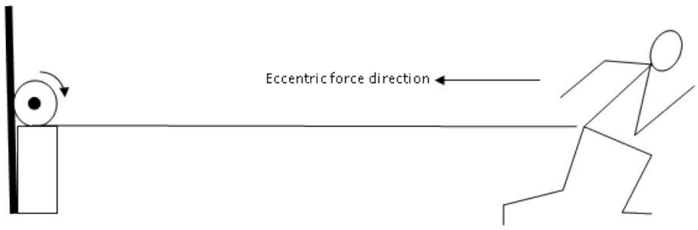
An Invitation

Hi, my name is Farhan Tinwala - I am a PhD student at AUT University. On behalf of my supervisors Professor John Cronin, Professor Enrico Haemmerle and Dr Angus Ross, I would like to personally invite you to participate in our project that aims to study the effects of horizontal eccentric towing on sprinting performance.

It is entirely your choice as to whether you participate in the project or not. If you decide you no longer want to participate you are free to withdraw yourself or any information that you have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Your consent to participate in this research will be indicated by you signing and dating the consent form. Signing the consent form indicates that you have read and understood this information sheet, freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT or HPSNZ.

What is the purpose of this research?

We have developed a new device that performs a novel type of exercise called horizontal eccentric towing. It is an eccentric exercise that is designed to focus on sprinting performance. Sprinting performance is related to lower limb stiffness and research shows that eccentric strength training improves stiffness characteristics. The lean angle and horizontal force production is shown to have a high correlation with faster acceleration during sprinting. Horizontal eccentric towing may improve the acceleration phase performance by increasing horizontal force production and improving the lean angle. High speed eccentric training can also provide a shift towards fast twitch muscle fibres. The device works by towing an athlete at a constant speed whilst the athlete tries to resist the pull. This is depicted in the diagram below:



We are looking to validate this device and prove that it improves sprinting performance.

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

You are eligible if you are between the ages of 18 and 35 years old; if you are a part of the women's national hockey squad or the development squad; if you are currently injury free and have consent from the team physiotherapist and the strength and conditioning coaches.

What will happen in this research?

If you agree to participate in the research, you will be randomly allocated into two groups; eccentric; and concentric. The two groups will be given two different interventions. The intervention will be a four-week block of two sessions a week during your regular S&C session at the carded athlete gym in AUT Millennium. There will be pre and post testing the week before and after the four-week intervention block. The study will run from 24th July 2017 to 1st September 2017 for a total of six weeks. We will be working with your S&C team to add this into your training programme if you agree to participate.

During the first and last week of the study, we will collect the following data:

- 50m sprint times – You will be asked to perform three max efforts 50m sprints. We will use a radar gun and a video camera to capture the timing data.

- Optimal Cadence – You will be asked to perform three max effort trials on the Optimal Cadence bike in the gym. The bike will give us a measure of your muscle fibre type composition based.
- Your height and weight.

Your intervention will vary depending on which group you are randomly allocated to. The eccentric group will have horizontal eccentric towing added to their programmes; and the concentric group will have a horizontal concentric towing added to their programmes.

The attached consent form also contains a medical questionnaire which has a few questions regarding your menstrual cycle. There is evidence that suggests performance measurements can be skewed due to the changing hormone levels during the menstrual cycle. The purpose of the questionnaire is to account for this effect by adding this as a covariate in the statistical analysis. The information you provide on the medical questionnaire will be completely confidential (see below on 'How my privacy will be protected?'). If you have any questions or concerns, please contact your strength and conditioning coach or Farhan Tinwala.

What are the discomforts and risks?

Since this is a new concept, there is a level of discomfort with being towed back whilst resisting. We will help you understand the technique and coach you throughout. We will be asking you to perform sub-maximal (moderate intensity) and maximal (very heavy intensity) exercises. You may experience fatigue and minor discomfort associate with high intensity exercises. You may experience transient muscle soreness 12-48 hours after each session. The pain is expected to decrease over consecutive testing sessions. There is also a risk or falling or tripping during the exercise. The device is equipped with a safety system which will stop device immediately in case of an emergency.

How will these discomforts and risks be alleviated?

Being active and strength trained individuals who regularly train at moderate to high intensity and are familiar with the risks associated with this type of training, this eccentric exercise should be similar to what you are used to or have experienced during regular strength and conditioning sessions. If excessive discomfort is felt at any stage during the testing, you are encouraged to inform the researcher with you at the time so that they can best address the problem. If you have any questions regarding risk or comfort that you anticipate, please feel free to address these concerns to the researcher so that you feel comfortable at all times throughout the process.

What are the benefits?

The participants get to be one of the first in the world to train using this novel concept on the custom built horizontal eccentric training device. You will help validate the device so that it can be used in everyday training. The researchers will also benefit by gaining new knowledge on this novel concept. You will also receive metrics such as your 50m sprint times with splits and optimum cadence which indicates your muscle fibre composition. The information gained from this study will help the researchers understand the effects of horizontal eccentric towing on sprinting performance. The results from this study will allow HPSNZ to periodize training for high performing athletes and add horizontal eccentric towing into their training programmes. This may have a potential impact on the world stage for these athletes. The results of this research are intended for publication, will contribute to part of my PhD thesis and will also be submitted to peer-reviewed journals for publication.

What compensation is available for injury or negligence?

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

How will my privacy be protected?

Testing procedures and subsequent data collection may occur in small groups, therefore confidentiality during this period will be limited between those within the same session. No results will be supplied during the testing occasion, your individual data will be protected and anonymous from other participants in your testing group. Outside of the testing occasion, your privacy will be protected by data being de-identified (an athlete code instead of name; e.g. 100m_A1), and the researcher will not disclose anyone's participation in this study. All participant data will be averaged and represented as group means. No names or pictures will be used in reporting (unless the participant gives explicit additional written consent for media purposes following AUT protocols and organised via the AUT university relations team). During the project, only the applicant and named investigators will have access to the data collected. The results of the study may be used for further analysis and submission to peer-reviewed journals or submitted at conferences. To maintain confidentiality, in all publications resulting from this research participants' data will be averaged and represented as group means.

All data will be stored on password protected computers or in locked files. Following completion of data analysis your data will be stored by the AUT University SPRINZ research office in the AUT University SPRINZ secure Ethics and Data facility at AUT Millennium campus. Given the progressive nature of research in this field, data will be kept indefinitely for the purposes of reanalysis (should future analysis methods arise) for purposes similar to that collected; however, (as per above) all forms of data will be de-identified and kept secure for the entirety of the data's storage lifetime.

What are the costs of participating in this research?

Other than your time and effort, there will be no financial cost for you being involved with this study. The sessions will be during your scheduled training time at the HPSNZ carded athlete gym.

What opportunity do I have to consider this invitation?

We would appreciate it if you could let us know by Fri 14th July whether you would be available to take part in the study or not. After consideration, you may withdraw your participation at any time.

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to Farhan Tinwala or your strength and conditioning coach via email or in person.

Will I receive feedback on the results of this research?

Yes, you will be given feedback based on your technique. Upon completion, each participant will be sent a link of the analysed results.

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, Professor John Cronin, john.cronin@aut.ac.nz, + 64 9 921 921 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* , +64 9 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:

Farhan Tinwala, farhan.tinwala@gmail.com, +64 21 188 0494

Dr Angus Ross, angus.ross@hpsnz.org.nz, +64 21 271 0595

Project Supervisor Contact Details:

John Cronin, john.cronin@aut.ac.nz, + 64 9 921 921 ext 7523.

Approved by the Auckland University of Technology Ethics Committee on 6th November 2015, AUTEC Reference number 15/375.

Appendix VII – Consent Form for Chapter 8

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Medical Questionnere & Consent Form

Project title: ***The effects of horizontal eccentric towing on sprinting performance in elite female field hockey players.***

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

Researcher: ***Farhan Tinwala***

First Name: ______________________________ **Last Name:** ______________________________

Email: ______________________________________ **Phone:** ______________________________

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

Playing Position(s): ____

Preferred Leg: Left **/** Right

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 ____

____

____

____

The following questions are regarding your menstrual cycle. There is evidence that suggests performance measurements can be skewed due to the changing hormone levels during the menstrual cycle. The purpose of the following questions is to account for this effect by adding this as a covariate in the statistical analysis. The information you provide on the medical questionnaire will be completely confidential (see 'How my privacy will be protected?' section in the attached information sheet). If you have any questions or concerns regarding the following questions, please contact your strength and conditioning coach or Farhan Tinwala.

When did your last menstrual cycle start? _____ / _____ / _______ *day / month / year*

Are you currently taking any contraceptive medication? Y / N

If you answered **Yes**, please give details on the brand and type *(e.g. Pill – Aviane)* ______

____

How long have you been taking contraceptive medication? ________ *Years* ________ *Months*

If you are NOT taking any contraceptive medication, how often have you had menstrual periods in the last year? (Please tick one)

_____ Once every 20 days or less _____ Every 21-27 days _____ Every 28-35 days

_____ Every 36-50 days _____ Every 3-4 months

_____ Very irregular, sometimes monthly, sometimes skip several months

_____ Other (Please specify) ____

☐ I have read and understood the information provided about this research project in the Information Sheet dated 14 July 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.

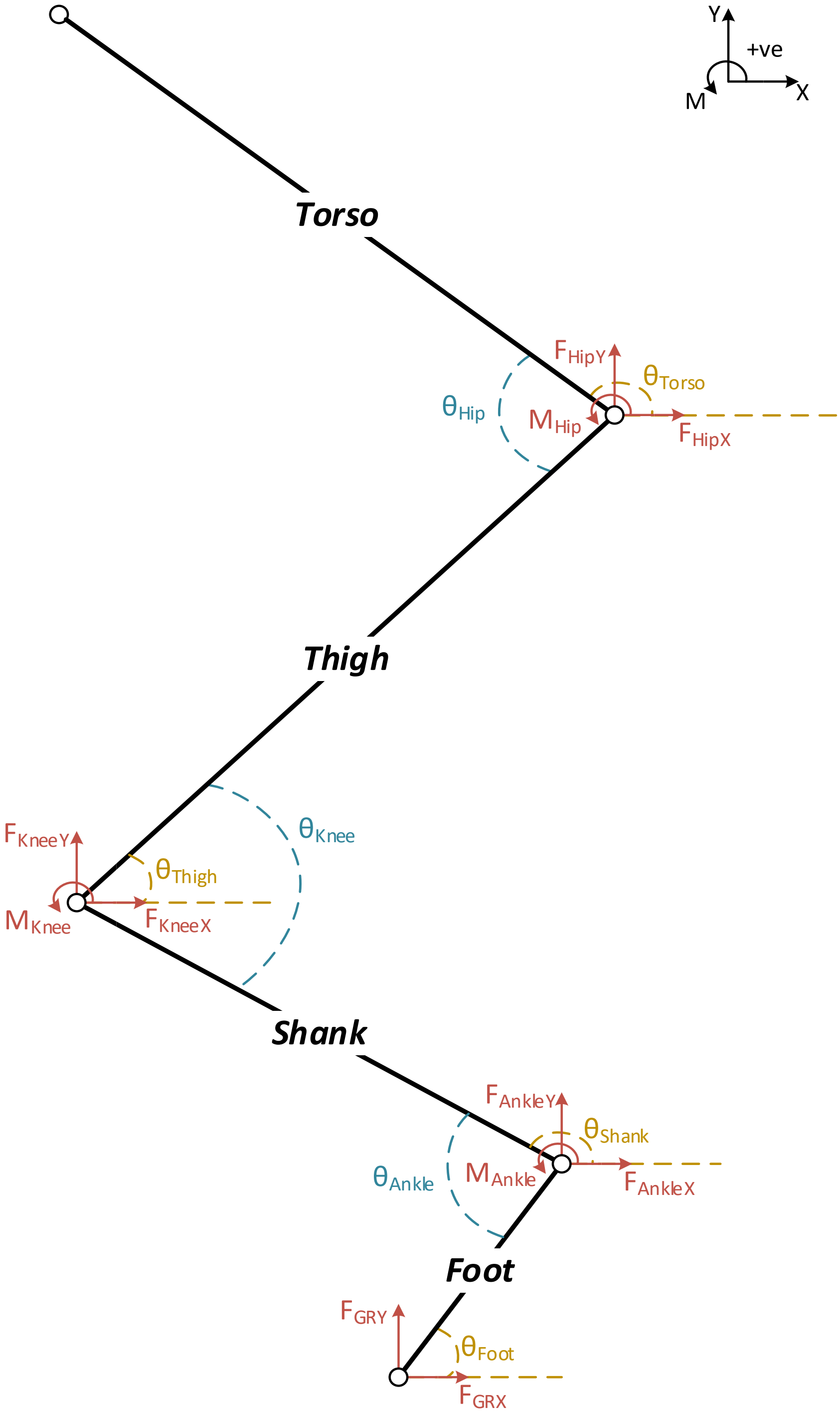
☐ I agree to take part in this research.

Participant's signature: ....

Date: ....

Approved by the Auckland University of Technology Ethics Committee on 6th November 2015 AUTEC Reference number 15/375.

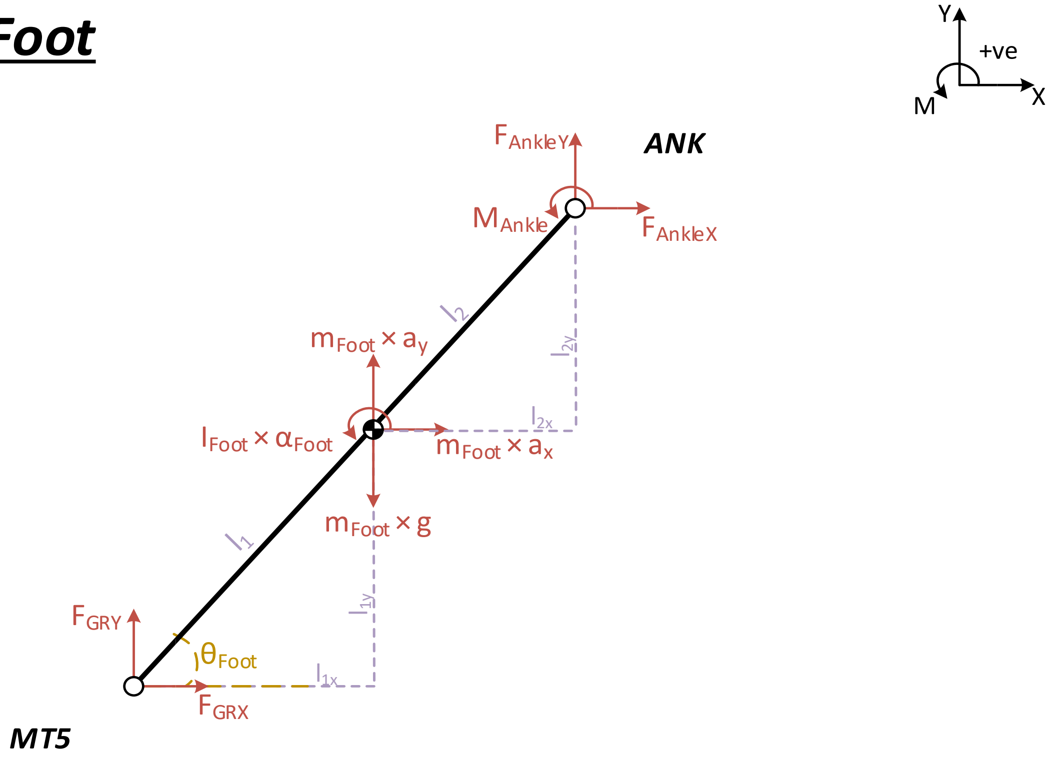
Appendix VIII – Inverse Dynamic Calculations



$$\alpha_{Foot} = \frac{d^2}{dt^2}(\theta_{Foot}), \quad \alpha_{Shank} = \frac{d^2}{dt^2}(\theta_{Shank}), \quad \alpha_{Thigh} = \frac{d^2}{dt^2}(\theta_{Thigh})$$

$$\dot{\theta}_{Ankle} = \frac{d}{dt}(\theta_{Ankle}), \quad \dot{\theta}_{Knee} = \frac{d}{dt}(\theta_{Knee}), \quad \dot{\theta}_{Hip} = \frac{d}{dt}(\theta_{Hip})$$

Foot



$$m_{Foot} = m_{Subject} \times 0.0145, \qquad I_{Foot} = m_{Subject} \times (length_{Foot} \times 0.475)^2$$

$$COM_{Foot}(x,y) = \big((1-t) \times MT5(x,y)\big) + \big(t \times ANK(x,y)\big), \qquad t = 0.5$$

$$a_x = \frac{d^2}{dt^2}\big(COM_{Foot}(x)\big), \qquad a_y = \frac{d^2}{dt^2}\big(COM_{Foot}(y)\big)$$

$$l_1 = length_{Foot} \times t, \qquad l_2 = length_{Foot} \times (1-t)$$

$$l_{1x} = COM_{Foot}(x) - MT5(x), \qquad l_{1y} = COM_{Foot}(y) - MT5(y)$$

$$l_{2x} = ANK(x) - COM_{Foot}(x), \qquad l_{2y} = ANK(y) - COM_{Foot}(y)$$

$$\sum F_x = m_{Foot}.a_x \quad \rightarrow \quad m_{Foot}.a_x = F_{GRX} + F_{AnkleX}$$

$$\therefore \quad \boldsymbol{F_{AnkleX} = m_{Foot}.a_x - F_{GRX}}$$

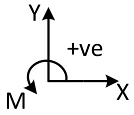
$$\sum F_y = m_{Foot}.a_y \quad \rightarrow \quad m_{Foot}.a_y = F_{GRY} + F_{AnkleY} - m_{Foot}.g$$

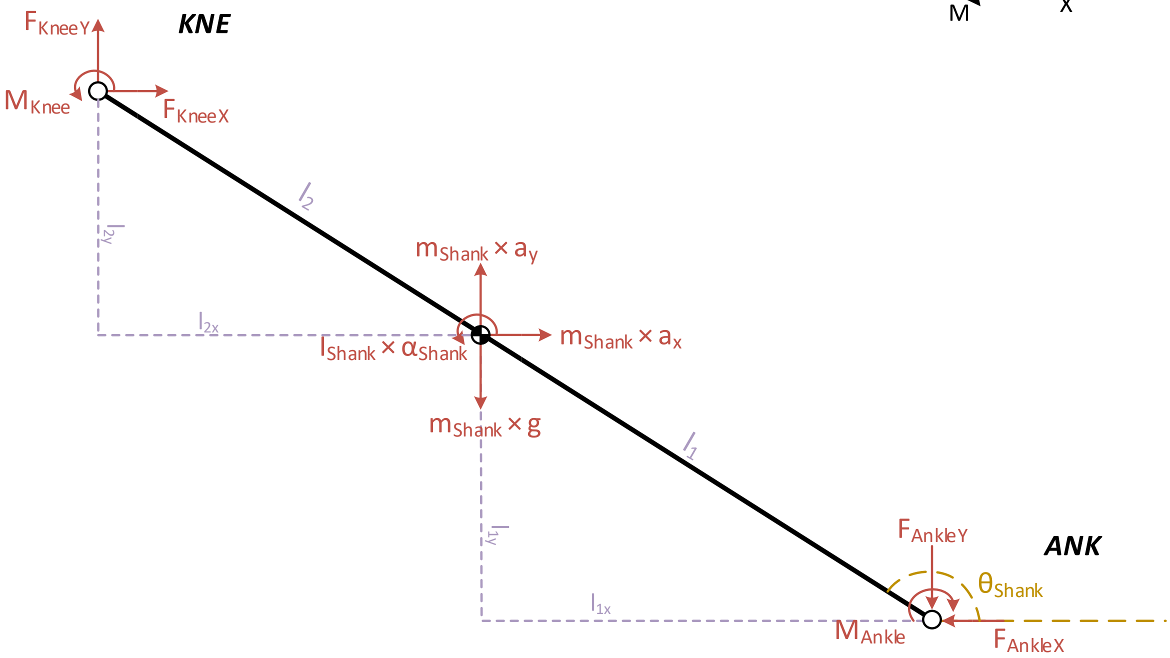
$$\therefore \quad \boldsymbol{F_{AnkleY} = m_{Foot}(a_y + g) - F_{GRY}}$$

$$\sum M_{COM} = I_{Foot}.\alpha_{Foot} = M_{Ankle} - F_{GRY}.l_{1x} + F_{GRX}.l_{1y} + F_{AnkleY}.l_{2x} - F_{AnkleX}.l_{2y}$$

$$\therefore \quad \boldsymbol{M_{Ankle} = I_{Foot}.\alpha_{Foot} + F_{GRY}.l_{1x} - F_{GRX}.l_{1y} - F_{AnkleY}.l_{2x} + F_{AnkleX}.l_{2y}}$$

Shank





$$m_{Shank} = m_{Subject} \times 0.0465, \qquad I_{Shank} = m_{Subject} \times (length_{Shank} \times 0.302)^2$$

$$COM_{Shank}(x, y) = \big((1-t) \times ANK(x, y)\big) + \big(t \times KNE(x, y)\big), \qquad t = 0.567$$

$$a_x = \frac{d^2}{dt^2}\big(COM_{Shank}(x)\big), \qquad a_y = \frac{d^2}{dt^2}\big(COM_{Shank}(y)\big)$$

$$l_1 = length_{Shank} \times t, \qquad l_2 = length_{Shank} \times (1-t)$$

$$l_{1x} = ANK(x) - COM_{Shank}(x), \qquad l_{1y} = COM_{Shank}(y) - ANK(y)$$

$$l_{2x} = COM_{Shank}(x) - KNE(x), \qquad l_{2y} = KNE(y) - COM_{Shank}(y)$$

$$\sum F_x = m_{Shank}.a_x \quad \rightarrow \quad m_{Shank}.a_x = F_{KneeX} - F_{AnkleX}$$

$$\therefore \quad \boldsymbol{F_{KneeX} = m_{Shank}.a_x + F_{AnkleX}}$$

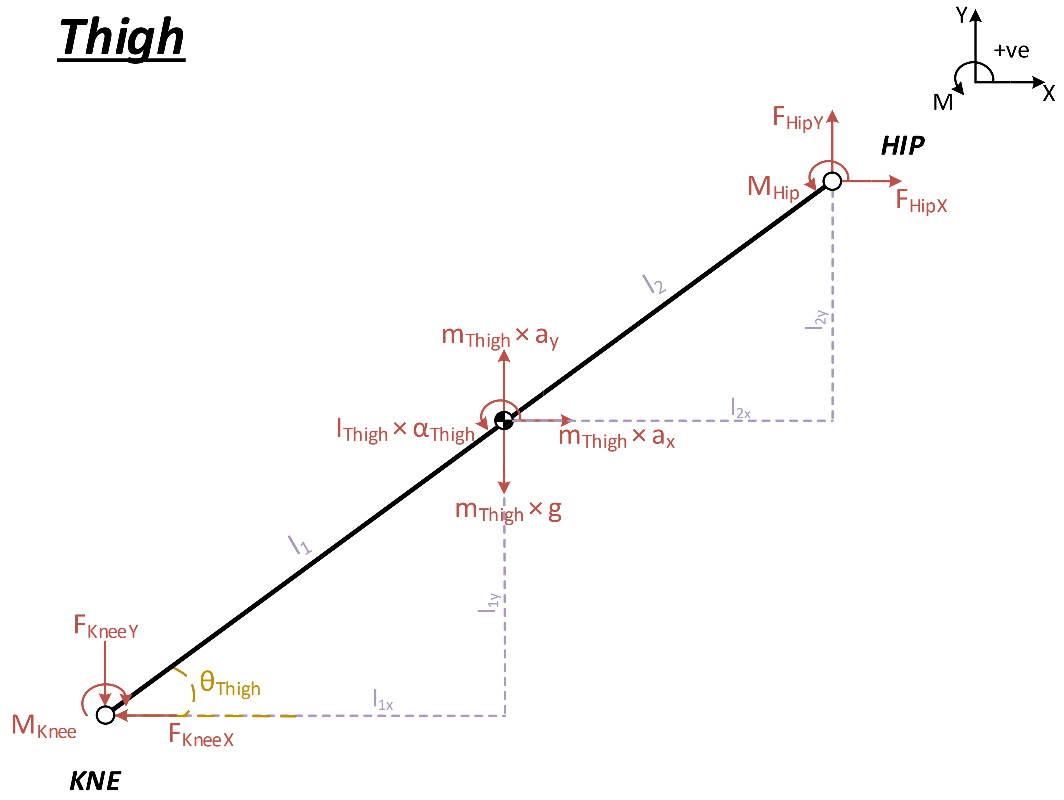
$$\sum F_y = m_{Shank}.a_y \quad \rightarrow \quad m_{Shank}.a_y = F_{KneeY} - F_{AnkleY} - m_{Shank}.g$$

$$\therefore \quad \boldsymbol{F_{KneeY} = m_{Shank}\big(a_y + g\big) + F_{AnkleY}}$$

$$\sum M_{COM} = I_{Shank}.\alpha_{Shank} = M_{Knee} - M_{Ankle} - F_{KneeY}.l_{2x} - F_{KneeX}.l_{2y} - F_{AnkleY}.l_{1x} - F_{AnkleX}.l_{1y}$$

$$\therefore \quad \boldsymbol{M_{Knee} = I_{Shank}.\alpha_{Shank} + M_{Ankle} + F_{KneeY}.l_{2x} + F_{KneeX}.l_{2y} + F_{AnkleY}.l_{1x} + F_{AnkleX}.l_{1y}}$$

Thigh



$$m_{Thigh} = m_{Subject} \times 0.1, \quad I_{Thigh} = m_{Subject} \times \left(length_{Thigh} \times 0.332\right)^2$$

$$COM_{Thigh}(x,y) = \left((1-t) \times KNE(x,y)\right) + \left(t \times HIP(x,y)\right), \quad t = 0.567$$

$$a_x = \frac{d^2}{dt^2}\left(COM_{Thigh}(x)\right), \quad a_y = \frac{d^2}{dt^2}\left(COM_{Thigh}(y)\right)$$

$$l_1 = length_{Thigh} \times t, \quad l_2 = length_{Thigh} \times (1-t)$$

$$l_{1x} = COM_{Thigh}(x) - KNE(x), \quad l_{1y} = COM_{Thigh}(y) - KNE(y)$$

$$l_{2x} = HIP(x) - COM_{Thigh}(x), \quad l_{2y} = HIP(y) - COM_{Thigh}(y)$$

$$\sum F_x = m_{Thigh}.a_x \quad \rightarrow \quad m_{Thigh}.a_x = F_{HipX} - F_{KneeX}$$

$$\therefore \quad \boldsymbol{F_{HipX} = m_{Thigh}.a_x + F_{KneeX}}$$

$$\sum F_y = m_{Thigh}.a_y \quad \rightarrow \quad m_{Thigh}.a_y = F_{HipY} - F_{KneeY} - m_{Thigh}.g$$

$$\therefore \quad \boldsymbol{F_{HipY} = m_{Thigh}\left(a_y + g\right) + F_{KneeY}}$$

$$\sum M_{COM} = I_{Thigh}.\alpha_{Thigh} = M_{Hip} - M_{Knee} + F_{KneeY}.l_{1x} - F_{KneeX}.l_{1y} + F_{HipY}.l_{2x} - F_{HipX}.l_{2y}$$

$$\therefore \quad \boldsymbol{M_{Hip} = I_{Thigh}.\alpha_{Thigh} + M_{Knee} - F_{KneeY}.l_{1x} + F_{KneeX}.l_{1y} - F_{HipY}.l_{2x} + F_{HipX}.l_{2y}}$$

Appendix IX – Joint Kinematics and Kinetics Analysis Results

Table 20: Means and standard deviations of the joint kinematic variables

Variables	CTD				ETD			
	0.75 m/s $\mu \pm \sigma$ n = 52	**1.00 m/s** $\mu \pm \sigma$ n = 43	**1.25 m/s** $\mu \pm \sigma$ n = 45	**Total** $\mu \pm \sigma$ n = 140	**0.75 m/s** $\mu \pm \sigma$ n = 52	**1.00 m/s** $\mu \pm \sigma$ n = 43	**1.25 m/s** $\mu \pm \sigma$ n = 45	**Total** $\mu \pm \sigma$ n = 140
Ankle Joint								
Maximum joint angle (°)	152 ± 14.6	155 ± 17.7	161 ± 10	**156 ± 14.8**	141 ± 12.6	141 ± 11	139 ± 10.5	**141 ± 11.5**
Minimum joint angle (°)	86.9 ± 7.26	86.6 ± 9	90.2 ± 7.23	**87.9 ± 7.94**	91.3 ± 8.03	92.8 ± 7.03	92 ± 8.37	**92 ± 7.77**
Peak plantarflexion velocity (°/s)	354 ± 93.4	480 ± 118	572 ± 142	**463 ± 149**	190 ± 72.3	144 ± 52.3	129 ± 46.9	**157 ± 64.8**
Peak dorsiflexion velocity (°/s)	-319 ± 97.4	-351 ± 108	-347 ± 76.2	**-338 ± 95.1**	-433 ± 144	-448 ± 118	-473 ± 176	**-449 ± 145**
Knee Joint								
Maximum joint angle (°)	161 ± 8.14	160 ± 9.76	162 ± 6.57	**161 ± 8.2**	146 ± 12.9	149 ± 11.4	150 ± 9.67	**148 ± 11.6**
Minimum joint angle (°)	80.5 ± 10.5	81.7 ± 8.2	86.1 ± 10.5	**82.7 ± 10.1**	100 ± 14.2	99.3 ± 16	101 ± 18.4	**100 ± 15.9**
Peak knee extension velocity (°/s)	243 ± 64.4	286 ± 73.4	339 ± 92.1	**287 ± 86.3**	421 ± 169	382 ± 174	385 ± 189	**398 ± 176**
Peak knee flexion velocity (°/s)	-421 ± 115	-384 ± 145	-409 ± 126	**-406 ± 128**	-172 ± 54.1	-207 ± 58.7	-211 ± 38.6	**-195 ± 54.5**
Hip Joint								
Maximum joint angle (°)	157 ± 15.2	155 ± 15.1	154 ± 13.3	**156 ± 14.6**	146 ± 12.9	147 ± 15	148 ± 15.2	**147 ± 14.2**
Minimum joint angle (°)	86.5 ± 15.1	84.9 ± 16	83.2 ± 14.6	**85 ± 15.2**	92.3 ± 15.8	87.2 ± 11.8	85.3 ± 11.3	**88.7 ± 13.6**
Peak hip extension velocity (°/s)	294 ± 60.2	350 ± 86.9	353 ± 65.6	**330 ± 75.7**	204 ± 74	197 ± 68.2	196 ± 102	**199 ± 80.3**
Peak hip flexion velocity (°/s)	-260 ± 70.1	-249 ± 88.1	-252 ± 87.7	**-254 ± 81.3**	-169 ± 42.8	-194 ± 35.8	-211 ± 45.4	**-189 ± 44.5**

Table 21: Percentage changes and one-way ANOVA results of the joint kinematic variables

Variables	**% Change between ETD and CTD**	**% Change between towing velocities only in ETD**		
	Overall	**1.00 m/s – 0.75 m/s**	**1.25 m/s – 1.00 m/s**	**1.25 m/s – 0.75 m/s**
Ankle Joint				
Maximum joint angle (°)	-9.74 % ♦ *(1.13)*	-0.0468 %	-1.79 %	-1.84 %
Minimum joint angle (°)	4.68 % ♦ *(0.523)*	1.71 %	-0.908 %	0.79 %
Peak plantarflexion velocity (°/s)	-66 % ♦ *(2.55)*	-24 % ♦ *(0.711)*	-10.7 %	-32.1 % ♦ *(0.966)*
Peak dorsiflexion velocity (°/s)	32.9 % ♦ *(0.930)*	3.61 %	5.50 %	9.31 %
Knee Joint				
Maximum joint angle (°)	-8.21 % ♦ *(1.34)*	2.34 %	0.54 %	2.89 %
Minimum joint angle (°)	21.2 % ♦ *(1.36)*	-1.1 %	1.89 %	0.772 %
Peak knee extension velocity (°/s)	38.9 % ♦ *(0.839)*	-9.18 %	0.69 %	-8.56 %
Peak knee flexion velocity (°/s)	-52 % ♦ *(2.05)*	20 %	2 %	22.4 % ♦ *(0.801)*
Hip Joint				
Maximum joint angle (°)	-5.59 % ♦ *(0.604)*	1.17 %	0.618 %	1.79 %
Minimum joint angle (°)	4.32 %	-5.61 %	-2.14 %	-7.63 %
Peak hip extension velocity (°/s)	-39.6 % ♦ *(1.68)*	-3.69 %	-0.265 %	-3.94 %
Peak hip flexion velocity (°/s)	-25.4 % ♦ *(0.952)*	14.9 %	8.65 %	24.9 % ♦ *(0.958)*

♦ = *significant difference between CTD and ECC (p<0.05)*
() = Cohen's d Effect Size

Table 22: Means and standard deviations of the joint kinetic variables

Variables	CTD				ETD			
	0.75 m/s $\mu \pm \sigma$ n = 52	**1.00 m/s** $\mu \pm \sigma$ n = 43	**1.25 m/s** $\mu \pm \sigma$ n = 45	**Total** $\mu \pm \sigma$ n = 140	**0.75 m/s** $\mu \pm \sigma$ n = 52	**1.00 m/s** $\mu \pm \sigma$ n = 43	**1.25 m/s** $\mu \pm \sigma$ n = 45	**Total** $\mu \pm \sigma$ n = 140
Ankle Joint								
Peak plantarflexor moment (N.m/kg)	1.33 ± 0.21	1.46 ± 0.28	1.6 ± 0.46	**1.46 ± 0.35**	1.43 ± 0.36	1.43 ± 0.34	1.56 ± 0.43	**1.46 ± 0.37**
Peak dorsiflexor moment (N.m/kg)	-0.1 ± 0.1	-0.13 ± 0.1	-0.15 ± 0.11	**-0.12 ± 0.1**	-0.09 ± 0.08	-0.1 ± 0.09	-0.09 ± 0.09	**-0.09 ± 0.09**
Mean plantarflexor moment (N.m/kg)	0.847 ± 0.12	0.92 ± 0.16	0.99 ± 0.26	**0.91 ± 0.2**	0.76 ± 0.14	0.83 ± 0.19	0.87 ± 0.23	**0.81 ± 0.19**
Mean dorsiflexor moment (N.m/kg)	-0.06 ± 0.06	-0.08 ± 0.06	-0.1 ± 0.07	**-0.08 ± 0.06**	-0.08 ± 0.06	-0.07 ± 0.06	-0.07 ± 0.06	**-0.07 ± 0.06**
Net impulse (N.m.s/kg)	0.61 ± 0.17	0.49 ± 0.11	0.46 ± 0.1	**0.53 ± 0.15**	0.68 ± 0.35	0.59 ± 0.18	0.54 ± 0.19	**0.61 ± 0.26**
Knee Joint								
Peak knee extensor moment (N.m/kg)	2.28 ± 0.5	2.28 ± 0.49	2.32 ± 0.54	**2.29 ± 0.51**	1.86 ± 0.63	1.88 ± 0.66	1.83 ± 0.7	**1.86 ± 0.65**
Peak knee flexor moment (N.m/kg)	-0.2 ± 0.17	-0.13 ± 0.21	-0.18 ± 0.2	**-0.17 ± 0.19**	-0.53 ± 0.22	-0.58 ± 0.32	-0.71 ± 0.25	**-0.6 ± 0.27**
Mean knee extensor moment(N.m/kg)	1.36 ± 0.37	1.44 ± 0.38	1.43 ± 0.36	**1.41 ± 0.37**	1.08 ± 0.38	1.12 ± 0.39	1.08 ± 0.45	**1.09 ± 0.4**
Mean knee flexor moment (N.m/kg)	-0.12 ± 0.09	-0.13 ± 0.09	-0.15 ± 0.1	**-0.13 ± 0.09**	-0.33 ± 0.11	-0.36 ± 0.2	-0.43 ± 0.17	**-0.37 ± 0.17**
Net impulse (N.m.s/kg)	-1.05 ± 0.47	-0.89 ± 0.35	-0.8 ± 0.32	**-0.92 ± 0.4**	-0.73 ± 0.49	-0.69 ± 0.45	-0.56 ± 0.4	**-0.67 ± 0.46**
Hip Joint								
Peak hip extensor moment (N.m/kg)	1.23 ± 0.52	1.32 ± 0.49	1.49 ± 0.41	**1.34 ± 0.49**	1.47 ± 0.64	1.55 ± 0.53	1.9 ± 0.56	**1.62 ± 0.61**
Peak hip flexor moment (N.m/kg)	-1.5 ± 0.75	-1.79 ± 0.64	-1.85 ± 0.64	**-1.7 ± 0.7**	-1.2 ± 0.7	-1.32 ± 0.67	-1.29 ± 0.67	**-1.26 ± 0.68**
Mean hip extensor moment (N.m/kg)	0.64 ± 0.3	0.72 ± 0.32	0.81 ± 0.25	**0.72 ± 0.3**	0.8 ± 0.29	0.89 ± 0.34	1.04 ± 0.32	**0.9 ± 0.33**
Mean hip flexor moment (N.m/kg)	-0.85 ± 0.44	-1.03 ± 0.35	-1.13 ± 0.35	**-0.99 ± 0.4**	-0.66 ± 0.41	-0.66 ± 0.33	-0.71 ± 0.38	**-0.67 ± 0.37**
Net impulse (N.m.s/kg)	-0.17 ± 0.34	-0.12 ± 0.34	-0.05 ± 0.25	**-0.12 ± 0.32**	0.16 ± 0.64	0.11 ± 0.35	0.17 ± 0.31	**0.15 ± 0.48**

Table 23: Percentage changes and one-way ANOVA results of the joint kinematic variables

Variables	% Change between ETD and CTD	% Change between towing velocities only in ETD		
	Overall	**1.00 m/s – 0.75 m/s**	**1.25 m/s – 1.00 m/s**	**1.25 m/s – 0.75 m/s**
Ankle Joint				
Peak plantarflexor moment (N.m/kg)	0.48 %	0.15 %	8.83 %	9 %
Peak dorsiflexor moment (N.m/kg)	-23.4 % ♦ *(0.31)*	1.64 %	-4.62 %	-3.05 %
Mean plantarflexor moment (N.m/kg)	-11.2 % ♦ *(0.53)*	9.41 %	4.91 %	14.8 %
Mean dorsiflexor moment (N.m/kg)	-9.98 %	-6.86 %	2.13 %	-4.88 %
Net impulse (N.m.s/kg)	16 % ♦ *(0.41)*	-12.8 %	-8.55 %	-20.3 % ♦ *(0.47)*
Knee Joint				
Peak knee extensor moment (N.m/kg)	-19 % ♦ *(0.76)*	0.98 %	-2.7 %	-1.75 %
Peak knee flexor moment (N.m/kg)	245 % ♦ *(1.83)*	8.41 %	23.1 %	33.5 % ♦ *(0.77)*
Mean knee extensor moment(N.m/kg)	-22.4 % ♦ *(0.83)*	3.75 %	-3.32 %	0.31 %
Mean knee flexor moment (N.m/kg)	176 % ♦ *(1.77)*	9.05 %	20 %	30.8 % ♦ *(0.73)*
Net impulse (N.m.s/kg)	-27.3 % ♦ *(0.59)*	-4.85 %	-19.6 %	-23.5 %
Hip Joint				
Peak hip extensor moment (N.m/kg)	20.6 % ♦ *(0.51)*	5.67 %	22.4 %	29.3 % ♦ *(0.71)*
Peak hip flexor moment (N.m/kg)	-25.7 % ♦ *(0.63)*	9.69 %	-2.07 %	7.42 %
Mean hip extensor moment (N.m/kg)	24.2 % ♦ *(0.52)*	12.5 %	16.4 %	30.9 % ♦ *(0.81)*
Mean hip flexor moment (N.m/kg)	-32.2 % ♦ *(0.82)*	-0.84 %	7.92 %	7.02 %
Net impulse (N.m.s/kg)	-222 % ♦ *(0.67)*	-26.7 %	49.5 %	9.54 %

♦ *= significant difference between CTD and ECC ($p<0.05$)*
() = Cohen's d Effect Size

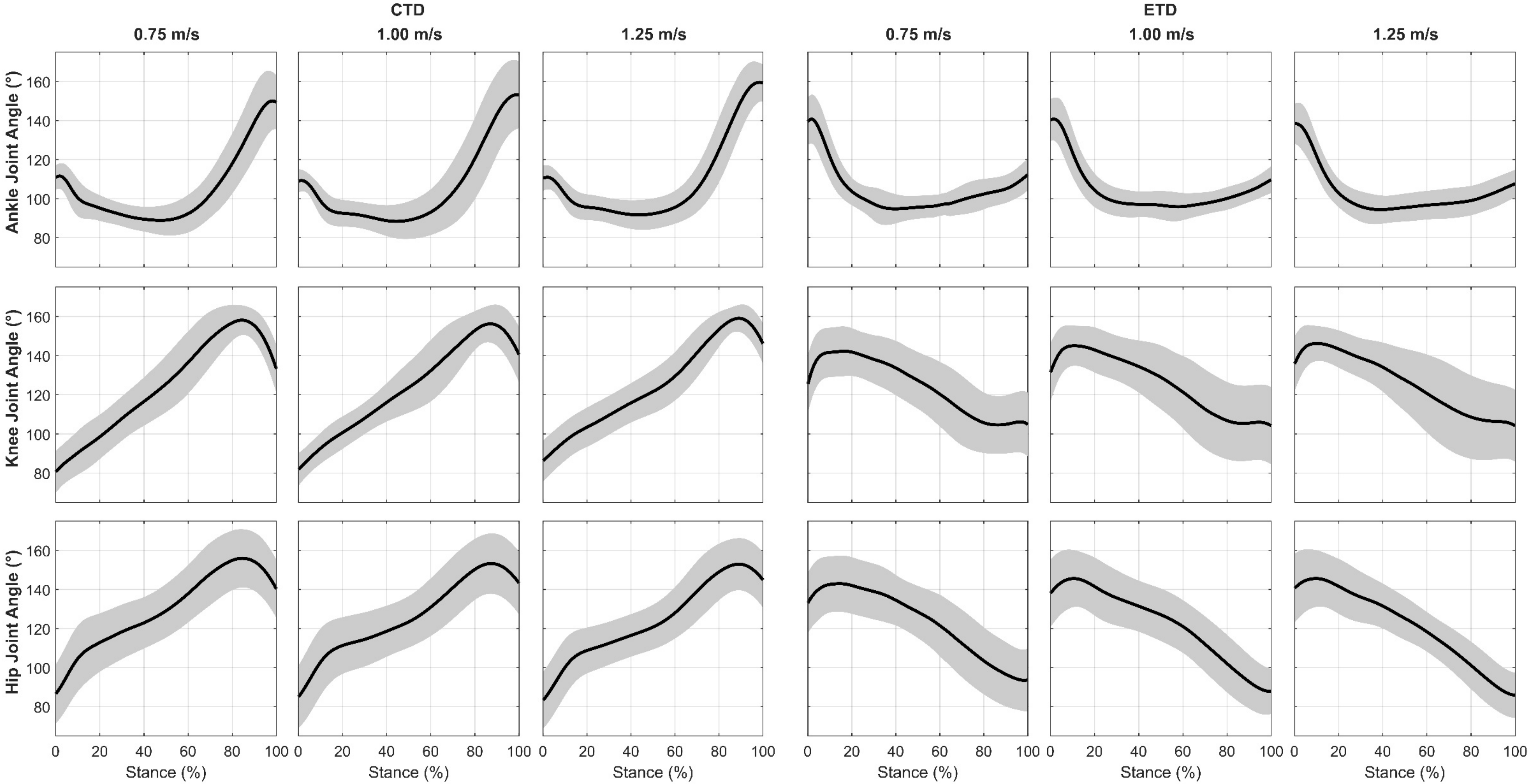


Figure 31: Joint angles

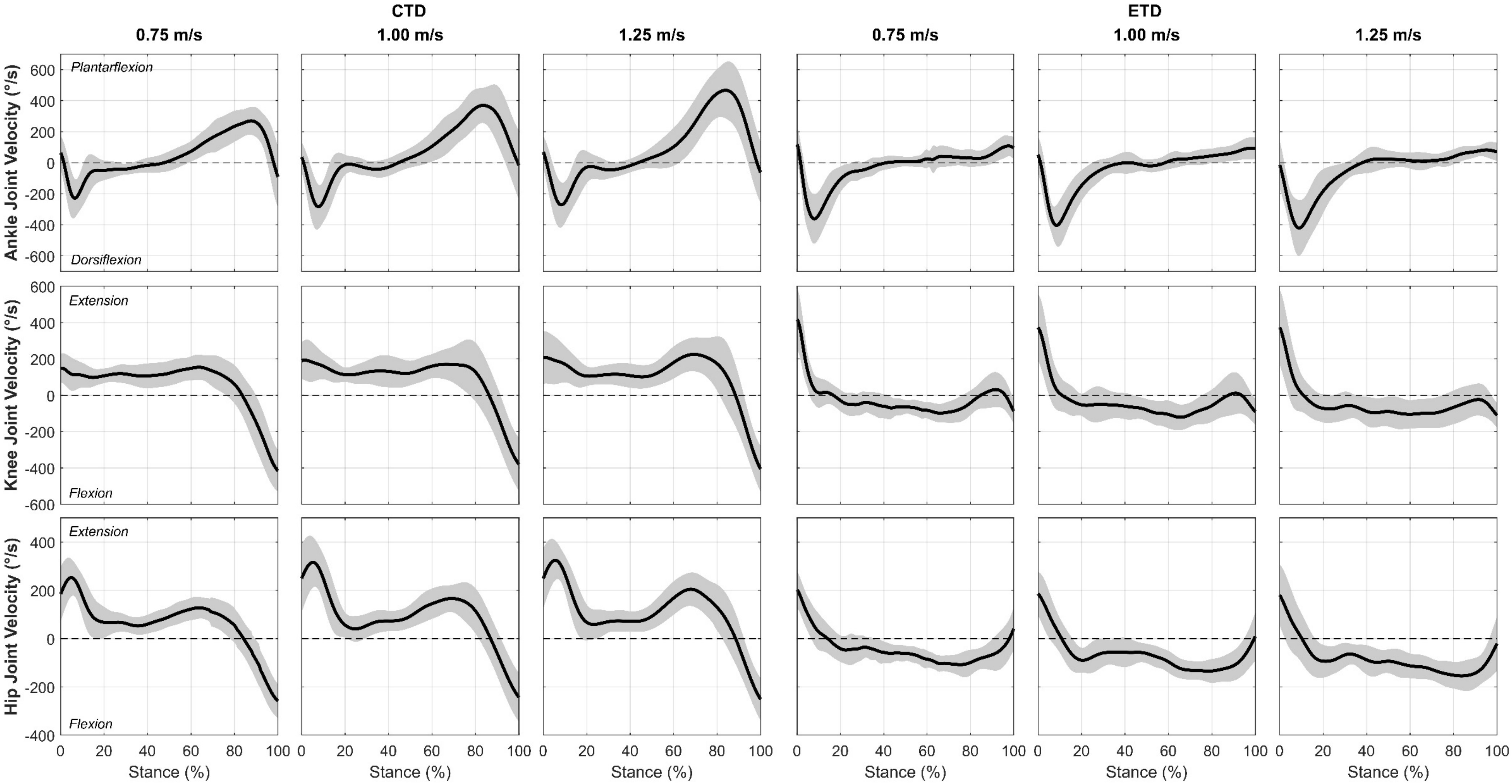


Figure 32: Joint velocities

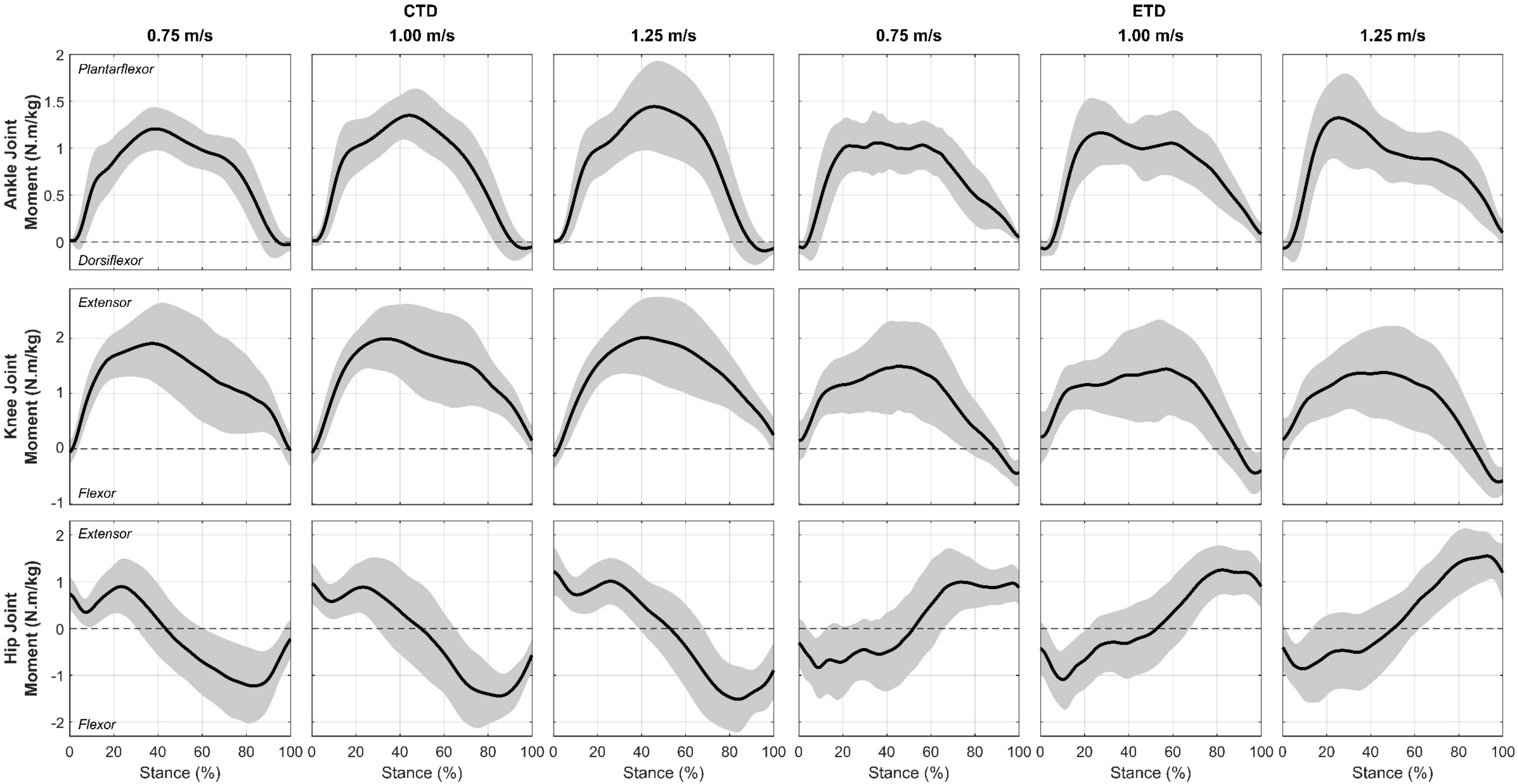


Figure 33: Joint moments

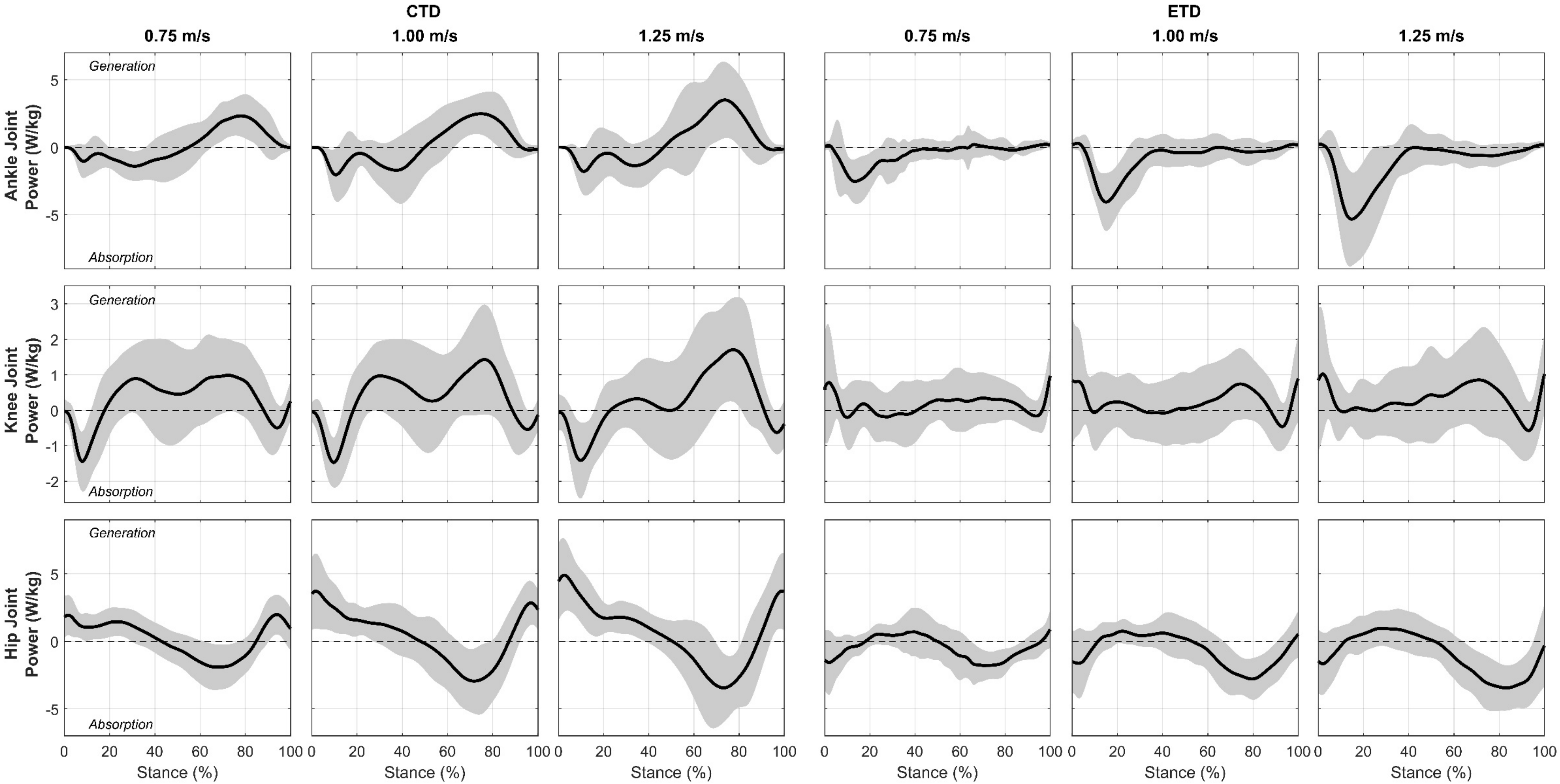


Figure 34: Joint power

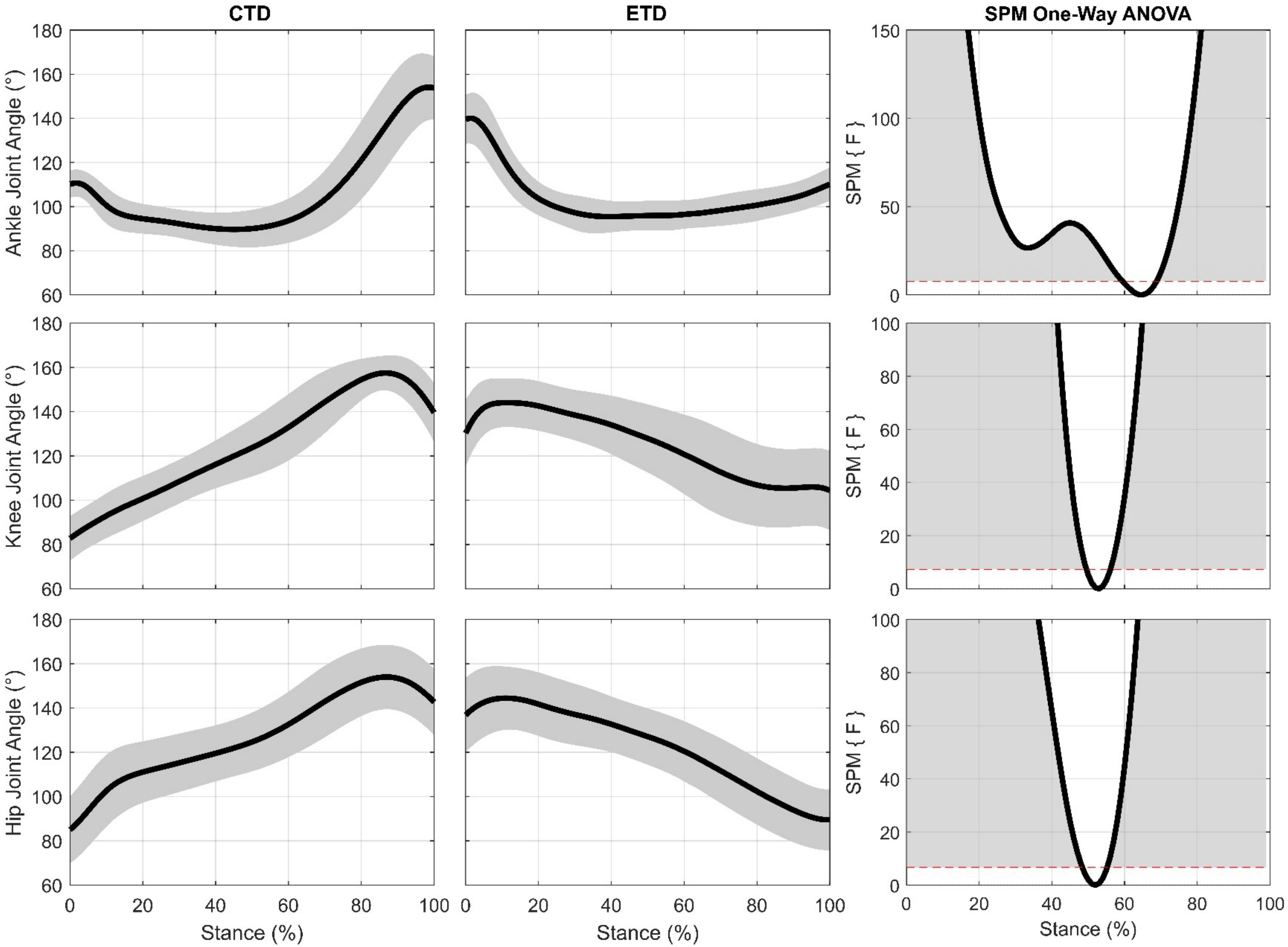


Figure 35: SPM One-Way ANOVA of joint angles between towing directions

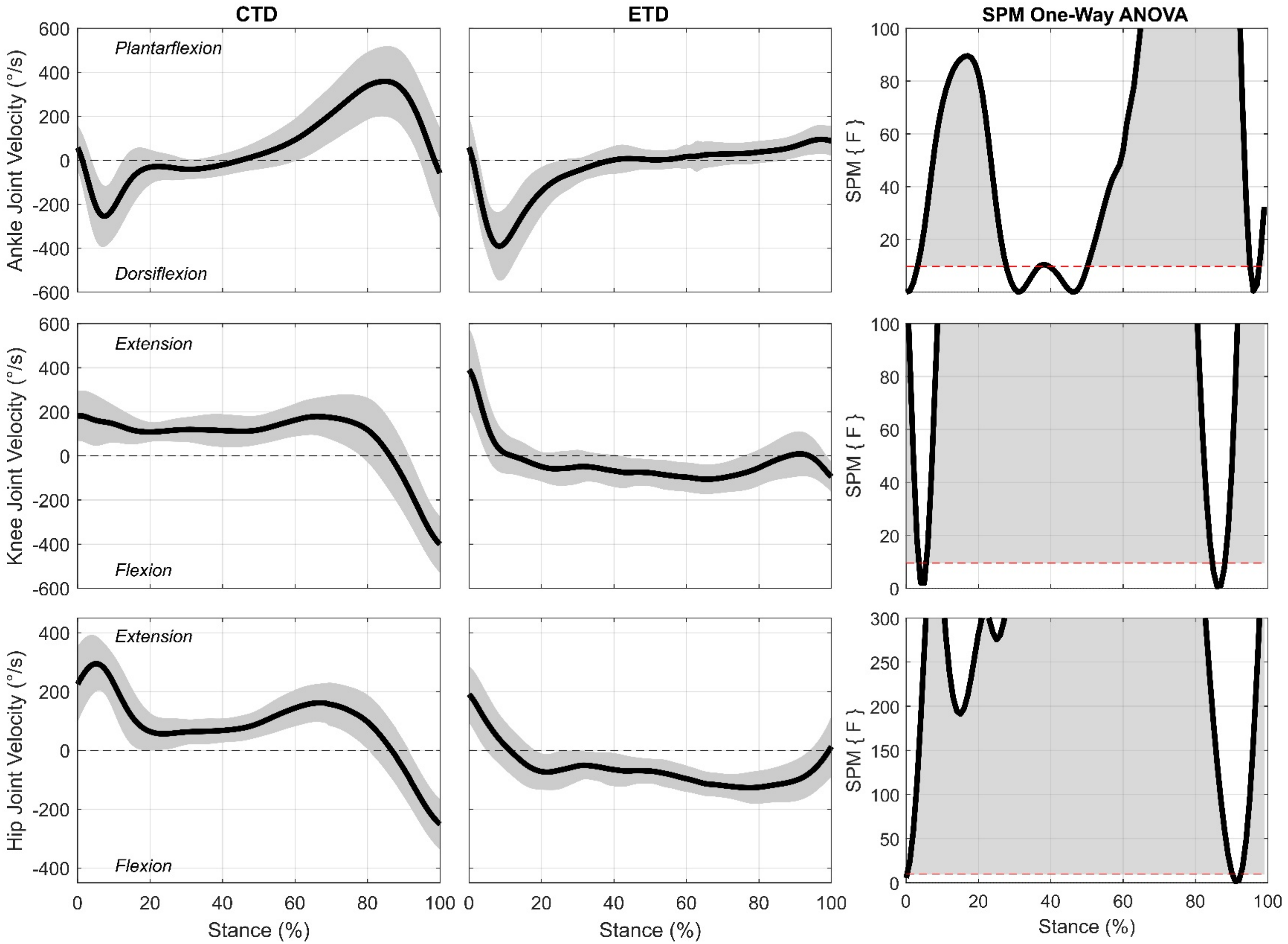


Figure 36: SPM One-Way ANOVA of joint velocities between towing directions

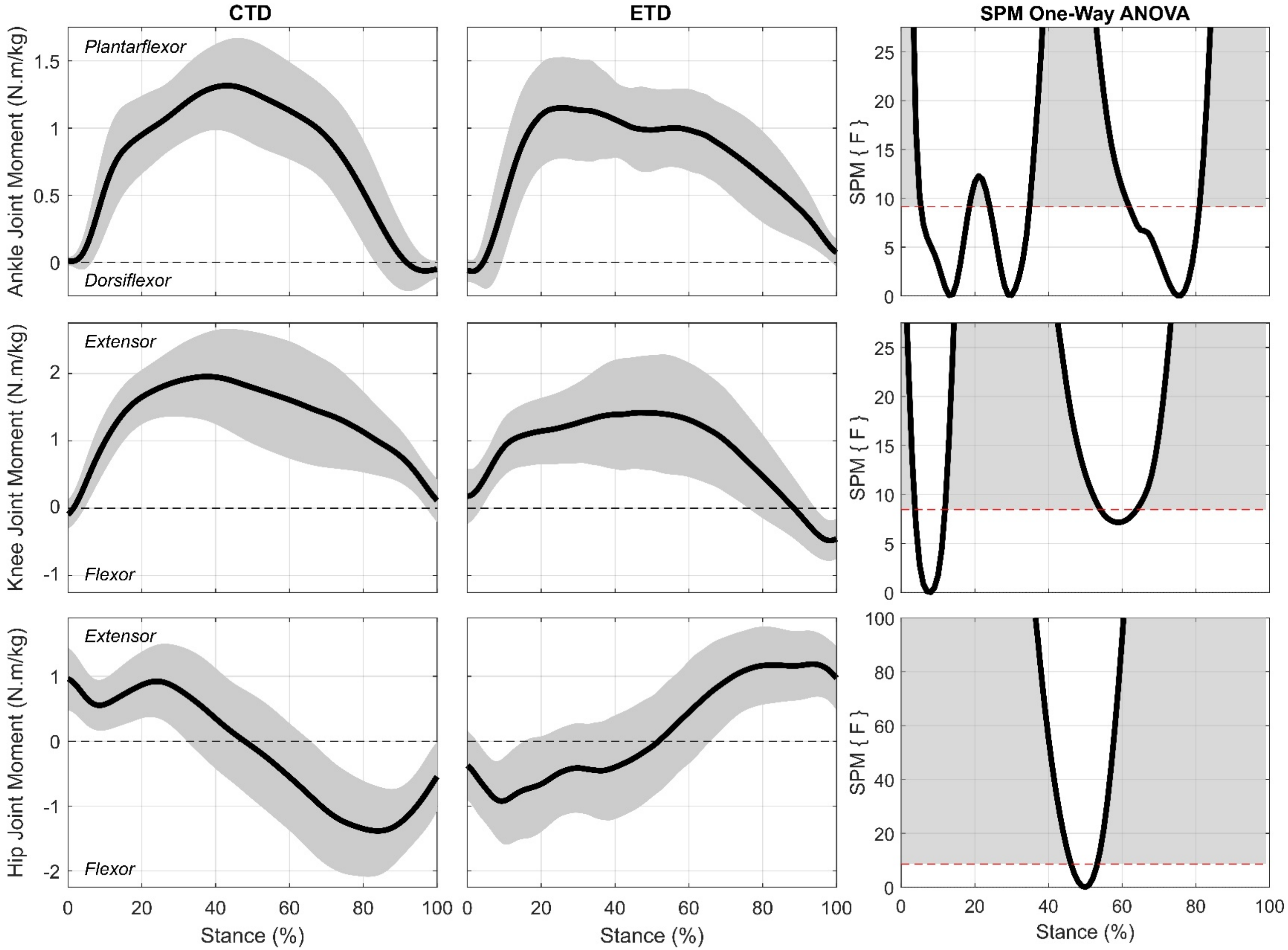


Figure 37: SPM One-Way ANOVA of joint moments between towing directions

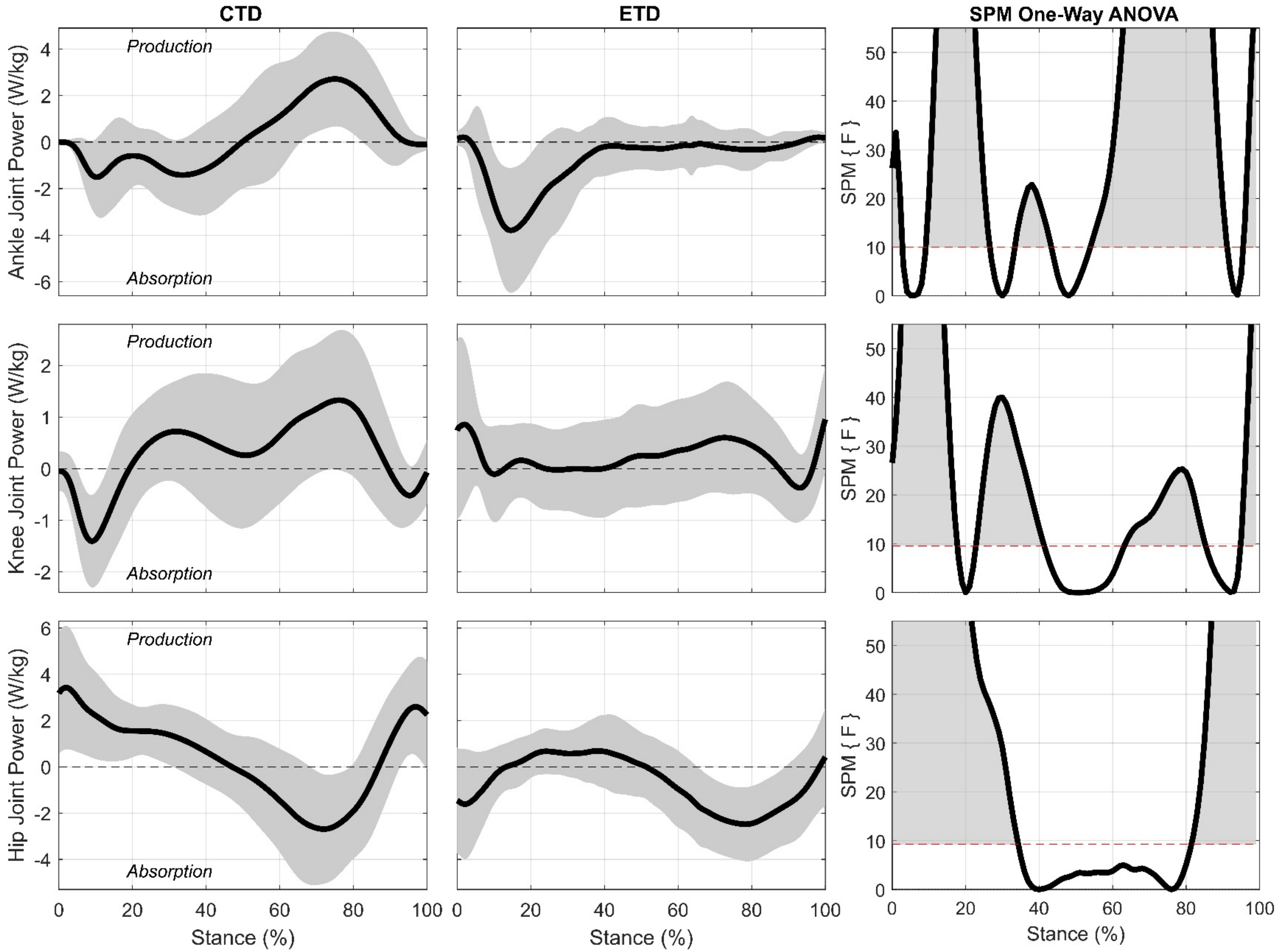


Figure 38: SPM One-Way ANOVA of joint power between towing directions

The End