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The Effect of Vertically- and Horizontally-Directed Plyometric Exercise on Sprint Running Performance

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USE OF THESIS

The Use of Thesis statement is not included in this version of the thesis.

Abstract

The purpose of this investigation was to determine the effect of 6 weeks of vertically- and horizontally-directed lower-body plyometric exercise with vertically versus horizontally biased ground force application, on 40 m sprint running time, vertical jumping height, body composition and gastrocnemius medialis (GM) muscle architecture. Male (n = 19) and female (n = 20) recreational athletes were recruited and stratified according to 40 m sprinting ability, then randomly allocated to one of two groups: horizontally-directed plyometric training (HT) and vertically-directed plyometric training (VT). The groups performed the experimental procedures twice each week with the same number of total ground contacts, while maintaining their usual weekly training load. During training the subjects performed bounding exercises with maximum effort with either a horizontal or vertical directional bias, depending on the allocated group. Sprinting performance was undertaken on an indoor, sprung-cork running track with the times recorded using infra-red timing gates recording to the nearest 0.01s. Ground reaction forces (GRFs) were recorded using in-ground, multi-component, peizo-electric force platforms. Changes in performance and muscle function were assessed during counter-movement jumps (CMJs), squat jumps (SJs), and depth jumps (DJs) from 0.20 m (reactive strength index (RSI-20)) and 0.40 m (RSI-40). Muscle fascicle length (FL) and angle pennation (AP) of the GM were assessed using ultrasonography, while dual-energy x-ray absorptiometry (DEXA) was used to determine body fat percentages (BF%) and composition of the shank of the subjects' dominant legs (push-off leg during sprinting). Multivariate, repeated measures analyses of variance were used to determine differences between training groups and percentage of change scores were calculated for each variable. Both HT and VT presented statistically significant ($p \leq 0.05$) with small-to-moderate standardised effect (d) improvements in 10 m (HT: d = 0.22; VT: d = 0.09), 20 m (HT: d = 0.20; VT: d = 0.15), 30 m (HT: d = 0.24; VT: d = 0.23) and 40 m (HT: d = 0.40; VT: d = 0.39) times, with no differences between the groups. No statistical change was seen for either experimental group at 5 m, however a small and trivial practical change was observed for HT (d = 0.20) and VT (d = 0.04) groups. Significant changes were observed for CMJ, SJ, RSI-20 and RSI-40 for both HT and VT groups, without a significant difference

between groups. No significant or practical benefit in the change following training was observed for FL (HT: d = 0.02; VT: d = 0.05) or AP (HT: d = 0.04; VT: d = 0.08), with no between group significant differences. Following training significant changes in both experimental groups were observed for BF% (HT: d = 0.13; VT: d = 0.18) and total body mass (HT: d = 0.09; VT: d = 0.09), however there was no significant difference between groups. The outcomes suggest that HT and VT were similarly effective at improving sprinting and vertical jumping performance, in recreational athletes. The observed outcomes support the use of either movement-specific training paradigms or kinetically dissimilar exercises for the purpose of improving sprinting performance, even though greater forces may be applied.

Declaration

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any institution of higher education; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference has been made in the text.

Signed: ________________________________

Date: 9 March 2015

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List of Abbreviations

1-RM	One repetition maximum
AP	Angle pennation
BF%	Body fat percentage
CMJ	Counter-movement jump
CSA	Cross-sectional area
DEXA	Dual-energy x-ray absorptiometry
DJ	Depth jump
FL	Fascicle length
GCT	Ground contact time
GL	Gastrocnemius lateralis
GM	Gastrocnemius medialis
GRF	Ground reaction forces
HT	Horizontally-directed plyometric training
ICC	Intra-class correlations
MTU	Muscle-tendon unit
PF	Peak force
PF/BM	Peak force divided by body mass
SI	Reactive strength index
SD	Standard deviation
SEM	Standard error of the mean
SJ	Squat jump
SSC	Stretch-shortening cycle
TtPF	Time taken to reach peak force
VT	Vertically-directed plyometric training

Chapter One

1 Introduction

1.1 Background

Sprinting is the fastest form of human locomotion [1, 2] and is a skill frequently performed during field- and court-based team sports. During match play, sprint distances can vary from very short (i.e. 0–10 m for Rugby Union forwards [3]) to (relatively) long distances (i.e. 66 m and more for Australian Football League players [4]). Sprinting is performed as a series of single-leg projections [5], with brief ground contact times (GCTs) [6, 7] and high rates of force development [8].

To produce the high forces and rates of force development required during sprinting, a rapid shortening of the muscle-tendon unit (MTU) is required [9-11]. The stretch-shortening cycle (SSC) involves an eccentric lengthening followed by a rapid concentric shortening (with a minimal delay, called the amortisation phase) [12]. During the eccentric phase, the active muscle develops force, potential elastic energy is stored in the series elastic structures [13, 14] and there is a significant increase in muscular activity, thus increasing the impulse produced when compared to a concentric-only movement [15]. Additionally, the series elastic structures within the MTU contribute significantly to movement speed as they recoil rapidly during the shortening phase, subsequent to the storage of elastic energy [16]. This series elastic structure allows a faster shortening of the whole MTU in comparison to the shortening speed of the muscle itself [17], which often changes very little during high-velocity movements [18].

Plyometric exercise is a popular method of training that is used to improve the performance of SSC movements [19-22]. Training using plyometric exercise has been reported to produce up-regulation of the stretch reflex [23], increase the stiffness of the MTU (particularly of the series elastic structures) [24, 25] and decrease the amortisation phase of the SSC [26] in various subject groups. Additionally, Malisoux [27] reported increases in cross-sectional area, improved fibre tension and maximal shortening velocity of Type I, IIa and IIx fibres following SSC exercises. These adaptations allow for more efficient storage and release of elastic energy [28, 29], complementing the findings of other researchers who have reported that plyometric exercise may increase peak force [30] and power production during rapid movements [27, 31], following multiple-week training interventions. Thus, plyometric exercise is considered to be effective for improving performance in high-speed movements, such as sprinting [32] and vertical

jumping [33]. Plyometric exercises can be performed in either a horizontal or vertical direction. However, the concept of training specificity suggests that horizontally-directed exercises are most likely to elicit positive adaptations and improvements in sprinting, whereas vertically-directed exercises are most likely to enhance vertical jumping performance, due to similar limb movements and velocities.

Sprinting-specific plyometric exercises are most often performed with maximal horizontal efforts development (i.e. bounding or hopping exercises) which closely mimic the limb movement velocities, horizontal propulsive forces and rates of force as sprinting itself [34, 35]. However, in comparison to maximum-speed running, some subjects have been reported to land with their foot further in front of their centre of gravity when performing horizontally-directed plyometrics [34-36]. This 'over-striding' affects flight time, GCT and the amount of time that braking forces are applied [34], potentially reducing the movement specificity of the exercise and subsequent adaptive response of the neuromuscular system. The alternative to horizontally-directed plyometric exercises is the performance of plyometric exercises with a vertical amplitude bias. The change of exercise focus allows gravitational forces to act upon the body for a longer period of time, and larger propulsive forces are required to overcome the greater gravitational and inertial forces [37]. Thus, while movement specificity may be reduced (compared to horizontally-directed exercises), the greater downward acceleration of the body provides greater loading and subsequently elicits greater ground reaction forces (GRFs), potentially providing a greater positive stimulus for change within the MTU [38]. Interestingly, it is yet to be systematically determined if smaller vertical GRFs or reduced movement specificity are limiting factors in the use of plyometric exercise as a training stimulus to improve sprinting.

The forces applied during vertically-directed plyometric exercises are more strongly correlated with sprinting performance than those applied during horizontally-directed plyometrics in well trained athletes [39]. Sprinting performance in well trained subjects improved following heavy-load training interventions inclusive of heavy back-squats [40], drop jumps [41] and the use of weighted vests and sleds [42] where large forces are produced. Therefore, the possibility exists that the greater forces applied during vertically-directed plyometric exercises may elicit superior adaptations in the

MTU than horizontally-directed exercises, thus producing greater improvements in sprinting performance.

Thus, the purpose of this Masters research is to compare the effects of a training intervention consisting of either horizontally- or vertically-directed plyometric exercises, performed with maximum effort and applied with equal volume and frequency. The primary performance criterion variable was sprint performance time, with changes in muscle architecture of the gastrocnemius medialis (GM) assessed as a potential underlying mechanism to assist in explaining any performance change, while the GRFs during acceleration (recorded at 5 m), vertical jumping height and kinetics were assessed to determine whether the training intervention elicited different changes in muscular force production.

1.2 Research Questions

The purpose of this Masters research is to answer the following research questions:

- Does a training program incorporating horizontally-directed plyometric exercises improve 40 m sprinting performance more than a training program incorporating vertically-directed plyometric exercises, in concurrently training sub-elite athletes?
- Does a training program consisting of bounding exercises performed with maximal effort in a horizontal direction improve vertical jumping performance as assessed by CMJ and SJ, more than a training program incorporated entirely of bounding exercises performed with maximal effort in a vertical direction, in concurrently training sub-elite athletes?
- Will a six-week lower-body plyometric training intervention elicit architectural adaptations in the GM including fascicle angle and length?
- Will a six-week lower-body plyometric training intervention alter body composition, including an increase in lean mass yet decrease in body mass and body fat percentage?

1.3 Significance of the Research

This research aims to determine whether vertically- and horizontally-directed plyometric exercises can effectively improve 40 m sprinting performance in concurrently training, sub-elite athletes. The findings of this study will provide strength and conditioning practitioners with an understanding of:

a) whether the addition of plyometric exercises to a training plan of already training athletes will elicit performance gains in sprinting performance; for comparison vertical jump performance was also examined
b) which method of plyometric exercise is more effective at enhancing sprinting and vertical jumping performance.

A greater understanding of training adaptations in response to plyometric exercise is important in determining how the training stimulus can be used most effectively. The criteria used to assess this will be: 40 m sprinting performance, vertical jumping performance and anthropometrical and muscle architectural changes. It is commonly purported that movement pattern (and skill) specific exercises are superior to non-specific forms of training. However, with regard to the influence of plyometric exercise on sprinting performance, there is no clear evidence of this, as no systematic direct comparison has been performed. To our knowledge this is the first study to examine the effects of a training intervention consisting entirely of horizontally- versus vertically-directed plyometric exercises on sprinting performance. Therefore, this study has important implications for strength and conditioning practitioners involved in the training of athletes who perform short distance sprint efforts.

1.4 Limitations

There are a number of limitations within this study that should be considered. These include:

- All subjects were required to be competing in recreational sports (at a minimum) with a sprinting component involved. However, no control was in place for which sport each subject played, thus subjects were participating in different sports and may have been in different phases of their training–

competition cycles. It is possible that this may have affected inter-individual variability.

- It was also not possible to completely determine the quantity of specific plyometric training performed by each subject, as training programs could only be modified by their coaches. If plyometric exercise was present outside of the current study parameters, it is possible that the volume, frequency and type (direction and GCT) may have impacted the results collected in this research. This may have contributed to an increased inter-individual variability in the response to the study's program.
- The Multi-Dimensional Fatigue Inventory questionnaire (Appendix D) was used to monitor each subject's motivation level throughout the study. The results showed that the subjects presented day-to-day variation in their self-motivation levels. These changes in motivation may have impacted upon their training intensity and potentially influenced the post-training assessment results. A competitive environment was fostered in training and testing in an attempt to maintain high motivations levels, thus optimising training performance. Pre-training testing results (40 m sprint time and counter-movement jump (CMJ) height) were partially divulged to the subjects (names were not allocated to results to maintain confidentiality), to improve their motivation.
- Due to the additional training the subjects completed outside of the study parameters, a risk of unplanned over-reaching was present. In an attempt to minimise the risk of over-reaching or over-training, a 10-point rate of perceived exertion scale was completed 20 minutes after each training session, as well as at the end of each training week.
- Dietary intake was not controlled during this study. It is possible that changes in dietary intake prior to the pre- and post-training assessment periods may have impacted DEXA results and introduced error into the reading of these results.
- It is important to note that while a control period was observed prior to the commencement of this study, in order to account for possible changes within the training groups, no control group was run in parallel to the training itself.

While it is unlikely, it is plausible that changes in performance would have been reported in a non-training control group and thus presented an increase or decrease in the magnitude of change reported by both plyometric training groups.

1.5 Delimitations

The subjects participating in the current study were all experienced strength- and sprint-trained team sport athletes, who were currently playing in recreational and sub-elite sporting leagues. The subjects had a minimum of two years of strength and/or resistance (i.e. plyometrics, calisthenics) training. Inferences made from the results of this study, therefore, most clearly represent this population group.

Chapter Two

2 Review of the Literature

2.1 Introduction to Sprinting

Sprinting is the fastest form of human locomotion [2] and is characterised by explosive forward motion [1] performed as a series of single-leg projections [5], using very brief ground contact times (GCTs) [6, 7]. Sprinting in team sport athletes can range from short (i.e. Rugby Union forwards [3]) to long (i.e. Australian Football League [4]) distances. Due to the short GCTs yet high power outputs required for maximum-speed sprint running, a high rate of force development [8], and thus a rapid shortening of the muscle-tendon unit (MTU) [11], is required. Resistance training is commonly used to improve running performance, via increased force and power output [43, 44]. Previous research has suggested that resistance training may improve descending neural drive, reduce neuromuscular inhibition [38, 45] and induce structural changes in skeletal muscle [46], which may contribute to improved sprinting performance. This chapter provides a critical review of the literature pertaining to the kinematics and kinetics of maximum-speed sprinting, as well as an overview of the resistance training methods used and their reported efficacy for improving sprint performance.

2.2 Sprint Mechanics: An Introduction

Sprinting is a complex multi-joint task, requiring specific muscle activation magnitudes and sequencing to produce peak performance. Importantly, running speed is a product of stride length and frequency [47, 48]. Therefore, theoretically, an increase in either stride length or stride frequency will lead to an increase in sprinting velocity [49, 50]. Typically, a rapid increase in stride frequency occurs during the acceleration phase and it most often reaches its maximum approximately 20 m (-11-16 m for untrained and ~25 m in trained subjects) after starting [51]. The increase in stride frequency is followed by a general increase in stride length (and flight time), as the sprinter progresses towards maximum speed [49, 50]. It has been previously reported that faster sprinters use stride lengths of 2.6 m at a rate of 5 strides per second while at maximum velocity [52]. However, a negative interaction between stride frequency and length has been reported, as an increase in one will typically result in a decrease in the other [47]. Thus, stride length is shorter during acceleration and stride frequency is reduced as maximum speed is approached (and as stride length increases).

Each stride taken during sprinting incorporates a stance phase, when the foot is in contact with the ground, and a swing phase (the time between when the lead foot leaves the ground and when it next makes contact with the ground). Murphy et al. [48] suggested that when seeking to improving sprinting performance, the training focus should be to reduce the time spent in the stance phase and increase stride frequency, which reflects the strength of the relationship between stride frequency (r = 0.41 to 0.64) and GCT (r = –0.44 to –0.65) with running velocity during the acceleration phase (recorded at 0–2.5 m) [53]. Furthermore, speed at 20 m is significantly correlated (r = –0.72 to –0.86) with stride frequency during the first six strides [54]. Given this, it is advisable to employ training stimuli that contribute to the improvement of these variables.

In an attempt to increase peak ground reaction force and the speed with which force is applied during the stance phase, thus improving stride rate and length, various modes of resistance training can be employed. As adaptation to exercise may be specific to loading characteristics, multiple modes of resistance training can be employed [55] as the optimal training paradigm may depend on whether an increase in peak (slow speed) force (e.g. strength training) or fast force production (e.g. plyometric exercise) is required [56, 57].

2.3 Sprint Mechanics: The Stance Phase

The stance phase is crucial to sprinting performance because downward acceleration induced by gravity during the flight phase is reversed and forward propulsion is re-initiated [58]. Furthermore, it is during this phase that any forward velocity lost during the flight phase (resulting from air resistance) and the application of braking forces during ground contact need to be regenerated [50, 59]. The stance phase may be considered as two component phases; the braking component and the propulsive component [58].

The braking component of the stance phase occurs at the onset of ground contact and causes the body's centre of mass to negatively accelerate. These braking forces are represented graphically as a *negative* horizontal ground reaction force, therefore

propulsive forces are shown as a *positive* horizontal ground reaction force. Propulsive forces are applied after the braking component occurs and positive acceleration (and forward momentum) of the body's centre of mass is achieved. Kinematic data obtained during sprint running indicates that ground contact is very short [48], particularly at maximum velocity (101–108 ms) [60, 61]. Thus, the production of a large impulse in minimal time is important for maximising forward propulsion [47, 62]. Increasing ground reaction force magnitude may have a two-fold effect: (a) the application of greater forces will allow a greater displacement of the body's centre of mass during the flight phase; and (b) the ability to produce and transfer greater forces may allow for shorter GCTs (and less time for braking forces to be applied). Thus, stride frequency will likely increase because it is determined by GCT and flight time. However, this is also influenced by the speed of recovery during the swing phase [62].

There is a possibility that joint kinematics, during ground contact, may influence performance. While propulsion is enabled by a rapid and powerful 'triple extension' of the ankle, knee and hip joints in the support leg, greater knee flexion in the recovery (non-support) leg will reduce the lower limb's moment of inertia around the hip joint and result in faster turnover of the lower limb and greater sprinting performance [48]. Experimental findings have reported that greater knee flexion is positively related to hip extension velocity and faster stride rate [63]. Furthermore, it is possible that increasing knee flexion during recovery will decrease the distance of the foot from the axis of rotation (the hip) and reduce moment of inertia [64]. Additionally, greater angles of knee flexion will increase the tendon length and storage of elastic potential energy, producing subsequently greater tendon recoil of the knee extensors [65]. Assuming stride length remains unchanged, the increase in leg turnover rate resulting from the reduction in moment of inertia and the increase in force produced by greater tendon recoil should translate to greater maximum running speeds.

2.4 Sprint Mechanics: The Swing Phase

The swing (or recovery) phase is sometimes known as protraction and can be further divided into two distinct segments. The first commonly described segment is referred to as the residual segment, beginning at foot take-off and ending when the

thigh of the non-support leg begins positive acceleration (i.e. begins to move forward) [66]. The second commonly described segment is the recovery segment, which begins when positive acceleration of the thigh commences and ends when ground contact is initiated [66]. The aim of the swing phase is to efficiently recover the trailing limb and position it for the next ground contact, so that forward propulsion can be re-initiated. It has been theorised that limb dynamics and positioning during this phase play an important role in stabilisation of the body [66].

The residual segment presents the greatest opportunity to reduce the time required to recover the trailing limb. Furthermore, movement during this segment is aimed at maximising thigh acceleration and reducing the time taken to recover the limb during the swing phase, via a complex interaction of limb segments. The rapid and powerful activation of the hip flexor muscles causes passive flexion of the knee, which results in very little hamstring muscle activation [9, 67]. The knee flexion encourages the foot of the push-off leg to be brought rapidly towards the hip muscles and the mass of the recovery leg to remain (relatively) close to the hip joint's axis of rotation, thus reducing the limb's moment of inertia and increasing its rate of rotation. In conjunction, dorsiflexion of the ankle joint facilitates a 'triple flexion' response of the ankle, knee and hip, which further encourages the foot to remain close to the hip joint centre (axis of rotation), thus contributing to generating high angular velocities around the knee and setting the position of the foot for optimal ground contact.

2.5 Velocity–Time Curves: An Introduction

Sprinting can be described in relation to different phases, which are typically identified as: (a) initial acceleration, (b) maximum speed and (c) speed endurance [32, 50, 68, 69]. It is commonly proposed that each of these phases require the ability to produce ground reaction force with a magnitude and timing unique to that individual phase [32, 70-72]. These differences are due to the particular muscle actions and limb positions of that phase [73], which may result in an athlete having good acceleration but not necessarily good maximum speed, and vice versa [72]. The acceleration phase can be characterised by a large degree of flexion at the hip (forward trunk lean) [74] and requires powerful leg extensions to produce forward motion. In contrast, the

maximum-speed phase is typically associated with an upright trunk position [70] and lower moments of inertia (of the lower limbs) [75].

Additionally, it is important to recognise which muscle groups are most active in producing movement at each phase of sprint running as they largely influence the production of the (relatively) large ground reaction forces required to accelerate the sprinters centre of mass (Newtons 2nd Law: Force = Mass × Acceleration). One method of determining which muscle groups are actively involved and play significant roles during maximum speed sprinting is using electromyography recordings (EMG). Several researchers [76, 77] have examined the activation levels of various muscle groups in he legs and hips during 0 – 30 m sprinting, from both standing and block starts. They found that knee extensors (i.e. vastus lateralis) contributed the most during the acceleration phase and that their contributions diminished as distance from the start point increased and maximum speed was reached. An opposite trend of increasing relative contribution to performance as speed increased, was reported for both the hip extensors (i.e. gluteus maximus and bicep femoris) and hip flexors (i.e. rectus femoris). Interestingly the plantar flexors (i.e. soleus and gastrocnemius) presented relatively consistent activation from start to finish. These findings are somewhat supported by studies [53, 70, 73, 78] showing correlations between sprinting performance and measures of single leg strength testing. In particular strong correlations were reported for concentric strength of the knee extensors and plantar flexors during initial acceleration (0 – 15 m) [70, 73]. Consequently it is important to determine which portion of the velocity–time curve and thus the muscle groups most relevant to that phase of running, to target during training and practice [32, 70].

2.6 Velocity–Time Curves: The Acceleration Phase

The ability to accelerate rapidly is an important skill in sporting performance and is reportedly a discriminating factor between elite and sub-elite playing ability [79]. Initial acceleration requires optimal vertical and horizontal ground reaction forces (GRFs) to be produced during the stance phase [80]. Effective production of this force is thought to be determined by concentric knee [78] and hip extensor forces [32, 50, 81, 82]. The resulting lower-limb extension drives the thigh of the grounded limb towards the

rear, producing a large horizontal impulse and subsequently propelling the body's centre of mass forward. Additionally the increase in impulse affects an increasing stride frequency (peaking at approximately 20 m from the start), which has been determined as a differentiating factor in slow and fast acceleration [48, 49, 53].

The time spent in stance phase decreases as running speed increases [67], thus GCT is subsequently much greater during acceleration (i.e. approximately 190 ms) when compared to maximum speed (i.e. approximately 101–108 ms) [60, 61]. The longer ground contact time during acceleration is due (in part) to the larger impulse required to overcome the body's inertia during acceleration, as opposed to later phases of sprinting when the body's centre of mass already has forward momentum [59]. The majority of time in the ground contact phase (during acceleration) is spent applying propulsive GRFs (approximately 87–95% of total GCT) [59-61, 83], which is paramount to sprinting success [60, 84]. With respect to the application of horizontal forces, the magnitude of force has a stronger positive relationship with acceleration than vertical forces [53, 59, 85]. Additionally, it is possible that horizontal forces applied during the braking phase may be stored as elastic potential (strain) energy, thus producing greater force during the subsequent tendon recoil (i.e. the propulsive phase) [86].

Mero et al. [53] reported a significant negative correlation between the vertical displacement of the body's centre of mass during the first two ground contacts following a crouched start (from starting blocks, as in competition) and velocity at 2.5 m (r = –0.57). The authors hypothesised that lowering the body's centre of mass [53, 84, 87] increased the eccentric component of the ground contact, thus negatively affecting stride frequency. Furthermore, faster athletes have been shown to elevate their centre of mass significantly less than slower athletes during the first ground contacts [84]. In effect, minimising the descent of the body's centre of mass during the braking phase and the subsequent elevation during the propulsive phase will shorten GCT and contribute to increased horizontal and vertical force production and faster stride frequency.

However, there are mechanical differences between a block start and a standing (or walking and jogging) start [88], thus the qualities of acceleration are not as

specific for team sport athletes as they are for track and field sprinters [89]. For example, the position of the centre of mass changes considerably during the initial steps following a block start. At the commencement of the first ground contact, the sprinter's centre of mass is 0.13 m ahead of the ground contact, decreasing to 0.04 m ahead by the second step and is then 0.05 m behind the ground contact by the third step [53]. To the author's knowledge, there is no data indicating whether a similar pattern exists for standing, walking and jogging starts. However, it seems unlikely that such a dramatic change in body positioning would occur considering the placement of the centre of mass during the respective starting positions.

2.7 Velocity–Time Curves: The Maximum-Speed and Speed-Endurance Phases

The maximum-speed phase of sprinting is reached when peak velocity is achieved. The speed-endurance phase is the maintenance of this velocity. As with acceleration, the action of the ground leg is critical to induce optimal performance. As speed is increased, the time spent in ground contact is reduced [60, 61], thus the time spent in the braking and propulsive phases is much shorter. However, the proportion of time spent in the braking phase is significantly greater during acceleration (approximately 5–13%) compared to maximum speed (approximately 43%). The duration of ground contact at peak velocity is considered to be a differentiating factor between 'fast' and 'slow' sprinters [62] and is likely to be representative of the athlete's ability to produce force rapidly. Given this, it is important that the vertical displacement of the centre of mass is minimised during braking and propulsion, to minimise the total time spent in ground contact [53, 84].

During maximum-speed and speed-endurance phases, forward propulsion is primarily enabled by MTU actions of the hip and ankle extensors [50, 76]. The hip extensors are emphasised more at maximum speed than during acceleration, due to the longer stride length during this phase compared to the acceleration phase [90]. It is possibly due to this increase in stride length and the greater action of the hip extensors, that the average (horizontal and vertical) braking forces reported during high-speed running are significantly greater than those reported during acceleration

[60]. However, the eccentric strength of the hip extensors may potentially reduce braking force during ground contact and thus be a limiting factor at maximum speed [91, 92]. It is thought that horizontal braking force may be beneficial to forward locomotion by allowing a greater capacity for the storage of elastic strain energy, to be used during subsequent tendon recoil [93]. The greater potential elastic energy that can be stored is likely to result in an increase in force production [65, 94, 95], thus providing greater forward propulsion [93] and an extended flight phase and stride length.

Stretch-shortening muscle actions are particularly important in attaining a high rate of force development due to the rapid movement speeds required for sprinting [96]. In particular, the stretch–recoil action of the plantar flexors is reportedly important at maximum velocity, which is in part confirmed by research suggesting that gastrocnemius medialis (GM) fascicle length (FL) is a discriminating factor in sprinting velocity [97-99] (i.e. longer fascicles are reportedly conducive to faster shortening velocity than shorter fascicles of the MTU, thus allowing for faster rates of force development) [100]. The 'catapult' action of the series elastic components is of particular importance during high-speed locomotion, as the plantar flexor muscles themselves have been shown to contract only quasi-isometrically during ground contact [18, 101]. The quasi-isometric muscle action means that the majority of force for forward propulsion is produced by the tendon's ability to store and release elastic energy during its stretch and subsequent recoil, rather than being produced by the muscle itself. Thus, it seems likely that the increased percentage of time spent in the braking phase of ground contact (compared to acceleration), allows for the storage of elastic energy in the series elastic components. Accordingly, training strategies aiming to improve the capacity of the plantar flexor MTU to rapidly store and release elastic energy may prove beneficial for sprinting performance.

2.8 Improving Sprinting Performance

Short distance sprinting is a fundamental requirement for success in a number of sports, thus improving performance in this skill is important to success [102]. The *principle of training specificity* suggests that the most effective method of training is the practice of sprinting itself [103]. This is particularly true of younger or lesser-trained

athletes who may have greater scope to improve their performance through skill (technique) development. More experienced athletes have a smaller magnitude for adaptation via the skill development pathway, thus they may require different methods of training to improve performance.

Resistance training is commonly used as an adjunct to sprint training, to improve performance. It encompasses a broad number of training modes in which an opposing force (typically barbells, dumbbells, medicine balls and/or body weight) is moved, or is attempted to be moved. Resistance training has been widely reported to increase muscle size [46, 104, 105], alter muscle architecture (fascicle length and angle) [46, 104], improve muscular endurance [106], decrease adipose tissue volume [107] and improve muscular force [38]. Manipulating the training variables (i.e. movement patterns, recovery times, load moved, volume, frequency and intensity of the training) will result in different outcomes [108, 109]. With respect to sprinting, increasing peak force (PF) capacity and decreasing the time required to reach PF is likely to be the main goal of any resistance training intervention.

It has been well established that resistance training can lead to an increase in muscular force production, however the specific mechanisms behind are not fully known. While numerous studies have reported changes in cross-sectional area [46, 110, 111], increased Type IIa fibre percentage [112, 113] and changes in muscle FL and pennation [46, 110] following resistance training, increases in muscle contractile force may not be fully explained by morphological or architectural changes, but rather by neurological changes that increase force production in the absence of morphological change [105]. Resistance training has been reported to increase motor neuronal output (driving the increased force production) by improving descending neural drive, elevating motor neuron excitability and reducing pre-synaptic inhibition [104]. Heavy strength training, in particular, has been shown to diminish Ia-afferent pre-synaptic inhibition during the pre-stretch (the eccentric phase of the movement) and down regulate inhibitory Ib-interneurons emanating from golgi Ib-afferents during muscle-tendon recoil (the concentric phase of the movement) [114, 115]. Taken together these affects contribute to a greater capacity for the MTU to produce force via increasing rate coding and doublet motor-unit firing [116]. The combination of these factors results

in an output that is reported as mechanical power and force production. These variables have been reported to be distinguishing factors in various athletic endeavours [117] and thus a great deal of emphasis has been placed on improving them.

For athletes competing in speed- and power-based sports, it is common practice to perform heavy strength training and/or (relatively) high-velocity training (i.e. plyometric exercise, weightlifting). These training methods typically target one portion of the force–velocity curve (Figure 2-1).

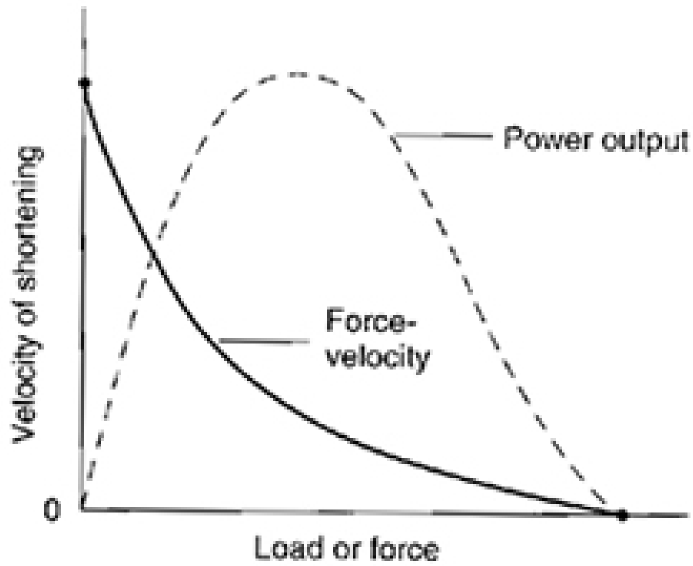

Figure 2-1: The force–velocity curve showing the inverse relationship between load or resistance and velocity of movement; as load is increased the velocity decreases, and vice versa

It has been suggested that adaptation to exercise may be specific to the mass of the load moved and the velocity at which it is moved, providing diminishing returns as the force–velocity curve moves away from the training variables [55]. While not to discount other training variables (e.g. time under tension, recovery time etc.), it can be suggested that strength training under heavy loading will improve the low-velocity, high-force portion of the force–velocity curve and faster movements under lighter loads are likely to improve the high-velocity, low-force portion of the curve [56, 57]. Therefore it is crucial that the training program is carefully manipulated to ensure the required adaptive changes are made for the success of the target endeavour.

2.9 Improving Sprinting: Strength Training

Strength training is a commonly practiced form of resistance training involving the lifting, pushing and/or pulling of heavy loads. In this form of training, ≥80% of the maximum load a person can move for a single repetition (one repetition maximum or 1-RM) is utilised [118, 119]. This mode of training is considered most effective for improving muscular strength [120].

Strength training recruits a large number of units, particularly those controlling the Type IIa and IIb muscle fibres. Type II fibres have a greater capacity to generate force [121] than Type I fibres and are able to contract (shorten) at higher velocities [120, 122]. Furthermore, strength training has been reported to increase the length and pennation angle of the fascicles in the working muscles [110], which may further increase force generation capabilities of these fibres. Importantly, maximum strength is reported to be a differentiating factor in sprinting performance [123, 124], as stronger athletes are able to apply a greater impulse relative to their mass, which has a strong positive relationship with running speed [59, 62, 125].

The current literature suggests that while sprint training alone is sufficient to improve running performance, significant improvements in running velocity have been reported following training interventions combining sprint training with strength training [32, 126]. Unfortunately, much of the current available literature reports data that has been obtained from (relatively) inexperienced subjects and uses single-joint exercises (i.e. leg extension) which have only weak to moderate correlations with running speed [78, 127]. Thus, it is unclear whether these results were due to a synergistic effect of both forms of training, or whether the subject population would have produced similar results following the completion of only one form of training, given their relative inexperience.

Measures of leg strength are reported to have varying degrees of effects on running velocity, with multi-joint exercises (i.e. back squat) having a stronger relationship than single-joint exercises [124]. Thus, traditional strength training exercises such as the back squat and deadlift are often employed in strength and conditioning programs [19-21]. That multi-joint exercises are more effective for improving sprinting

than single-joint exercises suggests that force generation may only have finite importance for a sprinter and that other (possibly biomechanical) factors become important. Furthermore, strength training is typically performed at low velocity due to the high resistance and may not entirely satisfy the principle of specificity with regards to movement velocity. Thus, further research to determine just how much 'strength' is enough is required.

2.9.1 Improving Sprinting: Ballistic Exercise

Ballistic exercise refers to a training mode in which the lifter attempts to move as rapidly as possible [128] and that once the movement has been initiated it cannot be modified (e.g. throwing a ball; once a ball has been thrown its trajectory cannot be altered). These typically encompass exercises in which the load is thrown (upper body) or the 'lifter' jumps (lower body) during the final stage of concentric movement [129] and are often performed with relatively light external loads (e.g. squat jumps (SJs)).

Ballistic training has been shown to enhance mechanical power output following training interventions [64, 130, 131]. This is likely (in part) because the 'throw' circumvents the inherent problem of negative acceleration reported to occur at the end of the concentric phase of traditional resistance training [132, 133]. It should be noted, however, that the optimal load responsible for producing peak power outputs is unclear, and some researchers have suggested the use of a range of resistance (between 0% and 60% of 1-RM [134, 135]), with the trend leaning towards lighter loads. McBride et al. [136] compared light (30% 1-RM) and heavy (80% 1-RM) training and reported that the lighter load group presented (non-significant) improvements in 20 m sprint performance whereas the heavier load group presented slower running speeds from 0 m to 5 m. Furthermore, loads equal to a 30% 1-RM back squat have been considered to be the 'optimal' load by some researchers after significant positive changes in short distance sprinting (up to 40 m) [64, 137] were observed following training interventions. It seems plausible that performing training at faster speeds and with relatively light loads (at least in addition to heavier loads) might be useful to improve sprinting performance. However, Blazevich and Jenkins [138] reported no significant differences in sprinting performance in elite junior sprinters, when resistance training was performed at slow or fast speeds in addition to sprint training.

It is unclear whether high-speed strength training performed without concurrent sprint training will enhance sprinting performance. While this mode of exercise is similar in its force–time and velocity–time characteristics compared to traditional resistance training, the practice of the skill itself may still be necessary to elicit changes in performance. The hypothesis that concurrently performing sprinting and ballistic training is necessary to improve sprinting performance was suggested by Wilson et al. [64] who found only small non-significant (p = 0.08) improvements (1.5%) in 0–30 m sprint running speed following weighted squat jumps (30% maximum Isometric force). However, McEvoy and Newton [137] found significant improvements in short distance (27.4 m) sprint velocity following concurrent SJs (with a 30% 1-RM loading) and normal baseball training (i.e. sprinting included). While the baseball training only group reported improvements in running speed (6.1%), significantly greater improvements were seen in the concurrent training group (9.0%). Thus, in a baseball-specific population, ballistic training is capable of improving running performance when performed concurrently with the practice of sprinting.

2.9.2 Improving Sprinting: Olympic Weightlifting

Weightlifting (i.e. snatch, clean and jerk) and its variations (i.e. power clean, high pull, split jerk) are becoming increasingly popular training methods for speed-power athletes [139, 140]. The nature of weightlifting movements, lifting relatively heavy loads rapidly, creates potential for the production of high power outputs across a continuum of loading conditions [129, 140-142]. During weightlifting movements, the lifter moves a load from the ground to an overhead position by performing a powerful concentric extension of the hip, knee and ankle joints [143]. This 'triple extension' will often produce sufficient power to project the lifter into the air [144, 145]. The ballistic nature of weightlifting maximises the vertical acceleration of the load being lifted, resulting from a reduced (eccentric) activation of antagonist muscle groups [129], compared to powerlifting movements. Furthermore, a high speed of movement has been reported to correlate with better lifting performance [146] and performance in these lifts are reportedly a differentiating factor in sub-elite level sporting performance [147]. While major elements of weightlifting require concentric muscle actions, the mechanism for absorbing impact during the receiving or 'catch' phase is largely

eccentric. This eccentric phase is similar to that of the weighted SJ, however the displacement of the body's centre of gravity is much greater during the weightlifting exercises [142] due to the greater loads being moved. It is possible that the smaller catch phase of the 'power clean' or 'power snatch' movements would show greater similarities to that of the squat jump movement. Improving the lower limbs' ability to absorb force eccentrically and decreasing neuromuscular inhibition in the weightlifting movement may translate to reduced displacement of the body's centre of mass during the stance phase of sprinting resulting in shorter GCTs and thus faster performance.

In accordance with the principle of specificity, lighter loads moved at greater speeds (i.e. the snatch as opposed to the clean) may be more efficient at producing power profiles similar to those of (relatively) rapid movements such as sprinting and jumping [145, 148]. In particular, positive correlations have been reported between weightlifting and vertical jump performance [149-151] and the acceleration phase of sprinting [152-154]. It is possible that this is due to the similarities in concentric muscle action between the two movement patterns.

Few studies have been conducted to determine the effectiveness of weightlifting training on sprinting performance. Improvements in 25-m sprinting performance following an intervention of weightlifting and traditional resistance training were reported by Moore et al. [155]. However, it is unclear whether the improvement is directly attributed to the training intervention or another mechanism, as no control group was used. In contrast, Tricoli et al. [153] reported significant improvements in 10-m speed following a weightlifting training intervention, although no improvement was reported at 30 m. Additionally, Hoffman et al. [151] reported no significant differences in 40-yard time, however a 'twofold greater difference ($p > 0.05$)' was presented following a log10 transformation.

Collectively, this data suggests that weightlifting training may be effective for the enhancement sprinting performance. However, given the variance in the results to date and considering that weightlifting training is widely utilised [19-21, 156], further research is required to determine whether this training methodology is useful for

improving sprinting performance in all phases of the velocity–time curve of a sprint race.

2.9.3 Improving Sprinting: Plyometric Exercise

Plyometric exercises are performed with an emphasis on utilising the stretch-shortening cycle [27, 157] (SSC; i.e. a lengthening of the MTU followed by a short amortisation phase and then a rapid shortening [13, 158, 159]) and are commonly prescribed in the lower body as a series of hops, bounds or jumps [160] performed as fast as possible [161]. Movements utilising the SSC produce greater force than concentric-only movements [9, 13, 29]. Thus, plyometric exercise is thought to effectively produce relatively high mechanical power outputs at fast movement speeds [27]. It has been suggested that plyometric training improves mechanical power output by increasing muscle contractile force [162-164] and only needs to be applied in small volumes [41, 165]. Furthermore, improvements in vertical jumping and sprinting performance following plyometric training interventions are reportedly due to improved muscle coordination [166], leg extensor force output [26, 167] and improved descending neural drive and decreased neural inhibition [38, 104].

Plyometric exercises can be movement-pattern specific [34], meaning the adaptations to the training should be optimised when performing these exercises. With respect to sprinting, lower-body plyometric exercises, including jumping and bounding, are generally performed using little or no external loading [168] so that movement kinematics are not altered and movement velocities and force–time curves are proposed to remain similar to sprinting itself. Any overload used is applied by increasing the stretch rate (decreasing the duration of the SSC) and/or stretch load (increasing force applied to the SSC, often via increasing the height of the depth jump (DJ)) [168]. Therefore, plyometric exercise can be used to target movements requiring both long and short duration SSC actions. These movements are typically low in load and high in velocity. Thus, researchers investigating the effects of training on sprinting [32, 169, 170], vertical jumping [111, 162, 163, 171] and throwing [130, 150, 172] performance have reported improvements following plyometric training interventions.

Sprinting-specific training with plyometric exercises can be performed using an emphasis on horizontal or vertical force application. Horizontally-directed plyometric exercises have shown to allow for similar limb movement speeds, horizontal propulsive forces and rates of force development to that of sprinting [34], and are therefore often considered to be the most suitable plyometric training stimulus for improving sprint performance. Interestingly, some individuals have been shown to land with their foot further in front of their centre of gravity when performing horizontally-directed plyometric exercises when compared to maximum-speed sprint running [34, 36]. This 'over-striding' affects flight time, GCT and the time that braking forces are applied [34]. Speculatively, this may reduce specificity and subsequent adaptation with regard to sprinting performance.

Alternatively, plyometric exercise can be performed with an emphasis on vertical amplitude, which produce greater GRFs but are more (movement and velocity) specific to vertical jumping than sprinting. During vertically-directed plyometric exercise, gravitational forces act for longer and result in greater downward acceleration of the body. Thus, the ground reaction force magnitude and the momentum of the athlete's body is greater during ground contact, when compared to horizontally-directed plyometric exercises [173]. To this effect, greater propulsive forces are required to perform the vertical movement [37]. This increase in force is likely to provide a greater stimulus for positive adaptive change in the MTU [38], which has been shown to be a discriminating factor in sprinting performance [39].

Researchers investigating the effect of vertically-directed plyometric interventions such as DJs have not reported improvements in sprint performance [64]. Wilson et al. [64] examined the effects of performing DJs from heights of 0.2 m to 0.8 m twice a week on 30 m sprinting performance. No significant improvement was observed, which may be explained by: (a) DJs not being kinematically similar to sprinting; (b) neuromuscular adaptations to the training intervention not being effectively transferred to sprinting performance, possibly due to a lack of sprinting practice; and/or (c) the plyometric training not being an effective method of improving sprinting performance. This final possibility is unlikely, as several studies have reported significant enhancements in sprinting performance following a variety of plyometric

exercise interventions [32, 169]. The first possibility seems plausible given that DJs are performed in a vertical plane, whereas sprinting is predominately performed horizontally. Therefore, the lack of movement specificity may have prevented the transfer of training effect between the DJ and sprint performance. However, while sprint performance did not improve, improved counter-movement jump (CMJ) performance was reported. The CMJ is specific in its movement pattern to the DJ training, which lends support to the idea that movement pattern specificity strongly influences the training outcome. Thus, it may be hypothesised that horizontally-directed plyometric exercise elicits greater improvements in sprinting performance. Examples of horizontally-directed plyometric exercises include horizontal hopping, bounding or stepping [34, 174]. Researchers using this mode of training have reported significant improvements in 10 m and 40 m sprinting, with a trend towards greater gains during initial acceleration (10 m) as opposed to at higher speeds (10–40 m). Researchers have attributed this improvement to a reduced stance phase duration due to a greater reactive strength of the athletes. Furthermore, Delecluse et al. [32] reported that horizontally-directed plyometric exercises concurrently performed with sprint training enhanced 10 m acceleration time and 100 m maximum speed times greater than sprint training alone. Taken together, the findings of these studies lend support to the hypothesis that training with movement specificity will have a greater transfer of training effect than non-specific movements and thus provide greater performance enhancements.

The second possibility, raised by the Wilson et al [64] study, that the adaptations to the training intervention were not effective in improving sprinting performance, is also likely. It has been suggested that resistance training should be coupled with the practice of the skill in question to properly take advantage of neuromuscular adaptations [175]. This suggestion would mean that concurrently performing plyometric and sprint training would significantly improve sprinting performance by allowing better coordination of movement and both activation and timing of the MTU, more than performing plyometric training alone. There is limited research examining the effects of concurrent sprinting and plyometric exercise, however Delecluse et al. [32] and McEvoy and Newton [137] examined the effects of horizontally-directed plyometric

exercise and jump squats, combined with sprint training. Both researchers reported significant positive changes in sprinting performance. These studies show improvements during the maximum-speed phase of sprint running, and even greater changes during the acceleration phase. Thus, it appears likely that plyometric exercise is an effective training mode for improving sprinting performance. However, the body of research directly comparing plyometric exercise alone, versus plyometric training concurrently performed with sprint training seems to be limited, so it is not clear if plyometric training alone is enough of a stimulus to significantly enhance sprinting performance. Plyometric exercise may be effective in providing supplementary benefits to sport-specific training, and enhancing sprint performance. Furthermore it seems likely that performing these exercises in a manner kinematically similar to the movement in question may produce the optimal result.

2.10 Conclusion

Sprinting is a complex skill performed as series of single-leg projections and can be described as a product of stride rate and frequency. An increase in stride rate and/or stride length should result in an increase in running velocity. Each stride contains a ground contact (or stance) phase and a flight time (or swing) phase, which both contribute to sprint speed. Forward momentum is initiated during the ground contact, with greater forces typically resulting in greater flight time and forward velocity. Typically, stride frequency is greater during the acceleration phase, reaching its maximum approximately 20 m after the start. Following this, as the sprinter progresses towards maximum speed, stride length is often increased. Thus, stride length is very short during acceleration and stride frequency is reduced towards maximum speed (with stride length increasing).

Sprinting requires high PFs and rates of force development. To adequately produce these, a rapid shortening of the MTU is required. The SSC involves an eccentric MTU lengthening followed by a rapid concentric shortening. Additionally, the series elastic structures within the MTU contribute significantly to movement speed as they recoil rapidly during the shortening phase, subsequent to the storage of elastic energy, which allows a faster shortening of the whole MTU. In addition to the action of

the MTU, the architecture of the muscle itself has been reported to influence force generation. In particular, muscles with longer FLs have the ability to contract at greater velocities (increasing the force production capabilities of the MTU) and generate greater force than muscles with shorter fibres [176, 177], which is thought to be important to sprinting performance [11, 99, 178].

Researchers have hypothesised that the training focus for sprinting should be to reduce GCT and increase stride frequency. To improve these, it has been suggested that the most effective method of training is the practice of sprinting itself. However, additional methods of training may be required to improve performance. To this end, various forms of resistance training have been employed. Resistance training has been widely reported to increase muscle size, improve muscular endurance, decrease adipose tissue and improve muscular force and power production. Mechanical power and force production have been shown to be distinguishing features in sprinting, thus a great deal of emphasis has been placed on improving these. In particular, heavy strength training and/or (relatively) high-velocity training (i.e. plyometric exercise and weightlifting) have been employed. These training methods typically target either the high-force, or the high-velocity portion of the force–velocity curve. As adaptation to exercise may be specific to the load moved and the velocity at which it is moved, it is crucial that training practices are carefully manipulated to ensure the required adaptive changes are achieved. Most modes of resistance training have been reported to improve running velocity. However, each method of training seems to improve either acceleration speed, or maximum speed, not both. Thus, it is important that the current strength and conditioning coach chooses to use the correct training intervention to improve the weaknesses of their athletes.

Chapter Three

3 Methodology

3.1 Experimental Approach to the Problem

This Masters research utilised a two-group, randomised, longitudinal design with subjects completing a six-week training intervention. Subjects were paired and stratified according to 40 m sprint running time and gender, and allocated to one of two plyometric training groups (Figure 3-1). One group performed vertically-directed plyometric exercises during the training intervention (called the VT group), whereas the other group performed horizontally-directed plyometric exercises (called the HT group). The main dependant variables were 40 m sprint time muscle fascicle length (FL) and muscle fascicle angle and kinetic measures of vertical jump performance. Consideration was given to a non-training control group as part of the experimental design, however it was considered not to have the ecological validity to ask athletes not to train. As such, a three-week non-intervention period was included to provide an indication of any potential variations in measured outcomes that could be attributed to each subject's regular training.

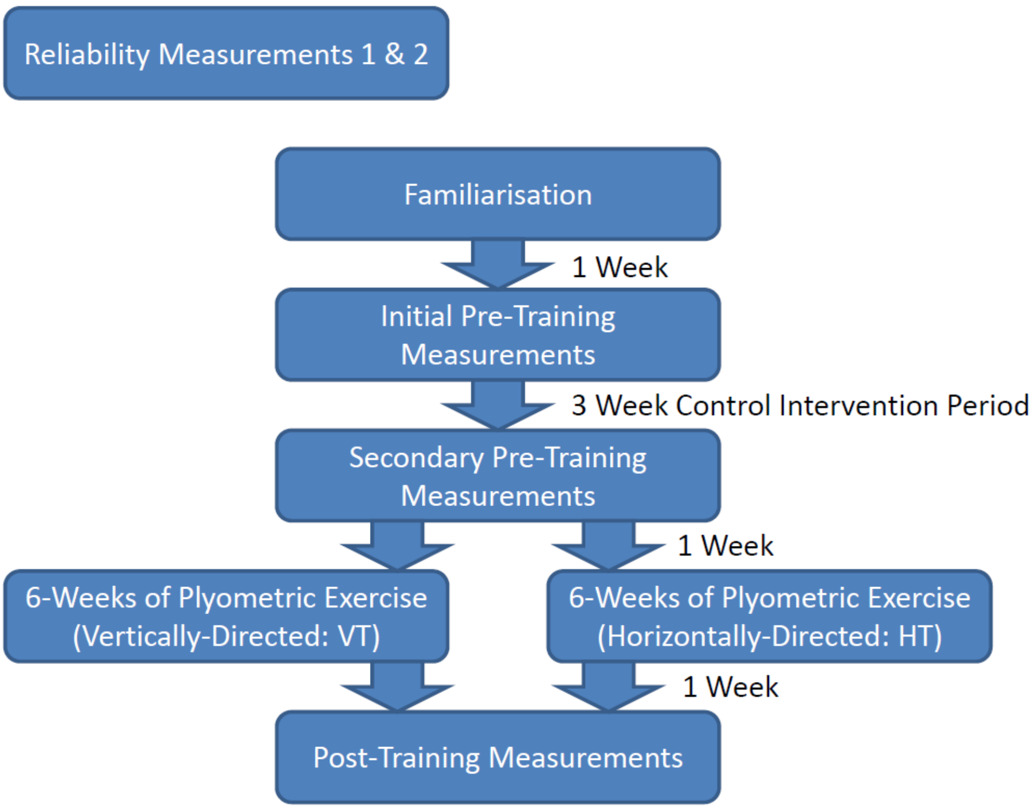

Figure 3-1: Time line of research, including reliability measurements taken prior to baseline data collection

Prior to commencing the training, the reliability of the measurements was ascertained (Figure 3-1). A sub-set of volunteers (n = 11) were recruited to take part and all testing was performed across a 72-hour period with a 24-hour period between the test and re-test. In line with prior research, intra-class correlation (ICC) values ≥0.75 and coefficient of variation values ≤10% were considered reliable [179, 180].

3.2 Subjects

Forty-four male (n = 22) and female (n = 22) recreationally trained athletes volunteered to participate in the study (Table 3-1). The subjects were all currently competing in field-based sports that incorporated a significant sprint running component (Table 3-2), as well as performing regular resistance training (minimum three times per week). The subjects were required to have had no injuries to the lower limbs prior to commencing the study. The subjects were fully informed of the study's procedures and signed an informed consent form, with approval for the study provided by the university's Human Research Ethics Committee.

Table 3-1: Characteristics of the subjects placed in the horizontally- and vertically-directed training groups prior to commencing the training intervention; mean ± standard deviation (SD) are reported, along with the range of measurements for each variable

	Horizontally-directed group (HT)	**Vertically-directed group (VT)**
Age (years)	22.14 ± 4.30 (18–33)	21.77 ± 3.18 (19–31)
Height (m)	175.72 ± 8.72 (159.70–195.30)	174.59 ± 7.55 (162.00–190.00)
Body mass (kg)	70.95 ± 7.33 (61.60–89.10)	71.68 ± 6.65 (62.30–85.20)

3.3 Testing Protocol Overview

Subject testing was completed over two non-consecutive days and was scheduled as close to the same time of day during each assessment day, during pre- and post-training assessments. The first day included an initial assessment of body

composition to determine height and mass, body fat percentage (BF%) and mass of each subject's shank (dominant leg only i.e. the leg primarily used to push off during the sprint start). Ultrasonography was performed on the each subject's gastrocnemius medialis (GM) of the dominant leg to determine muscle FL and angle (i.e. muscle pennation). Following this, the subjects were required to complete, in order, counter-movement jumps (CMJs), squat jumps (SJs) and depth jumps (DJs) tests. Following those, 10 m sprints were performed and both running times and ground reaction forces (GRFs) during the acceleration period were captured. The second session of testing was completed 48–96 hours following the initial acquisition day and the subjects were required to perform 3–5 maximal 50 m sprint running trials. Sprint times were recorded at 5 m, 10 m, 20 m, 30 m and 40 m, however subjects were required to run 50 m to eliminate any subconscious braking or slowing prior to the 40 m finish line.

Table 3-2: The athletic background of the subject population used in this study; male (M) and female (F) subjects are reported as well as the sport and level of competition in which they played

Sport	Number of subjects/ gender	Level of competition
Australian Rules Football	(M) 8 / (F) 2	(M) = recreational (4) and semi-professional (2) / (F) = recreational
Soccer	(M) 4 / (F) 4	(M & F) = recreational
Rugby Union	(M) 4	Recreational
Rugby League	(M) 2	Recreational
Touch rugby	(M) 1 / (F) 2	(M & F) = recreational
Cricket	(F) 11	State representative (7) and national representative (4)
Lacrosse	(M) 3	Recreational
Athletics	(F) 2	State representative

A three-week washout period (Figure 3-1) was observed before subjects were re-tested for all variables. The double-baseline method was performed so as to

maximise subject participation by having them act as their own control, thus negating the need for a control group. Post-training data acquisition was performed within seven days of completing the training intervention. The format of post-training test procedures mimicked that of those performed in pre-training assessments. The specific methodologies performed for each variable are as follows:

3.3.1 Body Composition

Body composition was assessed using dual-energy x-ray absorptiometry (DEXA; Discovery A, Hologic Inc., Bedford, MA, USA). In-built software was used to calculate each subject's BF% (ratio of adipose tissue to total body mass) and segment body composition (i.e. torso, head, individual legs). In addition, the software was manipulated to assess the shank (of the push-off leg used in the sprint start) as an individual segment. For the purposes of this study, the shank was determined to be all of the mass below the knee's axis of rotation. Subjects presented for testing at a similar time of day in an attempt to account for dietary and exercise considerations, however no active account of either variable was recorded. Additionally, DEXA assessments were performed prior to exercise-based tests such as the vertical jump testing (performed afterwards) in an effort to reduce error [181].

3.3.2 Muscle Architecture

GM FL and angle (i.e. pennation) were measured from each subject's dominant (push-off) leg using an Aloka SSD-α10 ultrasound apparatus (Aloka Inc., Tokyo, Japan) with a 7.5 MHz transducer. To ensure inter-testing reliability, the subjects were positioned face down (on a massage table) with their legs fully extended and a 90^{o} angle between the foot and the shank, with the soles of their feet positioned flat against a wall. The ultrasound probe was placed 30% proximal to the lateral malleolus of the fibula and lateral condyle of the tibia [99] and perpendicular to the GM, so as to obtain a longitudinal image. The location and two-dimensional orientation of the transducer relative to anatomical landmarks were mapped onto a sheet of clear plastic so that a constant measurement site could be used throughout all assessments. Additionally, during post-training assessments, on-screen images were compared to

the images collected during the baseline assessments. This visual representation allowed unique features (i.e. heterogeneities in the adipose tissue and/or echoes from interspaces amongst the fascicles) to be matched in an attempt to minimise differences in three-dimensional orientation of the transducer between pre- and post-training assessments [182]. Recorded images were analysed using Image J software (Rasband, National Institute of Health, USA) with GM FL, pennation and muscle thickness determined. FL was measured directly from the superficial to the deep aponeurosis.

The pennation angle was measured between the echo of the deep aponeurosis and the line of the fascicles (Figure 3-2), as delineated by the interspaces of the fascicles of the GM [99], and muscle thickness was determined to be the distance between the subcutaneous adipose tissue and inter-muscular interfaces [183].

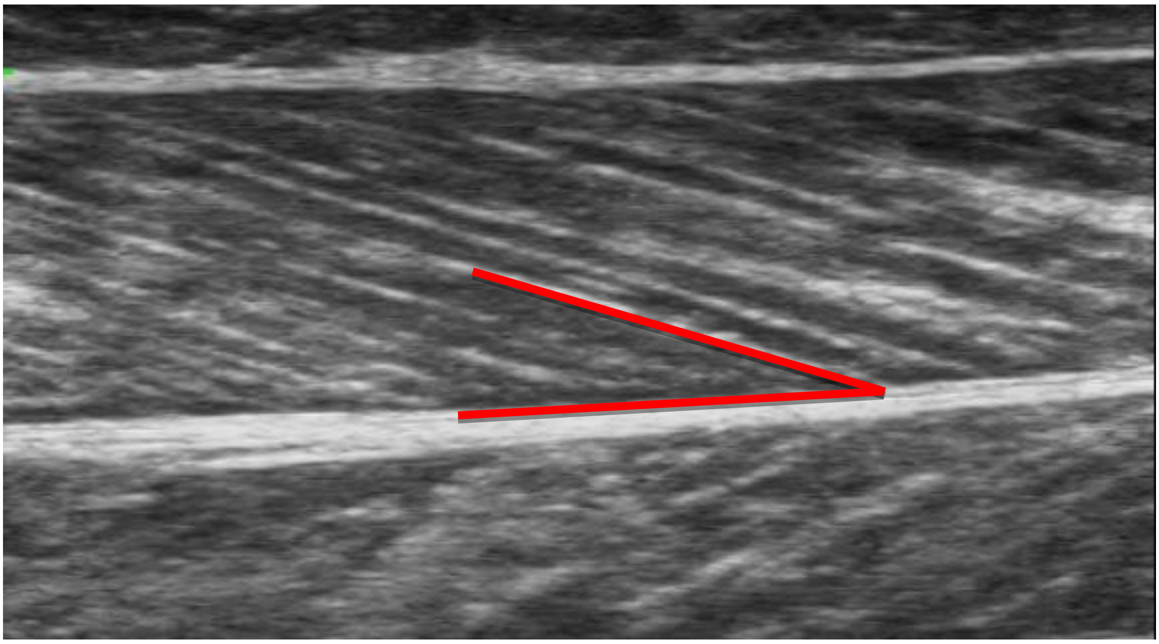

Figure 3-2: Image of GM obtained using ultrasonography. The lines drawn present the deep aponeurosis and the muscle fascicle. The angle of pennation was calculated as the line between the two.

3.3.3 Vertical Jumping

Multiple vertical jumping assessments were performed to assess changes in muscle power and reactive strength between pre- and post-training. Data acquisition was performed using one of three in-ground, multi-component force platforms (Type 9287BA, Kistler Instrument Corp., Winterthur, Switzerland) sampling at 2000 Hz. The

subjects were instructed to place their hands on their hips throughout the entirety of the jumping movement and three trials of each jump were performed. Means (of the respective variables collected) for each trial were used in analysis. Three types of jumps were performed, as described below:

Counter-movement jumps

CMJs were performed with the subject commencing in a standing position before squatting to a self-selected depth, then jumping as high as possible (with minimal horizontal movement). Instructions were given to perform this routine with minimal pause between the eccentric-concentric change. A recovery time of 60s was provided between trials. Peak vertical force, peak force relative to body mass (PF/BM) and rates of force development were recorded. Jump height was calculated from the peak vertical force data using a forward dynamics approach [184, 185].

Squat jumps

To perform the SJs, the subjects were instructed to begin in a standing position before squatting to a self-selected depth (approximately 110^{o} of knee flexion) and holding for 3 s (counted aloud by the researcher) before jumping as high as possible. The level of acceptance for a preparatory counter-movement was a drop in force ≥10% of the participants mass [186]. Trials that presented with a drop in force of <10% were not used in analysis and further trials were performed. Data was collected and analysed in the same manner as for CMJs.

Depth jumps

Leg extensor stretch-shortening cycle (SSC) function was assessed by performing a series of DJs from heights of 0.20m and 0.40m. Subjects were required to step off a raised platform (keeping their centre of mass level) onto an in-ground force platform (Type 9287BA, Kistler Instrument Corp., Winterthur, Switzerland). Upon foot strike, the subject was to jump as quickly and as high as possible. Three trials were performed from each height, with 60s of recovery between trials [187]. Force–time data was used to calculate flight time and ground contact time (GCT). The reactive strength

index (RSI) was then determined for each jump height, using the following formula [81, 119]:

Reactive strength index = Jump height/ground contact time

3.3.4 Ground Reaction Forces During the Sprint Start

Subjects were required to perform three 10 m sprint running trials with maximum effort. A dual-beam electronic timing system (Swift Performance Equipment, Lismore, Australia) was used to record time to the nearest 0.01s. The sprint trials were performed indoors so that subjects were able to run over the top of three in-series, in-ground force platforms. GRFs were recorded with a sampling frequency of 2000 Hz at the second ground contact after commencing the sprint (approximately 2.5 m). The recorded data was filtered with a fourth-order, Butterworth, low-pass filter with the cut-off frequency set to 100 Hz. Foot-strike and take-off times were identified from the filtered data when vertical force increased above and then below 10 N. Peak vertical force, PF/BM ground contact time and rates of force development were the variables used in analysis.

3.3.5 Sprint Running Time

Subjects were also required to perform three 40 m sprint-running trials with maximum effort, on an indoor, sprung-cork running track. Time was recorded to the nearest 0.01s at 5 m, 10 m, 20 m, 30 m and 40 m from the starting line. Prior to starting, all subjects completed a standardised warm-up (Table 3-3) before positioning themselves in a semi-crouched, standing, split-stance 0.30 m behind the first set of timing gates. Subjects were instructed to commence at their own discretion and to run through the last set of timing gates to a set of cones placed a further 10 m beyond the gate (50 m from the starting line) before beginning to decelerate. The recovery time provided between 40 m sprint running trials was 120s, in an attempt to minimise the effects of fatigue and ensure maximum effort [188].

3.4 Training Protocol

Each training session commenced with a standardised warm-up consisting of light jogging, side-steps, carioake, dynamic stretching and sub-maximal sprinting (Table

3-3). Subjects were then required to perform a pre-determined number of sets and repetitions of the particular plyometric exercises they were assigned (Table 3-4). Both experimental groups performed 'bounding' exercises, which may be described as exaggerated running during which the athlete produces as much force as possible with the goal to 'spring' as far as possible in between ground contacts. The HT group was instructed to jump as far forward as possible with each projection and the VT group was instructed to jump as high as possible with minimal horizontal movement.

The training intervention was completed over six weeks and both experimental groups performed it with equal volume and frequency. Two training sessions (supervised by the researchers) were completed each week, with a minimum of 48 hours separating each session. A minimal number of ground contacts was chosen to minimise the likelihood of unplanned over-reaching, which was deemed possible due to the concurrent training each subject was involved in. Furthermore, significant performance enhancements have been reported following training interventions with minimal, as opposed to moderate and higher, volumes of ground contacts [41]. Maximum effort was required from each subject at all times.

Table 3-3: Standardised warm-up performed by each subject prior to each training session; the same warm-up was performed prior to sprint running assessments in pre- and post-training data collection. A single set of lunges was followed by a set of A-drills, then lunges, so that the subject was in constant motion with no passive recovery time. The same pattern was used between side-steps and spidermans.

Exercise	Between repetition recovery	Between set recovery	Distance covered (metres)
Jog 300 m	N/A	Only 1 set performed	300
Straight walking lunges 2 x 50 m	N/A	N/A	100
A-drill with pause* 2 x 50 m	N/A	N/A	100
Low side-step 2 x 50 m	N/A	N/A	100
Spidermans 2 x 50 m	N/A	N/A	100
Sprint throughs 12 x 50 m (2 x 50%, 2 x 60%, 2 x 70%, 2 x 80%, 2 x 90%, 2 x 100%)	Walk back to starting point between each sprint.	Only 1 set performed.	600
2 minute light stretch (for comfort)			

*The pause during the A-drill was held for ~2s on the toes during the stance phase.

Table 3-4: The twice-weekly training schedule completed by both experimental training groups; ground contacts were increased by 20 each week as a progressive overload

Week	Ground contacts	Sets	Ground contacts	Sets	Total weekly ground contacts
1	10	4	10	6	100
2	10	5	10	7	120
3	10	6	10	8	140
4	10	7	10	9	160
5	10	8	10	10	180
6	10	9	10	11	200

3.5 Statistical Analysis

3.5.1 Baseline Test

An independent t-test was performed to determine whether significant differences were found between baseline tests. The percentage of change between initial and secondary baseline values was calculated using the following formula:

Percentage change = ((post-training values / pre-training values) – 1) × 100

Additionally smallest worthwhile change (SWC) was calculated as:

SWC = 0.2 × the pooled SD of test results.

3.5.2 Pre- to Post-Training Testing

Following assessments for significance of the baseline testing, pre-training values were calculated as the means between baseline 1 and baseline 2 tests. To determine the interaction effects and differences between the VT and the HT groups from pre- to post-training, an ANOVA (2 x 2 repeated measures of variance) was used. Confidence intervals were set at 95% and effect size (d), were calculated to assess the treatment effect for each variable. Effect size calculations were calculated using the following formula:

d = VT change – HT change / pooled standard deviation

In terms of interpreting the data, effect size was characterised using the following criteria determined by Cohen [189, 190]; small = f of 0.1 (η of 0.1, η^2 of 0.01), medium = f of 0.25 (η of 0.24, η^2 of 0.06), and large = f of 0.4 (η of 0.37, η^2 of 0.14). When a significant *F* value was observed ($p \leq 0.05$), significant differences were determined by applying paired comparisons with the Bonferroni method of controlling Type 1 error. The percentage change was calculated between pre- and post-training values with the same formula used during baseline analysis. The difference in the percentage change scores was then taken as a meaningful change in criteria values brought about by the training intervention.

To assess the strength of the relationship between sprint running performance and the secondary variables (muscle architecture, jumping ability, GRFs measured during jumping and body composition), Pearson's correlation analyses were performed. All of the data was analysed using SPSS software (version 14.1; SPSS Inc., Chicago, IL, USA) and is presented as mean ± standard deviation (SD).

Chapter Four

4 Results

4.1 Reliability

Using a sample population (n=11) of female recreational athletes (age: 19.9 years ± 1.29; height: 171.4 cm ± 5.96; and body mass: 65.7 kg ± 2.5) reliability of the outcome measures was determined from consecutive testing, 24 hours apart (Appendix F). The outcome measures were not statistically different (Table 4-1).

Table 4-1: Reliability data recorded from 11 female subjects, with 24 hours between measurements; Values are presented as mean (standard deviation), standard error of the mean (SEM), percentage of change (%Δ), intra-class correlations (ICC), coefficient of variation (CV%) and statistical significance (P value)

	Test 1	Test 2	Mean difference	%Δ	SEM	ICC	CV%	P value
5 m time (s)	1.31 (± 0.26)	1.29 (± 022)	-0.03	-2.1	0.05	-0.596	17.3	0.954
10 m time (s)	1.78 (± 0.20)	1.82 (± 0.27)	0.04	2.1	0.05	0.202	13.2	0.813
20 m time (s)	3.31 (± 0.39)	3.34 (± 0.43)	0.02	0.8	0.08	0.195	11.5	0.819
30 m time (s)	4.40 (± 0.32)	4.46 (± 0.40)	0.07	1.5	0.09	0.649	8.9	0.540
40 m time (s)	5.59 (± 0.47)	5.56 (± 0.40)	-0.03	-0.05	0.11	0.792	9.2	0.925
CMJ height (cm)	52.3 (± 2.7)	50.4 (± 3.6)	-1.90	-3.6	0.67	0.649	6.1	0.062
SJ height (cm)	46.9 (± 5.8)	44.7 (± 5.1)	2.2	-4.7	1.13	-0.047	11.6	0.277
RSI-20	2.54 (± 0.19)	2.58 (± 0.31)	0.04	1.7	0.05	0.252	9.4	0.669
RSI-40	1.92 (± 0.31)	2.03 (± 0.15)	0.11	5.7	0.05	0.189	12.1	0.428
FL (cm)	8.0 (± 1.1)	8.1 (± 0.8)	0.09	1.1	0.2	0.921	11.7	0.635
AP (^{o})	21.8 (± 0.9)	21.8 (±1.0)	-0.05	-0.2	0.2	0.797	4.4	0.455
Body fat percentage (%)	22.1 (± 2.2)	22.2 (± 2.2)	0.07	0.3	0.46	0.995	9.7	0.501

* CMJ = countermovement jump; SJ = squat jump; RSI = reactive strength index; FL = fascicle length; AP = angle of fascicle pennation

4.2 Control Period

The subjects in the horizontally-directed plyometric training (HT) (n: 22 age: 22.1 years ± 4.3 years; height: 175.7 cm ± 8.7 cm; and body mass: 70.9 kg ± 7.4 kg) and the vertically-directed plyometric training (VT) (n: 22 age: 21.8 years ± 3.2 years; height: 174.6 cm ± 7.6 cm; and body mass: 71.6 kg ± 6.7 kg) groups were assessed for differences in all experimental variables, with a three-week period of controlled intervention between measurements. During the three-week period, the subjects continued to perform their regular exercise and sport training, with no study-related exercise intervention. No significant interactions were evident between the HT (Table 4-2) and VT (Table 4-3) training groups for any variables during the baseline assessments.

Table 4-2: Control intervention period data recorded from the HT experimental group; the control intervention period was a three-week period consisting of no research-based training; individual test means (± standard deviation), differences in mean score, standard deviation, standard error of the mean (SEM), percentage of change (%Δ), effect size, statistical significance (P value) and smallest worthwhile change (SWC) are reported.

	Test mean	Re-test mean	Difference between the means	%Δ	SEM	Effect size	P value	SWC
5 m time (s)	1.07 (± 0.08)	1.07 (± 0.1)	0.01	0.80	0.01	0.09	0.258	0.21
10 m time (s)	1.80 (± 0.11)	1.82 (± 0.12)	0.01	0.80	0.02	0.13	0.155	0.36
20 m time (s)	3.12 (± 0.19)	3.13 (± 0.20)	0.01	0.40	0.03	0.06	0.102	0.62
30 m time (s)	4.43 (± 0.34)	4.43 (± 0.35)	0.00	0.10	0.05	0.01	0.703	0.89
40 m time (s)	5.63 (± 0.41)	5.62 (± 0.42)	0.00	0.10	0.06	0.01	0.738	1.12
CMJ height (cm)	49.0 (± 4.2)	49.0 (± 4.3)	0.18	0.30	0.63	0.04	1.000	9.79
SJ height (cm)	42.3 (± 7.4)	42.4 (± 7.0)	0.09	0.10	1.08	0.01	0.789	8.46
RSI-20	2.56 (± 0.19)	2.55 (± 0.19)	0.01	0.40	0.03	0.05	0.076	0.51
RSI-40	1.96 (± 0.09)	1.96 (± 0.09)	0.01	0.10	0.01	0.02	0.820	0.39
FL (cm)	8.83 (± 1.53)	8.83 (± 1.52)	0.00	0.00	0.23	0.00	0.893	1.77
AP (^{o})	21.11 (± 1.64)	21.10 (± 1.74)	–0.20	0.10	0.25	0.01	0.776	4.22

* CMJ = countermovement jump; SJ = squat jump; RSI = reactive strength index; FL = fascicle length; AP = angle of fascicle pennation

Table 4-3: Control intervention period data recorded from the VT experimental group; the control intervention period was a three-week period consisting of no research-based training; individual test means (± standard deviation), difference in mean scores, standard deviation, standard error of the mean (SEM), percentage of change (%Δ), effect size, statistical significance (P value) and smallest worthwhile change (SWC) are reported.

	Test mean	Re-test mean	Difference between the means	%Δ	SEM	Effect size	P value	SWC
5 m time (s)	1.07 (± 0.09)	1.06 (± 0.08)	0.00	–0.40	0.01	0.05	0.565	0.21
10 m time (s)	1.78 (± 0.18)	1.84 (± 0.25)	0.07	3.7	0.03	0.31	0.199	0.36
20 m time (s)	3.23 (± 0.31)	3.21 (± 0.33)	-0.02	-0.5	0.05	0.05	0.860	0.64
30 m time (s)	4.37 (± 0.29)	4.38 (± 0.29)	0.01	0.20	0.04	0.02	0.139	0.87
40 m time (s)	5.53 (± 0.42)	5.60 (± 0.46)	0.07	1.3	0.07	0.16	0.436	1.11
CMJ height (cm)	48.9 (± 5.1)	49.3 (± 4.3)	0.45	0.09	0.70	0.01	0.519	9.82
SJ height (cm)	41.27 (± 8.14)	42.32 (± 7.36)	1.05	2.5	1.15	0.10	0.537	8.36
RSI-20	2.55 (± 0.2)	2.55 (± 0.21)	0.00	–0.01	0.03	0.01	0.719	0.51
RSI-40	1.97 (± 0 .04)	1.97 (± 0.03)	0.00	0.10	0.01	0.08	0.613	0.39
FL (cm)	11.6 (± 6.9)	11.6 (± 6.9)	–0.01	–0.10	0.20	0.01	0.097	1.76
AP (^{o})	23.0 (± 17.2)	22.8 (± 17.2)	–0.02	–0.10	0.24	0.01	0.789	4.25

- CMJ = countermovement jump; SJ = squat jump; RSI = reactive strength index; FL = fascicle length; AP = angles of fascicle pennation

4.3 Training Compliance

Each subject completed a total of 12 training sessions over 6 weeks and any scheduled training session that were missed were rescheduled and completed within a 72-hour period. Complete compliance was not achieved during the course of the investigation, with 3 of the 22 males (13.6%) and 2 of the 22 females (9.1%) who commenced the study being unable to complete it due to injuries or illness. While the injuries were not directly attributed to the experimental procedures, they did preclude the subjects in question from completing the required training to reach the compliance level necessary. The following injuries and illnesses prevented the subjects from completing the study: ankle strain (2), dislocated shoulder (1), medial cruciate ligament strain (1), and tonsillitis (1).

4.4 Rate of Perceived Exertion Measured during Training

There were no significant changes from the commencement to cessation of the training intervention, nor was there a significant group interaction for RPE measured throughout the training regime. A pictorial depiction of the differences in RPE by each week of training and for both training paradigms is provided in Figure 4-1.

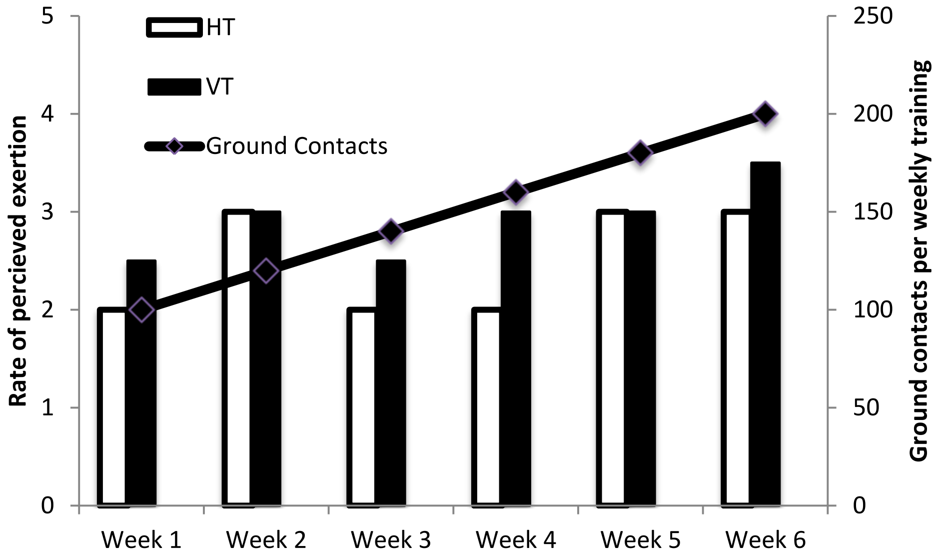

Figure 4-1: Mean rate of perceived exertion (RPE) for each week of training and the corresponding training load. RPE was taken just after each training session using a 10-point scale and is presented on the primary y-axis. Each week of training contained two training sessions with the weekly total presented on the secondary y-axis.

4.5 Sprint Running Times

4.5.1 Sprint Times

4.5.1.1 5 m Sprint Time

Sprint performance time to the 5 m split for the VT group ranged between 0.85 - 1.18s with a mean of 1.07s (± 0.08) pre-training. In comparison times for the HT group ranged between 0.85 - 1.18s with a mean of 1.07s (± 0.9) pre-training. Following the intervention, the post training 5m split time ranged between 0.89 - 1.18s with a mean of 1.06s (± 0.06), for the VT which was a 0.3% improvement in performance. However post intervention for HT the 5m split time ranged between 0.85 - 1.18s with a mean of 1.05s (± 0.08), which was a 1.6% improvement in performance. The 5 m sprint time did not significantly decrease pre- to post-training ($F_{(1, 42)} = 2.214$, $p = 0.144$, partial $\eta^2 = 0.05$, $\Lambda = 0.950$) and no significant difference was observed between groups for the magnitude of change pre- to post-training ($F_{(1, 42)} = 0.035$, $p = 0.853$, partial $\eta^2 = 0.001$). Cohen effect size show only trivial and small changes for VT (d = 0.04) and HT (d = 0.2) groups, respectively.

4.5.1.2 10 m Sprint Time

10 m sprint times significantly decreased from pre- to post-training ($F_{(1, 42)}$ = 4.368, p = 0.043, partial η^2 = 0.094, Λ = 0.906) by 0.01s in the VT group and 0.02s in the HT group (Figure 4-2). No significant difference was reported between groups for the magnitude of change between pre- and post-training ($F_{(1, 42)}$ = 0.037, p = 0.848, partial η^2 = 0.001). Sprint time for the VT group in pre-training ranged between 1.57s and 2.05s with a mean of 1.80s (± 0.11), and for post-training, ranged between 1.58s and 1.91s with a mean of 1.79s (± 0.08). This was a mean difference of 0.01s, which was a 0.5% improvement in performance (d = 0.09). Sprint times for the HT group in pre-training ranged between 1.57s and 2.05s with a mean of 1.81s (± 0.11), and for post-training, ranged between 1.57s and 1.91s with a mean of 1.79s (± 0.1). This was a mean difference of 0.02s, which was a 1.3% improvement in performance (d = 0.22).

4.5.1.3 20 m Sprint Time

The measured sprint-running times measured from 0-20 m in the VT group ranged between 2.76 - 3.51s with a mean of 3.09s (± 0.16) pre-training and between 2.76 - 3.30s with a mean of 3.07s (± 0.14) post-training. A mean difference of 0.02s and a 0.7% improvement in performance were reported. Sprint times for the HT group ranged between 2.76 - 3.66s with a mean of 3.12 s (± 0.19) pre-training and between 2.76 - 3.48s with a mean of 3.09s (± 0.6) post-training, with a mean difference of 0.03s, which was a 1.1% improvement in performance. No significant difference was reported between groups for the magnitude of change between pre- and post-training ($F_{(1, 42)}$ = 0.332, p = 0.567, partial η^2 = 0.008). 20 m sprint times significantly decreased from pre- to post-training ($F_{(1, 42)}$ = 7.041, p = 0.011, partial η^2 = 0.144, Λ = 0.856) by 0.02s in the VT group and 0.04s in the HT group. Furthermore, Cohen's effect size calculations suggest a small change for both VT (d = 0.15) and HT (d = 0.2) groups

4.5.1.4 30 m Sprint Time

Sprint-running times recorded by the VT group between 0-30 m ranged between 3.87 - 4.87s, with a recorded mean of 4.37s (± 0.29) during baseline testing and between 3.81 - 4.82s, with a mean of 4.31s (± 0.27) post-training. The mean difference between pre- and post-training was 0.06s, or a 1.4% improvement in performance (d = 0.23). Sprint times for the HT group ranged between 3.87 - 5.23s

with a mean of 4.43s (± 0.34) pre-training and between 3.87 - 5.06s with a mean of 4.36s (± 0.28) post-training, with a mean difference of 0.07s, which was a 1.7% improvement in performance (d = 0.24). No significant difference was reported between groups for the magnitude of change between pre- and post-training ($F_{(1, 42)}$ = 0.405, p = 0.528, partial η^2 = 0.010). 30 m sprint times significantly decreased from pre- to post-training ($F_{(1, 42)}$ = 10.632, p = 0.002, partial η^2 = 0.202, Λ = 0.798) by 0.06s in the VT group and 0.07s in the HT group (Figure 4-1).

4.5.1.5 40 m Sprint Time

40 m sprint times significantly decreased from pre- to post-training ($F_{(1, 42)}$ = 20.004, p = 0.000, partial η^2 = 0.323, Λ = 0.677) (Figure 4-2) in both experimental groups. Furthermore, Cohen's effect size suggests moderate changes for both VT (d = 0.39) and HT (d = 0.4) groups. The pre-training 40 m sprint time for the VT group ranged between 4.92s and 6.29s with a mean of 5.53s (± 0.31), and post-training ranged between 4.92s and 6.05s with a mean of 5.42s (± 0.28), with a mean difference of 0.12s, which was a 2.1% improvement in performance. Pre-training sprint times for the HT group ranged between 4.92s and 6.83s with a mean of 5.62s (± 0.42), and post-training ranged between 4.92s and 6.67s with a mean of 5.46s (± 0.37), and a mean difference of 0.16s, which was a 2.8% improvement in performance (Figure 4-2). No significant difference was reported between groups for the magnitude of change between pre- and post-training ($F_{(1, 42)}$ = 0.437, p = 0.512, partial η^2 = 0.010).

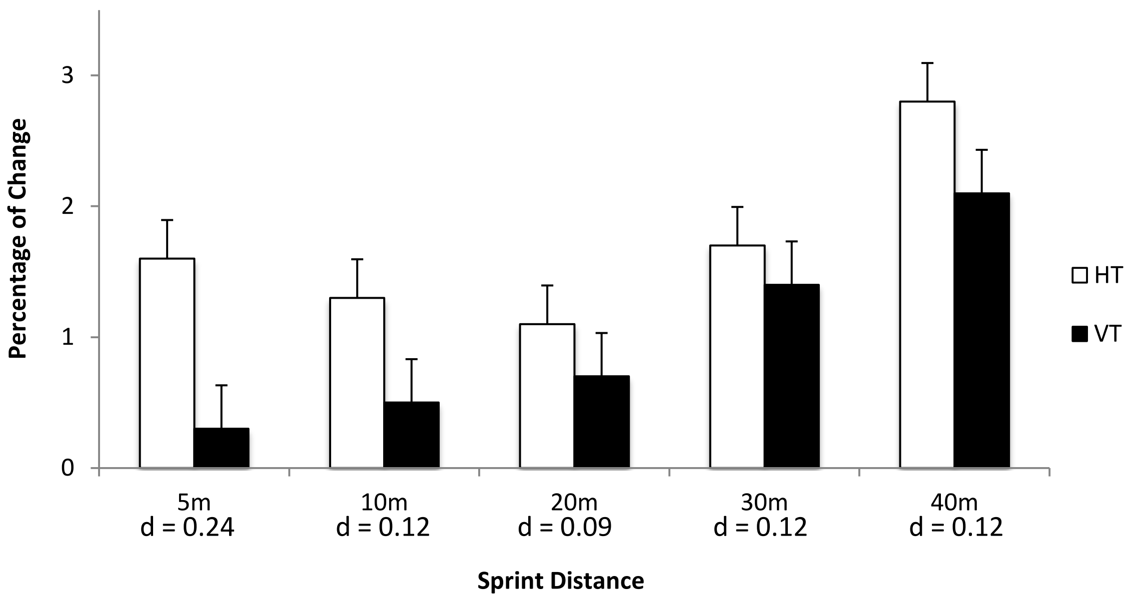

Figure 4-2: The mean (±SD) percentage of change between pre- and post-training sprint running performance at all measured distances for both experimental groups. Effect size (d) is presented for between group differences and error bars are presented for standard deviation.

4.5.1.6 Effect of Gender on Sprint Time

No significant difference was observed in the change of speed from pre- to post-training for men or women at 5 m ($F_{(1,42)} = 0.06$, $p = 0.807$, partial $\eta^2 = 0.001$), 10 m ($F_{(1,42)} = 0.776$, $p = 0.383$, partial $\eta^2 = 0.018$), 20m ($F_{(1,42)} = 1.696$, $p = 0.20$, partial $\eta^2 = 0.039$), 30m ($F_{(1,42)} = 0.901$, $p = 0.348$, partial $\eta^2 = 0.021$) and 40m ($F_{(1,42)} = 1.843$, $p = 0.182$, partial $\eta^2 = 0.042$) distances. In the VT group, males improved their sprint running time between 0.0–2.7% and female performance improved 0.5–1.6%. Male subjects in the HT group presented improvements of between 0.4–1.2% in sprint running time, and females in the HT presented a 1.9–4.3% change. Cohen's effects size calculations show trivial to moderate and moderate to large effects, in the magnitude of change between male and female subjects in the HT and VT training groups, respectively (Table 4-4).

Table 4-4: Effect sizes calculated for the magnitude of change presented between male and female subjects in the vertically-directed (VT) and horizontally-directed (HT) training groups.

	5 m	10 m	20 m	30 m	40 m
HT	0.22	0.42	0.28	0.10	0.20
VT	0.70	0.41	0.52	1.06	0.89

4.5.2 Ground Reaction Forces During the Sprint Start

4.5.2.1 Peak Vertical Force

Peak force (PF) significantly improved from pre- to post-training for both experimental groups ($F_{(1, 42)}$ = 45.834, p = 0.000, partial η^2 = 0.522, Λ = 0.478), however there was no significant difference between the groups ($F_{(1, 42)}$ = 0.045, p = 0.834, partial η^2 = 0.001). The changes from pre- to post-training for VT and HT were 4.2% (d = 0.30) and 4.6% (d = 0.32) respectively. Additionally no significant correlations between PF and sprint running time were reported at any measured distance for the VT group (Table 4-5) and the HT group (Table 4-6).

4.5.2.2 Peak Force at 50 ms

A significant difference was reported for PF at 50 ms from pre- to post-training for both experimental groups ($F_{(1,42)}$ = 70.216, p = 0.000, partial η^2 = 0.626, Λ = 0.374). No significant difference was found between the groups ($F_{(1, 42)}$ = 3.421, p = 0.071, partial η^2 = 0.075), although a moderate difference (d = 0.50) was found. PF increased by 16.4% (d = 1.50) in the VT group, measured at 50 ms, from pre- to post-training (Figure 4-3). A significant relationship (r = –0.43) was observed between PF at 50 ms and 5 m time. PF increased by 19.6% (d = 1.57) in the HT group, and significant correlations (p = 0.05) between PF at 50 ms and sprint running time at 20 m (r = 0.49), 30 m (r = 0.53) and 40 m (r = 0.51) distances (Table 4-6).

4.5.2.3 Peak Force at 200 ms

Peak force (PF) at 200 ms was calculated with an *n* of 17 for the HT group and 15 for the VT group, as some subjects completed the movement in less than 200 ms. Significant improvements were presented between pre- and post-assessments for both experimental groups ($F_{(1, 42)}$ = 31.162, p =0.000, partial η^2 = 0.426, Λ = 0.574). No significant difference was recorded between groups ($F_{(1, 42)}$ = 2.662, p = 0.11, partial η^2 = 0.060), however a large effect size difference (d = 0.88) was presented. Non-significant two tails correlations were reported between PF at 200 ms and sprint running time at each measured sprint running distance for both experimental groups (Table 4-5 and Table 4-6).

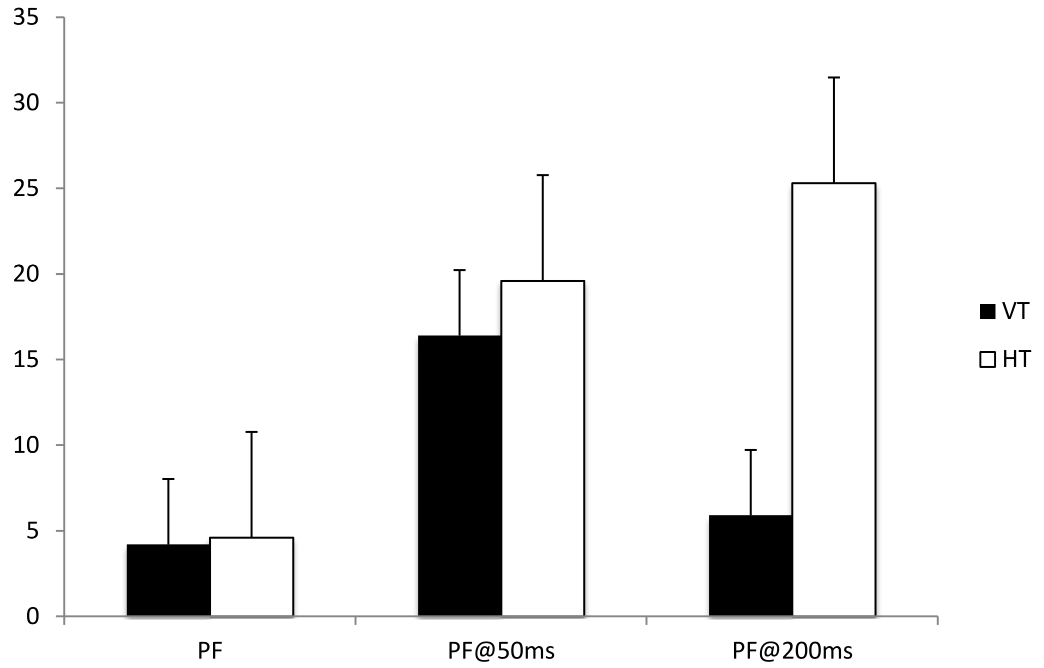

Figure 4-3: Percentage of mean change for measures of peak force at 50 ms (PF@50ms) and 200 ms (PF@200ms) during acceleration of sprint running between pre- and post-training for both experimental groups; data was recorded 5 m from starting point. Error bars are presented for standard deviation.

4.5.2.4 Time to Peak Force

The time taken to reach peak force (TtPF) significantly improved between pre- and post-assessments for both experimental groups ($F_{(1, 42)} = 19.036$, $p = 0.000$, partial $\eta^2 = 0.312$, $\Lambda = 0.688$), however no significant difference was recorded between groups ($F_{(1, 42)} = 0.887$, $p = 0.352$, partial $\eta^2 = 0.021$). The percentage change between pre- and post-training assessments for VT and HT ranged from –5% to 5% (d = 0.51) and –3.8% to 8.3% (d = 0.45), respectively. Non-significant two tails correlations were reported between TtPF and sprint running time at each measured sprint running distance for both experimental groups (Table 4-5 and Table 4-6).

4.5.2.5 Ground Contact Time during the Sprint Start

Ground contact time (GCT) during the second step of the acceleration phase for the VT group pre-training ranged between 0.35s and 0.19s with a mean of 0.24s (± 0.04) , and for post-training, ranged between 0.27s and 0.19s with a mean of 0.23s (± 0.03), and a mean difference of 0.01s. GCT for the HT group pre-training ranged between 0.57s and 0.19s with a mean of 0.26s (± 0.08), and post-training ranged

between 0.37s and 0.19s with a mean of 0.23s (± 0.04), and a mean difference of 0.03s. GCT significantly decreased from pre- to post-training ($F_{(1, 42)} = 5.24$, $p = 0.027$, partial $\eta^2 = 0.111$, $\Lambda = 0.889$) for both experimental groups, however no significant difference was reported between the groups ($F_{(1, 42)} = 1.064$, $p = 0.308$, partial $\eta^2 = 0.025$). The percentage range between pre- and post-training assessments for VT and HT ranged from –0.9% to 17.9% (d = 0.23) and –7.8% to 12.4% (d = 0.43), respectively. Non-significant two tails correlations were reported between GCT and sprint running time at each measured distance for the VT group (Table 4-5). The HT group presented significant correlations between GCT and sprint running performance at 20 m (r = 0.45), 30 m (r = 0.48) and 40 m (r = 0.54).

Table 4-5: Correlations between ground reaction force data recorded during acceleration (5m from start line) and sprint running performance for the VT experimental group. Peak force (PF), peak force at 50 ms and 200 ms, time take to reach peak force (TtPF) and ground contact time (GCT) are presented.

	5 m	10 m	20 m	30 m	40 m	PF	50 ms	200 ms	TtPF	GCT
5 m	1.00									
10 m	0.85**	1.00								
20 m	0.64**	0.85**	1.00							
30 m	0.63**	0.72**	0.84**	1.00						
40 m	0.47*	0.66**	0.77**	0.82**	1.00					
PF	0.36	0.09	0.04	0.04	0.07	1.00				
50 ms	–0.43*	–0.23	–0.09	–0.11	0.07	–0.40	1.00			
200 ms	–0.08	–0.06	0.15	0.22	0.17	–0.07	–0.21	1.00		
TtPF	–0.14	–0.25	–0.30	–0.24	–0.08	0.15	0.04	–0.08	1.00	
GCT	0.04	0.02	0.01	–0.02	–0.18	–0.21	–0.06	–0.34	0.18	1.00

** Correlation is significant at the 0.01 level (two-tailed) * Correlation is significant at the 0.05 level (two-tailed)

Table 4-5: Correlations between ground reaction force data recorded during acceleration (5m from start line) and sprint running performance for the HT experimental group. Peak force (PF), peak force at 50ms and 200ms, time take to reach peak force (TtPF) and ground contact time (GCT) are presented.

	5 m	**10 m**	**20 m**	**30 m**	**40 m**	**PF**	**50 ms**	**200 ms**	**TtPF**	**GCT**
5 m	1.00									
10 m	0.77**	1.00								
20 m	0.50*	0.83**	1.00							
30 m	0.46*	0.64**	0.90**	1.00						
40 m	0.24	0.54**	0.79**	0.85**	1.00					
PF	–0.36	–0.14	0.03	–0.04	0.05	1.00				
50 ms	0.08	0.34	0.49*	0.53*	0.51*	0.26	1.00			
200 ms	0.29	0.25	0.09	0.05	–0.10	0.07	0.02	1.00		
TtPF	0.456*	0.32	0.33	0.38	0.08	–0.38	–0.08	–0.04	1.00	
GCT	–0.07	0.15	0.45*	0.48*	0.54**	–0.25	0.15	–0.24	0.14	1.00

** Correlation is significant at the 0.01 level (two-tailed) * Correlation is significant at the 0.05 level (two-tailed)

4.5.2.6 Gender Effect on Ground Reaction Forces During Acceleration

Significant differences were reported between pre- and post-measurements for male and female subjects in peak vertical ground reaction forces (GRFs) ($F_{(1, 42)}$ = 8.352, p = 0.006, partial η^2 = 0.806). Male subjects in the VT and HT groups presented a 3.3% and 2.2% change in peak vertical GRF, respectively. Female subjects reported 5.3% (VT) and 7.4% (HT) changes. However, no significant difference was reported between pre- and post-measurements for vertical GRF at 50 ms ($F_{(1,42)}$ = 1.358, p = 0.25, partial η^2 = 0.207), vertical GRF at 200 ms ($F_{(1,42)}$ = 1.58, p = 0.216, partial η^2 = 0.233), TtPF ($F_{(1,42)}$ = 3.055, p = 0.088, partial η^2 = 0.401) and GCT ($F_{(1,42)}$ = 0.013, p = 0.91, partial η^2 = 0.051).

4.6 Vertical Jumping

4.6.1 Counter-movement Jumps

4.6.1.1 Jump Height

Jump height significantly improved between pre- and post-training ($F_{(1, 42)}$ = 41.431, p = 0.000, partial η^2 = 0.497, Λ = 0.503). The percentage change between pre- and post-training assessments for VT and HT groups ranged from –1.39% to 5.80% (d = 0.33) and –1.41% to 4.41% (d = 0.20), respectively (Figure 4-5). Non-significant two tails correlations were reported between CMJ height and sprint running time at each measured sprint running distance for both experimental groups (Table 4-6 and Table 4-7). CMJ height for the VT group ranged between 0.40 m and 0.58 m with a mean of 42.3c m (± 4.5) pre-training and between 0.42 m and 0.59 m with a mean of 50.7 cm (± 4.3) post-training, and a mean difference of 1.45 cm. CMJ height for the HT group ranged between 0.43 m and 0.58 m with a mean of 59.1 cm (± 6.8) pre-training and between 0.44 m and 0.57 m with a mean of 49.8 cm (± 3.7) post-training, and difference between means of 0.7 cm. No significant difference ($F_{(1, 42)}$ =0.209, p = 0.65, partial η^2 = 0.209) and only a small effect (d = 0.13) was reported between groups for the magnitude of change between pre- and post-training .

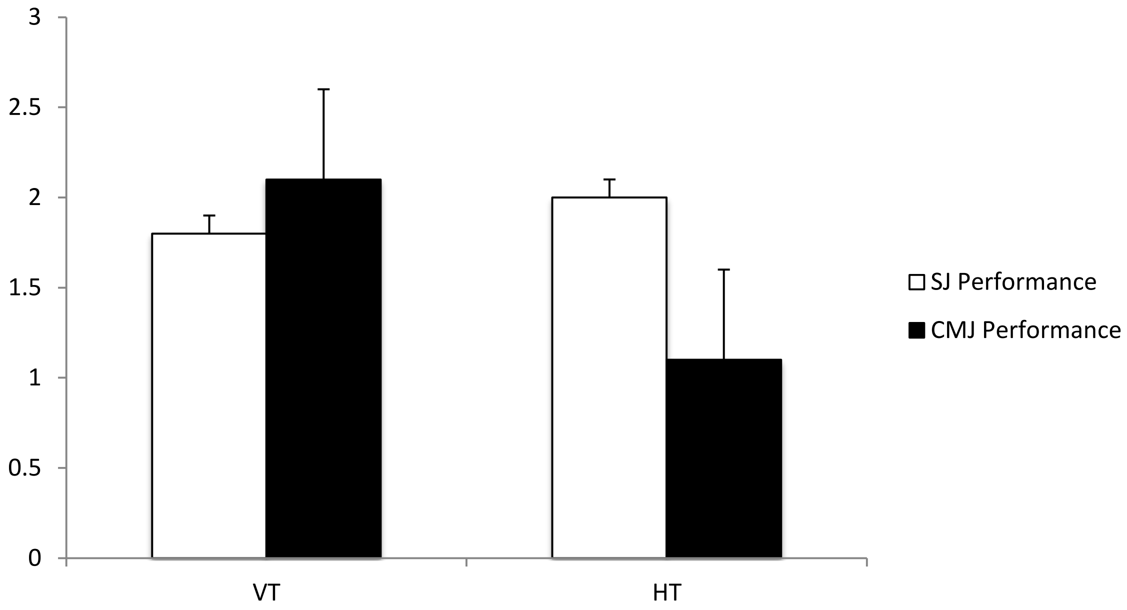

Figure 4-4: The percentage of change for CMJ and SJ height between pre- and post-training for both experimental groups. Error bars are presented for standard deviation.

Table 4-6: Correlations between vertical jump and sprint running performance in the VT experimental group. Countermovement jump (CMJ) height, squat jump height (SJ) and reactive strength index from 0.20 m (RSI-20) and 0.40 m (RSI-40) are presented.

	5 m	10 m	20 m	30 m	40 m	CMJ height	SJ height	RSI-20	RSI-40
5 m	1.00								
10 m	0.85**	1.00							
20 m	0.64**	0.85**	1.00						
30 m	0.63**	0.72**	0.84**	1.00					
40 m	0.47*	0.66**	0.77**	0.82**	1.00				
CMJ height	0.27	0.14	0.06	0.15	–0.13	1.00			
SJ height	0.40	0.34	0.20	0.30	0.14	0.51*	1.00		
RSI-20	–0.20	–0.35	–0.37	–0.21	–0.30	–0.11	–0.29	1.00	
RSI-40	–0.13	–0.10	0.02	0.06	0.12	0.09	–0.46*	0.06	1.00

** Correlation is significant at the 0.01 level (two-tailed) * Correlation is significant at the 0.05 level (two-tailed)

Table 4-7: Correlations between vertical jump and sprint running performance in the HT experimental group. Countermovement jump (CMJ) height, squat jump height (SJ) and reactive strength index from 0.20 m (RSI-20) and 0.40 m (RSI-40) are presented.

	5 m	10 m	20 m	30 m	40 m	CMJ height	SJ height	RSI-20	RSI-40
5 m	1								
10 m	0.77**	1							
20 m	0.50*	0.83**	1						
30 m	0.46*	0.64**	0.90**	1					
40 m	0.24	0.54**	0.79**	0.85**	1				
CMJ height	–0.31	–0.19	–0.27	–0.4	–0.13	1			
SJ height	–0.43*	–0.42	–0.42	–0.47*	–0.13	0.86**	1		
RSI-20	–0.48*	–0.33	–0.15	–0.05	–0.02	0	0.03	1	
RSI-40	–0.1	–0.09	–0.18	–0.26	–0.1	0.12	0.08	0.01	1

**: Correlation is significant at the 0.01 level (2-tailed) *: Correlation is significant at the 0.05 level (2-tailed)

4.6.1.2 Peak Force

PF significantly improved between pre- and post-assessments for both experimental groups ($F_{(1, 42)} = 9.555$, $p = 0.004$, partial $\eta^2 = 0.185$, $\Lambda = 0.815$), however no significant difference was recorded between groups ($F_{(1, 42)} = 0.189$, $p = 0.666$, partial $\eta^2 = 0.004$). The mean percentage of change between pre- and post-training assessments for VT and HT was 2.88% (d = 0.16) and 2.13% (d = 0.09), respectively (Figure 4-4). Non-significant two tails correlations were reported between PF (recorded during CMJ) and sprint running time at each measured sprint running distance for both experimental groups (Table 4-6 and Table 4-7).

4.6.1.3 Peak Force Relative to Body Mass

Peak force relative to body mass (PF/BM) significantly improved between pre- and post-assessments for both experimental groups ($F_{(1, 42)} = 21.391$, $p = 0.000$, partial $\eta^2 = 0.337$, $\Lambda = 0.663$). However, a significant difference was reported between the experimental groups ($F_{(1, 42)} = 0.283$, $p = 0.598$, partial $\eta^2 = 0.007$). The percentage change (minimum to maximum) between pre- and post-training assessments for VT and HT ranged from –2.97% to 9.8% (d = 0.34) and –14.6% to 12.1% (d = 0.22) respectively (Figure 4-6). Like PF, PF/BM presented non-significant two tails correlations between PF (recorded during CMJ) and sprint running time at each measured sprint running distance for the VT experimental group (Table 4-8). The HT group reported a significant relationship at 30 m (r = –0.43) but not at any other distance (Table 4-9).

4.6.1.4 Peak Force at 50 ms

PF at 50 ms significantly improved between pre- and post-assessments for both experimental groups ($F_{(1, 42)} = 35.353$, $p = 0.000$, partial $\eta^2 = 0.457$, $\Lambda = 0.543$), however no significant difference was recorded between groups ($F_{(1, 42)} = 0.544$, $p = 0.465$, partial $\eta^2 = 0.013$). The mean percentage change between pre- and post-training assessments for VT and HT was 29.3% (d = 0.86) and 17.8% (d = 0.58) respectively (Figure 4-6). Non-significant two tails correlations were reported between PF at 50 ms (recorded during CMJ) and sprint running time at each measured sprint running distance for both experimental groups (Table 4-8 and Table 4-9).

4.6.1.5 Peak Force at 200 ms

PF at 200 ms significantly improved between pre- and post-assessments for both experimental groups ($F_{(1, 42)}$ = 25.152, p =0.000, partial η^2 = 0.375, Λ = 0.625), however a significant difference was reported between the experimental groups ($F_{(1, 42)}$ = 7.720, p = 0.008, partial η^2 = 0.155). The percentage change between pre- and post-training assessments for VT and HT was 16.2% (d = 0.37) and 18.1% (d = 0.48) respectively (Figure 4-6). Non-significant two tails correlations were reported between PF at 200 ms (recorded during CMJ) and sprint running time at each measured sprint running distance for both experimental groups (Table 4-8 and Table 4-9).

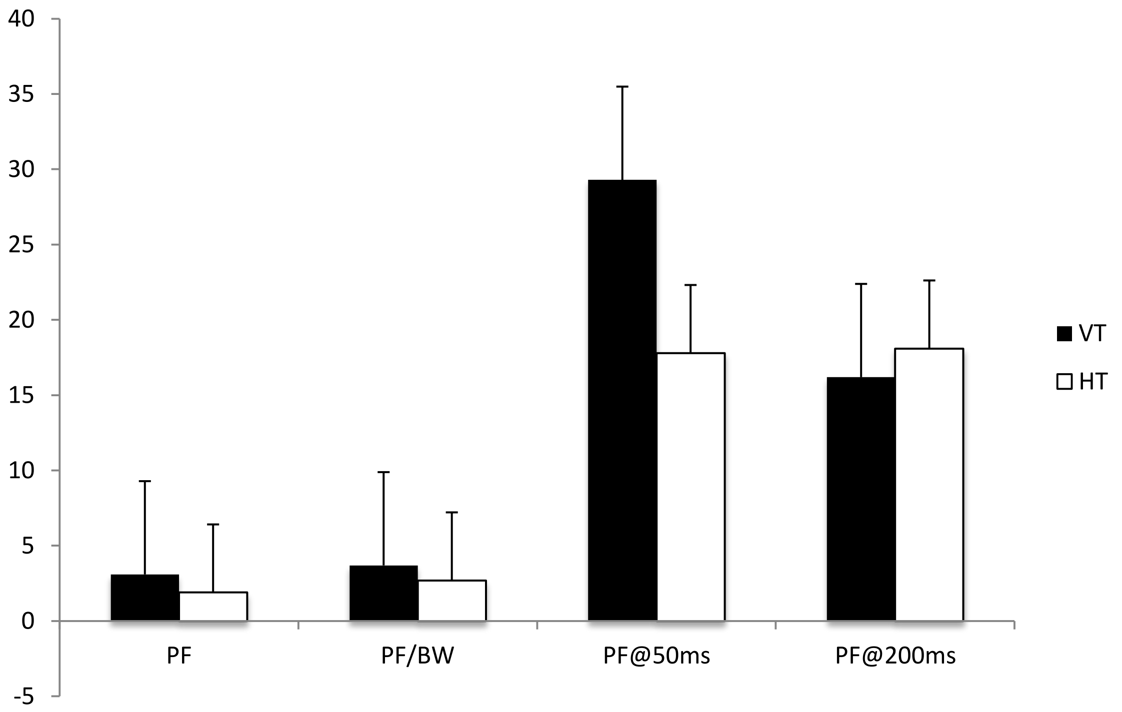

Figure 4-5: Vertical force measured during CMJ testing presented as a percentage of change, for both experimental groups. Error bars are presented fpr standard deviation.

4.6.1.6 Time to Peak Force

TtPF significantly improved between pre- and post-assessments for both experimental groups ($F_{(1, 42)}$ = 16.673, p = 0.000, partial η^2 = 0.284, Λ = 0.716), however no significant difference was recorded between groups ($F_{(1, 42)}$ = 1.414, p = 0.241, partial η^2 = 0.033). The percentage change between pre- to post-training assessments for VT and HT ranged from –15.8% to 4.0% (d = 0.47) and –14.7% to 8.0% (d = 0.42) respectively. PF/BM presented non-significant two tails correlations between

TtPF (recorded during CMJ) and sprint running time at each measured sprint running distance for the VT experimental group (Table 4-8). The HT group reported a significant relationship at 20 m ($r = -0.50$) but not at any other distance (Table 4-9).

Table 4-8: Correlations between ground reaction force produced during countermovement jump assessments and sprint running performance, in the VT experimental group. Peak force (PF), peak force at 50 ms and 200 ms, time take to reach peak force (TtPF) and ground contact time (GCT) are presented.

	5 m	10 m	20 m	30 m	40 m	PF	PF/BM	50 ms	200 ms	TtPF
5 m	1.00									
10 m	0.85**	1.00								
20 m	0.64**	0.85**	1.00							
30 m	0.63**	0.72**	0.84**	1.00						
40 m	0.47*	0.66**	0.77**	0.82**	1.00					
PF	0.36	0.19	0.09	0.31	0.08	1.00				
PF/BM	0.32	0.25	0.13	0.32	0.17	0.95**	1.00			
50 ms	0.09	–0.10	–0.30	–0.16	0.01	–0.04	–0.05	1.00		
200 ms	–0.18	–0.29	–0.19	–0.14	–0.35	0.00	–0.05	–0.32	1.00	
TtPF	0.11	0.09	0.16	0.30	0.32	0.36	0.43*	0.23	0.09	1.00

** Correlation is significant at the 0.01 level (two-tailed)   * Correlation is significant at the 0.05 level (two-tailed)

Table 4-9: Correlations between ground reaction force produced during countermovement jump assessments and sprint running performance, in the HT experimental group. Peak force (PF), peak force at 50ms and 200ms, time take to reach peak force (TtPF) and ground contact time (GCT) are presented.

	5 m	10 m	20 m	30 m	40 m	PF	PF/BM	50 ms	200 ms	TtPF
5 m	1.00									
10 m	0.77**	1.00								
20 m	0.50*	0.83**	1.00							
30 m	0.46*	0.64**	0.90**	1.00						
40 m	0.24	0.54**	0.79**	0.85**	1.00					
PF	–0.31	–0.35	–0.37	–0.42	–0.20	1.00				
PF/BM	–0.31	–0.37	–0.41	–0.43*	–0.20	0.96**	1.00			
50 ms	–0.18	–0.24	–0.07	–0.09	–0.02	0.03	–0.06	1.00		
200 ms	0.13	–0.09	–0.22	–0.25	–0.33	0.55**	0.46*	0.02	1.00	
TtPF	–0.30	–0.38	–0.50*	–0.35	–0.19	0.27	0.30	–0.10	0.13	1.00

** Correlation is significant at the 0.01 level (two-tailed) * Correlation is significant at the 0.05 level (two-tailed)

4.6.1.7 Gender Effect on Counter-Movement Jump Performance

Significant differences were reported between pre- and post-measurements in male and female subjects for maximum CMJ height ($F_{(1, 42)}$ = 36.821, p = 0.000, partial η^2 = 0.467), peak vertical GRF ($F_{(1, 42)}$ = 73.752, p = 0.000, partial η^2 = 0.637) and TtPF ($F_{(1, 42)}$ = 5.027, p = 0.03, partial η^2 = 0.591). Male subjects in the VT group presented a 2.5% difference between pre- and post-training measurements in CMJ height, and the female subjects reported a change of 1.6%. Male subjects in the HT group presented a 0.9% change and the female subjects in the HT group presented a 1.4% change in CMJ height. Male subjects in the VT and HT groups presented 4.9% and 4.8% changes in TfPF respectively, from pre-to post-training. Female subjects presented 3.4% (VT) and 1.9% (HT) differences in TtPF.

No significant differences were reported for peak vertical GRF relative to body weight ($F_{(1, 42)}$ = 56.614, p = 0.000, partial η^2 = 0.574), vertical GRF at 50 ms ($F_{(1, 42)}$ = 0.119, p = 0.732, partial η^2 = 0.063) and vertical GRF at 200 ms ($F_{(1, 42)}$ = 2.653, p = 0.111, partial η^2 = 0.357).

4.6.2 Squat Jumps

4.6.2.1 Jump Height

Jump height significantly improved between pre- and post-training ($F_{(1, 42)}$ = 38.885, p = 0.000, partial η^2 = 0.481, Λ = 0.519). The percentage change between pre- and post-training assessments for VT and HT ranged from –1.85% to 8.1% (d = 0.17) and –1.5% to 6.0% (d = 0.18), respectively (Figure 4-5). No significant difference ($F_{(1, 42)}$ = 0.219, p = 0.642, partial η^2 = 0.005) and a small effect (d = 0.15) was reported between groups for the magnitude of change between pre- and post-training. SJ height for the VT group ranged between 0.29 m and 0.55 m with a mean of 43.4cm (± 6.9) pre-training and between 0.31 m and 0.56 m with a mean of 44.5 cm (± 6.8) post-training, and a mean difference of 1.1 cm. Jump height for the HT group ranged between 0.30 m and 0.55 m with a mean of 42.3 (± 7.2) pre-training and between 0.32 m and 0.55 m with a mean of 43.6 cm (± 7.0) post-training, and a difference between the means of 1.3 cm. Non-significant two tails correlations were reported between CMJ height and sprint running time at each measured sprint running distance for the

VT experimental group (Table 4-6). A significant correlation was presented by the HT group at 30 m (r = –0.47) but not at any other distance (Table 4-7).

4.6.2.2 Peak Force

PF significantly improved between pre- and post-assessments for both experimental groups ($F_{(1, 42)}$ = 55.722, p = 0.000, partial η^2 = 0.570, Λ = 0.430), however no significant difference was recorded between groups ($F_{(1, 42)}$ = 0.070, p = 0.793, partial η^2 = 0.002). The mean percentage change between pre- and post-training assessments for VT and HT was 6.8% (d = 0.33) and 8.5% (d = 0.37) respectively (Figure 4-5).

4.6.2.3 Peak Force Relative to Body Mass

PF/BM significantly improved between pre- and post-assessments for both experimental groups ($F_{(1, 42)}$ = 79.564, p = 0.000, partial η^2 = 0.655, Λ = 0.345) and no significant differences were reported between the experimental groups ($F_{(1, 42)}$ = 0.033, p = 0.857, partial η^2 = 0.001). The mean percentage change between pre- and post-training assessments for VT and HT was 7.5% (d = 0.63) and 9.4% (d = 0.75), respectively.

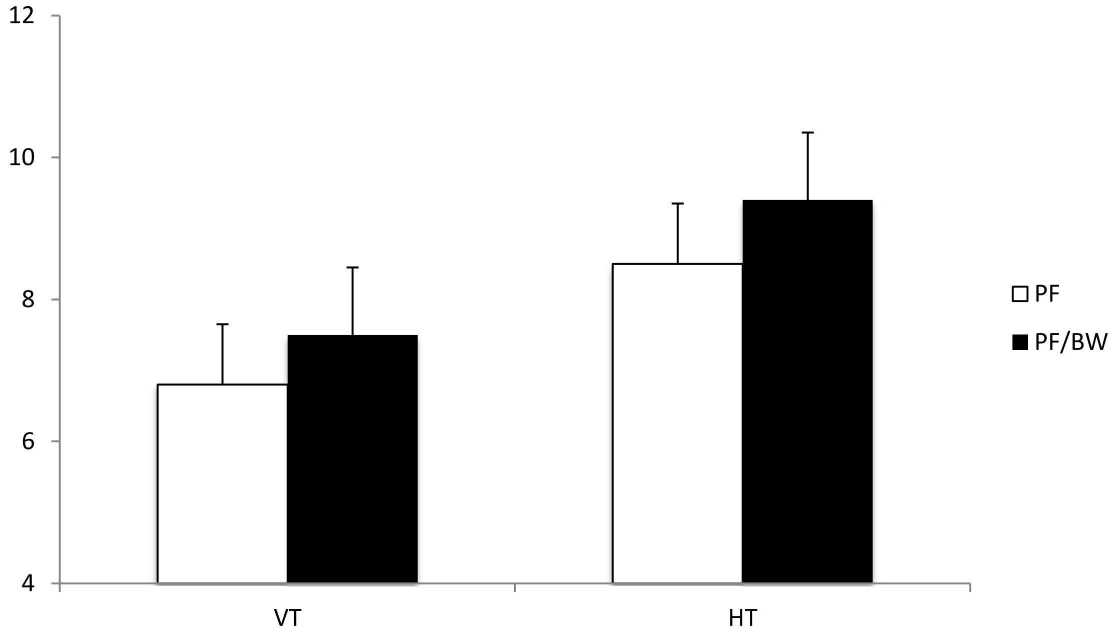

Figure 4-6: Percentage of change for peak force (PF) and peak force relative to body mass (PF/BM) for both experimental groups during SJ. Error bars are presented for standard deviation.

4.6.2.4 Gender Effect on Squat Jump Performance

Significant differences were reported between pre- and post-measurements in male and female subjects for maximum SJ height ($F_{(1, 42)}$ = 90.534, p = 0.000, partial η^2 = 0.683), peak vertical GRF ($F_{(1, 42)}$ = 57.393, p = 0.000, partial η^2 = 0.577) and peak vertical GRF relative to body weight ($F_{(1, 42)}$ = 34.699, p = 0.000, partial η^2 = 0.452). Male subjects in the VT group presented a 1.3% change in SJ height and female subjects similarly reported a moderate practical change (d = 0.27) of 2.4%. Male subjects in the HT group presented a 1.3% change and the female subjects in the HT group presented a 2.8% improvement in SJ height. Cohen's effect size suggests a large significance for male subjects in the VT group (d = 0.67), which was a 9.2% improvement from pre- to post- training measurements for PF. Female subjects in the VT group presented a moderate practical improvement (d = 0.36) between pre- and post- scores, with a 3.5% change in raw value. Male subjects in the HT group presented a 10.0% PF improvement (a large practical change, d = 0.82), and the female subjects presented a 6.6% improvement in performance (a large practical change, d = 0.70). Cohen's effect size suggests a large significance for male subjects in the VT group (d = 0.98), which was a 9.3% improvement from pre- to post- training measurements for PF/BW. Female subjects in the VT group also reported a large practical improvement (d = 0.81) between pre- and post- scores, with a 5.5% change in raw value. Male subjects in the HT group presented a 9.8% improvement (a moderate practical change, d = 0.52), whereas the female subjects presented a 9.0% increase in performance (a large practical change, d = 1.19).

4.6.3 Drop Jumps

4.6.3.1 Reactive Strength Index (0.20 m)

The RSI measured from a 0.20 m drop (RSI-20) was significantly improved between pre- and post-assessments for both experimental groups ($F_{(1, 42)}$ = 34.248, p = 0.000, partial η^2 = 0.449, Λ = 0.551) and no significant differences presented between the groups ($F_{(1, 42)}$ = 0.933, p = 0.340, partial η^2 = 0.022). The training-induced change was observed to be moderate and large for both VT (d = 0.36) and HT (d = 0.72) groups (Figure 4-8), respectively. A significant two tails correlation was reported between RSI-20 and sprint running time for the HT group at 5 m (r = 0.48). Non-significant

relationships were reported for all other distances (Table 4-7). The VT group presented non-significant correlations for each measured sprint distance (Table 4-6).

4.6.3.2 Reactive Strength Index (0.40 m)

The RSI measured from a 0.40 m drop (RSI-40) was significantly improved between pre- and post-assessments for both experimental groups ($F_{(1, 42)}$ = 26.569, p = 0.000, partial η^2 = 0.387, Λ = 0.613) and no significant difference was recorded between groups ($F_{(1, 42)}$ = 2.684, p = 0.109, partial η^2 = 0.06). The training-induced change was observed to be large for both VT (d = 1.31) and HT (d = 1.19) groups (Figure 4-8). Non-significant two tails correlations were reported between RSI-40 and sprint running time at each measured distance for the VT (Table 4-6) and the HT (Table 4-7) groups.

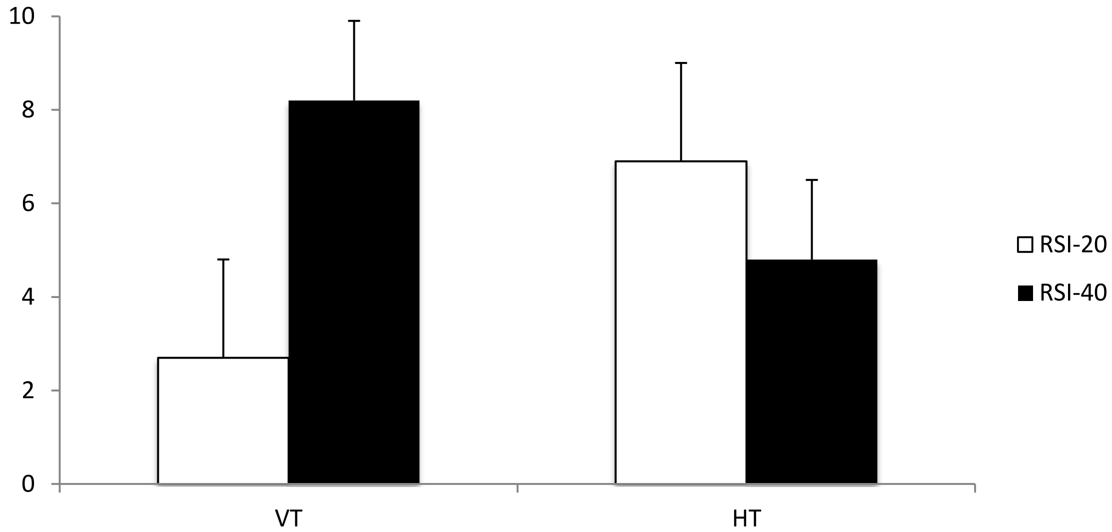

Figure 4-7: The percentage of change between pre-and post-training measurements for reactive strength index (RSI) scores, assessed during drop jumps from heights of 0.20 m (RSI-20) and 0.40 m (RSI-40) for both experimental training groups. Error bars are presented for standard deviation.

4.6.3.3 Gender Effect on the Reactive Strength Index

No significant differences were reported between pre- and post-measurements in male or female subjects for RSI-20 ($F_{(1, 42)}$ = 0.003, p = 0.956, partial η^2 = 0.000) or RSI-40 ($F_{(1, 42)}$ = 0.123, p = 0.728, partial η^2 = 0.003).

4.7 Muscle Architecture of the Gastrocnemius Medialis

4.7.1 Fascicle Length

FL was not significantly different between pre- and post-assessments for either experimental group ($F_{(1, 42)}$ = 0.133, p =0.718, partial η^2 = 0.003, Λ = 0.997) with only a small change found in the VT and HT groups (Figure 4-9). The training-induced change was only observed to be trivial for both VT (d = 0.05) and HT (d = 0.02) groups with no statistically significant difference was recorded between groups ($F_{(1, 42)}$ = 0.000, p = 0.986, partial η^2 = 0.000).

4.7.2 Fascicle Angle

Fascicle angle did not differ significantly following either training intervention ($F_{(1, 42)}$ = 0.123, p = 0.728, partial η^2 = 0.003, Λ = 0.997) with only a small change recorded in the VT and HT groups (Figure 4-9). This training-induced change was observed to be of trivial size for both VT (d = 0.08) and HT (d = 0.04) groups with no significant difference recorded between groups ($F_{(1, 42)}$ = 0.001, p = 0.982, partial η^2 = 0.000).

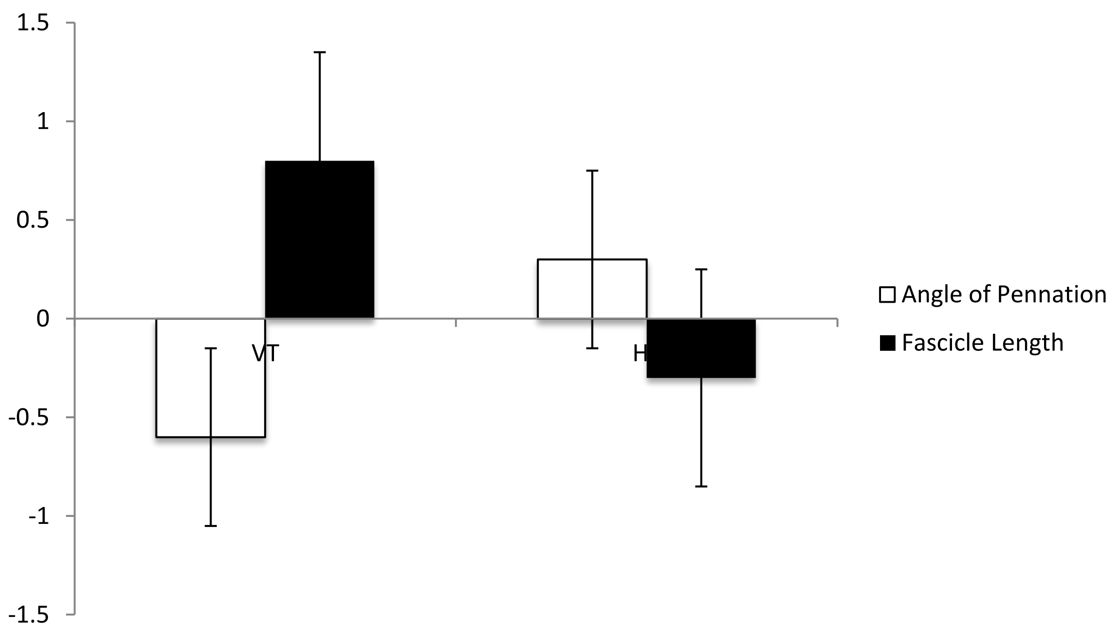

Figure 4-8: The percentage of change between pre-and post-training measurements for both experimental groups for fascicle length and the angle of fascicle pennation. Error bars are presented for standard deviation.

4.7.3 Muscle Thickness

Muscle thickness did not differ significantly following either training intervention ($F_{(1, 42)} = 0.134$, $p = 0.717$, partial $\eta^2 = 0.003$, $\Lambda = 0.997$) with only a small change recorded in the VT and HT groups. This training-induced change was observed to be of trivial practical effect for both VT (d = 0.03) and HT (d = 0.01) groups with no significant difference recorded between groups ($F_{(1, 42)} = 0.013$, $p = 0.911$, partial $\eta^2 = 0.000$).

4.7.4 Gender Effect on the Muscle Architecture

Significant differences were reported between pre- and post-measurements in male and female subjects for FL ($F_{(1, 42)} = 18.01$, $p = 0.000$, partial $\eta^2 = 0.3$), the angle of fascicle pennation ($F_{(1, 42)} = 9.684$, $p = 0.003$, partial $\eta^2 = 0.187$) and muscle thickness ($F_{(1, 42)} = 10.443$, $p = 0.002$, partial $\eta^2 = 0.199$). Male subjects in the VT group presented a 1.4% change in FL, which corresponded with a trivial practical change (d = 0.09) as determined by effect size. The female subjects reported a trivial practical change (d = 0.01) of 0.1% in FL. Male subjects in the HT group presented a 2.0% change in FL, which corresponded with a moderate practical change (d = 0.13) as determined by effect size and the female subjects in the HT group presented a 1.8% change in FL, which corresponded to a moderate practical change (d = 0.16) as determined by effect size. Cohen's effect size suggests a small change for male subjects in the VT group (d = 0.11), which was a 1.1% difference from pre- to post- training measurements for fascicle pennation. Female subjects in the VT group presented a trivial practical improvement (d = 0.05) in pennation between pre- and post- scores, with a 0.2% change in fascicle pennation. Male subjects in the HT group presented a 0.8% change (a trivial practical difference, d = 0.09), whereas the female subjects presented a 0.1% change in performance (a trivial practical change, d = 0.03). Male subjects in the VT group presented a –0.1% change in muscle thickness, which corresponded with a trivial change (d = 0.01) as determined by effect size. The female subjects also reported a trivial practical change (d = 0.01) of –0.01%. Males subjects in the HT group presented a –1.0% change in muscle thickness, which corresponded with a small practical change (d = 0.10) as determined by effect size and the females subjects in the

HT group presented a 1.9% change, which corresponded to a small effect size change (d = 0.19).

4.8 Body Composition

4.8.1 Body Fat Percentage

Body fat percentage (BF%) significantly decreased between pre- and post-assessments ($F_{(1, 42)} = 10.770$, $p = 0.002$, partial $\eta^2 = 0.204$, $\Lambda = 0.796$), however there was no significant difference in the magnitude of this change between groups ($F_{(1, 42)} = 0.00$, $p = 0.989$, partial $\eta^2 = 0.000$). The mean percentage change between pre- and post-training assessments for VT and HT was 5.1% (d = 0.18) and 3.6% (d = 0.13) respectively (Figure 4-8). The HT experimental group presented a significant relationship between BF% and sprint running performance at 20 m (r = 0.43) and 30 m (r = 0.50), but not at any other distance (5 m: r = 0.25; 10 m: r = 0.35; 40 m: r = 0.29). No significant relationships were presented by the VT group at any distance (5 m: r = –0.37; 10 m: r = –0.23; 20 m: r = –0.16; 30 m: r = –0.33; 40 m: r = 0.01).

4.8.2 Body Mass

Body mass significantly decreased between pre- and post- assessments ($F_{(1, 42)} = 22.068$, $p = 0.000$, partial $\eta^2 = 0.344$, $\Lambda = 0.656$), however there was no significant difference in the magnitude of this change between groups ($F_{(1, 42)} = 0.123$, $p = 0.727$, partial $\eta^2 = 0.003$). The percentage change between pre- and post-training assessments for VT and HT ranged from –2.9% to 0.0% (d = 0.09) and –5.1% to 0.6% (d = 0.09) respectively (Figure 4-8). Non-significant two tails correlations were reported between body mass and sprinting times for the VT group (5 m: r = 0.34; 10 m: r = 0.09; 20 m: r = 0.03; 30 m: r = 0.27; 40 m: r = –0.49) and the HT group (5 m: r = –0.26; 10 m: r = –0.29; 20 m: r = –0.31; 30 m: r = –0.38; 40 m: r = –0.18).

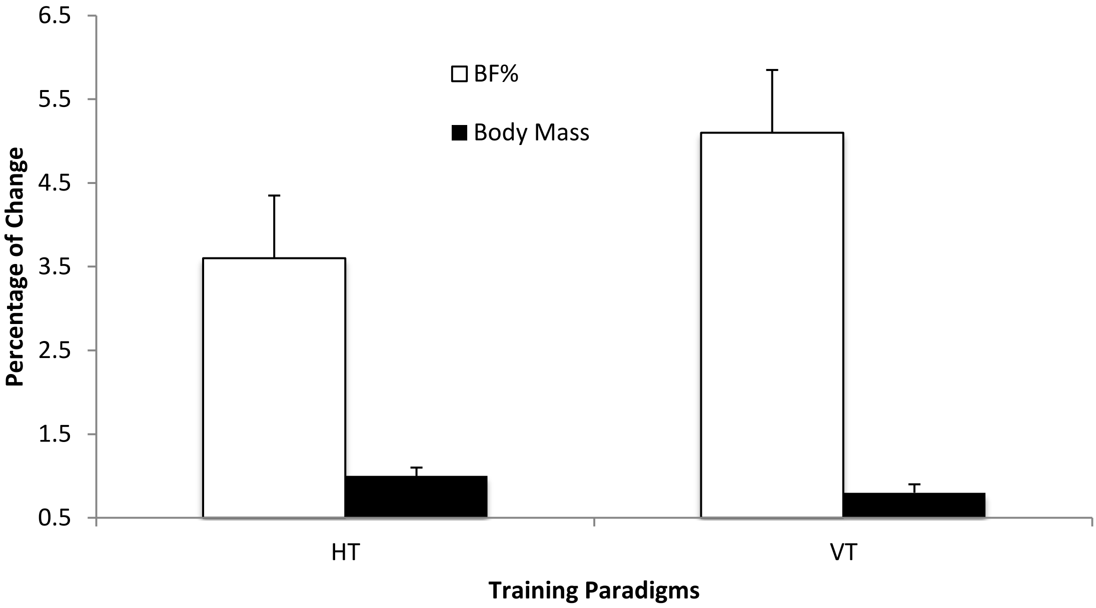

Figure 4-9: The raw percentage of change between pre- and post-training measurements for body mass and body fat percentage (BF%), for both experimental training groups. Error bars are presented for standard deviation.

4.8.3 Mass of the Shank

The mass of the shank was significantly different between pre- and post-assessments ($F_{(1, 42)} = 8.36$, $p = 0.006$, partial $\eta^2 = 0.166$, $\Lambda = 0.834$), however there was no significant difference in the magnitude of this change between groups ($F_{(1, 42)} = 0.830$, $p = 0.368$, partial $\eta^2 = 0.019$). The percentage between pre- and post-training assessments for VT and HT was –4.0% (d = 0.35) and –3.1% (d = 0.21) respectively. Non-significant two tails correlations were reported between body mass and sprint running times for the VT group (5 m: r = 0.10; 10 m: r = 0.07; 20 m: r = 0.10; 30 m: r = 0.13; 40 m: r = 0.23) and the HT group (5 m: r = 0.09; 10 m: r = 0.40; 30 m: r = 0.42; 40 m: r = 0.35). A significant correlation (p = 0.01) was reported between the mass of the shank and 20 m sprinting time (r = 0.56) in the HT group.

4.8.4 Gender Effect on Body Composition

Significant differences were reported between pre- and post-measurements in male and female subjects for BF% ($F_{(1, 42)} = 334.695$, $p = 0.000$, partial $\eta^2 = 0.889$) and body mass ($F_{(1, 42)} = 73.796$, $p = 0.000$, partial $\eta^2 = 0.637$). Male subjects in the VT group presented a 0.2% change in BF%, which corresponded with a trivial practical change (d

= 0.00) as determined by effect size. The female subjects reported a small practical change (d = 0.18) of –8.1%. Males subjects in the HT group presented no change (0.0%) in BF%, which corresponded with a trivial practical change (d = 0.00) as determined by effect size and the females subjects in the HT group presented a –5.6% change, which corresponded to a moderate practical change (d = 0.59) as determined by effect size (Figure 4-21). No difference was reported (d = 0.00) for the angle of fascicle pennation between pre- and post-training results in male subjects from the VT training paradigm. Female subjects in the VT group presented a small practical change (d = 0.09) between pre- and post- scores, with a -1.8% change in raw value. Male subjects in the HT group experienced no change (0.0% raw change and a trivial practical difference, d = 0.00), whereas the female subjects presented a –2.1% change (a moderate practical change, d = 0.61).

Chapter Five

5 Discussion

5.1 Sprinting Performance

The main finding of this study is that six weeks of plyometric training performed in either a horizontal (HT) or vertical (VT) direction, significantly ($p < 0.05$) improved 10 m, 20 m, 30 m and 40 m sprint times in concurrently training subjects. These finding produced improvements (10 – 40 m) in running performance and reflect the conclusions of previous researchers that plyometric training is an effective training method for the improvement of sprint performance. Additionally, both training groups also reported non-significant ($p = 0.85$) improvements (HT: d = 0.2; and VT: d = 0.04) in 5 m time following the training.

The training paradigms performed during this study presented positive changes in sprinting performance. However the changes slightly differed from those in previous literature regarding plyometric training interventions [73, 191-193]. Interestingly, effect size (d) differences for 0 m to 10 m and 20 m were less in the current study (10: d = 0.16 and; 20 m: d = 0.18;) and similar at 30 m (d = 0.24) and 40 m (d = 0.40) to the bulk of the literature (10 m: d = 0.32; 20 m: d = 0.39; 30 m: d = 0.20 and; 40 m: d = 0.39) [193]. Improvements in initial acceleration (0 -10 m) were also less than those seen following interventions of strength training (3.7%) [194] and sled towing (3.4% improvements) [195]. It should be noted, however, that the results of the current study were more closely aligned with relatively "light" loading than 'heavy loading' regarding the sled towing. Considering that greater concentric strength of the knee extensors and plantar flexors are strongly correlated to performance during initial acceleration (0 – 15 m) [70, 73], it might be plausible that stronger athletes (and training that effects greater strength gains in initially weaker athletes i.e. heavy loading during sled towing and strength training) is more effective in producing gains during the acceleration phase of sprinting.

The VT paradigm was conceived to produce greater force-related adaptations than the HT training, yet still retain some specificity of movement as both sprinting and bounding exercises are unilateral in nature. It was considered that training interventions performed for the purpose of increasing peak force generation and/or muscular strength [32, 126], as well as the use of vertically-directed plyometrics [32, 73, 169],

have resulted in improved running performances. Given the above it was theorised that the VT training would produce greater performance enhancements than the HT training. However the lack of significant difference between the groups observed in this study indicate no clear benefit of performing one paradigm instead of the other. Interestingly, while no statistical significance was detected between groups, the HT training group presented a trend of greater (percentages of) change between pre- and post-training assessments at each measured distance (Figure 4-1). This may have some practical benefit, particularly for initial acceleration and at maximum speed, in which the HT group improved by 0.02s (5 m; d = 0.24) and 0.04s (40 m; d = 0.12), respectively.

Regarding GRF analyses of the 5 m sprint, notable findings include significant improvements in ground contact time (GCT), time to peak force (TtPF) and peak force between pre- to post-training in both training groups. Typically, faster sprinters are reported to have shorter GCTs than slower sprinters [196], suggesting that shorter GCT results in the more effective utilisation of the elastic energy [197] stored during the braking segment (eccentric phase) of ground contact. In the present study, reductions in GCT showed a positive relationship with improvements in 5 m and 10 m sprinting performance for VT and HT groups (Table 4-4 and Table 4-5). Although correlation is not causation, the trends in the data support the findings of Lockie et al. [198] who reported a link between shorter GCT and faster acceleration. Interestingly, no significant difference was observed between groups for any GRF variables recorded. However it should be noted that the HT group decreased GCT by 6.8% more than the VT group, which may suggest some practical benefit (HT: d = 0.20 and VT: d = 0.04, respectively) considering the HT group presented (non-statistically) greater improvements in running performance at each measured distance.

It is reported that the magnitude of horizontal force has a strong positive relationship with acceleration [53, 59, 85], hence it seems plausible that horizontally-directed (or sprint-specific) training modes would produce greater improvements in short distance sprinting. The outcomes from this research neither refute nor provide conclusive justified support for training dominant in horizontally directed force applications. HT produced moderate practical benefits at 5 m and 10 m for females

and a small practical effect for males at 10m, whereas all other gender effects were considered trivial. These small improvements provide some support for the notion that plyometric exercises should be performed in a similar manner to the skill to be improved. However, the lack of a statistically significant difference between HT and VT plyometric training exercises suggests that both modes of plyometric exercise could be applied with similar effect, and thus both could be employed as part of a training program with regards to introducing variation in different training cycles.

Improvements in force production, and possibly running performance, may be underpinned by changes in muscle function. In the present study, muscle architectural adaptations were examined. However, following six weeks of training, only small and non-significant changes in gastrocnemius medialis (GM) fascicle length (FL) and angle pennation (AP) were observed. Increased force production (due to increased FL and AP of the muscle fibres) is thought to be important for sprint performance [11] and is a distinguishing feature of better sprinters, with elite-level sprinters shown to have longer FLs than sub-elite sprinters [178] and other runners [99]. Muscle thickness of the GM did not show a significant change after training (VT: –0.1% and HT: 0.4%), which is similar to previous literature showing a lack of change in plantar flexor cross-sectional area following plyometric exercise [199]. It is unlikely that the small and non-significant changes in muscle architecture would have influenced force production. The possibility exists, however, that changes occurred in other regions of GM, in other involved muscles or in tendon structures.

The data collected in this research suggests that performing vertically-directed bounding exercises (with body weight alone) may not be produce sufficient force to produce the magnitude of adaptive changes seen in weighted exercises such as ballistic training or weightlifting studies, despite also being vertically-directed in nature. Similar transfers of vertical force (i.e. a training effect) have been presented by multiple training studies regarding Olympic-style weightlifting and vertical jump performance, reporting 2.8–9.5% increases in vertical jump height [151, 153, 200-202] (compared to the 2.1% difference in the VT group of the current study). It is plausible that VT performed with weighted vests would result in greater force production during training, thus producing greater adaptive change. While any increase in mass may

slightly alter kinematic similarities that VT has with sprint running, MacKenzie et al. [203] suggests that rate of force development and muscular coordination may be more important variables when training. Although this rationale pertains to vertical jump training, the same theory might be applied to training to improve sprinting. Assuming that plantar flexor mass remains similar (thus not increasing inertia and subsequently decreasing running speed), increasing the force utilised in VT with additional loading (i.e. weighted vests) may continue to provide kinematic and kinetic similarity to sprinting, while provide a greater training adaptation than exercises using only body mass.

In the current study, a 5.1% and 3.6% reduction in body fat percentage (BF%) for VT and HT groups were observed, respectively. A lower BF% has been reported to be beneficial to sprinting performance [125, 126]. The decreased BF% is considered important for athletes requiring high movement speeds, as decreases in adipose tissue will reduce limb (and whole body) inertia. Although decreases in BF% in both experimental groups were observed overall, body mass (BM) (VT: 0.8% and HT: 1.0%) did not substantially change. It seems plausible that the loss of BM resulted from a decrease in body fat rather than a change in lean muscle mass. The shank mass also significantly decreased in both experimental groups (VT: –4.0% and HT: –3.1%) following training. The importance of the decrease in the shank mass allows the shank to be moved quicker and closer to the axis of rotation (the hip joint) with less energy, thus resulting in a quicker stride rate and improved sprinting performance. Speculatively, the greater decrease in BM and other associated changes seen by HT may have marginally contributed to the greater improvements observed in sprinting time and PF at each distance, and PF at 50 ms and at 200 ms observed during sprinting acceleration.

5.2 Vertical Jump Performance

A secondary finding of this study is that 6 weeks of plyometric bounding exercises performed either vertically or horizontally was effective in improving vertical jumping performance as assessed by counter-movement jump (CMJ) and squat jump (SJ) and that these changes were not significantly different between training modes.

Additionally, changes in biomechanical parameters of vertical jumping (peak force and the time take to reach peak force) were also very similar. Moreover, both vertically-directed and horizontally-directed paradigms improved CMJ height (HT: 0.8 cm and VT: 1.5 cm) and SJ height (HT: 1.3cm and VT: 1.1cm) significantly ($p < 0.05$) between pre- and post-training assessments, with no negative effects when compared with each other.

It was thought that the VT training would have greater specificity to vertical jumping movements and produce greater forces (due to gravity acting on the body for longer) than the HT group and thus would enhance vertical jumping performances. However the lack of significant difference between the groups observed in this study indicate no clear benefit of performing one paradigm instead of the other. Additionally, despite statistically significant improvements by both training groups, it should be noted that the raw changes in jump height presented in the current study are smaller than those reported in previous studies (approximately ~3.6 cm in the previous studies [44, 162, 204, 205]). Interestingly, while no statistical significance was detected between groups, the HT training group presented a greater percentages change for SJ ($d = 0.15$) and the VT group performed better at CMJ ($d = 0.13$) between pre- and post-training assessments (Figure 4-4). While the SJ is predominantly an assessment tool the marginal improvements presented in CMJ (VT: 1.1% and; HT: 2.1%) height may have some practical benefit, although it is plausible that the magnitude of change was small enough to be outside of normal biological variation.

Interestingly, the relative equality of change in vertical jumping performance from both training paradigms support the findings of Baker et al. [206] who suggested that both general and specific strength training can improve vertical jump performance. The findings of this study suggests that there may not be a negative impact of using horizontally- (non–movement specific) or vertically-directed (movement-specific) plyometric exercises, relative to each other, which is contrary to the findings of King and Cipriani [204] who reported significantly greater improvements in performance following vertically-directed (3.6 cm improvement in jump height) than horizontally-directed (0.8 cm improvement in jump height) plyometric exercise. However, the horizontally-directed group in that study started with a 3.68 cm greater

mean jump height, and thus the vertical jump training tended to equalise the groups. The training stimulus may not have been sufficient to effect meaningful change. In the present study, the VT group presented a 0.7 cm greater improvement in CMJ height than the HT group (VT: d = 0.33; HT: d = 0.20), and no meaningful change in SJ height (VT: d = 0.17, HT: d = 0.18), from pre- to post-training. These changes are somewhat less than reported in other studies, with mean effects for plyometric training on vertical jump height being d = 0.44 and d = 0.88, although the bulk of these studies were performed with smaller sample sizes than the current study. Additionally, in this study, data was collected during bilateral jumping tests and may not have replicated the unilateral paradigms performed during training.

Interestingly, in this study both training groups presented greater changes in PF (and peak force relative to body mass (PF/BM)) measured during SJs than measured during CMJs (Figure 4-4 and Figure 4-5). These changes in the force profiles did not seem to be associated with a change in vertical jump or sprinting performance, which contrasts previous studies where a relationship between vertical jump performance (CMJ, SJ and depth jump (DJ) [207]) and maximum-speed, short-distance sprinting ability was observed [53, 208-211]. Specifically, PF and jump height during CMJs have been reported to correlate with 10 m sprint time [61] and are somewhat able to predict 30 m time in elite sprinters [208]. However, the CMJ has different force–time characteristics than sprinting and thus may not utilise the same physiological mechanisms of stretch-shortening cycle (SSC) force potentiation [10]. Thus, it was not entirely surprising that no significant relationship was found between forces produced during vertical jumping and sprinting time measured to any distance in the current study.

The current results show that both training paradigms produced significant improvements in vertical jumping (CMJ, SJ and DJ) performance. However no substantial evidence was presented that suggests one mode produced greater changes than the other. Nonetheless, the underlying trend—as determined by effect size calculations—suggests that VT training may provide a slightly greater benefit, which may speculatively result from a greater requirement for force production in the training or the greater movement pattern similarity. It is interesting to note that the VT showed 3.4% and 1.0% greater (non-significant) improvements in reactive strength

index (RSI-40) and CMJ height than the HT group, thus it seems likely that similarity in muscle action between training and testing is of importance. However, HT training also improved CMJ performance following training, suggesting this mode of training could be performed to induce variety into a training program, but not as the main training stimulus.

5.3 Conclusions

For team sport athletes, the ability to accelerate faster is critical to success and plyometric exercise has been reported to improve this attribute. The data collected as part of this Masters research study indicates that both horizontally- and vertically-directed plyometric exercises can elicit improvements in sprinting (to 40 m) and vertical jumping (CMJ, SJ and DJ) performance in concurrently training sub-elite athletes. The findings of the current study support previous research showing that performing plyometric exercises as part of a training regime improves muscular force production [212, 213], and the ability to produce force quickly [212]. Both experimental groups presented a significant change in anthropometry following training.

Chapter Six

6 Conclusions and Directions for Future Research

6.1 Conclusions

The main theme of this thesis was the development and improvement of sprint running performance in team sport athletes. In team sports, the distance and duration of sprinting is relatively short (Appendix E) and thus maximising speed in short distances appears to be of great importance. A review of the current literature on sprinting mechanics implicated many factors as contributors to peak sprinting performance. It has been widely discussed that the ability to produce high force outputs as quickly as possible is important in determining sprinting ability. Furthermore, the production and application of this force can affect change in the architecture of the working muscles, which may further the muscle-tendon unit's ability to produce even greater force.

The practice of sprinting itself has been theorised to be the most effective method of training to improve sprint performance, due to a transfer of training effect elicited by performing similar movement patterns, muscle motor-unit firing sequences and limb velocities as in competition. Previous studies have shown that supplementary training methods (i.e. strength training, weightlifting) may also positively affect sprint performance. In this thesis, plyometric exercise was chosen as a focused training paradigm as it is a commonly performed mode of training with high-speed movements. Typically prescribed as a series of jumps, hops and/or bounds [160], plyometric exercise emphasises rapid movement speed and (relatively) short ground contact. Previous studies regarding plyometric exercise [32, 169, 170] training interventions have reported improved sprinting performances. It is thought that this may be due, in part, due to improvements in muscular coordination [214], leg extensor force production [26, 167], descending neural drive and decreased neural inhibition.

With regards to sprinting, horizontal bounding is typically performed as it is reported to require similar limb movement speeds, horizontal propulsive forces and rates of force development, when performed with maximal effort [34]. Thus, it is considered to be the most suitable (plyometric) training stimulus to improve sprint performance. However, sprinting has a stronger relationship with peak vertical forces reported during vertically-directed plyometric exercise, than those recorded during

horizontally-directed plyometric exercise [39]. Furthermore, vertically-directed plyometric exercises typically produce greater ground reaction forces than horizontally-directed, due to the longer period of time gravity has to act upon the body [38]. This increase in gravitational force subsequently requires greater propulsive forces to overcome it, thus providing greater stimulus for adaptive change of the neuromuscular apparatus.

The current research was an attempt to determine the effect that horizontally- versus vertically-directed plyometric training would have on 40 m sprinting performance. Secondary motives were to investigate changes in vertical jumping performance, muscle architecture of the gastrocnemius medialis (GM; dominant leg) and force production during early acceleration and vertical jumping. It was found that both horizontally- and vertically-performed plyometric training were equally as effective in improving short distance sprinting (to 40 m) and vertical jumping performance. Additionally, architectural changes of the GM and the magnitude of improvements in peak force were also statistically similar. These results question the notion that movement-specific plyometric exercises should be the predominant plyometric training stimulus performed when training for short distance sprinting or vertical jumping.

While attempts were made to eliminate error within the research, the findings within this dissertation should be restricted to the conditions detailed in the methodology. The following may contribute to differences of results obtained by past and future researchers in similar fields:

- The subjects participating in the current research were not elite-level athletes. It is possible that due to a sub-elite training history that they may have been more susceptible to neuromuscular and architectural change than elite population groups. Furthermore, it has been reported that athletes from different sports elicit different characteristics [8, 215-217], and it may be that the mixed groups in the current study would report different training adaptations than those constructed entirely of one sport only (i.e. all participants from soccer or track athletes only, etc.).

- The training intervention used in the current research was of relatively short duration and with minimal volume and frequency. Thus, this study in no way reflects the results that might be gathered following a longer and more intensive training intervention.
- The concurrently performed training that the subjects undertook outside the scope of the training intervention was uncontrolled and unrecorded. It is plausible that some subjects may have been performing other modes of training that might have either inhibited, exacerbated, or masked the adaptations resulting from the training paradigm of the current research.
- The current experimental design was not a crossover study and did not have a control group running in parallel to the training group. Thus it is plausible that future studies incorporating these variables would report different results.

6.2 Directions for Future Research

To further advance our understanding of plyometric exercise (particularly bounding-type exercises) as a training method for enhancing sprinting ability, more research is warranted. The following topics have arisen from this dissertation as directions for future research:

- Several researchers have recommended that plyometric exercise training interventions be of 10–16 weeks in length [164, 218]. A longer training intervention would potentially allow for greater adaptive changes to the neuromuscular apparatus and thus, lead to greater performance gains.
- While longer fascicle lengths (FLs) of the plantar flexors are reportedly a differentiating factor in sprinting ability, this study only monitored the GM muscle. The gastrocnemius lateralis (GL) reportedly has longer FLs than the GM, and thus may be of greater interest and more susceptible to changes in length. It is also possible that the longer lengths of the GL have a stronger relationship to sprinting performance than those of the GM, when considered in isolation [219].
- It may be that subjects with poor sprint mechanics may benefit from the addition of horizontally-directed plyometric exercises, as the exercise is similar

to sprint running itself and may provide additional 'technique'-type training while allowing for variation within the program. Thus, it is possible that non-elite sprint running subjects performing horizontal bounding exercises would find positive changes in sprint running technique. It is also likely that the similar nature of horizontally-directed plyometric exercises to sprinting may induce detrimental changes in technique in elite sprinting athletes. It is possible that these changes may be detectable using three-dimensional motion analyses and may provide further insight into the utilisation of plyometric exercises in sport-specific training programs.

- It has been reported that power output of the non-dominant leg has a positive (although moderate) relationship with agility performance [220]. By nature, bounding is performed as a series of single-leg projections, thus training in this manner *should* improve bilateral strength deficits in the lower limbs and improve force output in the dominant and non-dominant leg. Increasing force production in both limbs should allow for improved change of direction in both directions as both legs are used for "push-off" in changing direction, depending on direction of the movement.
- In this study, only body weight bounding exercises were performed and thus it is unknown if weighted movements (which would increase vertical ground reaction forces) would negatively affect training and sprinting mechanics. Thus, additional research examining the effects of performing vertical bounding with additional loading (i.e. wearing weighted vests) is required to identify the optimal training load for improving sprint performance.
- Bilateral strength deficits have been used to assess the risk of musculoskeletal injury in athletic populations [221]. As single-leg bounding is likely to strengthen both the dominant and non-dominant legs, it seems plausible that bilateral strength deficits could be reduced and subsequent injury risk could be decreased.
- To date, there has been little research regarding plyometric exercise and changes in anthropometry, despite a substantial body of anecdotal evidence suggesting that plyometric exercise is an effective 'fat-burner.' While

plyometrics are predominantly a product of tendon recoil (with the muscle itself remaining quasi-isometric), due to its high speed, it seems plausible that an increase in central nervous system activity could increase energy consumption. Furthermore, it is feasible that an aroused central nervous system may initiate a hormone response conducive to breaking down adipose tissue and building lean muscle mass.

Chapter Seven

7 References

7.1 References

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Appendices

8 Appendices

8.1 Appendix A

Information Letter and Informed Consent Form

INFORMED CONSENT LETTER TO PARTICIPANTS

Project Title

The Effect of Vertically- and Horizontally-Directed Plyometric Exercise on Sprint Running Performance

Purpose

The purpose of this study is to determine whether vertical or horizontal plyometric exercise will result in greater improvement in sprint running speed and muscle function in concurrently training speed-strength athletes.

Background

The stretch-shortening cycle is a type of muscle contraction that is characterised by a lengthening of the muscle-tendon unit, followed by a rapid shortening. It allows greater forces to be developed than when lengthening of the muscle is not imposed. To train this, strength and conditioning professionals often utilise a training modality termed plyometrics.

In sports involving sprint running, plyometric exercises are generally performed in a horizontal fashion, meaning that the participating athlete jumps as far as possible rather than as high as possible at rapid speeds. Alternatively, vertical plyometric exercise can be performed and may result in different adaptive changes in muscle function. However, there has been no research comparing horizontal and vertical plyometrics training and the effects on sprinting performance. This study will be the first to compare these two plyometric training modes, thus allowing the

strength and conditioning professional to prepare the most time effective and functional training stimuli for their speed-strength athletes.

Therefore, researchers at Edith Cowan University's School of Exercise, Biomedical and Health Sciences and Physiologists from the Australian Institute of Sport are seeking physically active, strength trained male and female volunteers aged 18-35 to participate in this research project.

Methods

This investigation will take a total of 12 weeks to complete. It will consist of a week of familiarisation tests for the participants before baseline testing. One week’s rest will be provided between familiarisation and baseline testing, and three weeks will be provided between baseline testing weeks. A six-week training intervention will follow before further testing. You will be randomly allocated to either a horizontal or a vertical plyometric exercise training group to train twice a week for the six-week period. The training will consist of a series of single-leg bounds and will last for approximately 30 minutes. The training sessions will be directed and supervised by the researcher, who is an experienced and accredited strength and conditioning coach. Both training groups will be tested prior to the commencement of training and following the six-week training intervention. Testing will occur over three days, with two days performed at the Edith Cowan University and the other at an indoor training venue. Testing will involve assessment of muscle architecture and function and performance of straight-line and change-of-direction sprinting.

Measurements

During testing you will be required to perform the following tests:

- Jump Squats – Exercises that involve lowering the body by bending the knees until the thighs are approximately parallel to the ground (knee angle of ~110^{o}) and explosively jumping upwards as fast as possible with feet leaving the floor. They will be performed in two ways; 1) the participant will pause for 3seconds with their thighs parallel to the ground before jumping straight up, and 2) as a counter-movement, meaning that the participant will lower their body by

bending their knees to the required angle and jump straight up without a delaying pause. Both jumps will be performed with bodyweight only.

- Depth Jumps – Involves stepping off a platform and explosively jumping upwards as fast as possible. Platform heights will be 0.2, 0.40 and 0.60 m.
- Maximum Sprint Speed – Involves running as quickly as possible in a straight line for 50 m. Times will be recorded to 10 m and between 40–50 m.

You will be thoroughly instructed on the correct jumps squat and depth jump technique prior to testing and will be supervised by professional coaches during this stage. Photographs of the muscle will be taken by ultrasound imaging. This involves placing a probe onto the surface of the skin covering the lower leg, while you remain lying face down in a relaxed position. Height and weight will be measured during the first testing session and body composition will be measured by dual-energy x-ray absorptiometry (DEXA). This a test in which you will lie still on a platform for approximately 5 to 10 minutes, while machine scans the whole body from head-to-toe with a moving arm positioned above your body. Reflective markers and electrodes will be placed will be placed upon your skin to monitor muscle activity and provide a 3-D view of you performing jumping and sprinting tests.

Benefits

Participants volunteering to complete this study will be supervised by high quality, professional sport scientists and strength and conditioners. They will provide all activities performed in the study, including testing and training, at no cost to the participants.

Substantial increases in performance are normally seen following plyometric training, and participants will be provided detailed information of their athletic performance, body composition, muscle power and function, following the completion of testing.

Participants will be the first group to know the results of this study, and thus will be able to alter their training to advantage before other competing athletes.

Risks

DEXA scans are routinely used in clinical settings and carry very small risk to the patient. DEXA involves exposure to small doses of radiation. The radiation levels are exceedingly small, even in comparison to the annual radiation western communities are naturally exposed to by environmental factors. To compare, a DEXA scan will expose you to 1 to 6 μSv as opposed to a typical chest x-ray, which will expose you to 30–40 μSv. The number of scans proposed in this study is well within the guidelines provided by the equipment manufacturer.

The placement of electrodes onto the skin to measure muscle activity, may cause temporary skin irritation, such as itching or inflammation of the skin. This is to be minimised by wiping the site with alcohol wipes, to clean and sterilise the area.

There are no inherent risks involved with this investigation. However, there is the possibility of muscle strains or pulls associated with the training and testing, common to any type of physical activity. As with most lower-body resistance training exercise, there is some risk of injury to the back associated with performing jumping movements. However, these injuries typically occur as a result of performing the movement with incorrect technique or warm-up. Correct technique and warm-up will be explained and demonstrated by trained sports scientists. Furthermore, with any training intervention there is some risk of delayed onset muscle soreness and/or injury to participants, but this will be minimised by having qualified trainers at training and testing sessions. Adequate warm-up procedures will be followed and testing will be monitored by qualified personnel with first aid and CPR certification to minimise these risks. Standardised procedures for physical activity testing will be followed as previously performed in the Edith Cowan University laboratory.

Feedback

As a participant in this research project you will be provided with your test results as soon as they are available. A summary and explanation of your personal results will be made available to you upon completion of the study.

Voluntary Participation

Whether you decide to participate in this study or not, your decision will not prejudice you in any way. If you decide to participate, you are free to withdraw from the study at any time.

Privacy Statement

The conduct of this research involves the collection, access and/or use of your personal information. This information collected is confidential and will not be disclosed to third parties without your consent, except to meet government, legal or other regulatory authority requirements. A de-indentified copy of this data may be used for other research purposes. However your anonymity will be safe guarded at all times.

Confidentiality

Your results will be kept confidential. All data will be kept in the possession of the investigators. If the results of the study are published in a scientific journal, participant names will not be revealed. You will not be referred to by name during research reports or study discussions. All records will be stored in a locked filing cabinet with restricted access in a private office. All computer records will be restricted by password.

Contacting the Investigators

We are happy to answer any questions you may have at this time. If you have any queries later, please do not hesitate to contact Ben Thomasian at (+61 8 6304 2242), email bthomasi@student.ecu.edu.au, Dr Anthony Blazevich at (08) (+61 8 6304 5472), email a.blazevich@ecu.edu.au or Dr Dale Chapman at (+61 2 6214 7387), email Dale.Chapman@ausport.com.au. If you have any concerns or complaints about the research project and wish to talk to an independent person, you may contact:

Research Ethics Officer

Human Research Ethics Officer

Edith Cowan University

100 Joondalup Drive

Joondalup WA 6027

Phone: (08) 6304 2170 Email: research.ethics@ecu.edu.au

8.2 Appendix B

Medical Questionnaire

MEDICAL QUESTIONNAIRE

The following questionnaire is designed to establish a background of your medical history, and identify any injury or illness that may influence your testing or performance.

Please answer all questions as accurately as possible and if you are unsure about anything please ask.

Answering 'yes' to a question will not automatically disqualify you from participating in the study.

Participant Details

Identification: ___________________________ Date of Birth: _____/_____/_____

Height: ______________ (cm) Weight: ______________ (kg) Gender: M/F

Medical History

Do you currently, or have you previously, have any of the following conditions?

High or Abnormal Blood Pressure	Yes	No
Heart Disease	Yes	No
High Cholesterol	Yes	No
Rheumatic Fever	Yes	No
Heart Abnormalities	Yes	No
Asthma	Yes	No
Diabetes	Yes	No
Epilepsy	Yes	No
Back Pain	Yes	No

Neck Pain	Yes	No
Muscle Pain	Yes	No
Joint Pain	Yes	No
Severe Allergies	Yes	No
Infectious Disease	Yes	No
Neurological Disorder	Yes	No
Neuromuscular Disorder	Yes	No

If you have answered ‘Yes’ to any of the following, please give details:

Are you currently on any medication?

Have you had the flu in the last two weeks?

Have you recently had any injuries?

Do you have any recurring muscle or joint injuries?

Is there any other condition, not previously mentioned, which may affect your exercise performance?

Lifestyle Habits

Do you smoke tobacco or other nicotine products? Yes No

If 'Yes,' how many per week?

Do you consume alcohol? Yes No

If 'Yes,' how many standard drinks per week?

Do you consume tea or coffee? Yes

No

If 'Yes,' how many cups per day (1 cup = 250ml)?

Declaration

I acknowledge that the information provided on this form, is to the best of my knowledge, a true and accurate indication of my current state of health.

Participant

Name:

____

Date of Birth:

_____/_____/_____

Signature:

____

Practitioner (if required)

Name:

Date of Birth:

______/______/______

Signature:

8.3 Appendix C

Subject Declaration

SUBJECT DECLARATION

Project Title

The Effect of Vertically- and Horizontally-Directed Plyometric Exercise on Sprint Running Performance

I (Print Name) ____ have read the information provided and any questions I have asked have been answered to my satisfaction. I agree to participate in this activity, realising that I may withdraw at any time without reason or prejudice.

I understand that all information provided is treated as strictly confidential and will not be released by the investigator unless required to do so by law. I have been advised as to what data is being collected, what the purpose is and what will be done with the data upon completion of the research. I agree that research data gathered for the study maybe published provided my name or other identifying information is not used.

Signature:

____

Date:

____

8.4 Appendix D

Fatigue Questionnaire

MULTI-DIMENSIONAL FATIGUE INVENTORY

*****MFI-20*****

Participant ID:__________________ **Session:**__________________ **Date:**_______________

Instructions:

By means of the following statements we would like to get an idea of how you have been feeling lately. There is for example the statement:

'I FEEL RELAXED'

If you think this is entirely true, that you indeed have been feeling relaxed lately, please, place an X in the extreme left box like this:

Yes, that is true	X					No, that is not true

The more you disagree with the statement, the more you can place an X in the direction of 'No that is not true'. Please, do not miss out a statement and place one X next to each statement.

1. I feel fit

Yes, that is true						No, that is not true

2. Physically I feel only able to do a little

Yes, that is true						No, that is not true

3. I feel very active

Yes, that is true						No, that is not true

4. I feel like doing all sorts of nice things

Yes, that is true						No, that is not true

5. I feel tired

Yes, that is true						No, that is not true

6. I think I do a lot in a day

Yes, that is true						No, that is not true

7. When I am doing something, I can keep my thoughts on it

Yes, that is true ☐☐☐☐☐ No, that is not true

8. Physically I can take on a lot

Yes, that is true ☐☐☐☐☐ No, that is not true

9. I dread having to do things

Yes, that is true ☐☐☐☐☐ No, that is not true

10. I think I do very little in a day

Yes, that is true ☐☐☐☐☐ No, that is not true

11. I can concentrate well

Yes, that is true ☐☐☐☐☐ No, that is not true

12. I am rested

Yes, that is true ☐☐☐☐☐ No, that is not true

13. It takes a lot of effort to concentrate on things

Yes, that is true ☐☐☐☐☐ No, that is not true

14. Physically I feel I am in a bad condition

Yes, that is true ☐☐☐☐☐ No, that is not true

15. I have a lot of pain

Yes, that is true ☐☐☐☐☐ No, that is not true

16. I tire easily

Yes, that is true ☐☐☐☐☐ No, that is not true

17. I get little done

Yes, that is true ☐☐☐☐☐ No, that is not true

18. I don't feel like doing anything

Yes, that is true ☐☐☐☐☐ No, that is not true

19. My thoughts easily wander

Yes, that is true ☐☐☐☐☐ No, that is not true

20. Physically I feel I am in an excellent condition

Yes, that is true ☐☐☐☐☐ No, that is not true

8.5 Appendix E

Time–Motion Analysis Table Regarding Sprint Running in Team Sports

Table 8-1: Mean sprint running distance and duration performed during team sport match play, as recorded during time–motion analysis

Sport	Subject population (M/F)	Mean duration (s)	Mean distance (m)	Percentage of game time spent sprinting (%)	Reference
Australian Football League	Elite players (M)	2.0–2.6	15.0–23.2	0.6–1.0	Dawson et al. (2004)
Basketball	Elite players (M)	1.7	n/a	4.7	McInnes et al. (1995)
Hockey (field)	Elite players (M)	1.8	n/a	1.5	Spencer et al. (2004)
Hockey (field)	Elite players (F)	3.13	n/a	n/a	Lothian & Farrally (1994)
Rugby (Union)		2.3–3.3	14.5–23.6	0.3–1.3	Deutsch et al. (1998)
Rugby (Union)		2.0	n/a	2.0	Docherty et al. (1988)
Rugby (Union)	Elite players (M)	2.0–3.0	n/a	0.4–1.6	Duthie et al. (2005)
Rugby (touch)	Elite players (M)	n/a	10.14	n/a	Allen (1989)
Soccer	Elite players (M)	2.0	n/a	0.7	Bangsbo et al. (1991)
Soccer	Sub-elite (M)	n/a	15.7	n/a	Mohr et al. (2003)

8.6 Appendix F

Reliability Data presented Graphically

Figure 8-1: Test 1 and Test 2 sprinting time data for recorded to determine reliability for 11 female subjects (Y-axis). Times are reported at 5-m for all subjects.

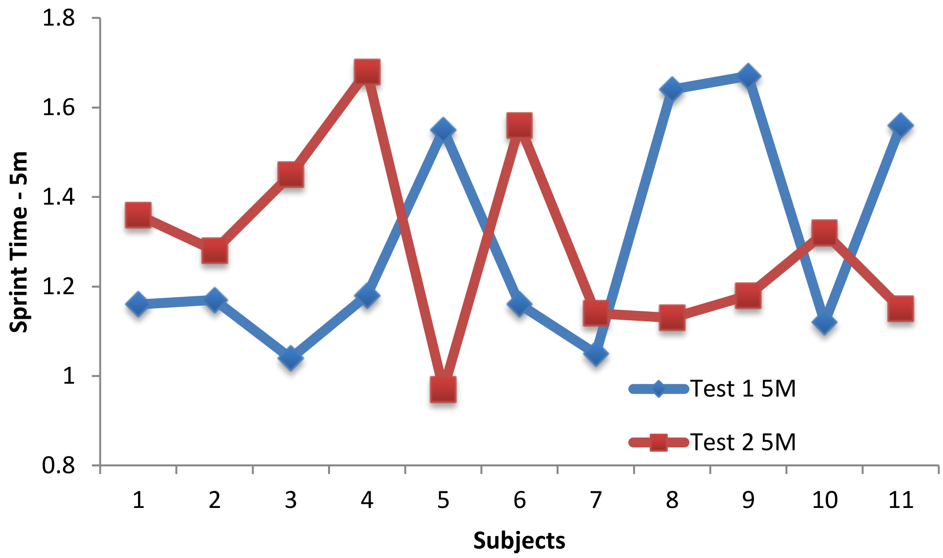

Figure 8-2: Test 1 and Test 2 sprinting time data for recorded to determine reliability for 11 female subjects (Y-axis). Times are reported at 10-m for all subjects.

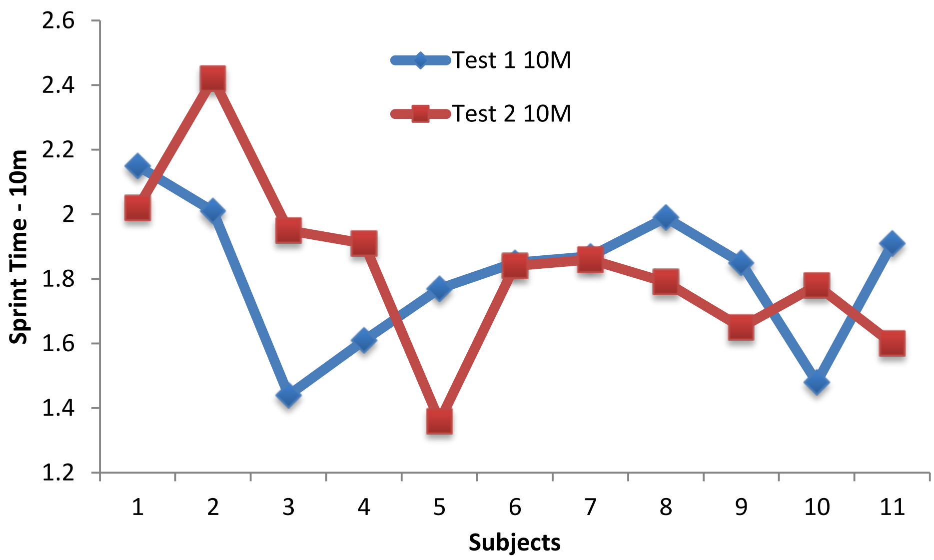

Figure 8-3: Test 1 and Test 2 sprinting time data for recorded to determine reliability for 11 female subjects (Y-axis). Times are reported at 20-m for all subjects.

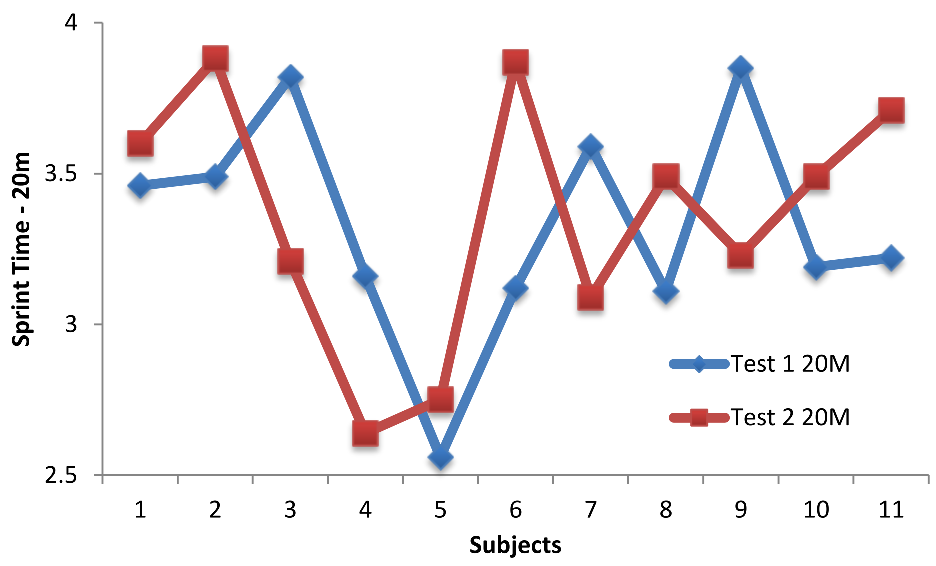

Figure 8-4: Test 1 and Test 2 sprinting time data for recorded to determine reliability for 11 female subjects (Y-axis). Times are reported at 30-m for all subjects.

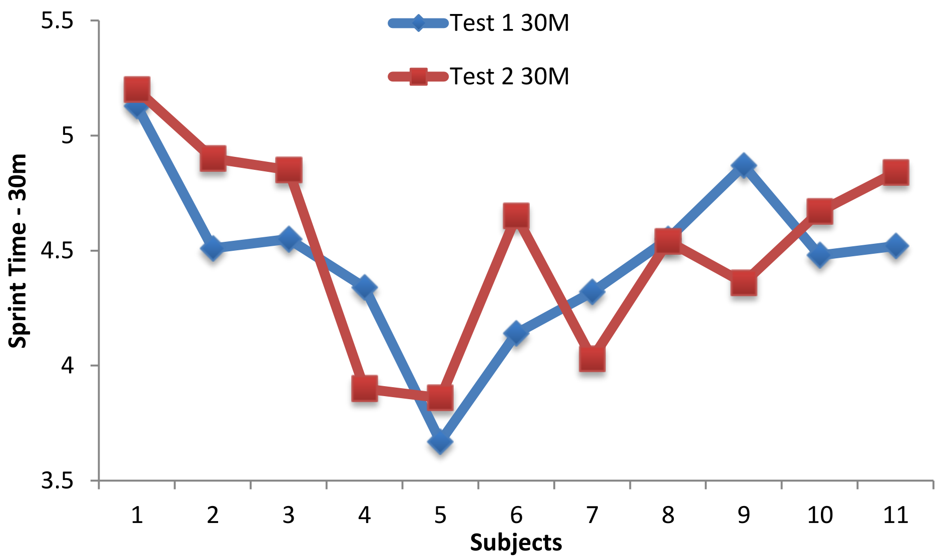

Figure 8-5: Test 1 and Test 2 sprinting time data for recorded to determine reliability for 11 female subjects (Y-axis). Times are reported at 40-m for all subjects.

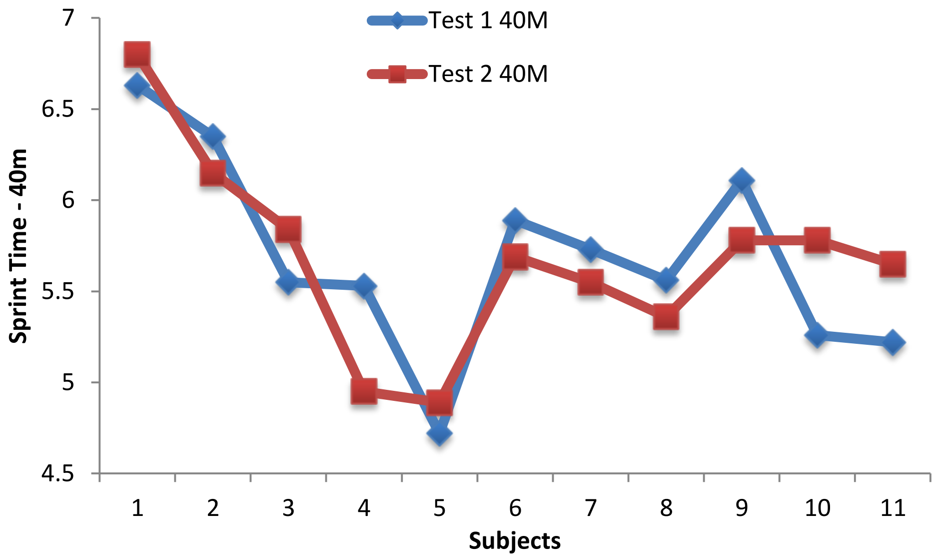

Figure 8-6: Test 1 and Test 2 muscle architecture data recorded for counter-movement jump (CMJ) to determine reliability for 11 female subjects (Y-axis). CMJ height is presented as cm.

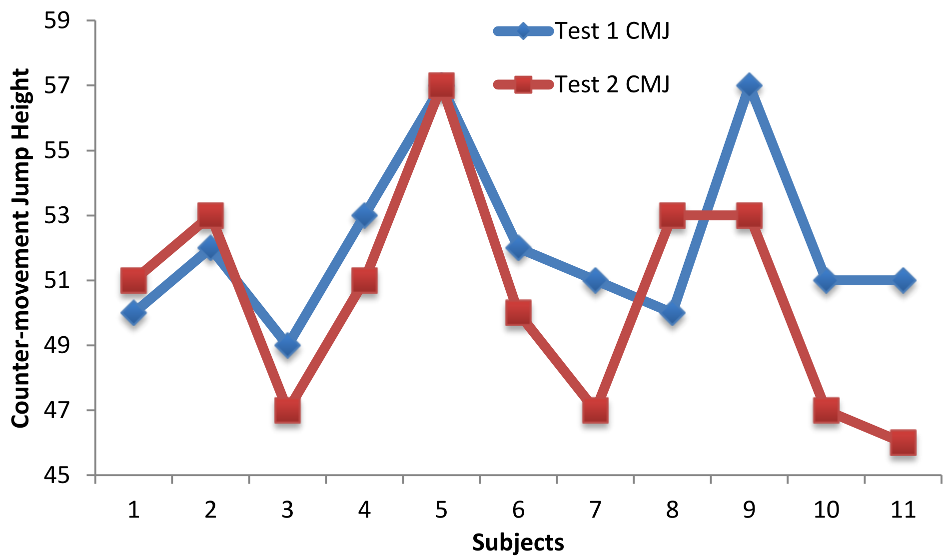

Figure 8-7: Test 1 and Test 2 muscle architecture data recorded for squat jump (SJ) to determine reliability for 11 female subjects (Y-axis). SJ height is presented as cm.

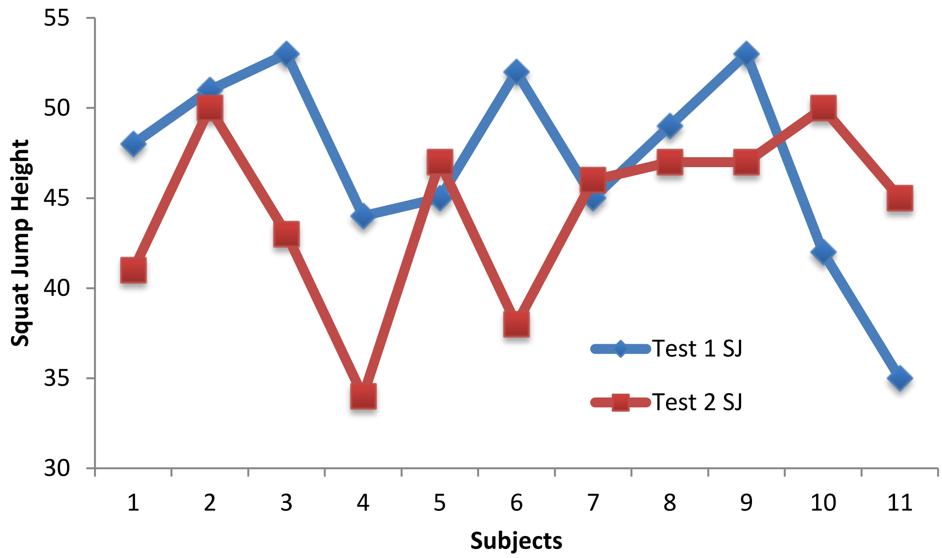

Figure 8-8: Test 1 and Test 2 muscle architecture data recorded to determine reliability for 11 female subjects (Y-axis). Fascicle length (FL) is presented as cm.

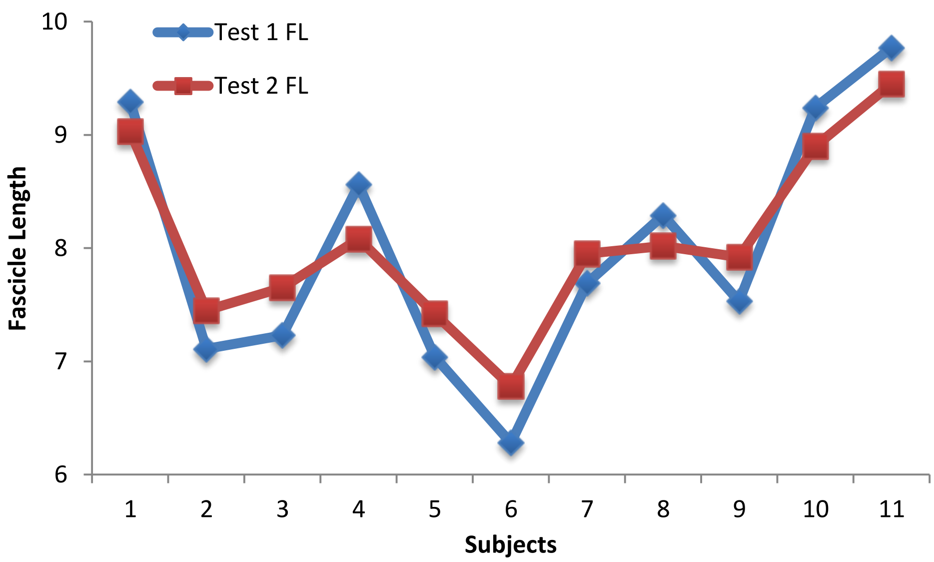

Figure 8-9: Test 1 and Test 2 muscle architecture data recorded to determine reliability for 11 female subjects (Y-axis). Angle of fascicle pennation (AP) is presented degrees (°).

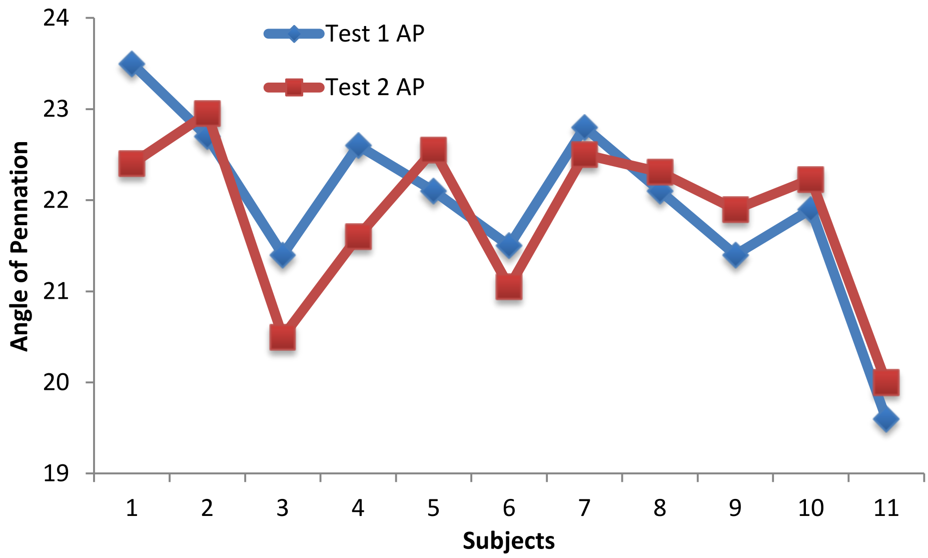

Figure 8-10: Test 1 and Test 2 drop jump data recorded to determine reliability for 11 female subjects (Y-axis). Reactive strength index is reported for DJ performed from 0.20m (RSI-20).

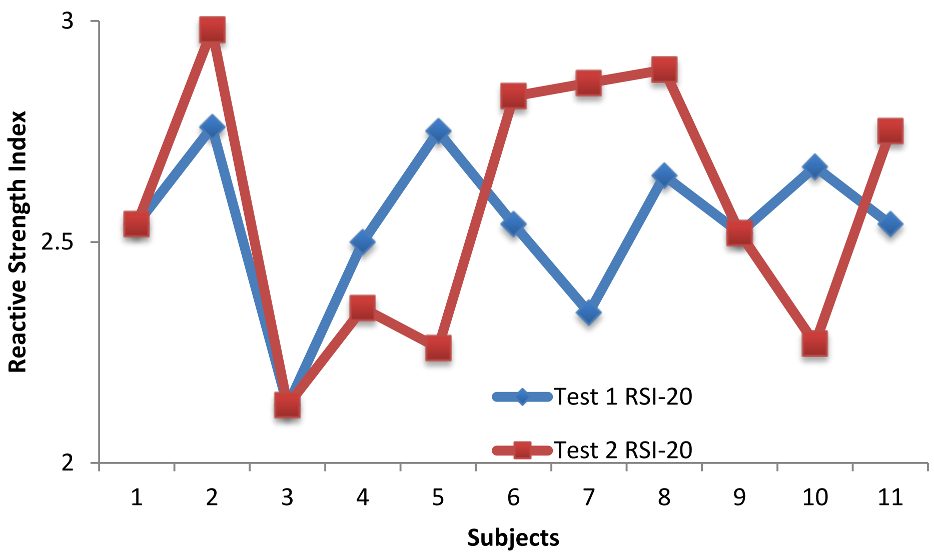

Figure 8-11: Test 1 and Test 2 drop jump data recorded to determine reliability for 11 female subjects (Y-axis). Reactive strength index is reported for DJ performed from 0.40m (RSI-40).