The relevance of calf muscle metrics and plyometric outcomes for athletic sprint performance

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Abstract

Introduction

Sprinting is a key performance marker in sports and involves the stretch-shortening cycle (SSC) of the lower limbs. The triceps surae or calf muscle complex is shown to be a key contributor to sprinting, but many calf function assessments used in athlete profiling do not fully consider the SSC. Similarly, lower-limb plyometric abilities are important for sprinting, but few studies explore how plyometrics in the horizontal and vertical axes relate to sprint performance. Therefore, we investigated the association between various calf metrics, single-leg plyometric outcomes, and sprint performances to determine which assessment metrics are the most relevant as athletic performance indicators.

Methods

Thirty active participants (14 male, 16 female) completed a test battery in two sessions that included 0-40 m maximum sprints; single-leg calf muscle isometric strength, power, and strength-endurance tests; and plyometrics in the vertical and horizontal axes. Sprint outcomes included maximal sprint acceleration (MSA, 0-10 m time), maximal sprint speed (MSS, 30-40 m time), and 0-40 m sprint time. Calf muscle metrics included single-leg seated and standing isometric strength (N), peak concentric power (W) from an eccentric-concentric task with an additional 30% body mass load, and total repetitions and positive work (J) from strength-endurance testing. Plyometric outcomes included vertical reactive strength index (RSI) and jump height (m) from a single-leg 30-cm drop jump, and two horizontal RSIs and total horizontal distance (m) from a forward triple hop for distance. Pearson correlation coefficients (*r*) were computed to assess the strength of relationships between sprints, calf, and plyometric measures. Significance was set to $p \leq 0.05$. Only significant values are presented in the results.

Results

Calf power showed *large* correlations with MSA ($r = -0.678$) and MSS ($r = -0.707$), as did total work during strength-endurance testing (MSA: $r = -0.588$; MSS: $r = -0.578$). Standing isometric calf strength was *largely* correlated to MSS ($r = -0.544$) and MSA ($r = -0.562$); whereas seated correlations were *moderate* (MSS: $r = -0.470$; MSA: $r = -0.459$).

Horizontal total distance ($r = -0.785$ to -0.694) and horizontal RSIs showed *large* correlations with MSA, MSS, and 40 m sprint times. Vertical RSI exhibited *moderate* correlations with MSA, MSS, and 40 m sprint times ($r = -0.422$ to -0.386). Vertical drop-jump height was not significantly related to any sprint metrics.

Plyometric outcomes within the same axes were *largely* interrelated, with only the vertical RSI exhibiting a *moderate* relationship to horizontal RSI2 ($r = 0.366$) and horizontal total distance ($r = 0.407$). The only *large* correlation between plyometric and calf metrics was between horizontal total distance and calf power ($r = 0.628$). Horizontal total distance *moderately* correlated with all other calf metrics ($r = 0.487$ to 0.381). Seated isometric strength *moderately* related to vertical plyometric outcomes ($r = 0.411$ to 0.447).

Conclusion

The calf power test was the most strongly associated calf metric to sprint performances, and horizontal total distance was the most strongly associated plyometric outcome to sprint performances. Both tests are easy to implement in practice and could be used as a maximal sprint acceleration and speed performance indicator. Future research should explore whether a causal relationship exists and explore the relevance of outcomes to high performance sports and rehabilitation.

Key words

Athlete testing, biomechanics, muscle strength, plyometrics, power, speed, strength-endurance, triceps surae.

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List of abbreviations

CRT – Calf raise test

CV – Coefficient of variation

ICC – Intraclass correlation coefficient

MSA – Maximum sprint acceleration

MSS – Maximum sprint speed

MTU – Muscle-tendon unit

SSC - Stretch-shortening cycle

TE – Typical error

Thesis overview

The main aim of this thesis was to establish the potential association between calf isometric strength, power, and strength-endurance metrics; vertical and horizontal plyometrics; and maximal acceleration, maximal speed, and sprint time derived from a 40 m sprint task. Secondly, we aimed to explore the interrelatedness between calf metrics and between plyometric outcomes and compare seated and standing isometric calf muscle strength metrics. This thesis consists of four chapters (Figure 1), with chapters two and three prepared for submission to peer-reviewed journals. Given this format, there may be some repetition between chapters. Chapter one introduces and outlines literature on the triceps surae muscle-tendon unit and calf muscle function. This chapter also provides an overview of testing methods used to assess the calf muscles, sprints, and plyometrics and how testing outcomes relate to athletic abilities. Chapter one concludes with the research statement for this thesis.

Chapter two is an observational cross-sectional study with repeated measures. The main aim of chapter two was to explore the association between calf isometric strength, power, and strength-endurance metrics with maximal sprint acceleration, maximal sprint speed, and sprint time derived from a 40 m sprint. We also sought to explore the existence of a potential relationship between seated and standing isometric strength and other calf muscle test metrics. Finally, this chapter also assessed the test-retest reliability of sprint outcomes performed on different days.

Chapter three is also an observational cross-sectional study with repeated measures. The primary aim of chapter three was to explore the potential association between single-leg plyometric outcomes on the horizontal and vertical axes with maximal sprint acceleration, maximal sprint speed, and total sprint time derived from a 40 m sprint task. The secondary aims of this chapter were to explore the interrelatedness of plyometrics outcomes, and the relationship between calf muscle metrics and plyometric outcomes.

Chapter four summarises the key findings, limitations, and strengths of the two experimental chapters of this thesis. It also addresses potential directions for future research.

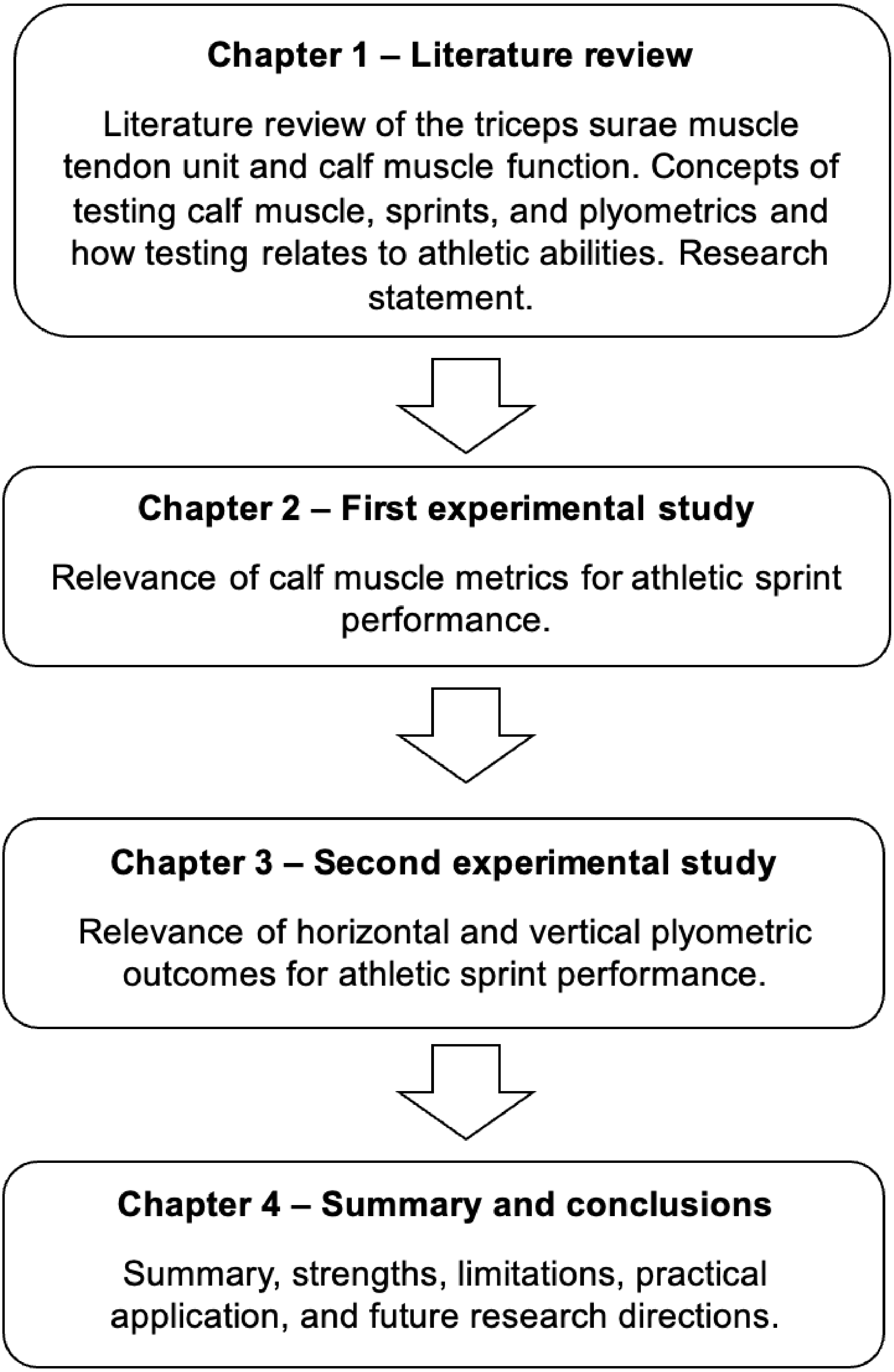

Figure 1. Flow diagram of the structure of this thesis.

Chapter 1 – Literature review

Triceps surae muscle-tendon unit

The triceps surae muscles are commonly known as the calf muscles and have been described as a relatively complex muscle group (Lee et al., 2023). The calf muscles are on the posterior aspect of the lower-limb, comprising of the gastrocnemius medialis, gastrocnemius lateralis, and soleus, which produce the majority of the plantarflexion forces needed for upright movement (Lee et al., 2023). The muscles share a common distal insertion onto the calcaneus via the Achilles tendon (Standring, 2016). The Achilles tendon is known to be the strongest and largest tendon in the human body and can accommodate very high force during exercise, but it is also one of the most commonly injured tendons (Cristi-Sánchez et al., 2019; Griffin et al., 2021). Indeed, the triceps surae muscle-tendon unit (MTU) is of considerable interest and concern in sports medicine as it is often a source of injuries in athletes, such as Achilles tendinopathies, Achilles tendon ruptures, and calf muscle strains (Cristi-Sánchez et al., 2019; O'Neill et al., 2023).

During functional activities and sports, the triceps surae MTU often relies on the stretch-shortening cycle (SSC). The SSC is described as an eccentric (lengthening) muscle action, immediately followed by a concentric (shortening) muscle action (Komi, 2000). The SSC ultimately enhances the contractile performance of the triceps surae MTU (Seiberl et al., 2021). The lengthening of the triceps surae MTU during the eccentric phase of the SSC facilitates force production during the subsequent concentric phase. The SSC impacts numerous lower-limb functions, including strength, endurance, flexibility, and motor control (Seiberl et al., 2021).

Triceps surae muscle function

The lower limbs are considerably involved in multidirectional, running-based sports and important to optimise performance. The triceps surae muscles are key contributors to dynamic maximum strength (Keiner et al., 2021), as well as short acceleration and sprint performances (Möck et al., 2018). Muscle power development is considered a key performance marker for sports performance and protection from lower-limb injuries (Green et al., 2022; Silbernagel et al., 2006), although triceps surae muscle power is not often assessed in athletes or during rehabilitation. From an injury perspective, it has been documented that 30-50% of all sporting injuries are related to overuse tendon disorders (Cristi-Sánchez et al., 2019; Smith & Sands, 2007; Tschopp & Brunner, 2017). While calf and lower-limb injuries are common across sports, a shortage of research regarding best practice for assessment, management, and prevention of these injuries has been identified (Green et al., 2022). To address this research gap, there is a need to firstly understand the specific function of the triceps surae muscles in athletes, establish benchmark values, and explore relevant clinical applications.

Triceps surae muscle testing

Testing of the triceps surae complex is common in practice, with the information gained being useful to inform strength and conditioning (Hébert-Losier et al., 2022) and rehabilitation programmes (Silbernagel et al., 2006). Strength, endurance, and power are some of the functional properties of interest in an athletic context (Ferna Ortega et al., 2022) and are important domains in the return-to-sport decision-making process following injury (Schwank et al., 2022). Testing of the triceps surae muscles should have a practical and user-friendly clinical application, justification, and benefit, and should encourage a common language amongst researchers and clinicians (Hébert-Losier et al., 2009). Testing of calf function in a capacity to improve performance and to inform return to play has often relied on isometric testing of calf strength due to the reported relative ease to implement with low injury risk to participants (Grgic et al., 2022; O'Neill et al., 2023). Whilst the clinical importance of calf muscle function is recognised, there is a variety of testing methods beyond isometric (O'Neill et al., 2019) and several parameters to consider (e.g., ankle and knee position) (Hébert-Losier et al., 2009), resulting in an overall lack of standardised test batteries used to inform practice, despite it’s importance for research translation and evidence-based practice.

The measurement of speed and velocity is important in sports analysis and human movement studies (Harrison et al., 2005). Modelling approaches indicate relatively high contributions of the triceps surae muscles to athletic tasks, i.e., up to 12 x body weight during the sprint acceleration phase (Dorn et al., 2012; Pandy et al., 2021; Schache et al., 2019; Werkhausen et al., 2017). However, there is a paucity of experimental studies supporting the existence of a relationship between calf muscle measures and sporting abilities. The available studies on the topic identify *moderate* to *large* significant correlations between one-repetition maximum calf strength and sprint section times over 30 metres (Möck et al., 2018), in addition to calf strength-endurance and power metrics to sprint times over 10 metres (Hébert-Losier, Ngawhika, et al., 2023). Together, these studies indicate that dynamic measures of calf muscle strength, strength-endurance, and power are all potentially useful indicators of acceleration and short-sprint abilities in active individuals. It would be helpful for one study to comprehensively examine the various functional abilities of the calf muscles in relation to acceleration and sprint abilities to better inform athletes and practitioners working in sports that rely on explosive sprint performances for successful outcomes. It is unclear whether isometric testing of the triceps surae muscles would exhibit similar levels of association to sprint performances than the more dynamic measures of calf function.

The diversity of demands placed on the triceps surae MTU between sporting codes means a universal injury prevention programme for the calf is not possible (Green et al., 2022). In sport, it should be questioned as to whether current test measures are serving their intended purpose. For the triceps surae muscles, it becomes relevant to understand whether calf metrics relate to sport performance outcomes. In presence of injury, a multi-faceted approach to testing of lower-limb function may benefit rehabilitation and seek to include strength, power, reactive strength, linear running, and multi-directional running measures (Griffin et al., 2021).

Isometric testing

One of the most common calf muscle testing methods implemented in practice and recent research is isometric testing (Leabeater et al., 2023; Leckie et al., 2023; O'Neill et al., 2023; Rhodes et al., 2022). Isometric testing involves strength testing of a muscle group with no significant change in muscle length or joint position (Douglas et al., 2017).

Isometric testing can be conducted using isokinetic dynamometers, handheld dynamometers, or force plates where muscle strength is measured with joints in a fixed position. Isometric calf testing is often performed with the knee flexed to 90° (Leabeater et al., 2023; Lee et al., 2023; O'Neill et al., 2019; O'Neill et al., 2023) or straight (Hébert-Losier et al., 2011; Keiner et al., 2021; Mattiussi et al., 2022). Given the force-length relationship and anatomical configuration of the calf muscles (Kawakami et al., 1998), the flexed knee position places the gastrocnemii muscles in active insufficiency and enhances the relative contribution of the soleus muscle to plantarflexion output (Cresswell et al., 1995). It is unclear how comparable or related isometric seated (90° knee flexion) and standing (0° knee flexion) calf muscle strength measures are, and which is more strongly related to athletic and functional abilities. Furthermore, isometric strength testing does not involve the SSC, which is the functional combination of eccentric and concentric actions involved during locomotive and dynamic tasks (Komi, 2000).

When the knee is in a flexed position, it places the gastrocnemii muscles at mechanical disadvantage, but the soleus produces similar forces regardless of knee flexion position (Cresswell et al., 1995). The soleus is one of the main contributors to walking and running, with the musculotendon forces reaching around 8 x body weight for the soleus and 3 x body weight for the gastrocnemii muscles during running (Dorn et al., 2012). Soleus injuries are more prevalent than gastrocnemius ones in long distance running, Australian Football, and football (soccer) due to volume of workloads, whereas gastrocnemius injuries are more common in rugby, basketball, and sprint distance running due to increased intensity of activities (Green et al., 2022). It hence appears important to consider (and potentially compare) knee position when assessing the calf muscles and appreciate the extent of altered force production in the shortened state of the gastrocnemius.

Whilst calf strengthening has been described to be a cornerstone of building muscle capacity and resilience (McMaster et al., 2014), there is sparse recent literature which defines the relevance of isometric calf testing for athletic performance. There are no studies to our knowledge that has compared seated and standing calf isometric outcomes and their relevance for sprint performance.

Strength-endurance testing

When it comes to performance outcomes in sport, isometric testing in isolation does not fully assess the dynamic properties or SSC abilities of the triceps surae MTU (Green et al., 2022; Lee et al., 2023; O'Neill et al., 2023). While isometric testing can provide an indication of maximal strength, there are shortcomings of strength alone to protect against calf muscle injuries relating to longer or repeated exposures of force. Often, experts in rehabilitation encourage integrating single-leg calf raises for endurance as soon as possible in rehabilitation to restore a foundation of muscle capacity, including in the rehabilitation of Achilles tendinopathy (Green et al., 2022; Lee et al., 2023; Silbernagel et al., 2006).

The calf raise test (CRT) involves repetitive concentric–eccentric muscle action of the plantarflexors and is used in clinical assessment and rehabilitation (Hébert-Losier et al., 2009). The main clinical outcome for the CRT is the number of repetitions completed, but this metric is not as sensitive to triceps surae MTU deficiencies as the peak height reached and total work completed during the test (Fernandez et al., 2023; Fernandez & Hebert-Losier, 2023; Silbernagel et al., 2010). The recently developed Calf Raise application is considered a valid and reliable tool for measuring CRT outcomes (including repetitions, peak height, and work), and provides a tool to align outcomes in research and practice (Fernandez et al., 2023). It also allows the valid and reliable calculation of peak power (Hébert-Losier et al., 2022). It provides a practical and affordable alternative to more expensive laboratory-based methods for the assessment of calf test outcomes, which would typically rely on 3D motion capture, linear position transducers, and force plates.

Power testing

Sport-related strength qualities of the calf, such as power, have been found to be relevant in athletes (Green et al., 2022; Hébert-Losier, Ngawhika, et al., 2023). Recommendations from research suggest that more than just endurance capacity of the calf muscles should be assessed in presence of Achilles tendinopathy (McAuliffe et al., 2019), with the same likely true in athletes based on their sport requirements. A group of experts recommended that dynamic calf exercises involving predominantly vertical actions, followed by exercises involving greater horizontal, lengthening, and stiffness demands would encourage use of the SSC in a graded fashion (Green et al., 2022), appropriate for rehabilitation. These same exercises may serve as graded tests in sports medicine and strength and conditioning to inform practice.

Calf power has been tested using a linear position transducer (Silbernagel et al., 2006) and the Calf Raise application (Hébert-Losier, Ngawhika, et al., 2023) while completing an eccentric-concentric movement in single-leg stance as quickly as possible. Unweighted and weighted calf power tests have been used in research (Hébert-Losier et al., 2022; Silbernagel et al., 2006), and suggested in rehabilitation of injured patients to enhance SSC abilities and build sport-specific exercise tolerance (Green et al., 2022). It has also been suggested that further research should consider implementing a relative load (e.g., percentage of body mass) to provide potentially more meaningful outcomes than using an absolute load when assessing power (Hébert-Losier et al., 2022).

Power assessments can be used to inform strength and conditioning programmes to optimise performance and assist in monitoring player status in-season (Hébert-Losier et al., 2022). Calf muscle power has been found to be the measure that correlates *largely* with 10 m sprint times in semi-professional rugby players (Hébert-Losier, Ngawhika, et al., 2023), indicating benefit in assessing a more dynamic and explosive calf muscle function when dealing with athletic performance.

Triceps surae and sprints

Lower body power is deemed an important characteristic in team sport athletes amongst clinicians, coaches, athletes, and sports therapist alike (Hébert-Losier et al., 2022). More specifically, fundamental knowledge of lower-limb muscle function during maximum acceleration sprinting is of interest to coaches looking to maximise sprint performance in elite athletes, as well as sports clinicians with a focus on improving injury prevention and rehabilitation practices (Pandy et al., 2021).

Sprinting has been described as a fundamental result-relevant movement for many sports (Möck et al., 2018). The plantarflexors have been found to play a critical role in sprinting performance, notably for accelerating rapidly (Möck et al., 2018; Pandy et al., 2021). There is, however, limited published literature exploring the relationship between plantarflexion abilities and sprint performance.

The available studies on the topic identify *moderate* to *large* significant correlations between one-repetition maximal calf strength and sprint section times over 30 m

(Möck et al., 2018); as well as between calf strength-endurance and power metrics and sprint times over 10 m (Hébert-Losier, Ngawhika, et al., 2023). Together, these studies indicate that calf muscle strength, strength-endurance, and power are all potentially useful indicators of acceleration and short-sprint abilities. It would be beneficial for one study to comprehensively examine the various functional abilities of the calf muscles in relation to acceleration and sprint abilities to better inform athletes and practitioners working in sports that rely on explosive sprint performances for successful outcomes.

Sprinting speed and acceleration

Sprinting is identified as a critical element to various sports (Buchheit et al., 2012; Haugen et al., 2014; Johnston & Gabbett, 2011; Young et al., 2008), and is therefore often assessed in athletes as a marker of sports performance. Sprinting demands a unique combination of explosive power, rapid force development, and efficient energy transfer using the SSC of lower-limb muscles (Mero et al., 1992).

Short sprint performances are often used as assessments in team-sport athletes as it is believed to be an important component to on-field performance (Gabbett, 2012; Girard et al., 2011; Haugen et al., 2019; Haugen et al., 2014; Taylor et al., 2017). These studies use various ways to quantify maximal sprint speed (MSS) and maximal sprint acceleration (MSA). Both are relevant motor tasks and athletic demands in many individual and team sports (Gabbett, 2012; Girard et al., 2011; Haugen et al., 2019; Haugen et al., 2014; Taylor et al., 2017). One approach is to use the initial 10 m and final 10 m sections of a 40 m sprint as representation of MSA and MSS abilities, respectively (Buchheit et al., 2012; Mero et al., 1992). Given the different demands of MSA and MSS, it becomes relevant to consider how various calf muscle performance measures relate to these specific sprint properties.

Triceps surae and plyometric testing

Plyometrics are movements characterised by rapid and powerful muscle contractions (Markovic & Mikulic, 2010) and are often performed with minimal or no equipment (Pardos-Mainer et al., 2021). Lower-limb plyometrics often refer to jumping, bounding, and hopping (Davies et al., 2015), and typically rely on the SSC where there are rapid eccentric contractions immediately followed by concentric contractions (Brink et al., 2022).

Lower-limb plyometric exercises have been found to elicit adaptations associated with improving the elastic function of the triceps surae MTU (Asadi et al., 2015; Chelly et al., 2014; De Villarreal et al., 2008; Seiberl et al., 2021) largely due to their reliance on the SSC. Indeed, plyometric exercises considerably load the triceps surae MTU and require use of the SSC (Baxter et al., 2021; Griffin et al., 2021; Silbernagel et al., 2006). A practical Achilles tendon loading index that considers peak loading, loading impulse, and loading rate has been developed and used to rate the Achilles tendon load of various tasks (Baxter et al., 2021). This index can also be useful in selecting tasks to assess the dynamic function of the triceps surae MTU in the context of sports performance and return to play (Baxter et al., 2021). Based on this study, single-leg movements involve a higher triceps surae MTU loading rate than double-leg movements, and movements of a cyclical nature that involve the SSC have a higher peak loading than non-cyclical movements (e.g., a seated heel raise is non-cyclical and is lower on the loading index in comparison to rebounding heel raises which are cyclical in nature). Figure 2 presents a summary of findings from Baxter et al. (2021), including the exercises which were used and the extent of their loading on the triceps surae MTU.

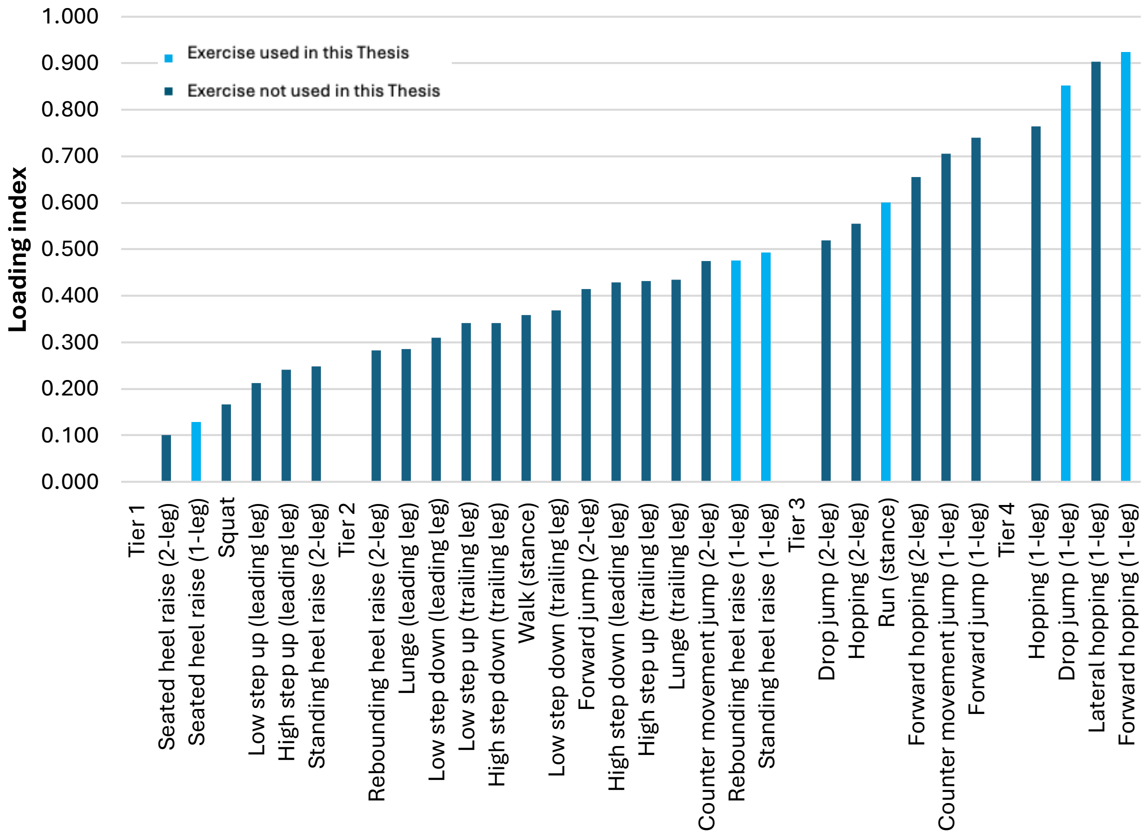

Figure 2. Achilles tendon loading index of different exercises adapted from Baxter et al. (2021).

Plyometrics can be performed in different planes of movement, horizontal or vertical, which results in different Achilles tendon loading indexes (Figure 2) and different loading planes. Although studies support the importance of horizontal and vertical plyometric training for sprint performance (Baca, 1999; Baena-Marin et al., 2022; Barker et al., 2018; Comyns et al., 2023; De Villarreal et al., 2008; Dorn et al., 2012; Hamner & Delp, 2013; Ramírez-Campillo et al., 2015), there is minimal literature exploring the relationship of plyometric-related measures between the two axes and their relation to athletic abilities. Furthermore, how various triceps surae MTU performance measures relate to plyometric measures remains unclear.

Plyometric measures

Reactive strength index (RSI) is a measure used in strength and conditioning and sport science to quantify SSC ability during plyometric-like tasks. Although there are different ways to calculate RSI, a reliable way is to divide flight time by ground contact time (Flanagan & Comyns, 2008; Healy et al., 2018). RSI is a measure which can be considered alongside other performance measures, such as maximal height jumped in the vertical axis and total distance hopped in the horizontal axis.

Vertical jump tests, specifically drop jump tests, are often used to assess lower-limb power and SSC ability in sport. Outcomes from these jumps have been shown to correlate with lower body strength and sprint performance (Barker et al., 2018; Lem et al., 2022; Maulder & Cronin, 2005; Mueske et al., 2018). Similarly, peak force from a horizontal drop jump test has been strongly associated with 30 m sprint performances as well as gastrocnemius lateralis muscle thickness (Dobbs et al., 2015), but the relationship between the calf muscle complex and plyometric testing has not been fully explored.

Vertical plyometric training is often associated with improved sprint times (Beato et al., 2018; Chelly et al., 2014; Chelly et al., 2015; De Villarreal et al., 2008; Lockie et al., 2014), with previous research identifying a *large* relationship ($r = -0.58$, $p \leq 0.01$) between drop jump rebound height and 20-m linear sprint outcomes (Schuster & Jones, 2016). Similarly, previous studies have found significant correlations between single-leg horizontal plyometrics and sprint acceleration measures ($r = -0.48$, $p < 0.001$) (Lin et al., 2023). While vertical and horizontal plyometrics have been used in studies to identify different muscle qualities and functional abilities (Maulder & Cronin, 2005), the association between vertical and horizontal plyometric measures and various sprint outcomes has not been widely explored.

Research statement

From the literature reviewed, there are knowledge gaps relating to triceps surae MTU testing measures and their overall relationship with athletic abilities, specifically sprinting and plyometric outcomes. There are numerous methods available to assess triceps surae muscle abilities and possibility for a multi-faceted testing approach, including isometric, power, and strength-endurance testing. Although there is substantial literature on the reliability of calf test methods (Al-Uzri et al., 2017; Argus et al., 2011; Chester et al., 2003; Fernandez et al., 2023; Hébert-Losier et al., 2022) there is limited empirical evidence relating calf outcomes to sports performance data, specifically sprint and plyometric outcomes. There are few studies exploring the association between the vertical and horizontal axes of plyometric assessments and their relationship to sprint performance.

With the above knowledge, the aims of this thesis were to explore the potential association between calf metrics (isometric strength, power, and strength-endurance) with MSA, MSS, and overall sprint time from a 40 m sprint task, and then to investigate the potential association between single-leg plyometric outcomes on the vertical and horizontal axes with these sprint performance measures. The thesis also aimed to examine the relationship between seated and standing calf muscle isometric strength, vertical and horizonal plyometric outcomes, and calf muscle and plyometric outcomes. Lastly, the test-retest reliability of sprint outcomes was explored.

We hypothesised that calf muscle power would exhibit a stronger relationship to MSA and MSS than isometric strength and strength-endurance metrics due to the involvement of the SSC and greater task specificity. We also expected standing isometric strength to be more strongly related to sprint outcomes than seated isometric strength due to greater functional relevance of the position. We expected a high degree of relatedness between calf muscle metrics, and excellent test-retest reliability of sprint measures.

We hypothesised that horizontal plyometric outcomes would be more strongly related to sprint metrics than vertical plyometric outcomes and this is due to similarity in muscular force production and task specificity (Samozino et al., 2022). We also expected *large* correlations between measures from the two plyometric axes, and between calf muscle metrics and plyometric outcomes as found by previous research (Warneke et al., 2022).

The information derived from this thesis may be beneficial to sport in establishing injury prevention, rehabilitation, and training strategies, as well as in talent identification, athlete monitoring, and benchmarking. The results may help answer the question: “To what extent does the triceps surae muscle complex relate to athletic sprint performance and plyometric outcomes?”. The findings from this research are believed relevant to researchers, clinicians, sports medicine teams, strength and conditioning practitioners, coaching staff, and athletes across many sports.

Chapter 2 – First experimental study

Relevance of calf muscle metrics for athletic sprint performance.

Abstract

Introduction

The seated isometric calf test is used to assess calf function in athletes, but it does not fully consider the muscle’s stretch-shortening cycle required for sports. Further, this limits gastrocnemius force production and functional relevance of the test to running and sprinting where gastrocnemius and soleus are involved. Therefore, we investigated the association between various calf test metrics and sprint performance outcomes to determine which calf metric is the most relevant to running and sprinting.

Methods

Thirty active participants (14 male, 16 female) completed a test battery of single-leg strength, power, strength-endurance calf tests, and 0-40 m maximum sprints. Sprint outcomes included maximal sprint acceleration (MSA, 0-10 m time), speed (MSS, 30-40 m time) and 0-40 m overall time. Calf muscle metrics included seated and standing isometric strength (N), peak eccentric-concentric reactive power under 20% body mass load (W), and total repetitions and work from strength-endurance testing. Pearson correlation coefficients were computed to assess the relationship between calf metrics and sprint outcomes.

Results

Peak power showed *large* correlations with MSA ($r = -0.678$, $p < 0.001$) and MSS ($r = -0.707$, $p < 0.001$), as did total work during strength-endurance testing (MSA: $r = -0.588$, MSS: $r = -0.578$, both $p < 0.001$). Peak force in the standing isometric calf test was *largely* correlated to MSS ($r = -0.544$, $p = 0.002$) and MSA ($r = -0.562$, $p = 0.001$); whereas in seated, correlations were *moderate* (MSS: $r = -0.470$, $p = 0.009$; MSA: $r = -0.459$, $p = 0.011$).

Conclusions

The power test was the most strongly associated calf metric to sprint outcomes. This test is easy to implement and could be used in team-sport athletes as a maximal sprint acceleration and speed performance indicator. Our findings emphasise that when completing the strength-endurance calf test, total work should be considered rather than repetitions as the former is more representative of function, congruent with research in Achilles tendinopathy patients. When completing isometric calf testing, standing is more strongly linked to sprinting ability than seated.

Key words

Athlete testing, biomechanics, muscle strength, power, speed, strength-endurance, triceps surae.

Introduction

The triceps surae muscles, commonly referred to as the calf muscles, are key contributors to dynamic maximum strength (Keiner et al., 2021) along with acceleration and sprint performance (Möck et al., 2018). Testing of this muscle group is common in practice, with the information gained useful to inform strength and conditioning (Hébert-Losier et al., 2022) and rehabilitation programmes (Silbernagel et al., 2006). Strength, endurance, and power are some of the functional properties of interest in an athletic context (Ferna Ortega et al., 2022) and are important domains in the return-to-sport decision-making process following injury (Schwank et al., 2022). Rugby expert sports clinicians agree that adequate levels of strength are required to maximise explosive on-field performance as well as to protect against calf injuries in rugby (Green et al., 2022). Whilst the clinical importance of calf muscle function is recognised, there are various testing methods (e.g., isometric and isokinetic) (O'Neill et al., 2019) and parameters (e.g., ankle and knee position) (Hébert-Losier et al., 2009) used, resulting in a lack of standardised test batteries to inform practice.

One of the most common calf muscle testing methods used in sport and research is isometric testing (Leabeater et al., 2023; Leckie et al., 2023; O'Neill et al., 2023; Rhodes et al., 2022). This can be performed with either the knee flexed to 90° (Leabeater et al., 2023; Lee et al., 2023; O'Neill et al., 2019; O'Neill et al., 2023) or straight (Hébert-Losier et al., 2011; Keiner et al., 2021; Mattiussi et al., 2022). Given the force-length relationship and anatomical configuration of the calf muscles (Kawakami et al., 1998), the flexed knee position places the gastrocnemius in active insufficiency and enhances the relative contribution of the soleus to plantarflexion output (Cresswell et al., 1995). It is unclear how comparable or related isometric seated (90° knee flexion) and standing (0° knee flexion) calf muscle strength measures are to each other, and which knee flexion angle is more strongly related to athletic and functional abilities. Furthermore, isometric strength testing does not involve the stretch-shortening cycle, defined as the functional combination of eccentric and concentric actions involved during locomotive and dynamic tasks (Komi, 2000). James et al. (2023) reported an absence of agreement and proportionality between isometric and dynamic strength measures, evidencing that these two forms of strength represent separate neuromuscular domains. Similarly, metrics from strength-endurance testing of the calf muscles only explain up to 41.8% of the variance in power metrics measured in athletes (Hébert-Losier, Ngawhika, et al., 2023). Clinicians, therefore, need to either select a battery of tests to fully encapsulate the various functional properties of the calf muscles or select a single test that best reflects the sporting load or specific athletic ability of interest to inform their practice.

Modelling approaches indicate relatively high contributions of the calf muscles to athletic tasks (i.e., up to 12 x body weight during the sprint acceleration phase) (Dorn et al., 2012; Pandy et al., 2021; Schache et al., 2019; Werkhausen et al., 2017). However, there are only a few experimental studies supporting the existence of a relationship between calf muscle measures and sporting abilities. The available studies on the topic identify *moderate* to *large* significant correlations between one repetition maximum calf strength and sprint section times over 30 metres (Möck et al., 2018), as well as calf strength-endurance and power metrics and sprint times over 10 metres (Hébert-Losier, Ngawhika, et al., 2023). Together, these studies indicated that calf muscle strength, strength-endurance, and power may all potentially be useful indicators of acceleration and short-sprint abilities. It would be helpful for one study to comprehensively examine the various functional abilities of the calf muscles in relation to acceleration and sprint abilities to better inform athletes and practitioners working in sports that rely on explosive sprint performances for successful outcomes. For example, if isometric testing is strongly related to acceleration abilities, sprint performances, and other calf muscle abilities, this form of testing could be recommended and would allow a quick assessment of calf muscle function in sports.

We aimed to explore the potential association between calf isometric strength, power, and strength-endurance metrics with maximal acceleration and speed derived from a 40 metre sprint task. We also aimed to explore the interrelatedness between calf metrics including a comparison between seated and standing isometrics. Furthermore, as the sprint tests were performed on two different days, an additional aim was to examine the test-retest reliability of sprint outcomes. We hypothesised that standing isometric strength would more strongly relate to acceleration and sprint times than seated isometric strength, with calf muscle power more strongly relating to acceleration and sprint times than isometric strength and strength-endurance metrics due to the involvement of the stretch-shortening cycle and greater task specificity. We anticipated significant interrelatedness between calf muscle metrics, and excellent test-retest reliability of sprint measures.

Methods

Research design

An observational cross-sectional study design with repeated measures was used to examine the correlation between calf metrics and sprint times, and within calf metrics. Given the participants would be completing 10 calf tests as well as sprints, participants were tested on two separate occasions to mitigate the risk of fatigue and calf injury. On the first occasion, participants completed 40 m sprints, followed by isometric calf muscle strength testing in seated and standing (in a random order). On the second occasion, 4-weeks later, participants completed calf muscle power and strength-endurance testing. A subset of individuals completed a third session, 10 days later, to reassess 40 m sprint times, providing data to determine test-retest reliability of sprint times (see Figure 3).

Participants

The research was carried out in line with the Declaration of Helsinki and was approved by the Human Research Ethics Committee of the University of Waikato [HREC(Health)#2017-54]. Sample size was based on previous research by Möck et al. (2018), which identified *large* correlations between one repetition maximum calf strength and 30 m sprint times. On this basis, twenty-nine participants were required to detect a *large* correlation ($r = 0.50$) at a 5% significance level with 80% power. Inclusion criteria involved a willingness to provide written informed consent and being physically 'active', determined using a validated 6-point Likert scale (Grimby, 1986; Grimby & Frändin, 2018). Participants that scored 3 (light physical exercise around 2-4 h per week) or less on this scale were excluded as deemed not reflective of the target population. Participants with a current or recent (<3 months) lower-limb or lower back injury were excluded due to risk of injury/reinjury. Potential participants were informed of the potential risks (i.e., delayed onset muscle soreness and potential injury due to the maximal efforts required) and benefits (i.e., individualised performance reports) of study participation.

Fifty-two university students from the University of Waikato studying Health, Sport and Human Performance were recruited through word-of-mouth, with thirty individuals (16 females, 14 males) meeting inclusion, agreeing to participate, and completing the two first testing sessions (see Figure 3B). Most of them (73.3%) participated in team sports, and 96.6% in sports that involved plyometric or sprint training. The mean and standard deviation (SD) values for age, body mass, and height of participants are shown in Table 1. A subset of the 30 participants (*n* = 19, 70%) agreed to participate in the 40 metre sprint test-retest reliability portion of the study, which involved a third day of testing. The reliability testing was completed under similar conditions as the first round of sprint testing, including the same time of day (Pullinger et al., 2020), test method, and footwear.

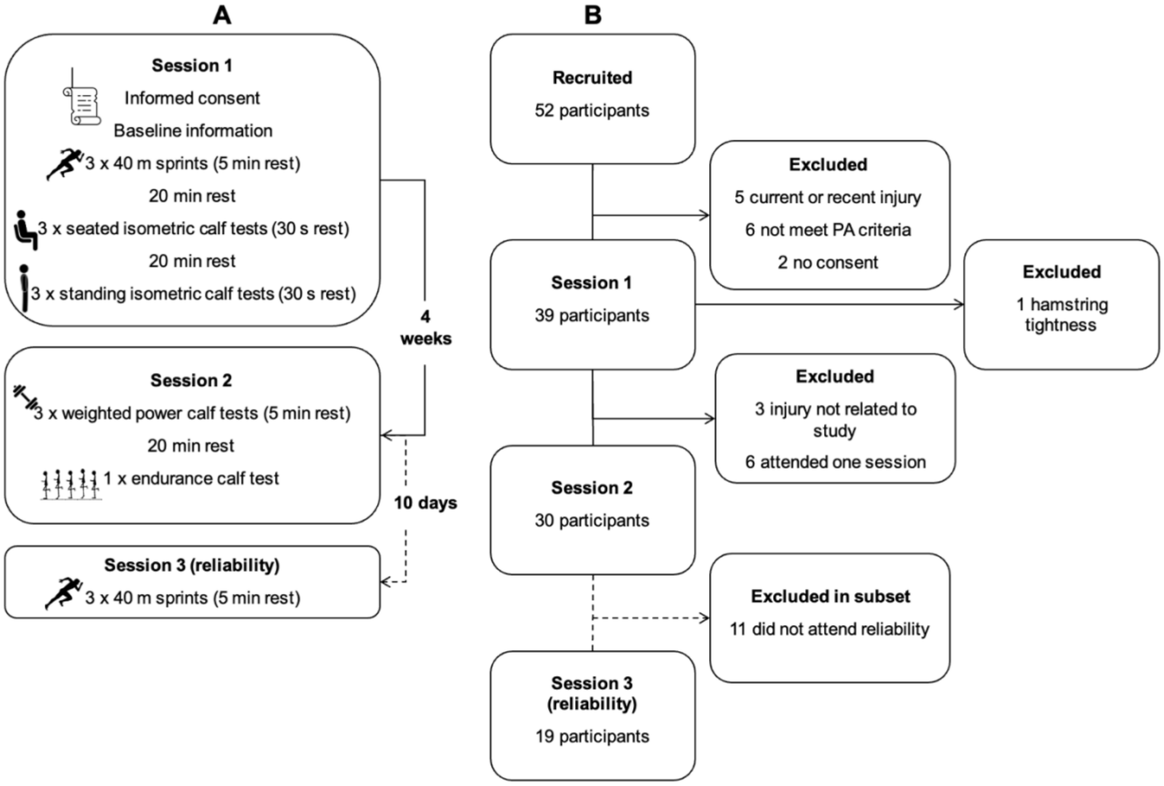

Figure 3. Flow chart of (A) the experimental design, and (B) participants.

Abbreviations: PA, physical activity.

Table 1. Baseline characteristics of participants in the correlation (n = 30) and reliability (n = 19) portions of the study by gender. Values are means ± standard deviations and frequency.

Correlation	All (*n* = 30)	Female (*n* = 16)	Male (*n* = 14)
Mass (kg)	75.4 ± 14.3	68.9 ± 11.1	83.7 ± 13.6
Age (y)	20.0 ± 1.4	20.0 ± 1.3	20.0 ± 1.1
Height (cm)	174.9 ± 10.1	168.3 ± 8.4	182.5 ± 5.5
Dominance (Left:Right)[a]	1:29	0:16	1:13
Sport participation (h/week)	6.8 ± 4.9	6.7 ± 6.2	6.9 ± 3.1
Sport participation (days/week)	3.9 ± 2.3	3.7 ± 2.7	4.3 ± 1.8
Physical activity scale (mod:hard)	12:18	7:9	5:9
Ethnicity (MP:NZEU:O[b])	4:18:8	2:10:4	2:8:4
Reliability	**All (*n* = 19)**	**Female (*n* = 10)**	**Male (*n* = 9)**
Mass (kg)	73.7 ± 10.1	70.7 ± 11.8	77.1 ± 7.1
Age (y)	20.8 ± 1.2	20.9 ± 1.6	20.7 ± 0.9
Height (cm)	174.9 ± 8.5	170.5 ± 9.1	179.9 ± 4.2
Dominance (Left:Right)[a]	1:18	0:10	1:8
Sport participation (h/week)	7.1 ± 5.5	7.6 ± 7.3	6.7 ± 3.2
Sport participation (days/week)	4.1 ± 2.4	4.4 ± 3.1	3.8 ± 1.8
Physical activity scale (mod:hard)	7:12	4:6	3:6
Ethnicity (MP:NZEU:O[b])	2:13:4	1:7:2	1:6:2

Notes. [a]Leg used to kick a ball. *Abbreviations:* mod, moderate. MP, Māori & Pasifika. NZEU, New Zealand. O, other. [b]Other includes Australian, Japanese, and European.

Experimental procedures

Following informed consent, participants completed a baseline data collection form that included their age, dominant leg, sports participation information, injury history, and the 6-point physical activity Likert scale (Grimby, 1986; Grimby & Frändin, 2018). Body height was recorded to the nearest millimetre using a stadiometer (seca model 0123, Hamburg, Germany). Prior to each testing session, body mass was captured (barefoot) using a Kistler 9260AA6 force plate (Kistler, Winterthur, Switzerland) connected to Measurement, Analysis and Reporting Software (MARS, Version 5.2, Type 2875A1, S2P Ltd., Ljubljana, Slovenia) to the nearest 10 grams.

Prior to each test, participants were provided with explanations and familiarised with the procedures. All tests were completed barefoot to avoid any potential influence of footwear on performance outcomes (Hébert-Losier, Boswell-Smith, et al., 2023). Although previous studies have shown limited difference between limbs in calf muscle function (O'Neill et al., 2023), all single leg tests were completed on the dominant leg of participants.

Session 1

A ten-minute dynamic warm-up was completed prior to the sprint tests, led by the research team. Warm-up started with a 100-m jog, followed by dynamic exercises completed over 10 m (i.e., dynamic hamstring stretch, hip openers, glute extension, skips, high knees, high knee skips, dorsiflexion heel walk, lunges, lateral walks, walking on tip toes, backwards jog, and backwards run). The last exercises involved completing 3 x 10 m accelerations (at 50%, 70%, and 80% of self-perceived maximum speed) in preparation for the 40 m sprints. Participants were given the opportunity to add any further components to their warm-up they felt their body required.

Sprint tests

The 40 m sprint tests were performed outside on a flat grass area with a 40 m run off beyond the testing area. A four gate, tripod mounted, dual-beam photoelectric system (Swift Speed, Swift, Queensland, Australia) was set at 0, 10, 30, and 40 m. Laser sprint gates have been shown to have excellent test-retest reliability over 50-m, with intra-class correlation (ICC) values and 95% confidence intervals (CI) of 0.986 [0.975-0.993] (Harrison et al., 2005). This set up was selected as the initial 10 m and final 10 m sections of a 40 m sprint are deemed representative of maximum sprint acceleration (MSA) and maximum sprint speed (MSS) abilities, respectively (Buchheit et al., 2012); both of which are relevant motor tasks and athletic demands in many individual and team sports (Gabbett, 2012; Girard et al., 2011; Haugen et al., 2019; Haugen et al., 2014; Taylor et al., 2017). The Swift Speed system was connected to an iPad (model A1822, Apple Inc., California, USA) where the output data was automatically collated in the Swift Syncro application (Swift Performance Equipment, Version 600.1.3, Deotome P/L). Participants started the sprint in an upright position with their front foot placed 50-cm behind the first timing gate to avoid breaking the beam inadvertently prior to propulsion. Verbal encouragement was given throughout the sprint and at the finish to ensure no deceleration prior to the final gate. Participants completed three sprints with a 5-minute rest between repetitions. The fastest 0-10 m, 30-40 m and 0-40 m sprint times were extracted for MSA and MSS and overall sprint performance as these are considered the more reliable performance outcome than the mean due to potential performance decrement across repeated sprints (Girard et al., 2011; Lam et al., 2018).

Isometric tests

Isometric single-leg calf testing was completed 20 minutes after the final 40 m sprint of participants (see Figure 3A). Participants completed three maximal plantarflexion isometric contractions in both conditions, allocated in a random order: seated (90° knee flexion) or standing (0° knee flexion). Each maximal contraction was sustained for three seconds, and 30 seconds rest was provided between repetitions, as done elsewhere (O'Neill et al., 2019). Participants rested 20 minutes between conditions. Before maximal trials, participants completed three practice repetitions at self-identified 50%, 60%, and 70% efforts for familiarisation and warm-up. During maximal trials, strong verbal encouragement was given and participants were able to see their force-time curves during testing as shown to positively influence outputs (Amagliani et al., 2010). Only valid trials with no visible compensations were included in the analysis. In all trials, participants were asked to push as hard as possible downwards into the force plate using their calf muscles.

All tests were completed on a hard flat surface indoors. A Kistler 9260AA6 force plate sampling at 1000 Hz was positioned inside a power rack and zeroed prior to each test. Participants were set-up so their ankles were in a neutral position when exerting maximal plantarflexion efforts in the centre of the force plate (see Figure 4).

For the seated condition, participants sat on a chair placed outside the rack with a 90° knee flexion position. A ratchet strap was tightened across the distal end of the femur to secure the leg, similar to that reported elsewhere (Lee et al., 2023; O'Neill et al., 2019) (Figure 4A). A yoga mat was placed between the leg and strap for comfort. The same member of the research team positioned and pre-tensioned the strap for all tests.

For the standing condition, participants stood under a horizontal rigid bar inside the power rack, with their upper trapezius regions against the bar (Figure 4B). The uprights of the rack had 25 equally distanced holes, 2 cm apart, that allowed the rigid bar to be adjusted to individuals in a manner that ensured their ankle was in neutral when exerting maximal efforts upwards. A barbell pad was placed across the bar for comfort. The same member of the research team positioned participants for all testing. The force plate recorded isometric outputs in Newtons (N). Isometric outcomes normalised to body mass (BM) were also calculated, with data provided as supplementary material (Table S1).

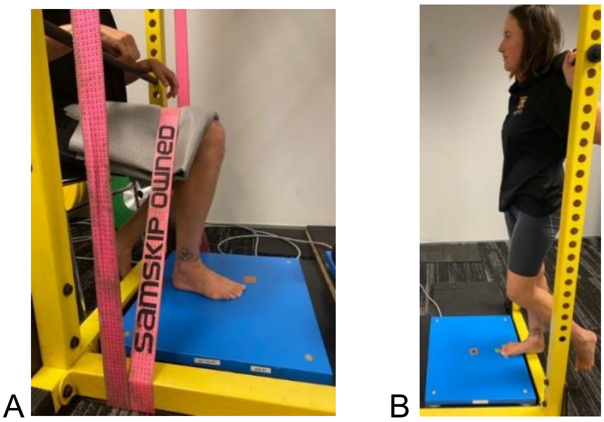

Figure 4. Images of the isometric calf test set up (A) seated (90° knee flexion) and (B) standing (0° knee flexion).

Session 2

Calf muscle power and strength-endurance tests followed procedures described elsewhere (Hébert-Losier et al., 2009; Hébert-Losier, Ngawhika, et al., 2023; Hébert-

Losier et al., 2017; Silbernagel et al., 2006), and shown valid and reliable (Fernandez et al., 2023; Hébert-Losier et al., 2022). The eccentric-concentric power test was completed before the strength-endurance test to limit the potential effect of fatigue on outcomes. Prior to testing, round black stickers (24 mm diameter) were placed below the lateral malleolus, in line with the calcaneus. The black stickers allowed for tracking of vertical displacement of the foot from video recordings captured at 60 frames per second in portrait using the Calf Raise application (version 1.5) running on an iPad (model A1822, Apple Inc., California, USA) placed 50 cm to the side of participants. A single researcher conducted all testing and analysis of videos.

Eccentric-concentric power test

Participants stood with their feet on the edge of a flat 20 cm box and were asked to keep their knee straight. For balance, participants were permitted to use the fingertips of one hand on the wall 50 cm in front of them at shoulder height. Participants were familiarised with the testing procedure by completing the test with no additional weight and then with a dumbbell prior to testing.

For testing, a dumbbell was placed on the ipsilateral shoulder of participants (on top of a towel for comfort) and held stable with their ipsilateral hand. Hébert-Losier, Ngawhika, et al. (2023) used a set mass of 35 kg for this power test in semi-professional rugby players, which was approximately 30% of their body mass. Due to heterogeneity in gender, mass, and sport participation of participants in our study, a dumbbell was chosen (to the nearest 2.5 kg) to approximate 30% of the body mass of individuals. Once the dumbbell was placed, participants lifted both heels as high as possible, then lifted their non-testing leg behind them. Participants were given the instruction to go “down and back up” as quickly as possible on their test leg, returning their heel to the starting position. Participants completed three repetitions with approximately 2 seconds rest in the “up” position between repetitions. The procedure was completed three times in total, with a 5-minute rest between sets. The largest peak power (W) from any of the three repetitions during the concentric (upwards) phase was extracted using the Calf Raise application and used as main outcome measure.

Strength-endurance test

Twenty minutes following the power test, the strength-endurance test was conducted on a 10° incline (Hébert-Losier, Ngawhika, et al., 2023; Hébert-Losier et al., 2017). Participants completed as many single-leg calf raise repetitions as possible. Participants were requested to keep the knee of their test leg straight and were allowed to use their index fingertips on the wall 50 cm in front of them at shoulder height to aid with balance. Participants raised and lowered their heel to a 60 beats per minute metronome, going up in one beat and down in one beat (i.e., 30 calf raise repetitions per minute). The test was stopped once participants could no longer complete a repetition, could no longer maintain the beat of the metronome, demonstrated marked reduction in range of motion, or exhibited compensatory movement. Strong verbal encouragement was given throughout testing. Participants were given one warning to re-establish correct calf raise performance before test cessation. The number of repetitions (*n*), total positive work (J), and total positive displacement (cm) were extracted using the Calf Raise application and used as main outcome measure for this test.

Statistical analysis

All data were collated and managed using Microsoft Excel (version 16.72, Microsoft Corporation, Redmond, WA) once extracted from their respective software. Since the best trial from three repetitions is more reliable than the average (Al-Uzri et al., 2017), the best sprint, isometric strength, strength-endurance and power metrics were used for analysis.

Descriptive characteristics were computed for variables and normal distributions confirmed using the Kolmogorov-Smirnov test. Test-retest reliability analysis included extracting $ICC_{(3,1)}$ to quantify relative reliability using a two-way mixed effects, single measurement model (Shrout & Fleiss, 1979), as well as typical error (TE) and coefficient of variation (CV) to quantify absolute reliability. Relative reliability was considered *poor* (ICC <0.50), *moderate* (ICC <0.75), *good* (ICC <0.90), and *excellent* (ICC ≥0.90) based on ICC thresholds (Gross, 2020), and absolute reliability was deemed acceptable when the CV was less than 10% (Atkinson & Nevill, 1998). Paired *t*-test was used to examine the presence of systematic bias.

To determine the strength of the relationship between metrics, Pearson's correlation coefficient (*r*) and 95% CI [lower, upper] were computed using Fisher's *z* with bias adjustment. The magnitude of the correlation was qualified according to Cohen (1992) as: *trivial r* <0.10, *small r* ≥0.10, *moderate r* ≥0.30, and *large r* ≥0.50. The level of significance was set to $p \leq 0.05$ for all analyses, which were conducted using IBM SPSS for Windows, Version 29.0.1.0 (171) (IBM Corporation, Armonk, NY) and Microsoft Excel.

Paired t-tests were also used to compare seated and standing isometric strength values. Mean differences between positions were quantified using Cohen's *d* for paired samples using an average variance with 95% confidence intervals [lower, upper], and interpreted as reflecting small, moderate, and large effect sizes when reaching thresholds of 0.20, 0.50, and 0.80, respectively.

Results

The sprint test showed excellent test-retest reliability across MSA, MSS, and 40 m sprint times (Table 2) based on relative (ICC ≥0.95) and absolute (CV ≤2.7%) reliability measures. There was, however, a systematic bias between sessions ($p \leq 0.001$), with slower times in the second session.

Table 2. Mean and standard deviation (mean ± SD) values from maximal-effort 40 m sprint times (0 - 10 m, 10 - 30 m and 0 - 40 m) from 19 active participants across two sessions. Test-retest reliability statistics provided and expressed as change in the mean, typical error (TE), intraclass coefficient correlation (ICC), and coefficient of variation (CV, %) with 95% confidence interval [lower, upper], alongside the p-value from paired t-tests.

	Best sprint		**Reliability statistics**				
	Session 1 (s)	**Session 2 (s)**	**Change in mean (s)**	**TE (s)**	**CV%**	**ICC**	***p*-value**
0 – 10 m (MSA)	1.851 ± 0.145	1.900 ± 0.154	0.049 [0.02, 0.08]	0.04 [0.03, 0.06]	2.1 [1.6, 3.1]	0.938 [0.85, 0.98]	**0.001**
30 – 40 m (MSS)	1.298 ± 0.163	1.389 ± 0.202	0.092 [0.06, 0.12]	0.04 [0.03, 0.06]	2.7 [2.0, 4.0]	0.953 [0.88, 0.98]	**<0.001**
0 – 40 m	5.884 ± 0.614	6.168 ± 0.686	0.285 [0.21, 0.36]	0.10 [0.08, 0.15]	1.5 [1.2, 2.3]	0.978 [0.94, 0.99]	**<0.001**

Notes. Data are from the best sprint time of three maximal 40 m sprints. Significant p-values (p ≤ 0.05) are **emboldened**. Abbreviations: MSA, maximum sprint acceleration; MSS, maximum sprint speed.

Descriptive data from calf tests are presented in Table 3 and correlations between best sprint times and calf muscle metrics are in Table 4. The most strongly correlated metric with MSA, MSS, and 40 m sprint times was the power test (r = -0.678 to -0.707). MSA, MSS, and 40 m sprint times also showed *large* (r = -0.545 to -0.578) significant correlations with the standing isometric metrics, and strength-endurance test total work metrics. MSA, MSS, and 40 m sprint times exhibited *moderate* (r = -0.459 to -0.478) significant correlations with seated isometric strength. When normalised to body mass, seated isometrics were only significantly and *moderately* correlated to MSA (see Table S2). Number of repetitions completed during strength-endurance testing was not significantly related to any of the sprint metrics.

Table 3. Descriptive data from calf tests (n = 30). Values are means ± standard deviations and counts.

Calf Test	All (*n* = 30)	Female (*n* = 16)	Male (*n* = 14)
Seated (N)	1236.289 ± 323.091	1285.255 ± 351.935	1184.478 ± 302.008
Standing (N)	1835.303 ± 494.662	1963.939 ± 533.953	1696.137 ± 437.748
Power (W)	530.458 ± 194.070	387.299 ± 71.341	712.431 ± 137.343
Strength-Endurance (TW)	1666.944 ± 613.515	1301.419 ± 234.711	2093.484 ± 566.181
Strength-Endurance (R)	25.71 ± 8.15	23.46 ± 5.72	28.5 ± 9.338

Abbreviations: N, Newtons; R, repetitions; TW, total positive work.

Table 4. Correlations between best sprint times and best calf muscle metrics of active participants (n = 30). Values are Pearson correlations and 95% confidence intervals [lower, upper] with bias adjustment.

	MSA: 0 – 10 m time (s)	MSS: 30 – 40 m time (s)	0 – 40 time (s)
Seated (N)	-0.470 [-0.706, -0.124] ***p* = 0.009**, *moderate*	-0.478 [-0.711, -0.134] ***p* = 0.008**, *moderate*	-0.459 [-0.699, -0.111] ***p* = 0.011**, *moderate*
Standing (N)	-0.544 [-0.752, -0.219] ***p* = 0.002**, *large*	-0.574 [-0.770, -0.260] ***p* = < 0.001**, *large*	-0.562 [-0.763, -0.244] ***p* = 0.001**, *large*
Power (W)	-0.678 [-0.831, -0.441] ***p* = < 0.001,** *large*	-0.701 [-0.844, -0.446] ***p* = < 0.001,** *large*	-0.707 [-0.847, -0.456 ***p* < 0.001,** *large*
Strength-Endurance (TW)	-0.588 [-0.779, -0.280] ***p* = < 0.001,** *large*	-0.572 [-0.769, -0.258] ***p* = < 0.001,** *large*	-0.578 [-0.772, -0.265] ***p* < 0.001,** *large*
Strength-Endurance (R)	-0.334 [-0.616, 0.036] *p* = 0.071, *moderate*	-0.319 [-0.605, 0.053] *p* = 0.086, *moderate*	-0.326 [-0.611, 0.044] *p* = 0.079, *moderate*

Notes. Significant p-values (p ≤ 0.05) are **emboldened**. Correlations considered *small*, *moderate*, and *large* when reaching 0.10, 0.30, and 0.50 (Cohen, 1992). Abbreviations: MSA, maximum sprint acceleration; MSS, maximum sprint speed; N, Newtons; R, repetitions; TW, total positive work.

The interrelatedness of calf metrics can be seen in Table 5. The strength-endurance metrics of total work and repetitions were *largely* and significantly interrelated (*r* ≥0.796). Standing and seated isometrics were also *largely* and significantly correlated (*r* =0.761), and standing isometric metrics showed a stronger correlation to other calf metrics than seated. Total work from strength-endurance testing was generally either *moderately* or *largely* related to isometric metrics, with the strength of association being stronger with standing. Repetitions from strength-endurance testing were not significantly correlated to metrics from power and isometric tests, except for standing isometrics when normalised to BW (*r* =0.371). Power metrics exhibited significant *moderate* to *large* correlations with all other calf metrics, except for seated isometric outputs. Differences between seated and standing isometric measures were *large* (Cohen *d* 1.715 [1.142, 2.276]) and overall, standing calf strength was significantly greater than seated (*p* <0.001).

Table 5. Correlations between active participants' best calf muscle metrics (n = 30). Values are Pearson correlations and 95% confidence intervals [lower, upper] with bias adjustment.

	Seated (N)	Standing (N)	Power (W)	Strength-Endurance (TW)	Strength-Endurance (R)
Seated (N)		0.761 [0.470, 0.852] **p = < 0.001**, *large*	0.652 [0.372, 0.816] **p = < 0.001,** *large*	0.607 [0.307, 0.790] **p = < 0.001**, *large*	0.256 [-0.119, 0.561] *p* = 0.173, *small*
Standing (N)			0.652 [0.371, 0.816] **p = < 0.001**, *large*	0.692 [0.433, 0.839] **p = < 0.001**, *large*	0.323 [-0.047, 0.609] *p* = 0.081, *moderate*
Power (W)				0.698 [0.441, 0.842] **p = < 0.001**, *large*	0.333 [-0.036, 0.616] *p* = 0.072, *moderate*
Strength-Endurance (TW)					0.796 [0.601, 0.896] ***p* = < 0.001**, *large*

Notes. Significant p-values (p ≤ 0.05) are **emboldened**. Correlations considered *small*, *moderate*, and *large* when reaching 0.10, 0.30, and 0.50. Correlations considered *unclear* when 95% interval spans *small* positive and negative (i.e., ±0.10) (Cohen, 1992) Abbreviations: N, Newtons; TW total positive work.

Discussion

We aimed to determine if there was an association between calf isometric strength, power, and strength-endurance metrics with MSA (0-10 m), MSS (30-40 m), and 40 m sprint times, and to explore the interrelatedness between calf metrics. Our results show *large* significant correlations between calf muscle power, strength-endurance (total work), and standing isometric strength metrics with the sprint outcomes. These correlations align with previous findings on the considerable involvement of the calf muscles in sprinting (Pandy et al., 2021), one repetition maximum calf strength relationships with 5-m split times over 30 m sprints (Möck et al., 2018), and calf power and strength-endurance relationships with 10 m sprint times (Hébert-Losier, Ngawhika, et al., 2023). Furthermore, we explored the interrelatedness between calf metrics to inform practice and the relevance of various testing approaches, identifying *large* correlations within strength-endurance measures, within isometric outcomes, between standing and seated isometric outcomes, and between power metrics and most other calf metrics. The number of repetitions from strength-endurance testing was generally not related to other calf muscle test metrics. Altogether, our findings suggest that calf muscle power is the most relevant as a proxy of accelerating and sprint abilities in active individuals; standing isometric testing is more relevant from an athletic context than seated; and the number of repetitions performed during strength-endurance testing is not as scientifically robust and functional as total work.

Kawakami et al. (2002) found that gastrocnemius muscle fibres work almost isometrically in the lengthening phase, which could suggest that isometric outcomes have a strong relationship to sprinting. However, the strength-endurance and power tests were far superior correlating to sprint outcomes than the isometric testing in either 0° or 90° knee flexion and should be considered when designing testing protocols and by practitioners when seeking to conduct performance profiling.

Calf muscle peak power metrics were the most strongly related to all sprinting performance metrics (MSA, MSS, and 40 m times), followed by strength-endurance metrics, and lastly, isometric outcomes. This ordered relationship is unsurprising given the evidence that dynamic and isometric strength represent separate neuromuscular domains (James et al., 2023), with both power and strength-endurance tests performed herein being dynamic. Whilst seated isometric testing has been shown to be valid and reliable (Lee et al., 2023; O'Neill et al., 2023), the relationships between seated isometric strength and sprint metrics were not as strong or significant in contrast to standing, reflecting greater functional relevance of standing than seated isometric testing in athletic performance.

The methodology used for the power test was based on testing methods used in a study on semi-professional male rugby players where a set external load of 35 kg was implemented (approximately 30% of mean body mass reported) (Hébert-Losier, Ngawhika, et al., 2023). Our participant pool was inherently more heterogenic with many of the variables (i.e., BW, sport, gender, strength) which may have impacted the peak power output. Some researchers recommend individualisation of external loads based on one repetition maximal efforts rather than body mass (Bevan et al., 2010; Loturco et al., 2022; Siegel et al., 2002; Thomas et al., 2007) or determining what load elicits maximal power for each individual to account for differences in body size (Argus et al., 2014). Furthermore, load placement relative to the body for this testing methodology could also influence output. Suchomel et al. (2019) found relative peak power during countermovement jumping to peak at around 40% of added body mass and was greater when loads were held in outstretched arms than at the upper back (similar to this study). Further investigation is needed to identify what specific external load and how placement of the load elicits peak power during this test, as peak power could be maximised at greater or loads less than 30% of BW or with external loads held elsewhere, such as in outstretched arms.

The lesser contribution of gastrocnemius to plantar flexor output due to active insufficiency in extreme flexion angles (Landin et al., 2015) highlighted the importance of conducting isometric tests in both a knee straight and knee flexed position. Due to this force-length relationship, it is generally accepted that changing the knee position during calf tests can help differentiate soleus and gastrocnemius involvement (Green et al., 2022; O'Neill et al., 2023). This is due to the knowledge that the soleus contributes to running acceleration at around 12 times BW and the gastrocnemius at around six times BW (Hamner & Delp, 2013; Pandy et al., 2021). Although the soleus has the greatest work demands during running (Green et al., 2022), the isometric tests completed with a knee straight showed a stronger relationship across MSA, MSS, and 40 m sprint times, indicating that standing calf muscle testing is, overall, more relevant to acceleration and short sprint performance than seated. It may be that in the presence of injury, however, the two positions help differentiate calf muscle injuries.

Practical application

This study adds to the literature and supports the concept of the relationship between calf muscle function and sprint performance. Calf muscle maximum isometric strength, power, and strength-endurance qualities vary across individuals due to differences in physical characteristics and sports-specific demands. When considering performance profiling, practitioners should consider the benefits and limitations of testing procedures. Based on our findings, calf muscle profiling would be the most relevant performance indicator of sprinting ability. Calf strength-endurance (based on total work) and isometric calf strength in standing are potential alternatives, with seated isometrics being the least relevant.

Limitations

There are limitations to acknowledge. Although valid and reliable, the power protocol has been used sparingly in the literature (Hébert-Losier, Ngawhika, et al., 2023; Silbernagel et al., 2006) and there are limited normative values available. Further research is required to determine what load and method of testing elicits the greatest peak power (Argus et al., 2011). Load placement could also impact relative peak power and should be considered alongside establishing external load to enhance optimal power outputs.

Additionally, the test-retest reliability of sprint data was excellent between sessions, comparable to previous findings on sprint test-retest reliability (Harrison et al., 2005; Young et al., 2008), albeit six weeks apart. This excellent relative and absolute reliability of sprint times within our cohort suggest the relationship between calf muscle and sprint metrics should remain relatively unaffected irrespective of whether they were collected on the same day as the sprints (i.e., isometrics) or 4-weeks later (i.e., power and strength-endurance), though would ideally be completed on the same day.

Another limitation to consider is that correlation does not ensure causation. An intervention study would be required to determine whether training calf muscle power, isometric strength, or strength-endurance abilities lead to improvements in sprint performances. Likewise, future studies could explore whether targeted training and improvements in sprint times are linked with changes in calf muscle abilities.

Conclusion

The strength of association between maximal sprinting and the power metrics are the ones most likely to provide insight into the influence of the triceps surae on sprint and acceleration abilities, closely followed by the strength-endurance metrics, both of which involve minimal equipment and can be measured using a free-to-use validated application (Fernandez et al., 2023). It is recommended to use the quantitative measure of total work over total repetitions in strength-endurance calf raise testing. Based on the strong relationship to sprint performance and standing calf measures, it would be our recommendation that when using isometric testing, practitioners should use standing protocols over seated when considering performance outputs such as sprints.

Whilst we identified a relationship between calf muscle and sprint performance metrics, future research is required to determine a causal link and assess if enhancing calf muscle abilities enhances sprint performance; or inversely, if acceleration and sprint training influences calf function.

Chapter 3 – Second experimental study

Relevance of horizontal and vertical plyometric outcomes for athletic sprint performance.

Abstract

Introduction

Horizontal and vertical plyometric abilities have been found important to sprinting performance, but there is minimal literature exploring the relationships between the two plyometric axes. Furthermore, the triceps surae or calf muscles are important contributors to plyometric-based tasks. This study investigated the potential association between single-leg plyometric outcomes on the horizontal and vertical axes with sprint performance metrics, each other, and calf muscle metrics.

Methods

Thirty active participants (14 male, 16 female) completed a test battery in two separate sessions that included 0-40 m maximum sprints, plyometric performance in the vertical and horizontal axes, as well as single-leg strength, power, and strength-endurance calf tests. Sprint outcomes included maximal sprint acceleration (MSA, 0-10 m time) and speed (MSS, 30-40 m time), as well as 0-40 m overall time. Plyometric outcomes included vertical reactive strength index (RSI) and total height (m) from a single-leg drop jump from a 30 cm box, and two horizontal RSIs and total horizontal distance (m) from a single-leg forward triple hop. Calf muscle metrics included seated and standing isometric strength (N), peak eccentric-concentric power (W) with a 30% body mass load, and total repetitions and work (J) from

strength-endurance testing. Pearson correlation coefficients were computed to assess the relationship between plyometric, sprint, and calf metrics.

Results

Horizontal total distance (r = -0.785 to -0.694) and both horizontal RSIs showed *large* significant correlations with MSA, MSS, and 40 m sprint times. The vertical RSI exhibited *moderate* significant correlations with MSA, MSS, and 40 m sprint times (r = -0.422 to -0.386), whereas vertical height was not significantly related to any of the sprint metrics. Plyometric outcomes within the same axes were *largely* interrelated, with only the vertical RSI exhibiting a significant *moderate* relationship to horizontal RSI2 and horizontal total distance. The only *large* and significant correlation of plyometric with calf metrics was between horizontal total distance and calf power (r = 0.628). Horizontal total distance also *moderately* and significantly correlated with all other calf metrics (r = 0.487 to 0.381), whereas only seated isometric strength *moderately* relating to vertical plyometric outcomes (r = 0.411 to 0.447).

Conclusion

The horizontal total distance was the most strongly associated plyometric outcome to sprint metrics. This measure is easy to collect and could be used as a maximal sprint acceleration and speed performance indicator in athletes. Our findings imply that although related, plyometric testing on horizontal and vertical axes assess different muscle qualities and functional abilities. Horizontal plyometric testing appears more representative of sprint function, congruent with previous research. Calf muscle power abilities were more strongly related to horizontal plyometric outcomes than

calf strength-endurance and isometric strength, highlighting its importance in explosive forward performance.

Key words

Athlete testing, muscle strength, plyometrics, power, speed, triceps surae.

Introduction

The relationship between plyometric outcomes and sprint performance has interested researchers, clinicians, coaches, and athletes alike for years (Beato et al., 2018; Chelly et al., 2015; Lockie et al., 2014; Pardos-Mainer et al., 2021; Turner et al., 2003). Sprinting is a critical element to various team and individual sports (Buchheit et al., 2012; Haugen et al., 2014; Johnston & Gabbett, 2011; Young et al., 2008), and as athletes continually seek avenues to enhance their sprinting abilities, plyometric exercises have become a cornerstone in athlete training and testing (Haugen et al., 2019; Voisin & Scohier, 2019). Sprinting demands a unique combination of explosive power, rapid force development, and efficient energy transfer using the stretch-shortening cycle (Mero et al., 1992), hence the interest in plyometrics. Fundamental knowledge of lower-limb muscle function during maximum acceleration sprinting is not only of interest to athletes and coaches looking to optimise sprint performance, but also to sports medicine practitioners looking towards injury prevention and rehabilitation (Green et al., 2022; Hébert-Losier et al., 2022; Maniar et al., 2022; Möck et al., 2018).

Plyometric exercises, characterised by rapid and powerful muscle contractions (Markovic & Mikulic, 2010), offer a targeted approach to developing neuromuscular qualities attributed to sprinting performance, with little to no clinical equipment needed (Pardos-Mainer et al., 2021). Lower-limb plyometric exercises often refer to jumping, bounding, and hopping (Davies et al., 2015). Plyometric exercises mirror the dynamics of sprinting in that rapid eccentric contractions immediately follow concentric contractions (Brink et al., 2022). The efficiency of the stretch-shortening cycle has been shown to directly influence force generation in sprinting (Komi, 2000; Samozino et al., 2022). Similarly, training programmes that enhance plyometric ability also benefit sprint performance (Kilding et al., 2008; Moran et al., 2024; Turner et al., 2003). Plyometrics can be performed in different planes of movement – horizontal or vertical. Although studies support the importance of horizontal and vertical plyometric training on sprint performance (Baca, 1999; Baena-Marin et al., 2022; Barker et al., 2018; Comyns et al., 2023; De Villarreal et al., 2008; Dorn et al., 2012; Hamner & Delp, 2013; Ramírez-Campillo et al., 2015), there is minimal literature exploring the relationship of plyometric-related measures between the two axes.

The triceps surae or calf muscle complex (made up of the gastrocnemius medialis muscle, gastrocnemius lateralis muscle, soleus muscle, and Achilles tendon) plays a pivotal role in the execution of plyometric exercises, with a significant relationship between isometric seated calf strength and vertical plyometrics being previously identified ($r = 0.52$) (Warneke et al., 2022). Calf muscle power and strength-endurance metrics are more dynamic assessments of calf function than isometric and have been shown to more strongly relate to maximal sprint acceleration (Hébert-Losier, Ngawhika, et al., 2023). To our knowledge, no research has explored the association between various calf metrics and plyometric abilities in both the vertical and horizontal axes.

Our primary aim was to explore the potential association between single-leg plyometric outcomes on the horizontal and vertical axis with maximal sprint acceleration (MSA), maximal sprint speed (MSS), and total sprint time derived from a 40 metre sprint task. As a secondary aim, we sought to explore the relationship between horizonal and vertical plyometric outcomes, as well as the relationship between calf muscle and plyometric outcomes. We hypothesised that horizontal plyometric outcomes would more strongly relate to sprint metrics than vertical plyometric outcomes due to similarity in muscular force production and task specificity (Samozino et al., 2022). We also expected *large* correlations between plyometric axes, as well as between calf muscle metrics and plyometric outcomes based on previous findings (Warneke et al., 2022). In exploring these associations, we aimed to provide an understanding of how plyometric testing could be strategically employed in a clinical setting.

Methods

Research design

An observational cross-sectional study design with repeated measures was used to examine the potential correlation between single-leg plyometric outcomes and sprint times. Participants were tested on two separate occasions (Figure 5A) to mitigate the risk of fatigue and musculoskeletal injury (Davies et al., 2015). Session one consisted of 40 metre sprint testing and seated and standing isometric calf testing. Session two was conducted four weeks later and involved plyometric testing on the horizontal and vertical axis along with calf power testing and strength-endurance testing.

Participants

The research was carried out in line with the Declaration of Helsinki and was approved by the Human Research Ethics Committee of the University of Waikato [HREC(Health)#2017-54]. Sample size was based on previous research by Möck et al. (2018), which identified large correlations between one repetition maximum calf strength and 30 m sprint times. On this basis, a sample size of twenty-nine participants was required to detect a large correlation ($r = 0.50$) at a 5% significance level with 80% power.

Inclusion criteria involved a willingness to provide written informed consent and being physically active, determined using a validated 6-point activity Likert scale (Grimby, 1986; Grimby & Frändin, 2018). Participants that scored 3 (light physical exercise around 2-4 h per week) or less on this scale were excluded as deemed not reflective of the target population. Participants with a current or recent (< 3 months) lower-limb or lower back injury were excluded due to the risk of injury/re-injury. Potential participants were informed of the potential risks (i.e., delayed onset muscle soreness and potential injury due to the maximal effort required) and benefits (i.e., individualised performance reports) of study participation.

Fifty-two university students from the University of Waikato studying Health, Sport and Human Performance were recruited through word-of-mouth, with thirty individuals (16 females, 14 males) meeting inclusion, agreeing to participate, and completing the two testing sessions (see Figure 5B). Most of them (73.3%) participated in team sports, and 96.6% in sports which involve plyometric or sprint training. The mean and standard deviation (SD) values for age, body mass, and height of participants are shown in Table 6. The sprint and plyometric testing was completed at the same time of day to mitigate diurnal effects on performance (Pullinger et al., 2020), and barefoot to avoid any potential influence of footwear on performance outcomes (Hébert-Losier, Boswell-Smith, et al., 2023).

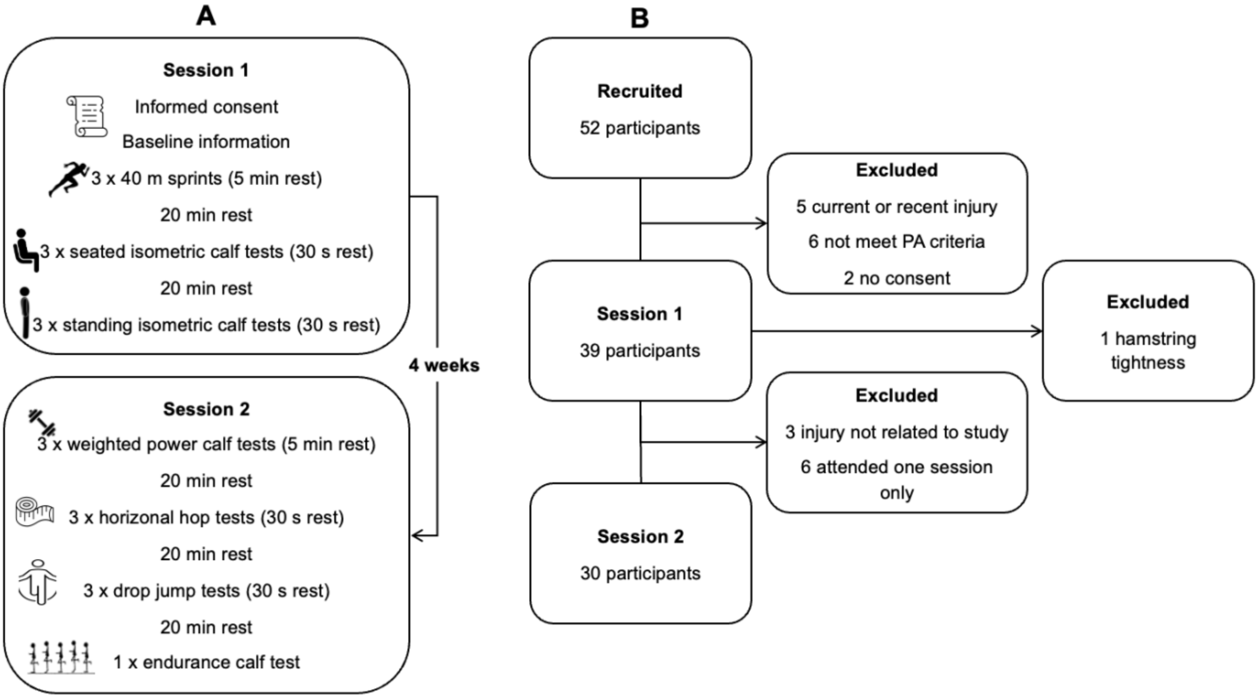

Figure 5. Flow diagram of (A) the experimental design, and (B) participants. Abbreviations: PA, physical activity

Table 6. Baseline characteristics of participants (n = 30) by gender. Values are means ± standard deviations and counts.

	All (*n* = 30)	Female (*n* = 16)	Male (*n* = 14)
Mass (kg)	75.4 ± 14.3	68.9 ± 11.1	83.7 ± 13.6
Age (y)	20.0 ± 1.4	20.0 ± 1.3	20.0 ± 1.1
Height (cm)	174.9 ± 10.1	168.3 ± 8.4	182.5 ± 5.5
Dominance (Left:Right)[a]	1:29	0:16	1:13
Sport participation (h/week)	6.8 ± 4.9	6.7 ± 6.2	6.9 ± 3.1
Sport participation (days/week)	3.9 ± 2.3	3.7 ± 2.7	4.3 ± 1.8
Physical activity scale (mod:hard)	12:18	7:9	5:9
Ethnicity (MP:NZEU:O[b])	4:18:8	2:10:4	2:8:4

Notes. [a]Leg used to kick a ball. [b]Other includes Australian, Japanese, and European. *Abbreviations:* mod, moderate. MP, Māori & Pasifika. NZEU, New Zealand. O, other.

Experimental procedures

Following informed consent, participants completed a baseline data collection form that included their age, dominant leg, sports participation information, injury history, and the 6-point physical activity Likert scale (Grimby, 1986; Grimby & Frändin, 2018). Body height was recorded to the nearest millimetre using a stadiometer (seca model 0123, Hamburg, Germany). Prior to each testing session, body mass was captured (barefoot) using a Kistler 9260AA6 force plate (Kistler, Winterthur, Switzerland) connected to Measurement, Analysis and Reporting Software (MARS, Version 5.2, Type 2875A1, S2P Ltd., Ljubljana, Slovenia) to the nearest 10 grams. Data from

MARS and the Swift Syncro application were collated and manged using Microsoft Excel (version 16.72).

Prior to each test, the same member of the research team provided participants with explanations and participants were familiarised with the procedures. Although previous studies have shown limited difference between limbs in calf muscle function (O'Neill et al., 2023), all single-leg tests were completed on the participant's preferred leg.

Session 1

Three tasks were performed during session 1 (Figure 3B). Sprints were performed first, followed by the two isometric calf muscle tests allocated in a random order. An investigator-led ten-minute dynamic warm-up was completed prior to the sprint tests. Warm-up started with a 100-metre jog, followed by dynamic exercises completed over a 10 metre area (i.e., dynamic hamstring stretch, hip openers, glute extension, skips, high knees, high knee skips, dorsiflexion heel walk, lunges, lateral walks, walking on tip toes, backwards jog, and backwards run). The last exercises involved completing 3 x 10 metre accelerations (at 50%, 70%, and 80% of self-perceived maximum speed) in preparation for the 40 metre sprints. Participants were given the opportunity to add any further components to their warm-up they felt their bodies required.

Sprint tests

The 40 metre sprint tests were performed outside on a flat grass area with a 40 metre run off beyond the testing area. A four gate, tripod mounted, dual-beam photoelectric system (Swift Speed, Swift, Queensland, Australia) was set up at 0, 10, 30, and 40 metres. Sprint timing gates have been shown to have excellent test-retest reliability over 40 metres for MSS, with intra-class correlation (ICC) values of 0.95 (Cormier et al., 2023). This set up was selected as the initial 10 metre and final 10 metre of a 40 metre sprint are deemed representative of maximum sprint acceleration (MSA) and maximum sprint speed (MSS) abilities, respectively (Buchheit et al., 2012); both of which are relevant motor tasks and athletic demands in many individual and team sports (Gabbett, 2012; Girard et al., 2011; Haugen et al., 2019; Haugen et al., 2014; Taylor et al., 2017). A start marker was placed 50 cm from the first timing gate where participants placed their front foot to avoid breaking the gate inadvertently prior to propulsion. The Swift Speed system was connected to an iPad (model A1822, Apple Inc., California, USA) where the data were automatically collated in the Swift Syncro application (Swift Performance Equipment, Version 600.1.3, Deotome P/L). Participants started the sprint in an upright position. Verbal encouragement was given throughout the sprint and at the finish to ensure participants did not decelerate prior to the final gate. The participants completed three sprints with a 5-minute rest between repetitions. The fastest times were extracted from the three repetitions as these are considered the more reliable performance outcome than the mean due to potential performance decrement across repeated sprints (Girard et al., 2011; Lam et al., 2018). Specifically, the fastest 0-10 metre and 30–40 metre times were extracted as corresponding measures of MSA and MSS.

Isometric tests

The procedures for isometric calf testing were the same as described in chapter two.

Session 2

Four tasks were completed in session 2 interspersed by a 20-minute rest (Figure 3B). The tasks were randomly allocated to participants, except for the calf muscle strength-endurance test always being performed last to minimise the impact of fatigue on the more explosive outcomes. Two plyometric tests were completed in session 2 as recommended by Noyes et al. (1991). Single-leg forward hops and single-leg drop jumps are two exercises that involve some of the greatest Achilles tendon loading (Baxter et al., 2021), and hence were selected as likely to exhibit a relationship to sprint outcomes given the contributions of the soleus and gastrocnemius to sprinting (Bohm et al., 2021; Brearley et al., 2017; Hamner & Delp, 2013; Pandy et al., 2021). No formal neuromuscular warm-up other than familiarisation to the task was completed prior to plyometric testing as previous studies have found no effect of such warm-ups on plyometric performance outcomes (Lindblom et al., 2012).

Plyometric testing was performed inside a well-lit room on a hard flat vinyl surface laid over concrete. In both horizontal and vertical tests, participants were asked to keep their hands on their hips to limit the influence of upper body movements on centre of mass distribution (Barker et al., 2023), and hold their final landing (Prapavessis & McNair, 1999). For both plyometric tests, reactive strength index (RSI) measures were calculated by dividing the flight time by contact time, some authors have proposed this method is described as reactive strength ratio (RSR) (Flanagan & Comyns, 2008; Healy et al., 2018).

Horizontal plyometric test

A 15-m testing area was set up consisting of a modular optical detection system of transmitters and receivers (OptoJump Next, Microgate, Bolzano, Italy) sampling at 1000 Hz attached to a laptop running OptoJump software version 1.13.0. OptoJump has been shown to be valid and reliable for capturing jump performance with ICC and 95% confidence interval [CI] values of 0.98 [0.96-0.99] (Comyns et al., 2023).

Participants completed three consecutive maximal single-leg forward hops three times, separated by a 30-second rest. During maximal trials, strong verbal encouragement was given and participants were able to see their total distance during testing as test feedback is shown to positively influence outputs (Amagliani et al., 2010). For the forward triple hop for distance test, participants began by standing single leg inside the testing area and were asked to hop as far, and as quickly, as possible and to hold the final landing for 2 seconds. Only valid trials with no visible compensations were included in the analysis. Two RSI were gathered, the first being from the first ground contact (RSI1) and the second from the second ground contact (RSI2) of the triple hops. In addition to RSI, the total distance (cm) hopped was extracted from each repetition. The best RSI and total distance from any one of the three repetitions extracted were used as the main outcome measure (Moran et al., 2022; Moran et al., 2024; H. Nobari et al., 2023; Hadi Nobari et al., 2023).

Vertical plyometric test

Vertical plyometric ability was assessed via a single-leg 30 cm drop jump with participants landing on a Kistler 9260AA6 force plate sampling at 1000 Hz via the MARS. The force plate was zeroed prior to each trial. A landing marker was placed in the middle of the force plate 30 cm from the edge of the box, as described elsewhere (Kim & Lim, 2014; Y. Nagano et al., 2007; Orishimo et al., 2009).

Participants completed three trials with 30 seconds rest between trials. For testing, participants stood, single-leg, on the box with the forefoot at the edge of the box. They were required to jump down from the box landing in the middle of the force plate and to jump upwards as high, and as fast, as possible. Participants were requested to hold their landing position for two seconds upon landing. The force plate recorded RSI and jump height from flight time as recommended by Baca (1999). The best RSI and jump height from any one of the three repetitions were extracted and used as the main outcome measure.

Eccentric-concentric power test

The procedures for the eccentric-concentric power testing were the same as described in chapter two.

Strength-endurance test

The procedures for the strength-endurance testing were the same as described in chapter two.

Statistical analysis

All data were collated and managed using Microsoft Excel (version 16.72, Microsoft Corporation, Redmond, WA) once extracted from their respective software. Since the best trial from three repetitions is more reliable than the average of repetitions (Al-Uzri et al., 2017), the best MSA, MSS, 40 m time, horizontal RSI1 and RSI2, total horizontal distance, vertical RSI, vertical jump height, peak isometric strength, and peak power metrics were used for analysis. The number of repetitions, total positive work, and total positive displacement were used for the strength-endurance test.

Descriptive characteristics were computed for variables and normal distributions confirmed using Kolmogorov-Smirnov. To determine the strength of relationship between metrics, Pearson's correlation coefficient (*r*) and 95% CI [lower, upper] were computed using Fisher's *z* with bias adjustment to determine the strength of the relationships between metrics. The magnitude of the correlation was qualified according to Cohen (1992) as: *trivial r* <0.10, *small r* ≥0.10, *moderate r* ≥0.30, and *large r* ≥0.50. Correlations considered *unclear* when 95% interval spans *small* positive and negative (i.e., ±0.10) (Cohen, 1992). The level of significance was set to *p* ≤0.05 for all analyses, which were conducted using IBM SPSS for Windows, Version 29.0.1.0 (171) (IMB Corp, Armonk, NY) and Microsoft Excel.

Results

Descriptive data from the plyometric and sprint tests are presented in Table 7 and correlations from the tests are in Table 8. Horizontal total distance (*r* = -0.785 to -0.694) and both horizontal RSI metrics showed *large* significant correlations (RSI1 *r* = -0.657 to -0.624 and RSI2 *r* = -0.608 to -0.589) with MSA, MSS, and 40 m sprint times. The vertical RSI exhibited *moderate* significant correlations with MSA, MSS, and 40 m sprint times (*r* =-0.422 to -0.386), whereas vertical height was not significantly related to any of the sprint metrics.

Table 7. Performance outcome measures of participants (n = 30) by gender. Values are mean ± standard deviation.

Metric	All	Female (*n* = 16)	Male (*n* = 14)
Horizontal plyometrics			
RSI 1	0.912 ± 0.208	0.831 ± 0.123	1.005 ± 0.249
RSI 2	1.069 ± 0.272	0.955 ± 0.172	1.199 ± 0.310
Total distance (m)	4.752 ± 0.923	4.119 ± 0.531	5.475 ± 0.723
Vertical plyometrics			
RSI	0.919 ± 0.270	0.773 ± 0.173	1.075 ± 0.272
Height (m)	0.130 ± 0.047	0.098 ± 0.027	0.164 ± 0.040
40 m sprints			
MSA: 0 – 10 m (s)	1.851 ± 0.145	1.846 ± 0.143	1.843 ± 0.145
MSS: 30 – 40 m (s)	1.298 ± 0.163	1.284 ± 0.170	1.305 ± 0.185
0 – 40 m (s)	5.884 ± 0.614	5.835 ± 0.580	5.906 ± 0.667

Notes. Data are from the best outputs. RSI is unitless. Abbreviations: MSA, maximum sprint acceleration; MSS, maximum sprint speed; RSI, reactive strength index.

The interrelatedness of plyometric metrics is presented in Table 9. All horizontal measures were *largely* and significantly interrelated (*r* = 0.884 to 0.644), as were the two vertical measures to each other (*r* =0.977). Between horizontal and vertical plyometric measures, only vertical RSI exhibited significant *moderate* correlations with horizontal RSI2 (*r* = 0.366) and total horizontal distance (*r* = 0.407). Vertical height was not significantly correlated to any of the horizontal measures.

Table 10 shows the interrelatedness of plyometric outcomes and calf muscle metrics. The only *largely* and significantly interrelated measures were the calf power and horizontal total distance (*r* = 0.628). Horizontal total distance also *moderately* and significantly correlated with all other calf metrics (*r* = 0.487 to 0.381).

Table 8. Correlations between best sprint times and best plyometric outcomes of active participants (*n* = 30). Values are Pearson correlations and 95% confidence intervals [lower, upper] with bias adjustment.

	MSA: 0 – 10 m time (s)	MSS: 30 – 40 m time (s)	0 – 40 m time (s)
Horizontal RSI 1	-0.589 [-0.783, -0.290] ***p* = < 0.001**, *large*	-0.608 [-0.795, -0.318] ***p* = < 0.001**, *large*	-0.592 [-0.785, -0.294] ***p* = < 0.001**, *large*
Horizontal RSI 2	-0.654 [-0.821, -0.385] ***p* = < 0.001**, *large*	-0.657 [-0.823, -0.389] ***p* = < 0.001**, *large*	-0.624 [-0.804, -0.340] ***p* = < 0.001**, *large*
Horizontal total distance (cm)	-0.785 [-0.893, 0.592] ***p* = < 0.001,** *large*	-0.741 [-0.869, -0.519] ***p* = < 0.001,** *large*	-0.694 [-0.843, -0.445] ***p* = < 0.001**, *large*
Vertical RSI	-0.386 [-0.655, -0.030] ***p* = 0.035,** *moderate*	-0.396 [-0.662, -0.042] ***p* = 0.020,** *moderate*	-0.422 [-0.679, -0.072] ***p* = 0.030,** *moderate*
Vertical height (cm)	-0.317 [-0.608, 0.048] *p* = 0.087, *moderate*	-0.324 [-0.612, 0.041] *p* = 0.054, *moderate*	-0.356 [-0.635, 0.005] *p* = 0.081, *moderate*

Notes. Significant *p*-values (p ≤ 0.05) are **emboldened**. Correlations considered *small*, *moderate*, and *large* when reaching 0.10, 0.30, and 0.50 (Cohen, 1992). Abbreviations: MSA, maximum sprint acceleration; MSS, maximum sprint speed; RSI, reactive strength index.

Table 9. Correlations between best plyometric outcomes of active participants (*n* = 30). Values are Pearson correlations and 95% confidence intervals [lower, upper] with bias adjustment.

	Horizontal RSI1	Horizontal RSI2	Horizontal total (cm)	Vertical RSI	Vertical height (cm)
Horizontal RSI1		0.884 [0.769, 0.944] ***p* = < 0.001**, *large*	0.649 [0.377, 0.818] ***p* = < 0.001,** *large*	0.282 [-0.087, 0.583] *p* = 0.132, *unclear*	0.150 [-0.222, 0.484] *p* = 0.428, *unclear*
Horizontal RSI2			0.644 [0.370, 0.815] ***p* = < 0.001**, *large*	0.366 [0.006, 0.641] ***p* = 0.047**, *moderate*	0.248 [-0.123, 0.559] *p* = 0.185, *unclear*
Horizontal total (cm)				0.407 [0.055, 0.669] ***p* = 0.026**, *moderate*	0.283 [-0.086, 0.584] *p* = 0.129, *unclear*
Vertical RSI					0.977 [0.951, 0.989] ***p* = < 0.001**, *large*

Notes. Significant *p*-values (p ≤ 0.05) are **emboldened**. Correlations considered *small*, *moderate*, and *large* when reaching 0.10, 0.30, and 0.50. Correlations considered *unclear* when 95% interval spans *small* positive and negative (i.e., ±0.10) (Cohen, 1992). Abbreviations: RSI, reactive strength index; TW, total positive work.

Table 10. Correlations between plyometric performance outcomes and calf muscle metrics of active participants (*n* = 30). Values are Pearson correlations and 95% confidence intervals [lower, upper] with bias adjustment.

	Horizontal RSI1	Horizontal RSI2	Horizontal total distance (cm)	Vertical RSI	Vertical height (cm)
Seated (N)	-0.037 [-0.392, 0.328] *p* = 0.846, *unclear*	0.053 [-0.313, 0.406] *p* = 0.781, *unclear*	0.381 [0.024, 0.652] ***p* = 0.038**, *moderate*	0.411 [0.059, 0.672] ***p* = 0.024**, *moderate*	0.447 [0.104, 0.695] ***p* = 0.013**, *moderate*
Standing (N)	0.004 [-0.357, 0.364] *p* = 0.984, *unclear*	0.054 [-0.312, 0.406] *p* = 0.777, *unclear*	0.397 [0.043, 0.663] ***p* = 0.030**, *moderate*	0.240 [-0.132, 0.552] *p* = 0.202, *unclear*	0.279 [-0.090, 0.581] *p* = 0.135, *small*
Power (W)	0.241 [-0.130, 0.553] *p* = 0.199, *unclear*	0.293 [-0.075, 0.591] *p* = 0.116, *small*	0.628 [0.346, 0.806] ***p* < 0.001**, *large*	0.321 [-0.045, 0.610] *p* = 0.084, *moderate*	0.287 [-0.082, 0.586] *p* = 0.125, *small*
Endurance (TW)	0.228 [-0.144, 0.543] *p* = 0.226, *unclear*	0.155 [-0.217, 0.488] *p* = 0.412, *unclear*	0.487 [0.153, 0.721] ***p* = 0.006**, *moderate*	0.162 [-0.210, 0.494] *p* = 0.392, *unclear*	0.151 [-0.221, 0.485] *p* = 0.425, *unclear*
Endurance (R)	0.337 [-0.027, 0.662] *p* = 0.069, *moderate*	0.147 [-0.225, 0.482] *p* = 0.437, *unclear*	0.381 [0.024, 0.652] ***p* = 0.038**, *moderate*	0.125 [-0.247, 0.464] *p* = 0.512, *unclear*	0.054 [-0.312, 0.406] *p* = 0.777, *unclear*

Notes. Significant p-values (p ≤ 0.05) are **emboldened**. Correlations considered *small*, *moderate*, and *large* when reaching 0.10, 0.30, and 0.50. Correlations considered *small*, *moderate*, and *large* when reaching 0.10, 0.30, and 0.50. Correlations considered *unclear* when 95% interval spans *small* positive and negative (i.e., ±0.10) (Cohen, 1992) Abbreviations: RSI, reactive strength index; TW, total positive work. R, repetitions.

Discussion

Our primary aim was to examine the potential association between single-leg plyometric outcomes on the horizontal and vertical axes with MSA (0-10 m), MSS (30-40 m), and 40 m sprint times. Our results showed *large* significant correlations between horizontal plyometric outcomes and all sprint metrics. These correlations align with previous findings on the positive impact of a horizontal plyometric intervention on sprint outcomes (Dobbs et al., 2015; Jiménez-Reyes et al., 2018; Maulder & Cronin, 2005; A. Nagano et al., 2007). Our findings indicate *moderate* correlations between vertical plyometric outcomes and all sprint outcomes, which aligns with previous findings of improved sprint performance subsequent to a vertical plyometric intervention (Hasan, 2023; Markovic & Mikulic, 2010; Pandy et al., 2021; Pardos-Mainer et al., 2021). The stronger correlation between all sprint outcomes and horizontal plyometric measures than vertical ones agree with our hypothesis and enhanced task specificity (Samozino et al., 2022).

Understanding the intricate relationship between plyometric outputs and the relationship to sprint performance is essential for optimising athletic training and sport performance. Previous studies have found that plyometric exercises are valuable to enhance performance in the initial portion of a sprint (< 40 m) (Beato et al., 2018; Chelly et al., 2014; Chelly et al., 2015; De Villarreal et al., 2008; Lockie et al., 2014), with previous research identifying a *strong* relationship ($r = -0.58$, $p \leq 0.01$) between drop jump rebound height and 20-m linear sprint (Schuster & Jones, 2016). Similarly, previous studies have found significant correlations between single-leg horizontal plyometrics and sprint acceleration ($r = - 0.48$, $p < 0.001$) (Lin et al., 2023). While the existing body of literature recognises the importance of plyometric training for acceleration and short sprint abilities, this study highlights the association between horizontal and vertical plyometric measures and various sprint outcomes. Altogether, our findings indicate that horizontal rather than vertical plyometric testing is more relevant as a proxy of acceleration and sprint abilities in active individuals.

As secondary aim, we explored the interrelatedness of plyometric outcomes within and between horizontal and vertical axes to inform practice and the relevance of these various testing approaches. We identified *large* significant correlations between measures within the same axis, and only *moderate* significant correlations between vertical RSI and both horizontal RSI2 and horizontal total distance. The *moderate* correlation between the measures from the separate axes indicates that, although related, vertical and horizontal plyometrics assess different muscle qualities and functional abilities (Maulder & Cronin, 2005).

In examining the relationship of calf muscle metrics with plyometric outcomes, we identified calf power was *largely* related to horizontal total distance, and all other calf muscle metrics were *moderately* related to horizontal total distance (r = 0.381 to 0.487, $p \leq 0.038$). Modelling studies have identified the gastrocnemius to be a strong contributor to propulsive impulse (Bohm et al., 2021; Hamner & Delp, 2013; Pandy et al., 2021). Given the role of the plantarflexor muscles in sprint and rapid acceleration performance (Pandy et al., 2021), it is perhaps unsurprising that the calf power metric was the most strongly related calf metric to plyometric outcomes due to it being more explosive in nature.

After calf power, total work from strength-endurance testing and peak isometric standing strength were the metrics most strongly related to horizontal total distance. Total repetitions in strength-endurance and seated isometric strength metrics showed the weakest relationship. These findings align with previous research where calf power and total work from strength-endurance testing were *largely* related to 10 m sprint measures in semi-professional male rugby players (Hébert-Losier, Ngawhika, et al., 2023) presumably due to the dynamic nature of these calf tests. The current results also align with those from chapter two where calf muscle power was the most strongly related calf metric to sprint outcomes in physically active male and female individuals. Strength-endurance total work was a more relevant measure than total repetitions in the context of sprints, and standing isometric testing appeared more functional and related to sprints than seated.

For the vertical plyometric outcomes, only seated isometric strength was significantly related with vertical height and RSI. Since soleus contributes to plantarflexion outputs to a greater extent when the knee is flexed (Landin et al., 2015), our findings indicate soleus is potentially more involved in vertical jumping performance than gastrocnemius. It is recognised that vertical drop jump considerably loads the Achilles tendon, with the maximal output of soleus specifically linked with this amount of loading (Baxter et al., 2021). These observations support findings that the soleus and gastrocnemius behave differently during drop jumps (Sousa et al., 2007). Exploring the activation of the soleus and gastrocnemius specifically during vertical and horizontal plyometric tasks might help elucidate their relative contributions to the separate axes.

Practical application

This study adds to the literature addressing sprint performance and plyometrics. Our findings indicate that practitioners should consider horizontal plyometric testing in relation to the sprinting abilities of their athletes. Horizontal plyometric testing could be used in-season as a marker of sprint performance and readiness, or within test batteries used for talent identification. Horizontal total distance is simple to measure with little equipment needed and is more strongly correlated to sprints than vertical plyometrics. Similarly, calf muscle profiling could be a relevant performance indicator of sprinting ability, specifically using power testing and calf strength-endurance (based on total work).

Limitations

A cyclical movement pattern in testing has been found to elicit stronger correlations to sprint metrics than non-cyclical patterns (Dobbs et al., 2015), and we acknowledge that the horizontal testing was cyclical in nature, but not the vertical one. Furthermore, the participant population studied was active, but not trained or elite. Therefore, results may differ in more highly trained athletes. Given their relatively low RSI values, our participants would not be classified as well trained in plyometrics, which may impact the relationship between RSI and sprint metrics. Also, our study was sufficiently powered to detect *large* correlations, and not *moderate* ones. Several of the correlations were *unclear*, however with a larger sample size, significant correlations between sprint outcomes and vertical plyometric measures might have surfaced with tighter confidence intervals. Nonetheless, the strength of the relationship to sprint performance was still greater between horizontal plyometric outcomes than vertical ones.

Another limitation to consider is that correlation does not ensure causation. It has been recommended previously to use both axes of plyometrics within training protocols (Beato et al., 2018). An intervention study would be required to determine whether training horizontal plyometrics, vertical plyometrics, or a combination of both leads to superior improvements in sprint performances.

Conclusion

Given the strength of the association identified between maximal sprinting and horizontal plyometric outcomes, it is recommended that practitioners use horizontal total distance from a single-leg forward triple hop over either vertical RSI or vertical height from a single-leg drop jump as outputs when considering sprinting abilities. Although we identified this relationship, future research is required to identify a causal link and assess the extent of horizontal plyometrics impact on sprint performance. It could be interesting to examine whether plyometric training on the horizontal axis leads to superior gains in sprint performance than plyometric training on the vertical axis or a combination of both axes.

Chapter 4 – Summary and conclusions

Summary

In chapter two, we aimed to determine if there was an association between calf isometric strength, power, and strength-endurance metrics with MSA (0-10 m), MSS (30-40 m), and 40 m sprint times, and to explore the interrelatedness between calf metrics. Our results show *large* significant correlations between calf muscle power, strength-endurance (total work), and standing isometric strength metrics with sprint outcomes, the strongest association being the former. Furthermore, there were *large* correlations within strength-endurance measures, within isometric outcomes, between standing and seated isometric outcomes, and between power metrics and most other calf metrics

The primary aim in chapter three was to examine the potential association between single-leg plyometric outcomes on the horizontal and vertical axes with MSA (0-10 m), MSS (30-40 m), and 40 m sprint times. Our results show *large* significant correlations between horizontal plyometric outcomes and all sprint metrics. These correlations align with previous findings on the positive association between horizontal plyometric measures and sprint outcomes (Dobbs et al., 2015; Jiménez-Reyes et al., 2018; Maulder & Cronin, 2005; A. Nagano et al., 2007). Secondary aims included exploring the interrelatedness of plyometrics outcomes, as well as the relationship between calf muscle metrics and plyometric outcomes. Plyometric outcomes within the same axes were *largely* interrelated, with no *large* correlations between axes. The only *large* and significant correlation between plyometric and calf metrics was between horizontal total distance from the single-leg horizontal plyometric test and calf power.

Based on the strength of correlations detected, assessing calf muscle power is the most likely to provide insight into maximal 40 m sprint performance, followed by calf strength-endurance (total work). These two calf muscle tests can be conducted using minimal equipment and quantified using a free-to-use validated mobile application (Fernandez et al., 2023). It is recommended to use the total work metric instead of total repetitions to quantify triceps surae MTU strength-endurance using the CRT as this metric was more strongly related to sprint performances, in agreement with previous literature on its greater functional relevance (Hébert-Losier, Ngawhika, et al., 2023) and sensitivity to deficits (Silbernagel et al., 2010).

Based on the stronger relationship to sprint performances, we recommend practitioners relying on isometric test outcomes use standing isometric calf test protocols over seated ones when considering athletic sprint performances. As correlations do not ensure causation, future research is required to determine a causal link and assess if enhancing calf muscle abilities enhances sprint performance; or inversely, if acceleration and sprint training influences calf function.

In terms of plyometric outcomes, the strength of the associations detected suggest horizontal plyometric outcomes are more likely to provide insight into maximal sprint abilities than vertical ones. It is recommended that practitioners use horizontal total distance from a single-leg horizontal plyometric test over either horizontal RSI from the same test or vertical RSI and vertical height from a single-leg drop jump as performance metrics when considering sprint abilities in athletes. Similarly to the calf findings, although a significant relationship was identified, future research is required to identify a causal link and assess whether improving horizontal plyometric abilities impacts sprint performance, and whether improving sprint performances impacts horizontal plyometric metrics.

When considering all the examined calf metrics, calf power was the most likely to be a valid proxy of both 40 m sprint and horizontal plyometric performance. Strength-endurance total work was a more relevant measure than total repetitions, and standing isometric strength seemed more functional than seated isometric strength. All considered, we recommend use of the calf muscle power test to strength and conditioning coaches, sports medicine practitioners, and clinical medical personnel for athlete profiling specifically in relation to sprint and horizontal plyometric performance. Future research is required to determine the relevance of the various calf muscle test outcomes to determine risk of injury or readiness to return to play post injury.

Strengths

A strength of this thesis is the addition of test-retest reliability assessment of sprint performance outcomes in a subgroup of 19 participants. The between-day relative reliability was excellent across measures (ICC 0.938 to 0.978), and the absolute reliability was acceptable for most measures (CV < 2.2%), indicating that the sprint testing was reliable. There was, however, a systematic bias between sessions ($p \leq 0.001$), with slower times in the second session – likely due to inclement weather the day before testing.

Another identified strength of this thesis is the practical implications of findings that are translatable to laboratory, clinical, and field environments. The two metrics that were the most strongly related to sprint performances were peak power from the weighted power calf test and the horizontal plyometric total distance from a forward triple hope for distance. Although different equipment can be used to measure these outcomes, (including force plates, 3D motion capture, and linear position transducers for calf power and 3D motion capture and infrared light sensor systems for horizontal distance) it is possible to use low cost, portable equipment for quantification of these outcomes. For instance, the Calf Raise application is free-to-use and relies on 2D video recordings for quantifying calf power. A tape measure or 2D video can be used to quantify plyometric horizontal total distance from a forward triple hop for distance as a main horizontal plyometric performance measure. These systems are easy to use and quick to set up. As such, it becomes feasible to assess large cohorts of athletes in an efficient manner, indicating the potential of using these approaches for talent identification, athlete monitoring, and benchmarking in sport.

Limitations and future research directions

One limitation to the experimental studies of this thesis is that the participants were considered active, but not elite athletes, and were actively participating in a range of sports. Whilst we identified significant correlations between measures in our cohort, future studies are required to determine the strength of these correlations in elite athletes and athletes from specific sports. Such data would provide valuable benchmark data that are sport specific. Further, the participant pool in this study was of a mixed gender. The heterogeneity of participants favours the identification of correlations, but the diversity and relatively low sample size may have contributed to the wide confidence intervals. Although exploring gender-specific correlation within our data would have been possible, we elected not to do so given the low gender-specific sample size.

Another limitation is linked to the design of the experimental studies as these were cross-sectional in nature and not longitudinal. While relationships were identified, correlation does not ensure causation and future intervention studies are needed for this latter purpose.

Finally, this thesis focused on athletic performance, but there are potential implications of findings for injury prevention, rehabilitation, and return to play yet to be explored. In this context, assessing both sides are warranted as focusing only on the preferred side might overlook inter-limb differences.

Conclusion

The power test was the most strongly associated calf metric to sprint outcomes. This test is easy to implement and can be used in team-sport athletes as a maximal sprint acceleration and maximal speed performance indicator. Our findings emphasise that when completing the strength-endurance CRT, total work should be considered rather than repetitions as the former is more representative of function, congruent with research in both healthy and injured populations (Hébert-Losier et al., 2022; Silbernagel et al., 2006). When completing isometric calf testing, standing is more strongly linked to sprinting ability than seated likely due to its greater functional relevance.

The horizontal total distance from the horizonal plyometric assessment was the most strongly associated plyometric outcome to 40 m sprint metrics. This horizontal plyometric measure is easy to collect and could be used as a maximal sprint acceleration and speed performance indicator in athletes. Our findings imply that although related, plyometric testing on horizontal and vertical axes assess different muscle qualities and functional abilities. Horizontal plyometric testing appears more representative of sprint function, consistent with previous research (Dobbs et al., 2015). Calf muscle power abilities were more strongly related to horizontal plyometric outcomes than calf strength-endurance and isometric strength, highlighting its importance in explosive forward performance.

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Appendices

Appendix A – Supplementary documents

Table S1. Descriptive data from isometric calf outcomes – raw data and normalised to body mass (n = 30). Values are means ± standard deviations and counts.

Calf Test	All (n = 30)	Female (n = 16)	Male (n = 14)
Seated (N)	1236.289 ± 323.091	1285.255 ± 351.935	1184.478 ± 302.008
Seated (BM)	1.641 ± 0.316	1.644 ± 0.385	1.624 ± 0.253
Standing (N)	1835.303 ± 494.662	1963.939 ± 533.953	1696.137 ± 437.748
Standing (BM)	2.433 ± 0.438	2.514 ± 0.551	2.324 ± 0.292

Abbreviations: N, Newtons. BM, body mass.

Table S2. Correlations between best sprint times and best isometric calf muscle metrics (raw data and normalised to body weight) of active participants (n = 30). Values are Pearson correlations and 95% confidence intervals [lower, upper] with bias adjustment.

	MSA: 0 – 10 m time (s)	MSS: 30 – 40 m time (s)	0 – 40 m time (s)
Seated (N)	-0.470 [-0.706, -0.124] ***p* = 0.009**, *moderate*	-0.478 [-0.711, -0.134] ***p* = 0.008**, *moderate*	-0.459 [-0.699, -0.111] ***p* = 0.011**, *moderate*
Seated (BW)	-0.379 [-0.646, -0.015] **p = 0.039**, *moderate*	-0.341 [-0.621, 0.028] *p* = 0.065, *moderate*	-0.320 [-0.606, 0.052] *p* = 0.085, *moderate*
Standing (N)	-0.544 [-0.752, -0.219] ***p* = 0.002**, *large*	-0.574 [-0.770, -0.260] ***p* = < 0.001**, *large*	-0.562 [-0.763, -0.244] ***p* = 0.001**, *large*
Standing (BW)	-0.559 [-0.761, -0.240] ***p* = 0.001,** *large*	-0.555 [-0.759, -0.234] ***p* = 0.001**, *large*	-0.545 [-0.753, -0.221] ***p* = 0.002**, *large*

Notes. Significant p-values (p ≤ 0.05) are **emboldened**. Correlations considered *small*, *moderate*, and *large* when reaching 0.10, 0.30, and 0.50 (Cohen, 1992). Abbreviations: BW, normalised to body weight; MSA, maximum sprint acceleration; MSS, maximum sprint speed; N, Newtons.

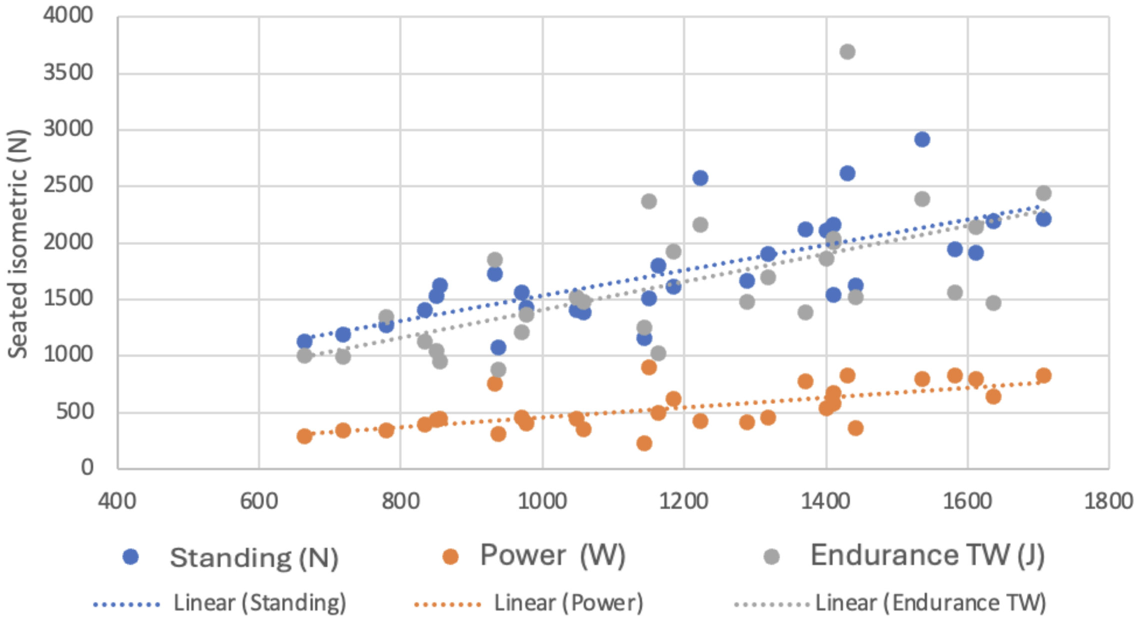


Figure S1.. Scatterplot of seated isometric calf muscle metrics against isometric standing, weighted power, and endurance total work metrics. Linear trend lines provided on plots. TW, total work.

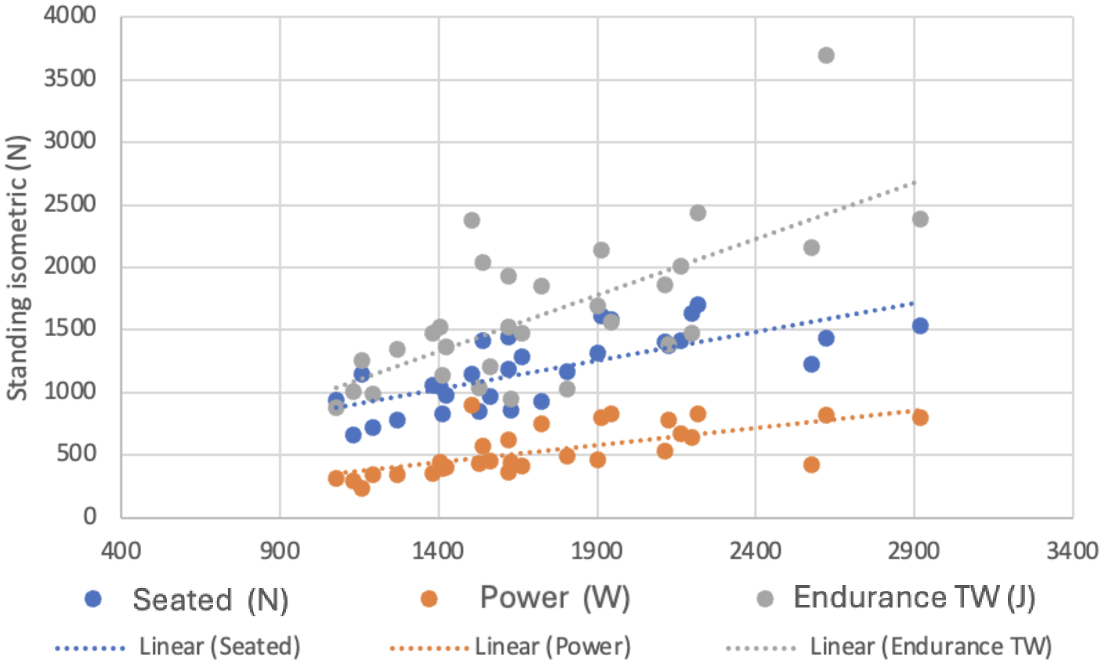


Figure S2. Scatterplot of standing isometric calf muscle metrics against isometric seated, weighted power, and endurance total work metrics. Linear trend lines provided on plots. TW, total work.

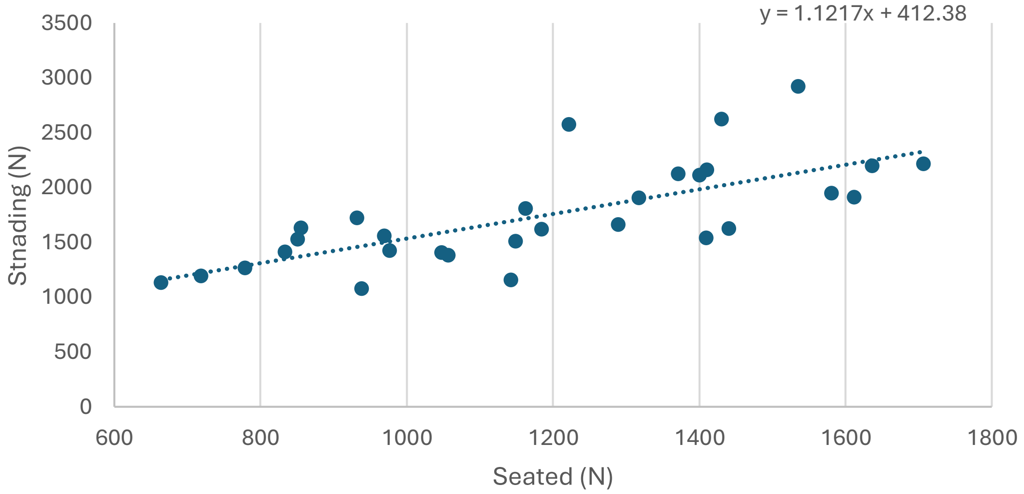


Figure S3. Scatterplot of seated isometric calf muscle metrics against isometric standing. Linear trend line and prediction equation provided on plot.

Appendix B – Ethics approval form

The University of Waikato
Private Bag 3105
Gate 1, Knighton Road
Hamilton, New Zealand

Human Research Ethics Committee
Julie Barbour
Telephone: +64 7 837 9336
Email:humanethics@waikato.ac.nz

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

25th April 2018

Kim Hébert-Losier

Dear Kim,

UoW HREC(Health)#2017-54: An examination of human movement and sport mechanics

Thank you for submitting your amended application HREC(Health)#2017-54 for ethical approval.

We are now pleased to provide formal approval for your project, where you will recruit sports people to perform a variety of typical sporting movements, and that you will monitor the movements using different types of technology, with a view to (a) preventing injury and (b) enhancing the movement.

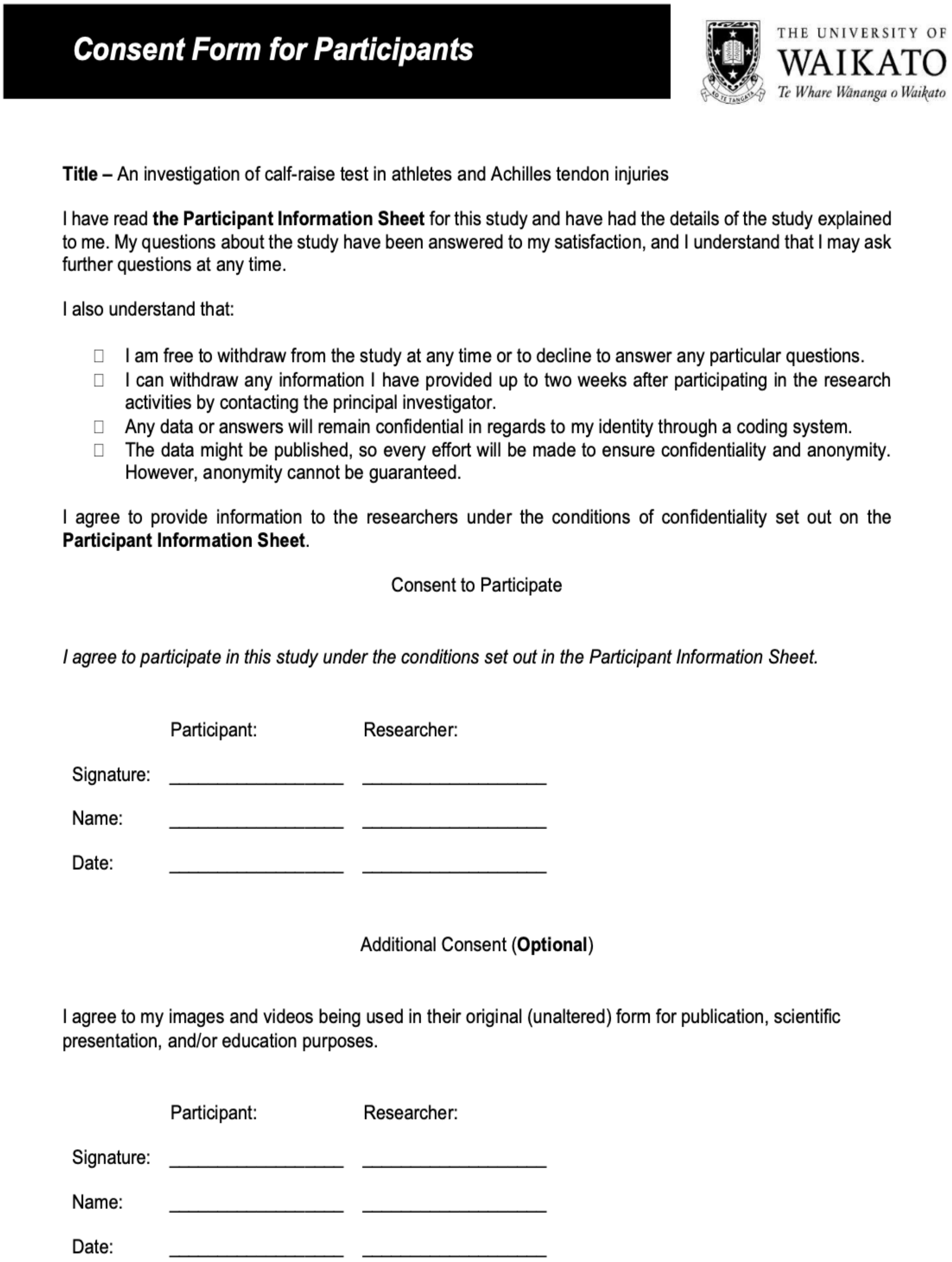
Please contact the committee by email (humanethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,

Julie Barbour PhD
Chairperson
University of Waikato Human Research Ethics Committee

Appendix C – Consent form for participants



Consent Form for Participants

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

Title – An investigation of calf-raise test in athletes and Achilles tendon injuries

I have read **the Participant Information Sheet** for this study and have had the details of the study explained to me. My questions about the study have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I also understand that:

- ☐ I am free to withdraw from the study at any time or to decline to answer any particular questions.
- ☐ I can withdraw any information I have provided up to two weeks after participating in the research activities by contacting the principal investigator.
- ☐ Any data or answers will remain confidential in regards to my identity through a coding system.
- ☐ The data might be published, so every effort will be made to ensure confidentiality and anonymity. However, anonymity cannot be guaranteed.

I agree to provide information to the researchers under the conditions of confidentiality set out on the **Participant Information Sheet**.

Consent to Participate

I agree to participate in this study under the conditions set out in the Participant Information Sheet.

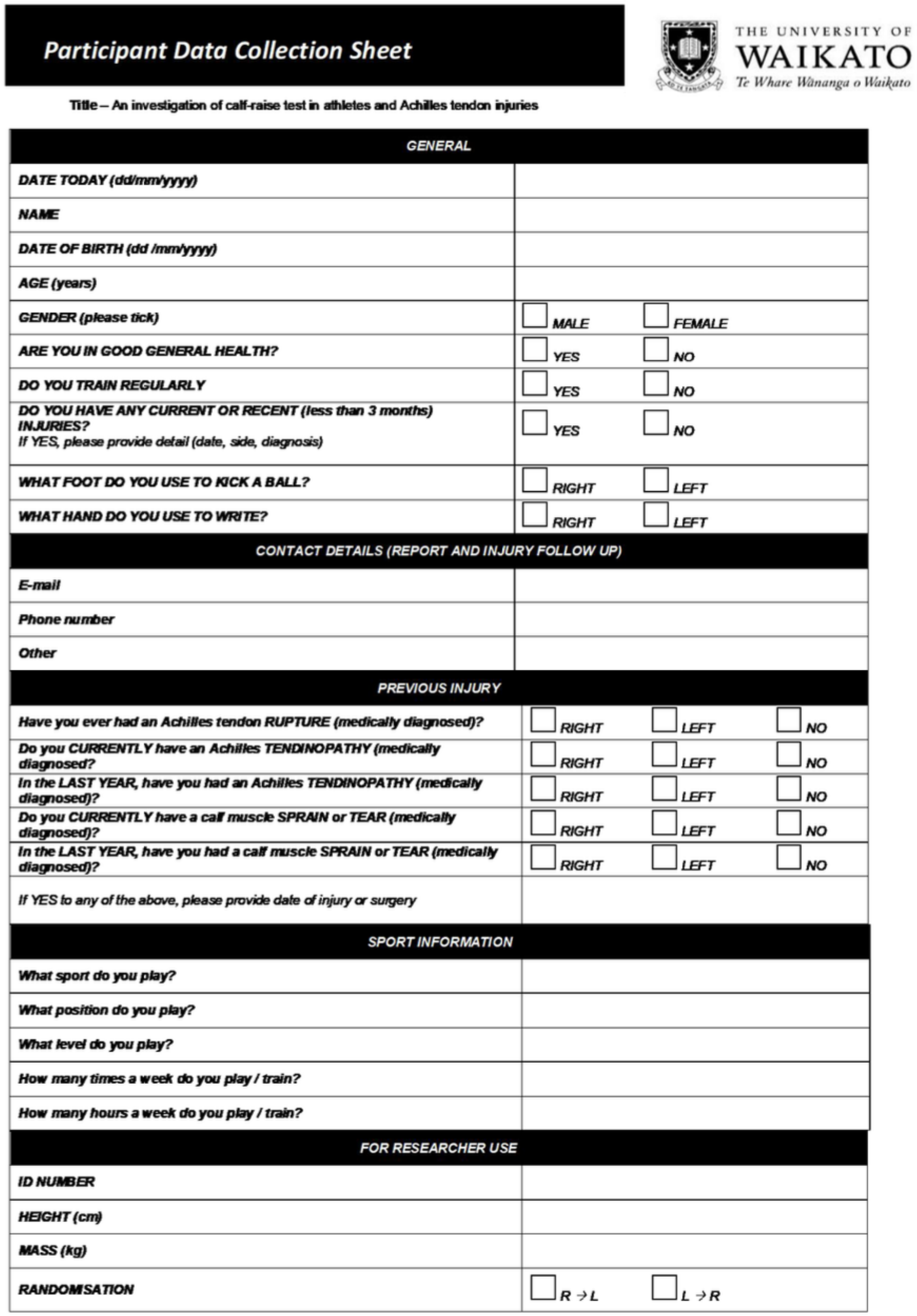
	Participant:	Researcher:
Signature:	__________________	___________________
Name:	__________________	___________________
Date:	__________________	___________________

Additional Consent (**Optional**)

I agree to my images and videos being used in their original (unaltered) form for publication, scientific presentation, and/or education purposes.

	Participant:	Researcher:
Signature:	__________________	___________________
Name:	__________________	___________________
Date:	__________________	___________________

Appendix D – Participant data collection sheet



Participant Data Collection Sheet

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

Title – An investigation of calf-raise test in athletes and Achilles tendon injuries

GENERAL			
DATE TODAY (dd/mm/yyyy)			
NAME			
DATE OF BIRTH (dd /mm/yyyy)			
AGE (years)			
GENDER (please tick)	☐ MALE	☐ FEMALE	
ARE YOU IN GOOD GENERAL HEALTH?	☐ YES	☐ NO	
DO YOU TRAIN REGULARLY	☐ YES	☐ NO	
DO YOU HAVE ANY CURRENT OR RECENT (less than 3 months) INJURIES? *If YES, please provide detail (date, side, diagnosis)*	☐ YES	☐ NO	
WHAT FOOT DO YOU USE TO KICK A BALL?	☐ RIGHT	☐ LEFT	
WHAT HAND DO YOU USE TO WRITE?	☐ RIGHT	☐ LEFT	
CONTACT DETAILS (REPORT AND INJURY FOLLOW UP)			
E-mail			
Phone number			
Other			
PREVIOUS INJURY			
Have you ever had an Achilles tendon RUPTURE (medically diagnosed)?	☐ RIGHT	☐ LEFT	☐ NO
Do you CURRENTLY have an Achilles TENDINOPATHY (medically diagnosed?	☐ RIGHT	☐ LEFT	☐ NO
In the LAST YEAR, have you had an Achilles TENDINOPATHY (medically diagnosed)?	☐ RIGHT	☐ LEFT	☐ NO
Do you CURRENTLY have a calf muscle SPRAIN or TEAR (medically diagnosed)?	☐ RIGHT	☐ LEFT	☐ NO
In the LAST YEAR, have you had a calf muscle SPRAIN or TEAR (medically diagnosed)?	☐ RIGHT	☐ LEFT	☐ NO
If YES to any of the above, please provide date of injury or surgery			
SPORT INFORMATION			
What sport do you play?			
What position do you play?			
What level do you play?			
How many times a week do you play / train?			
How many hours a week do you play / train?			
FOR RESEARCHER USE			
ID NUMBER			
HEIGHT (cm)			
MASS (kg)			
RANDOMISATION	☐ R → L	☐ L → R	