Establishing normative calf muscle function values in male rugby union athletes in New Zealand

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Abstract

Rugby union is a popular and fast-growing sport played internationally that involves high levels of physical contact and running activities. Unfortunately, these physical requirements can often lead to soft-tissue injuries. Some of the most common injuries resulting from rugby union occur to the triceps surae muscle-tendon unit (MTU). The calf raise test is one of the most commonly used tests in clinical practice to assess triceps surae muscle function, especially endurance. Clinicians and researchers have also used variations of this test in the assessment and management of individuals with Achilles tendinopathies or Achilles tendon ruptures, such as eccentric-concentric power tests. These data, however, generally derive from general or injured populations. To date, limited research has assessed triceps surae muscle function in rugby union athletes. Chapter One explores literature focusing on the triceps surae MTU (anatomy and injuries), rugby union, rugby-related injuries, and calf muscle testing procedures, specifically the calf raise test and eccentric-concentric power tests. Chapter Two aims to establish normative calf muscle function values in uninjured male rugby union athletes, examine the test-retest reliability of key measures across repeated testing sessions, and assess the validity of clinical testing methods using a novel Calf Raise application against research-grade laboratory equipment. Finally, Chapter Three summarises and discusses the key findings, limitations, and strengths of the experimental chapter, and addresses potential future research directions.

In Chapter Two, 120 rugby union athletes participated in establishing normative calf muscle function values, and were categorised into playing position (forwards and backs) and level of professionalism (International, Super Rugby, Provincial, and Club), while also considering age, leg dominance, body mass index (BMI), and previous MTU injuries. Eighteen athletes participated in test-retest reliability and performed an additional two testing sessions 1 week apart, whereas 20 athletes participated in validation of the Calf Raise application outcomes. All participants completed three calf muscle tests: 1) eccentric-concentric bodyweight power test; 2) eccentric-concentric weighted power test; and 3) concentric-eccentric endurance test. Reliability was acceptable across outcomes following familiarisation (coefficient of variation < 10%, intraclass correlation ≥ 0.83). Validity of the application outcomes against 3D motion capture and force plate data was also acceptable (coefficient of variation ≤ 6.6%, intraclass correlation ≥ 0.84). Forwards produced superior power during the bodyweight (59 W, $p = 0.007$) and weighted (73 W, $p < 0.001$) power tests, with playing level significantly influencing outcomes ($p < 0.009$). Super Rugby players were more powerful than Club and Provincial players in both power tests, and International in the bodyweight test. Backs completed more repetitions (3 repetitions, $p = 0.001$) and positive displacement (30 cm, $p = 0.001$) than forwards during endurance testing, with no influence of level. When accounting for the clinically relevant factors, BMI, age, and previous injury explained some of the differences observed between positions and levels. These findings support previous research highlighting differences in rugby union athletes based on position and level, and provide initial benchmark values of calf muscle function for rugby union players in New Zealand. Given the results stem from uninjured male rugby union athletes, results cannot be generalised to females, different rugby codes, and those with a current or rehabilitating MTU injury.

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We made it!

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List of Abbreviations

BMI – Body mass index

CRT – Calf raise test

CV – Coefficient of variation

ICC – Intraclass correlation coefficient

MTU – Triceps surae muscle-tendon unit

TE – Typical error

Thesis Overview

The main aim of this Thesis was to use the Calf Raise application to establish normative values of calf muscle function in uninjured male rugby union athletes in New Zealand. This Thesis consists of three chapters (**Figure 1**), with Chapter Two suitable for submission to a peer-reviewed journal. Chapter One assesses and reviews the literature on the triceps surae muscle-tendon unit, injuries to the triceps surae muscles and Achilles tendon, rugby union, rugby-related injuries, calf raise test, and eccentric-concentric power tests. The chapter concludes with the research statement for this Thesis. Chapter Two is an experimental study. The main aim was to provide normative values for calf muscle function in uninjured male rugby union athletes in New Zealand that accounted for rugby-related factors (position and level), but also considered age, leg dominance, body mass index, and previous injury. Since a novel Calf Raise application was used to quantify calf muscle function in rugby union athletes, a secondary aim was to assess the validity of outcomes and the test-retest reliability of key measures across repeated testing sessions. Chapter Three summarises and discusses the key findings, limitations, and strengths from Chapter Two, and addresses potential directions of future research.

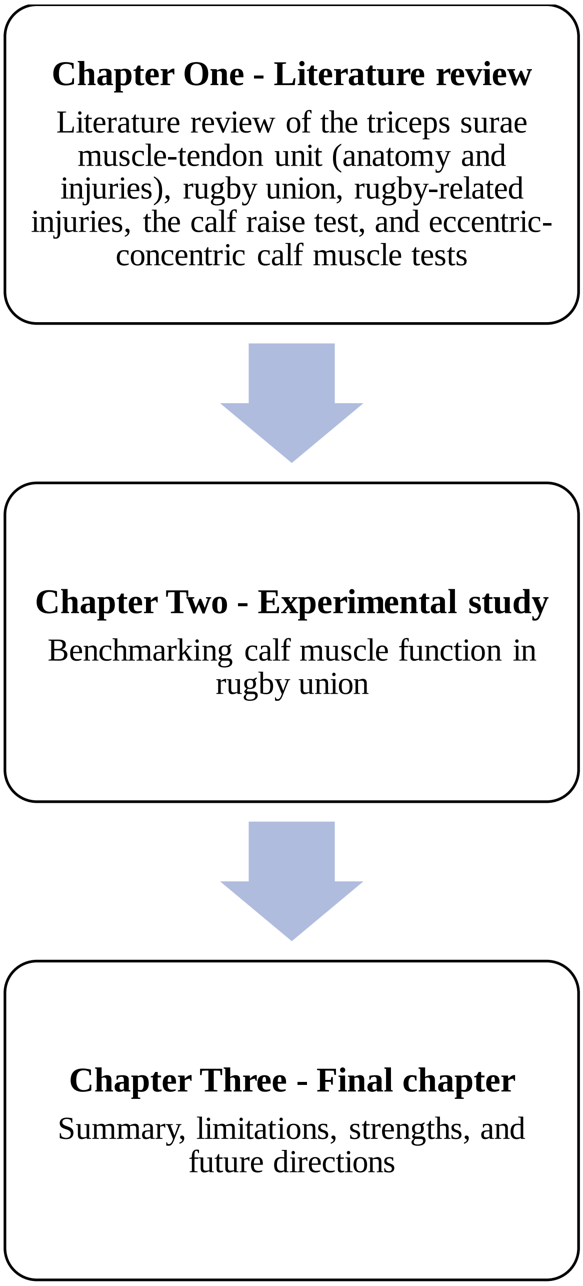

Figure 1. Flow diagram of the structure for this Thesis

Chapter 1 – Literature review

1.1 Abstract

Chapter One is a literature review that explores and assesses the scientific literature focusing on the anatomy and injuries to the triceps surae muscle-tendon unit (MTU), rugby union, rugby-related injuries, and calf muscle testing procedures, specifically the calf raise test (CRT) and eccentric-concentric power tests. The triceps surae MTU is an intricate and complex biological structure in humans. This unit plays a crucial role in locomotion and other movements, with the Achilles tendon specifically being able to withstand high amounts of loads. However, soft-tissue injuries to this region from running and sport-related activities are common. Rugby union is a team contact sport plated globally across all ages, genders, and ethnicities. The sport is best known for its physicality, long periods of play, and high intensity levels. Due to the number physical collisions, high-speed running, accelerations and decelerations, explosive movements, and continuous periods of play, soft-tissue injuries, particularly to the triceps surae MTU, are of particular concern. Previous literature has stated that rugby-related injuries to the triceps surae MTU are inevitable given the match demands and physicality of the sport, speed and intensity of match play, and enhanced physiological and training demands in rugby union with professionalisation of the sport. MTU injuries are of great concern in rugby union athletes due to the severity and recurrence rate of triceps surae muscle and Achilles tendon injuries, and reported Achilles tendon ruptures in presence of an ultrasonographically ‘normal’ tendon. The CRT has been used in numerous studies to assess triceps surae MTU function, especially endurance, and establish benchmark values within the general population. Researchers and clinicians have also used eccentric-concentric power tests to assess the power abilities of the triceps surae muscles in healthy and injured individuals. The use of the currently reported calf muscle function values in the literature, however, would be inappropriate for rugby union athletes given the unique anthropometric, physical, and physiological characteristics of rugby union players versus the general population. Given the limited research assessing triceps surae MTU function in rugby union athletes, calf muscle function values specifically for rugby union athletes should be established.

1.2 Triceps surae muscle-tendon unit

1.2.1 Triceps surae muscle-tendon anatomy

The human body is a complex organism with many different biological systems interacting with one another, but each with their own unique purpose to allow bodily functions to operate effectively (Bilder, 2016). The musculoskeletal system involves skeletal muscles that connect to bones via tendons, which work together as a unit alongside other muscle groups to produce movement, assist in joint stability, and help maintain proper body posture (Bilder, 2016; Hamill, Knutzen, & Derrick, 2015). The triceps surae muscle-tendon unit (MTU) is located on the posterior aspect of the lower leg and is the main contributor to plantar flexion (Floyd, 2009; Fukunaga, Ichinose, Ito, Kawakami, & Fukashiro, 1997; Murray, Guten, Baldwin, & Gardner, 1976). The triceps surae MTU consists of the triceps surae muscles and the Achilles tendon (Brazier et al., 2019; Hamill et al., 2015; Maffulli, Sharma, & Luscombe, 2004), which is the longest and one of the strongest tendons in the human body (McNutt & DeSilva, 2020; O'Brien, 1992). The triceps surae muscles are commonly referred to as the “calf muscles” and comprise of two gastrocnemius muscles (lateral and medial), the soleus muscle, and the plantaris muscle (Floyd, 2009). The gastrocnemius muscles are more superficial, while the soleus muscle is deeper and located beneath the gastrocnemius muscles. The plantaris muscle is a small muscle with a long thin tendon (Spina, 2007), absent in 7 to 20% of lower legs (Simpson, Hertzog, & Barja, 1991). While the plantaris muscle may be considered as part of the triceps surae muscle group, it has its own plantaris tendon separate of the Achilles tendon that connects the muscle to the calcaneus (Spina, 2007), and contributes to less than 1% of the total ankle plantar flexion force (Silver, de la Garza, & Rang, 1985). Hence, for the purpose of this Thesis, the triceps surae muscles will refer to the gastrocnemius (lateral and medial) and soleus muscles only.

The soleus and gastrocnemius muscles are a key muscle group involved in walking, running, jumping, and numerous sport-related activities (Hof, Geelen, & Van den Berg, 1983; Hof, Van Zandwijk, & Bobbert, 2002; Ishikawa, Komi, Grey, Lepola, & Bruggemann, 2005). Individual lower extremity muscles play crucial roles in contributing to accelerated sprinting (Pandy, Lai, Schache, & Lin, 2021). In fact, the plantar flexor muscles considerably contribute to maximal-effort accelerated sprints, wherein the soleus muscle primarily contributes to generating the upward impulse and the gastrocnemius muscles primarily contribute to generating propulsive and upward impulses during the early acceleration phase. Due to the high amounts of forces and loads on the triceps surae MTU during high speed running, sprints, accelerations, and decelerations (Green & Pizzari, 2017), it could be relevant to examine triceps surae muscle function in athletes to minimise risks of injury and inform training programmes.

Tendons are comprised of fibrous connective tissue and connect muscles to bones (Floyd, 2009). The extracellular matrix of tendons are composed primarily of collagen, accounting for ~60 – 85% of the tissue's dry weight (Kastelic, Galeski, & Baer, 1978). Tendons are able to store and release energy, and transmit forces generated by muscles to bones (Floyd, 2009). The Achilles tendon plays an important functional role in humans due to its involvement in locomotion and other movements linked with its ability to absorb large forces (Floyd, 2009; Fukashiro, Komi, Järvinen, & Miyashita, 1995). In Greek mythology, Achilles was deemed the greatest warrior to fight in the Trojan War. Post-Homeric myths state that Achilles was physically invulnerable after his mother dipped him into the River Styx as a child (Jones, 2010; Shampo & Kyle, 1992). Holding Achilles by his ankles, his ankles remained vulnerable having not touched the water. Achilles eventually died after being shot in the heel with a poisonous arrow, leading to the naming of the 'Achilles tendon'. The Achilles tendon is located in the inferior posterior region of the lower leg, and attaches the triceps surae muscles to the posterior surface of the calcaneus. Due to its large cross-sectional area and length, this tendon is able to withstand large amounts of forces and loads, as well as store and release a considerable amount of energy.

The Achilles tendon is estimated to store 35 J of elastic energy per step during running at 4.5 m/s (Ker, Alexander, Kester, Bibby, & Bennett, 1987) and 38 J during one-legged hopping (Lichtwark & Wilson, 2005). The peak force that the Achilles tendon can withstand is reported to reach 5.3 to 10 times body weight (Burdett, 1982). The average peak Achilles tendon forces during running are reported to increase from 6.46 to 7.71 times body weight and loading rates to increase from 70 to 110 body weights per second when running speeds increase from 3.3 to 5.6 m/s (Starbuck, Bramah, Herrington, & Jones, 2021). Whilst increased running speeds can be associated with increased plantar flexor moments, they may also contribute to an increase in Achilles tendon load and risk of Achilles tendinopathy or injury (Starbuck et al., 2021). A battery of clinically relevant exercises has been designed and proposed to gradually increase the magnitude of Achilles tendon loads in clinical practice and research (Baxter, Corrigan, Hullfish, O'Rourke, & Silbernagel, 2021). This study revealed that single-leg standing calf raises increase the peak Achilles tendon loads from 0.7 to 3 times body weight and loading rates from 3.6 to 13.1 body weights per second compared to a single-leg seated calf raises (Baxter et al., 2021). One-leg hopping, drop jumps, lateral hops, and forward hops resulted in the greatest loading indices, with peak Achilles tendon loads between 5.5 to 7.3 times body weight and loading rates reaching 67.7 body weights per second (Baxter et al., 2021). These figures underline the considerable amounts of loadings placed on the Achilles tendon in dynamic activities relevant to athletes. Furthermore, a recent study investigated the effects of implementing a specific muscle-tendon training on the mechanical efficiency of the soleus muscle during running (Bohm, Mersmann, Santuz, & Arampatzis, 2021).

Specifically, a 14-week triceps surae MTU training programme increased plantar flexion strength (10%) and tendon stiffness (31%), and reduced the metabolic cost of running (4%), supporting the importance of the soleus muscle for running and metabolic efficiency of locomotion. Together, these figures highlight how the triceps surae MTU is critical for locomotive and other activities ranging from walking to explosive power or endurance (Floyd, 2009; Hamill et al., 2015). These figures are also useful to guide rehabilitation, reconditioning, and conditioning practices specific for the triceps surae MTU. Gradual increases in training and exercise loads are not only important to promote adaptation and load tolerance of tissues and structures, but also to prevent injuries (Gabbett & Domrow, 2007).

Charles Darwin, the father of evolutionary theory, stated that humans are a product of evolution and the result of natural selection (Godfrey-Smith, 2009; Ruse, 2008). It was Darwin's theory that humans evolved from our closest relatives, the ape, particularly at a biological, physical, and physiological level (Ruse, 2008). One distinctive evolutionary trait of humans compared to apes is bipedal rather than quadrupedal locomotion, which involved the lengthening of the Achilles tendon, causing a cursorial adaptation (Bramble & Lieberman, 2004; Malvankar & Khan, 2011; McNutt & DeSilva, 2020). The length of the Achilles tendon allows humans to conserve around 35% of the metabolic cost for running, thereby enhancing endurance running abilities (Alexander, 1991; Bramble & Lieberman, 2004). In other words, lengthening of the Achilles tendon has enabled humans to adopt bipedal locomotion compared to our evolutionary relatives, and has enhanced the efficiency of locomotion. As bipedal mammals, humans rely heavily on our legs for regular locomotion and other everyday movements, such as standing, ascending and descending stairs, and other actions required for work, transportation, recreational activities, and exercise. Hence, injuries to the triceps surae muscle-tendon unit can impose a substantial burden and have a profound impact on individuals (Turner, Malliaras, Goulis, & Mc Auliffe, 2020).

1.2.2 Triceps surae muscle-tendon unit injuries

Physical activity participation results in many physical, physiological, and psychological benefits, including increased longevity; decreased risk of obesity, diabetes, cardiovascular diseases, certain cancers, and a range of chronic diseases; and enhanced mental and psychological wellbeing (Aune, Norat, Leitzmann, Tonstad, & Vatten, 2015; Eime, Young, Harvey, Charity, & Payne, 2013; Ghorbani et al., 2014; Lee et al., 2017; Lee, 2003). Unfortunately, sport participation is also linked with risk of musculoskeletal injuries, particularly to soft tissues and the lower extremities (Brazier et al., 2019; Yeung & Yeung, 2001). Calf muscle strain injuries are some of the most common soft-tissue injuries to occur during sport and other physical activities (Bengtsson, Ekstrand, & Hägglund, 2013; Hägglund, Waldén, & Ekstrand, 2013; Orchard, 2001), particularly when activities involve high-speed running, high volumes of running, and frequent accelerations and decelerations (Green & Pizzari, 2017). Despite the Achilles tendon being one of the most resilient tendons in the human body, it is also one of the most commonly injured ankle tendons (Maffulli et al., 2004). The Achilles tendon is an area that is susceptible to overuse injuries, and can lead to pain in other areas of the lower leg if not rehabilitated (Hamill et al., 2015). One of the most common injuries to occur in tendons is tendinopathy. Achilles tendinopathy is a type of overuse injury, and is associated with pain, swelling, stiffness, impaired tissue healing, and decreased performance (Abate et al., 2009; Brazier et al., 2019; Morrey, Dean, Carr, & Morrey, 2013). Achilles tendinopathy is considered one of the most common overuse injuries to occur in elite athletes, and may cause impairments in lower-leg function (Silbernagel, Gustavsson, Thomeé, & Karlsson, 2006). Cases of Achilles tendinopathy can be subdivided into two types based on the location of injury (Knobloch et al., 2006). Insertional Achilles tendinopathies are located at or in vicinity of the calcaneal insertion point, whereas midportion Achilles tendinopathies are typically located around 2 to 6 cm proximal to the calcaneal insertion. Achilles tendinopathies are common among both elite and recreational athletes, with midportion symptoms affecting around 9% of elite athletes involved in sports with running and jumping movements (Kingma, de Knikker, Wittink, & Takken, 2007) and between 5 and 13% of recreational runners (Lagas et al., 2020; Lysholm & Wiklander, 1987). The pathogenesis of tendinopathy are still unclear and are difficult to assess due to limited tendon biopsies obtained pre tendon rupture (Riley, 2004). Tendon structures are constantly changing due to different intrinsic (e.g., increased age affecting cell activity) and extrinsic (e.g., repetitive loads and overuse activity) factors. Degenerating tendons show an increase in cellular remodelling, resulting in a less mechanically stable tendon that is susceptible to tendon damage (Riley, 2004). In more serious cases, the Achilles tendon can sustain partial or complete ruptures often the result of reactive push-off movements, explosive actions, or stepping into a hole while walking (Hamill et al., 2015). During the early stages of rehabilitation of an Achilles tendon rupture, it is not advised to perform maximal effort exercises, as the risk of a reoccurring Achilles tendon ruptures is greatest during the first three months (Pajala, Kangas, Ohtonen, & Leppilahti, 2002; Rettig, Liotta, Klootwyk, Porter, & Mieling, 2005). Despite treatment, long-term consequences of Achilles tendon ruptures often include residual plantar flexion weakness and reduced functional performance (Möller, Lind, Movin, & Karlsson, 2002; Möller et al., 2001; Mullaney, McHugh, Tyler, Nicholas, & Lee, 2006).

Musculoskeletal injuries in sport are multi-factorial in nature (Meeuwisse, Tyreman, Hagel, & Emery, 2007) and difficult to predict (Bahr, 2016). Meeuwisse et al. (2007) have developed an injury aetiology model in which intrinsic factors determine an individual’s predisposition to injury, exposure to extrinsic factors affect the susceptibility of injury of individuals, and in the presence of an inciting event, an injury will occur. Some of the most common intrinsic risk factors linked with injuries resulting from physical activity include age, previous injury, bone and muscle strength, and neuromuscular control. Extrinsic factors take different forms in the context of physical activity participation, and include behavioural ones (e.g., competitors), match conditions, officiating decisions, and level of importance of a particular match (e.g., in-season versus final match). Should a serious sporting injury occur, the typical pathway is to withdraw the individual from further injurious exposure, enter the recovery and rehabilitation stage (medical attention and advice, rehabilitation, gradual return to play scenarios, and eventually full recovery) to then proceed to re-entering the athlete to full participation following re-conditioning. In the context of triceps surae MTU sport-related injuries, the incidence of calf muscle strains is higher in those with a history of calf muscle strains and in older athletes (Green & Pizzari, 2017). Return to play times are considerably longer in athletes with reoccurring calf muscle injuries (Green et al., 2020), which is of concern in sport. The injury aetiology model mentioned above assists in conceptualising injury; nonetheless, the aetiology of injury remains complex, dynamic, multifactorial, and context dependant (Bittencourt et al., 2016; Windt, Zumbo, Sporer, MacDonald, & Gabbett, 2017). A complex systems approach for sports-related injuries moving from risk factors to risk pattern recognition is needed to consider the interconnected and multidirectional interactions between all factors that contribute to sport-related injuries (Bittencourt et al., 2016). In the context of risk factors for sustaining an Achilles tendinopathy, there is limited high-quality studies relating to clinical risk factors based on a recent systematic review (Vlist, Breda, Oei, Verhaar, & Vos, 2019). Of relevance to sport, risk factors for Achilles tendinopathy include previous Achilles tendon injury (Brazier et al., 2019) and decreased plantar flexor strength (Mullaney et al., 2006).

There is emerging evidence that subgroups of Achilles tendinopathy exist that may require tailored approaches to rehabilitation (Hanlon, Pohlig, & Silbernagel, 2021). This emerging evidence has identified three latent subgroups associated with the development of Achilles tendinopathy: activity-dominant, psychosocial-dominant, and structure-dominant tendinopathies. The activity-dominant subgroup was the largest Achilles tendinopathy subgroup within the study. Patients in this group had higher physical activity levels, functional abilities, and quality of life scores; reported moderate symptoms; and were younger in age. It was recommended that rehabilitation methods for this subgroup consider load management, progressive rehabilitation, and gradual return-to-play scenarios to optimise recovery. The psychosocial-dominant subgroup had the worst reported symptoms, heightened psychological factors, poorest quality of life, high obesity levels, and were predominantly female. The authors suggested treating this subgroup more cautiously and with care, as patients were more psychologically susceptible. Addressing patients' beliefs and fears, and focusing on improving functional abilities and quality of life in this subgroup was emphasised. The structure-dominant subgroup was the smallest subgroup of patients. These patients were predominantly male and demonstrated the greatest tendon structural alterations, severe functional deficits and obesity levels; moderate levels of psychological factors and symptoms; low quality of life; and oldest age. To address patients within this subgroup, the authors strongly advised that treatment consider age, obesity, and co-morbidities, with rehabilitation progressing gradually in terms of intensity and frequency based on individual rehabilitation progression and level of function. The majority of athletes who sustain an Achilles tendinopathy, including rugby union, would fall under the activity-dominant subgroup; however, it remains important to consider all subgroups as potential causes of Achilles tendinopathy.

1.3 Rugby union

Many people believe that, in 1823, a man by the name of William Webb Ellis ignored the rules of traditional football, picked up the ball, and ran with the ball in his hands, creating the sport we now know as rugby union (Baker, 1981). While there are still many individuals who disagree with this story, William Webb Ellis continues to be recognised as the man who was responsible for the creation of rugby union. The Webb Ellis cup is still the name of the trophy awarded to the winning nation of the Rugby World Cup. On the 27th of March 1871, the first recorded international rugby union test match between Scotland and England took place in Edinburgh, Scotland, which saw the home side win the match (Collins, 1998). Since then, rugby union has evolved into the world-renowned sport we know today.

Nowadays, rugby union is a contact team-sport played globally across ages, genders, and ethnicities. A single team consists of 15 players on the field at one time that are subdivided into two main playing positions of eight forwards and seven backs (Brooks, Fuller, Kemp, & Reddin, 2005; Nicholas, 1997). A single match consists of two 40-minute halves with a 10 minute rest period in between halves, whereby the goal is to outscore the opposition before the conclusion of the match. The first Rugby World Cup took place in 1987, with the most recent Rugby World Cup (9th edition) taking place in Japan in 2019. Since the first World Cup, the match intensity, match speed, and physical demands of 'test' matches have grown considerably, especially since the professionalisation of the sport in 1995 (Smart, Hopkins, & Gill, 2013). Increased training intensity and training demands parallel the more competitive and intense match demands, with teams continuously seeking to improve on-field performance (Argus, Gill, & Keogh, 2012; Austin, Gabbett, & Jenkins, 2011; Black & Gabbett, 2014; Clarke, Anson, & Pyne, 2017; Clarke, Presland, Rattray, & Pyne, 2013; Smart et al., 2013; Yamamoto et al., 2020).

Rugby union is considered the national sport of New Zealand, with more than 160,000 players participating every season (New Zealand Rugby, 2021). In New Zealand, the majority of players involved at the Club level and below participate in rugby for recreation and leisure, while players involved at the Provincial, Super Rugby, or International level play rugby as a profession. Secondary school rugby in New Zealand (e.g., First-XV competitions, Condor 7's tournaments, etc.) can often lead to opportunities for student athletes to proceed to higher levels of play and competition. These athletes are often invited to join provincial rugby academies to improve and develop their rugby knowledge, skills, and performance. A typical goal for these younger athletes is to reach higher levels of professionalism. For younger athletes to achieve this goal, they need to attain certain levels of power and strength during their time within rugby academies or development squads. These steps will help to increase their chances of playing at the higher levels, being physically prepared for the increased match demands of professional rugby union, and ensure player succession (Argus et al., 2012). Individuals playing at the higher levels of rugby union demonstrate specific characteristics that vary based on position, spanning physiology (strength, power, speed, endurance etc.), anthropometry (height, mass, body mass index, etc.), and tactical skills. Several of these characteristics are deemed essential for success in professional rugby and to meet the physical demands of the sport (Argus, Gill, Keogh, Hopkins, & Beaven, 2009, 2010; Brazier et al., 2020; Posthumus et al., 2020; Quarrie & Hopkins, 2007; Smart et al., 2013). Forwards are involved in the more physical aspects of rugby union, such as scrums, mauls, rucks, and lineouts. Forwards therefore require greater body mass, body height, power, and strength to be successful in these components of the game (Gabbett, 2009; Olds, 2001). In contrast, backs display greater amounts of open play running, speed, and acceleration, which are needed to successfully beat defenders and score tries (Duthie, Pyne, & Hooper, 2003). With match characteristics (e.g., intensity and speed) constantly changing, athletes must adapt to meet these changes to continue being successful. Due to the different anthropometric and physiological characteristics between rugby union athletes of different levels and positions, rugby teams often implement baseline and in-season assessments (e.g., strength and power, bronco fitness test, speed and agility, etc.) to inform training programmes and provide insight in terms of how to optimise performance (Argus et al., 2012).

1.3.1 Rugby-related injuries

Given the considerable physical demands of rugby union, it is unsurprising that there is considerable risk of injury in this sport (Brazier et al., 2019; Brooks & Kemp, 2011; Williams, Trewartha, Kemp, & Stokes, 2013). These injuries range from minor and short-term injuries (e.g., cuts, gashes, contusions, etc.) to severe and long-term injuries (concussions, tendon and ligament ruptures, fractures, etc.). The age of a player, history of injury, and injury location influence the severity of injuries (Green & Pizzari, 2017; Uitenbroek, 1996). In New Zealand, soft tissue injuries represent 76% of rugby union related claims to the Accident Compensation Corporation, the nationwide personal injury claim scheme (Quarrie, Gianotti, & Murphy, 2020). Lower extremity injuries accounted for approximately one third (32.1%) of all soft-tissue injury claims, with athletes in the 21 – 30 years bracket ~4% more likely to register an injury claim than athletes 18 – 20 years and ~35% more likely than athletes 13 – 17 years (Quarrie et al., 2020). The rugby-related injury claims from males aged between 31 – 40 years was ~10% lower than males aged between 21 – 30 years, which is speculated due to the change in the competition level of rugby union; more specifically, the decrease in intensity and frequency of matches and trainings and more recreational and social nature of participation in the older age group. This study highlighted that male athletes moving into their 30's opt to play in social grades, resulting in less soft tissue injury claims (Quarrie et al., 2020). The higher odds of injury claims in the 21 – 30 years group versus the younger ones may be due to increases in training load, training and playing intensity, anthropometric and physical characteristics, history of injury, and duration of play in this particular age group of athletes.

Previous literature highlight that calf muscle and Achilles tendon injuries are of major concern in rugby union given their high recurrence rate, severity of injuries based on time needed to treat and return to play, and reported ruptures despite 'normal' tendon health on ultrasound imaging specifically shown in rugby athletes (Alfredson & Masci, 2019; Fitzpatrick, Naylor, Myler, & Robertson, 2018). Triceps surae MTU injuries are amongst the most common lower extremity injury in rugby union, particularly calf muscle strains and Achilles tendinopathies (Gabbett, 2003, 2005). As highlighted in the Triceps Surae Muscle Tendon Unit section of this Chapter, the triceps surae MTU is considerably involved in running, change of direction, acceleration, deceleration, jumping, and other physical activities relevant to rugby. To date, there is limited research highlighting 'normative' triceps surae MTU function in rugby union athletes. Benchmarking normative values of triceps surae MTU function in rugby union athletes should assist in their clinical and performance management by informing injury prevention, rehabilitation, reconditioning, and conditioning of athletes.

1.4 Calf muscle testing procedures

There are a range of triceps surae MTU assessment procedures used in the scientific literature (McAuliffe et al., 2019), including isokinetic, isoinertial, explosive and reactive strength, and clinical power and endurance testing procedures. In clinical and sport practice, teams and athletes do not always have access to advanced testing equipment, such as force plates or isokinetic dynamometers. Therefore, the use of more clinical-friendly tests is preferred, particularly for testing large cohorts.

The calf raise test (CRT) is the most commonly used test in clinical settings to assess the endurance capacity of the triceps surae muscles (Hébert-Losier, Newsham-West, Schneiders, & Sullivan, 2009a). However, assessing other functions of the triceps surae MTU is recommended in clinical practice (McAuliffe et al., 2019). In presence of Achilles tendinopathy, eccentric-concentric power is reduced (Silbernagel et al., 2006). Power is an important characteristic in team sport athlete, including rugby union (Gannon, Stokes, & Trewartha, 2016; Hansen, Cronin, Pickering, & Douglas, 2011). Therefore, the CRT and eccentric-concentric power tests are addressed in this section.

1.4.1 Calf raise test

Clinicians and researchers use the CRT in sports medicine to assess the endurance of the triceps surae MTU (Hébert-Losier et al., 2009a; Hébert-Losier, Schneiders, Newsham-West, & Sullivan, 2009b; Hébert-Losier, Wessman, Alricsson, & Svantesson, 2017). The objective of this test is to complete as many single-legged calf raise repetitions as possible, whilst following specific testing protocols. Testing ends once participants are no longer able to perform a single calf raise or to perform a proper repetition.

Counting the total number of repetitions performed is a common metric used to assess outcomes during the CRT. A number of studies have used the concentric-eccentric calf raise endurance test, although variations in protocol exists (Hébert-Losier et al., 2009a) that are likely to influence outcomes. For the number of repetitions, normative outcomes reported include 20 to 25 in the uninjured leg of patients 2 years post Achilles tendon rupture (Svensson et al., 2019), 24 repetitions across males and females aged 20 to 81 years (Hébert-Losier et al., 2017) and the least symptomatic leg of individuals with Achilles tendinopathy (Silbernagel et al., 2006), 32 to 35 repetitions on the uninvolved side of patients with Achilles tendon ruptures (Silbernagel, Nilsson-Helander, Thomeé, Eriksson, & Karlsson, 2010), and 40 repetitions in uninjured young adults (Hébert-Losier et al., 2011). This clinical metric, however, is not sensitive to variations in calf raise height or body mass displaced. The use of the total amount of concentric work (J) completed during the CRT is a more sensitive metric in the presence of Achilles tendon injury (Silbernagel et al., 2006). Previous studies using variations of the CRT to assess calf muscle function in general populations will typically use the number of repetitions (Hébert-Losier et al., 2011; Hébert-Losier et al., 2017; Silbernagel et al., 2010), as well as total positive displacement (cm) (Hébert-Losier et al., 2011) or total work (J) (Andreasen, Hansen, Bencke, Hölmich, & Barfod, 2021; Silbernagel et al., 2010) as their primary outcome measures.

While these studies have reported normative CRT outcomes in general populations, these results would not be appropriate to use for rugby union athletes due to physiological, anthropometric, and physical activity differences between populations. Previous studies in athletic populations have assessed calf muscle function in dancers primarily (Nunes, Tessarin, Scattone Silva, & Serrão, 2019; Zellers, van Ostrand, & Silbernagel, 2017); however, research of calf muscle function in contact sports using the CRT has not yet been reported. The literature mentioned above stating the high risks of sustaining injuries in rugby union, high loads that the Achilles tendon can be subjected to during sporting activities, and the long-term effects that triceps surae MTU injuries can have on performance and function further highlight the need to establish normative values of calf muscle function in rugby union athletes.

1.4.2 Eccentric-concentric power tests

Whilst the traditional concentric-eccentric CRT has been commonly used to assess the endurance capacity of calf muscles (Hébert-Losier et al., 2009a), assessing other functions of the triceps surae MTU is recommended in clinical practice (McAuliffe et al., 2019). A previous study has used eccentric-concentric testing protocols to assess the power of the triceps surae MTU using a linear position transducer (Silbernagel et al., 2006). Power was measured under a series of 23 and 33 kg loads in injured individuals while standing single-legged in a weight machine, and 43 kg loads when assessing the reliability of measures in uninjured participants. When tested under a 33 kg load, differences of ~22% in power output between the most and least symptomatic or uninjured side of individuals with Achilles tendinopathies were evident, indicating sensitivity of the test protocol. Similar to the CRT to assess the endurance, there is currently a lack of research specifically assessing triceps surae muscle power in rugby union athletes.

This Thesis proposes to assess the endurance and power abilities of the triceps surae MTU in rugby union athletes in New Zealand. The testing battery includes the CRT for endurance, and two eccentric-concentric power tests. Specifically, the three tests used in the experimental Chapter of this Thesis to assess triceps surae MTU function in rugby union athletes are: 1) eccentric-concentric bodyweight power test; 2) eccentric-concentric weighted power test; and 3) concentric-eccentric endurance test. The bodyweight and weighted eccentric-concentric calf muscle tests require athletes to perform three single-legged calf raise repetitions from the edge of a 20-cm box on each leg, whilst exerting maximal effort during each repetition. Beginning in full plantar-flexion active range of motion, athletes drop their heel as low as possible (eccentric contraction), then return to the starting position as quickly as possible (concentric contraction). In the weighted version, athletes are required to hold a 35 kg dumbbell on their ipsilateral shoulder to increase the load. The load of 35 kg was selected based on the previous study where the weighted power test performed under a 33 kg load was sensitive to Achilles tendinopathy (Silbernagel et al., 2006). The concentric-eccentric endurance test requires athletes to perform a maximal number of single-legged calf raises to the beat of a 60 Hz metronome, whereby athletes begin in dorsiflexion, lift their heel as high as possible on one beat (concentric contraction), and return back to the beginning position on the next beat (eccentric contraction). Testing is stopped when athletes are no longer able to perform repetitions, cannot maintain their repetitions to the beat of the metronome, or can no longer complete a proper repetition. These three calf muscle tests were selected to assess and better understand calf muscle function (power and endurance) in uninjured rugby union athletes, and chosen based on the scientific evidence reviewed and their clinical friendliness.

There are various tools and equipment used in the scientific literature to assess triceps surae muscle function. Some of the tools used include linear position transducers (Andreasen et al., 2021; Silbernagel et al., 2006; Silbernagel et al., 2010; Svensson et al., 2019), motion capture (Andreasen et al., 2021; Hébert-Losier & Holmberg, 2013), and force plates (Andreasen et al., 2021; Hébert-Losier, Schneiders, García, Sullivan, & Simoneau, 2012). Mobile technologies and smartphone applications are becoming increasingly prevalent in science and sport (Peart, Balsalobre-Fernández, & Shaw, 2019; Shaw et al., 2021). This Thesis uses a novel Calf Raise application (Hébert-Losier & Balsalobre-Fernandez, 2020) to extract relevant calf muscle test outcomes. The position of a circular marker placed on the foot (beneath the lateral malleolus and in line with the calcaneus) is tracked according to validated algorithms designed to track barbell motion (Balsalobre-Fernández, Geiser, Krzyszkowski, & Kipp, 2020). The bodyweight (kg) of individuals is entered into the application to compute work and power outcomes. One of the major benefits of using the Calf Raise application is that it allows testing both in and outside of a laboratory setting, allowing clinicians, researchers, medical staff, and strength and conditioning coaches to conduct calf muscle testing in convenient locations with minimal equipment needed.

1.5 Research statement

The CRT is commonly used to assess triceps surae endurance. Normative values in the general population has been established, allowing clinicians to evaluate an individual's outcomes against a set of normative values (Hébert-Losier et al., 2017). Given our limited knowledge of calf muscle function in rugby players, the high occurrence rate of injuries from participating in rugby union, and burden of triceps surae MTU in rugby, there appears to be a need for normative values of calf muscle function in rugby union athletes. Therefore, the aims of Chapter Two is to establish normative values of calf muscle function in uninjured rugby union athletes in New Zealand accounting for playing level and position, while taking into consideration age, leg dominance, body mass index, and previous MTU injury. The information may be beneficial in establishing injury prevention, rehabilitation, and training strategies. The results may help answer the question: “What is normal calf muscle function in rugby union athletes?”, which could be of interest to researchers, clinicians, medical teams, strength and conditioning practitioners, coaching staff, and rugby union athletes.

Chapter 2 – Experimental study

Benchmarking calf muscle function in rugby union

2.1 Abstract

Rugby union involves high levels of physical contact and running activities, often resulting in soft-tissue injuries, including to the calf muscle-tendon unit. To date, there is limited research assessing calf muscle function in rugby union athletes. We aimed to establish normative values of calf muscle function in male rugby union athletes accounting for rugby-related factors (position and level), while considering age, leg dominance, body mass index, and previous injury. We also examined test-retest reliability and validity of a novel Calf Raise app to quantify calf muscle function. In total, 120 athletes performed three single-legged calf muscle tests following familiarisation. A subset of 18 athletes performed these tests three times, 1 week apart, to assess reliability, and 20 athletes participated in validation of the app. Reliability was acceptable across outcomes following an initial familiarisation (coefficient of variation < 10%, intraclass correlation ≥ 0.83). Validity of the app outcomes against 3D motion capture and force plate data was also acceptable (coefficient of variation ≤ 6.6%, intraclass correlation ≥ 0.84). Forwards produced superior power during the bodyweight (59 W, $p = 0.007$) and weighted (73 W, $p < 0.001$) power tests, with playing level significantly influencing outcomes ($p < 0.009$). Super Rugby players were more powerful than Club and Provincial in both power tests, and International in the bodyweight test. Backs completed more repetitions (3 repetitions, $p = 0.001$) and positive displacement (30 cm, $p = 0.001$) than forwards during endurance testing, with no influence of level. When accounting for additional factors, body mass index, age, and previous injury explained some of the differences observed between positions and levels. This study provides initial benchmark values of calf muscle function for rugby union players in New Zealand.

Keywords: Biomechanics, endurance, football, strength and conditioning, sport science, triceps surae

2.2 Introduction

Rugby union is a team-contact sport played globally across all ages, genders, and ethnicities. The sport is best known for its physicality, physiological demands, levels of high-intensity, and continuous periods of play (Nicholas, 1997). Fifteen players per team take the field during games, with players assuming different positions that require unique physical, physiological, and tactical abilities. New Zealand-based research have shown playing level and position are linked with different attributes and demands (Smart et al., 2013), including body composition, speed, strength, power, and repeated sprint performance. Rugby union athletes with a greater body mass displayed superior strength, but slower running speeds, than those with a lower body mass. Differences across measures assessed were small-to-large between playing levels when comparing players not selected for provincial teams, provincial team players, and professional players (i.e., Super Rugby and International).

Rugby union also involves a considerable amount of running, change of direction, acceleration, deceleration, and sprinting. Research in elite English rugby union has identified position-specific speed and physical demands (Roberts, Trewartha, Higgitt, El-Abd, & Stokes, 2008). Inside and outside backs on average cover a significantly greater distance (6127 vs 5581 m) and perform more high-intensity runs (448 vs 298 m) than tight and loose forwards who are involved in more high-intensity activities (9:09 vs 3:04 min) during match play. Both New Zealand (Smart et al., 2013) and United Kingdom (Roberts et al., 2008) studies highlight different physical demands and attributes based on playing level and position. These differences between levels likely result from numerous factors, including variations in skills needed, experience, playing and training environments, training loads, and match intensity.

Given the known differences between playing positions and levels in rugby union, it is unsurprising that injury risk and incidence differ on this basis (Brazier et al., 2019; Brooks & Kemp, 2011; Williams et al., 2013). Rugby union positions can be categorised into forwards (tight and loose) and backs (inside and outside). Forwards are more at risk of sustaining injuries due to physical collisions in scrums, rucks, set pieces, and mauls, while backs are at greater risk of sustaining injuries in tackles (Bathgate, Best, Craig, & Jamieson, 2002; Brooks et al., 2005; Kaux et al., 2015). Analysis of Rugby World Cup injury rates revealed backs suffered more injuries than forwards (93.8 vs 85.0/100,000 match hours), with serious injuries in backs more often resulting from matches than trainings (Kaux et al., 2015). Research into specific playing positions provide conflicting views. Bird et al. (1998) found second row players (tight forwards) were at greater risk of lower extremity strains and sprains than other positions, followed by front row players; whereas Brooks et al. (2005) identified hookers, first-fives, and props as having the greatest injury rate, and loose forwards and locks as sustaining more severe injuries. In contrast, Best, McIntosh, and Savage (2005) indicated that openside-flanker, number 8, and outside centre players were the positions most frequently injured, with loose-head props sustaining the more severe injuries. Across these studies (Best et al., 2005; Bird et al., 1998; Brooks et al., 2005), the majority of injuries were to the lower-extremity soft tissues. A retrospective cohort study assessing rugby-related injury claims in New Zealand between 2005 – 2017 identified that 76% of reported cases were soft-tissue injuries, with 21% of these injuries being to the lower extremity (Quarrie et al., 2020).

Calf muscle (Green & Pizzari, 2017) and Achilles tendon (Brazier et al., 2019; Brooks & Kemp, 2011) injuries are of particular concern in rugby union due to their high recurrence rates, severity based on time needed to return to sport, and documented ruptures despite 'normal' tendon health on ultrasound imaging specifically shown in rugby union athletes (Alfredson & Masci, 2019; Fitzpatrick et al., 2018). To date, there is limited research on what constitutes 'normal' calf muscle function in rugby union athletes. This information could help guide injury prevention efforts and training strategies to improve performance. The traditional concentric-eccentric endurance calf raise test (CRT) is commonly used in research and clinical practice to measure the endurance capacity of the calf muscles (Hébert-Losier et al., 2009a). However, assessing more than the endurance capacity of the calf muscles in clinical practice is recommended (McAuliffe et al., 2019). Therefore, we aimed to establish normative values of calf muscle function for power and endurance in uninjured rugby union athletes accounting for playing level and position, while considering age, leg dominance, body mass index (BMI), and previous Achilles tendon or calf muscle injury. A secondary aim was to assess the reliability of key outcomes measures across repeated testing sessions and the validity of clinical outcomes collected using a novel mobile application.

2.3 Methods

2.3.1 Experimental approach to the problem

This cross-sectional study aimed to establish a normative dataset of calf muscle function from a New Zealand population of rugby union athletes that allowed exploration of potential differences between two playing positions (forwards, backs) and four levels of professionalism (International, Super Rugby, Provincial, and Club). A total of 126 athletes were required to detect a moderate difference (Cohen $f = 0.3$) with 80% power ($\beta = 0.20$) at a 5% significance level ($\alpha = 0.05$) based on ANCOVA F tests using G*Power 3.1.9.7. A subset of these individuals participated in test-retest reliability and concurrent validity testing (explained below).

2.3.2 Participants

A Human Research Ethics Committee [HREC(Health)2020#11] approved the research protocol that adhered to the Declaration of Helsinki. All participants were informed of the risks (delayed onset muscle soreness) and benefits (performance reports) of this investigation prior to signing an informed consent document. The inclusion criteria required athletes to: willingly provide informed consent; be New Zealand Rugby Union contracted rugby players or involved with a Provincial rugby union franchise; be able to complete all three calf muscle tests; have no current Achilles or calf muscle-tendon unit injuries; have no recent (less than 3 months) injuries to the lower extremity; and be cleared by their medical team to participate. Provincial athletes tested were involved with the Mitre 10 Cup competition, which took place during the 2020 New Zealand season. Testing of female and rugby sevens athletes was considered, but sample size for group comparisons was insufficient and availability of players was limited for inclusion.

Athletes from eight different rugby union provinces were recruited through word-of-mouth and invitation emails. In total, 130 male rugby union athletes were recruited and agreed to participate, achieving sample size requirements. Ten athletes were excluded on the day of testing due to current or recent injury, resulting in 120 athletes completing the calf muscle testing procedures. A subset of 23 athletes agreed to participate in the test-retest reliability study, which required them to complete an additional two testing sessions spread seven days apart. The reliability sessions were conducted at the same time of day to limit diurnal fluctuations in performance. Participants were encouraged to replicate their sleep, hydration, dietary, and training patterns between weeks. Five athletes sustained injuries or were unavailable for all retest occasions, and were excluded from the reliability dataset (n = 18 athletes in total). Another subset of 20 athletes agreed to participate in the validity portion of the study, which required them to attend one session in a biomechanics laboratory.

2.3.3 Procedures

Upon arrival for testing, participants signed the informed consent document and completed a short baseline questionnaire to collect clinically relevant factors. These factors included age, leg dominance (i.e., side used to kick a ball), and previous injury to the calf muscle tendon unit requiring medical attention. Body height to the nearest cm and mass to the nearest 0.01 kg were recorded barefoot using a stadiometer (seca model 0123) and scale (seca Model ESE813), respectively, from which BMI was computed. Black circular adhesive stickers (24 mm diameter) were placed onto white ones (32 mm diameter) to track test performance using the Calf Raise mobile application (Hébert-Losier & Balsalobre-Fernandez, 2020) and ensure colour contrast across skin tones (**Figure 2**). The markers were affixed to the skin of participants beneath the lateral malleolus in-line with the calcaneus. Participants were then required to perform three single-legged tests barefoot on a 20-cm high box on both right and left legs. Side was randomised, but test sequence was kept consistent and involved performing an: 1) eccentric-concentric bodyweight power test; 2) eccentric-concentric weighted power test; and 3) concentric-eccentric endurance test. Before each test, participants were familiarised with the protocol and performed three practice repetitions under supervision. These tests were based on procedures shown to have acceptable reliability (intraclass correlation coefficients, ICC 0.76 to 0.96) (Byrne, Keene, Lamb, & Willett, 2017; Hébert-Losier et al., 2017; Silbernagel et al., 2006), validity in Achilles tendinopathy patients (Silbernagel et al., 2006), and ability to identify meaningful differences in function (Silbernagel, Brorsson, & Lundberg, 2011). The tests were modified for ease-of-implementation in rugby union settings, such as using free-weights rather than a weight machine for the weighted power tests and a box rather than an incline for the endurance test.

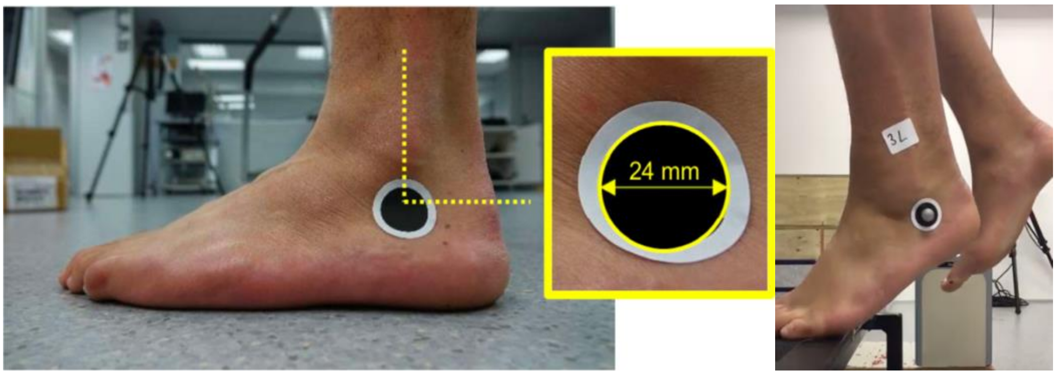

Figure 2. Calf muscle test marker placement (beneath the malleolus, in-line with the calcaneus) with and without reflective marker.

All testing was performed in a well-light environment on a flat hard surface. The edge of the box was positioned 50 cm from a wall and a strip of tape was placed on the midline of the box to indicate where participants needed to place their tested foot. An iPad (model A1822, Apple Inc., California, USA) was positioned on a stand 50 cm from the midline of the box on both the right and left sides in portrait orientation to enable marker tracking through full range of motion. Videos during testing were recorded using the Calf Raise application at 60 frames per second, and analysed by a single investigator (TN). The inter-rater reliability of the Calf Raise application was assessed internally. Three independent raters novice to the Calf Raise application performed the analysis independently of each other on 106 endurance videos and 119 bodyweight and weighted power test videos. Between rater reliability was excellent based on intraclass (ICC) and typical errors expressed as coefficients of variation (CV) values for both power tests (ICC ≥ 0.93, CV ≤ 5% for peak power) and the endurance test (ICC ≥ 0.99, CV ≤ 3% for number of repetitions, total positive displacement, and total positive work).

For the validity portion of this study, data were collected concurrently using the Calf Raise app and laboratory equipment. Specifically, a retroreflective marker of 12.5 mm in diameter was placed in the centre of the 24 mm black marker (**Figure 2**) to collect 3D motion using an 8-camera Oqus 700 3D motion capture system sampling at 60 Hz and the Qualisys Track Manager software v.2019.3.4930 (Qualisys AB, Gothenburg, Sweden). Ground reaction forces were recorded using a Kistler 9260AA6 multicomponent force plate and 5695B2 DAQ system (Kistler Group, Winterthur, Switzerland) sampling at 120 Hz, synchronised to the 3D motion capture, and collected within the Qualisys Track Manager.

2.3.3.1 Eccentric-concentric bodyweight power test

Following warm-up and familiarisation (3 repetitions per leg), participants completed three repetitions of the eccentric-concentric bodyweight power test (**Figure 3**). Participants started standing with their forefeet on the edge of the box, with the tested foot on the midline. Participants were permitted index and middle fingertips support from both hands on the wall at shoulder height for balance, and asked to maintain the knee of their tested leg straight during testing. Participants then lifted both heels as high as possible, raised the non-tested foot, and went “down and up” as quickly as possible, returning their heel to the initial position. Participants had ~2 seconds between repetitions, and 30 seconds rest between legs. The repetition with the greatest peak power (W) during ascent was used as primary outcome for each leg.

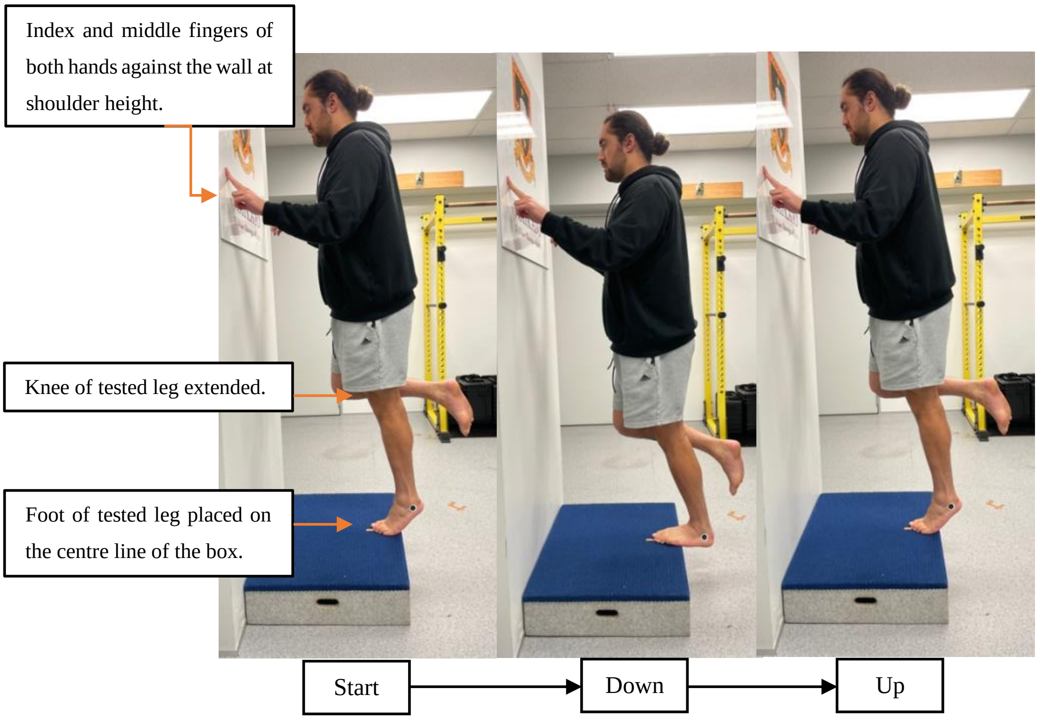

Figure 3. Eccentric-concentric bodyweight power test. Start, down, up = 1 repetition. Test involves completing 3 repetitions.

2.3.3.2 Eccentric-concentric weighted power test

Following warm-up and familiarisation (1 repetition per leg), the eccentric-concentric weighted power test was similar to the previous test, except participants held a 35 kg dumbbell on their ipsilateral shoulder and were permitted to place five fingertips of their opposite hand on the wall at shoulder height for balance support (**Figure 4**). A towel was placed over the shoulder to increase comfort.

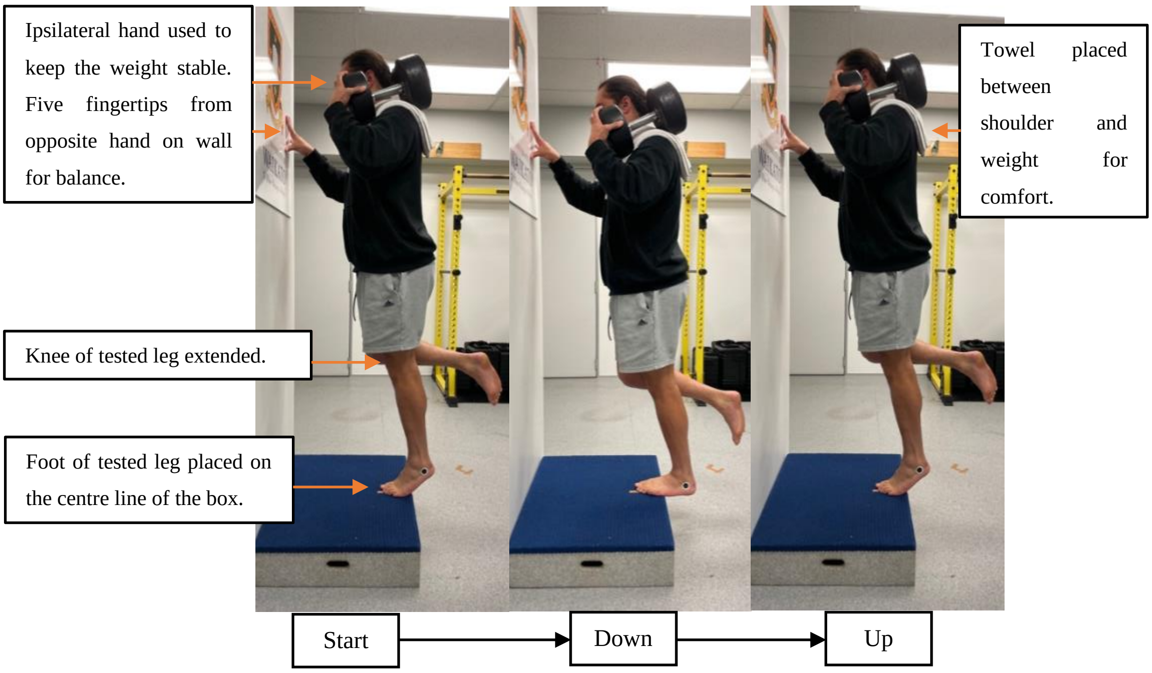

Figure 4. Eccentric-concentric weighted power test. Start, down, up = 1 repetition. Test involves completing 3 repetitions.

2.3.3.3 Concentric-eccentric endurance test

Following warm-up and familiarisation (3 repetitions per leg), participants were required to perform as many single-legged concentric-eccentric calf raises as possible (**Figure 5**). Participants started standing with their forefeet on the edge of the box, with the tested foot on the midline. Participants were permitted index and middle fingertips support from both hands on the wall at shoulder height for balance, raised their non-tested foot, and asked to maintain their knee of their tested leg straight during testing. Participants then raised and lowered their heel to the beat of a 60 Hz metronome, lifting their heel as high as possible in one beat and lowering it in one beat (i.e., 30 calf raise repetitions per minute). Participants were encouraged to go through the full range of available motion. The test was terminated once participants were no longer able to perform a single calf raise, could not maintain the beat of the metronome, demonstrated compensatory movements (e.g., knee flexion, trunk lean, hip strategy), or showed marked reduction in heel range of motion. Verbal encouragement was provided at regular intervals throughout testing. Two minutes rest was allocated between legs. The number of repetitions (*n*), total positive displacement (cm), and total positive work (J) were used as primary outcomes for each leg as is commonly done in the scientific literature (Andreasen et al., 2021; Hébert-Losier et al., 2011; Hébert-Losier et al., 2017; Silbernagel et al., 2010).

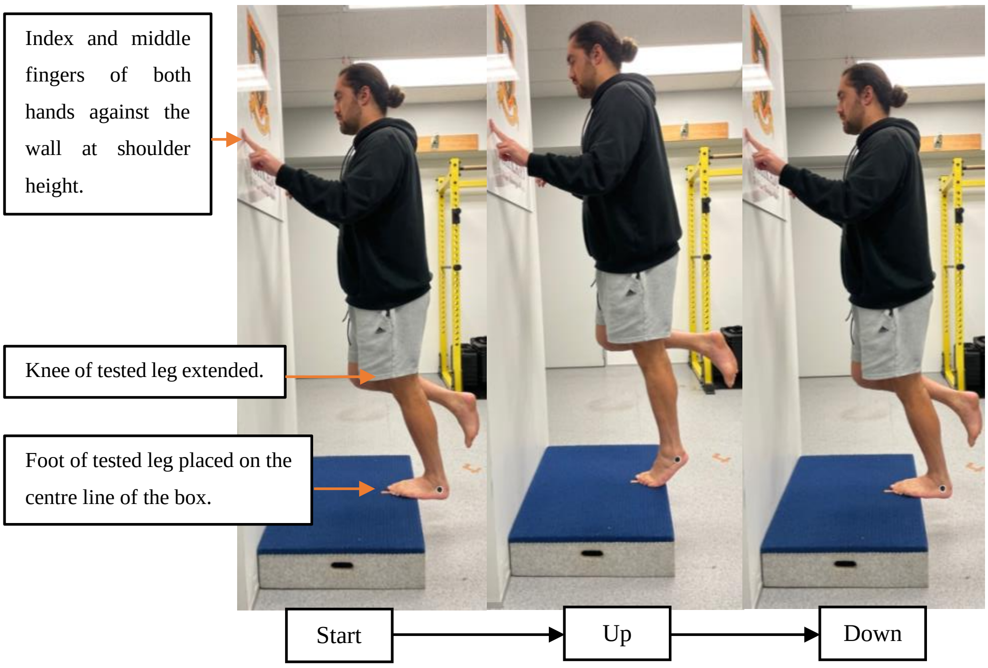

Figure 5. Concentric-eccentric endurance test. Start, up, down = 1 repetition. Test involves completing as many repetitions as possible.

2.3.4 Data extraction

The Calf Raise application (Hébert-Losier & Balsalobre-Fernandez, 2020) tracks a circular marker placed on the foot according to validated tracking algorithms used to track barbell motion (Balsalobre-Fernández et al., 2020). From the vertical displacement curve, the number of repetitions (*n*) is extracted, as is the total positive (vertical) displacement (d, in cm). Prior to data extraction, the mass of individuals recorded on the day is entered to enable positive work (J) computation during the endurance test as:

$$Work = F_g \times d$$

where F_g is computed as mass times gravitational acceleration (g = 9.81 m/s^2). Peak power (*W*) for the two power tests is extracted from the power curve, which is generated using:

$$Power = \frac{Work}{\Delta time} = \frac{F_g \times d}{\Delta time}$$

where $\Delta time$ is based on the sampling frequency (i.e., 0.0167 s). Note that the additional weight of 35 kg was added to the body mass when calculating power for the eccentric-concentric weighted power test.

The raw data collected using the Qualisys Track Manager software were exported to the .c3d format and processed using Visual3D Professional software version 2021.01.1 (C-Motion Inc., Germantown, Maryland, USA). Any marker data gaps up to 6 frames were interpolated using a third order polynomial fit algorithm, and a fourth order low-pass Butterworth filter with a cut-off frequency of 15 Hz was applied to the force plate data. From the marker vertical position data, peak positive power was extracted for the power tests and the number of repetitions, total positive displacement, and total positive work were extracted for the endurance test using the same approach described for the Calf Raise application data processing and extraction. In addition, work and power curves were generated using the force plate vertical ground reaction force and marker vertical displacement rather than using a fixed force based on the body mass and external weight.

2.3.5 Statistical analysis

Descriptive statistics were computed for all dependent and independent variables. Baseline characteristics of players were compared between positions and levels using two-way ANOVAs for continuous variables (age, mass, height, BMI) and contingency tables for binomial data (dominance, previous injury) with Chi Square or Fischer exact tests. From our data, we assessed the effect of position (forwards, backs) and level (International, Super Rugby, Provincial, Club) on peak power from the two power tests, and number of repetitions, total positive displacement, and positive work from the endurance test using Generalized Estimation Equation (GEE) (Liang & Zeger, 1986). We selected the GEE approach as estimates consider the variation within individuals in presence of multiple observations. The GEE approach provides an estimate with its 95% confidence interval [lower, upper] of the average effect in a population, applying robust standard errors to account for within-individual correlations.

The GEE models applied a Gaussian (normal) distribution for continuous variables (peak power, total displacement, and positive work), and Poisson distribution for count (number of repetitions). All GEE models clustered within-participant measures and applied an exchangeable correlation structure, which assumes observations have the same amount of correlation over time.

A stepwise regression technique was applied, wherein non-significant effects were sequentially removed from the model resulting in a final model containing only significant effects. The intercept and coefficients from these final models were extracted to provide researchers and clinicians a means of estimating outcomes from the calf muscle testing procedures under a known set of conditions. Forwards and International were the defined position and level references from which all estimates were derived. Two separate models were constructed. The first model contained rugby-related factors only (Model A: Position + Level), whereas the second contained rugby-related and other clinically relevant factors (Model B: Position + Level + BMI + Age +

Previous Calf Muscle Tendon Unit Injury + Leg Dominance). In presence of a significant main effect of level, pairwise comparisons of marginal linear predictions and their 95% confidence intervals were extracted.

Both reliability and validity of measures was analysed using a customizable statistical spreadsheet (Hopkins, 2015). Two-way mixed effects single measurement ICC (1,3), typical error (TE), and TE expressed as a coefficient of variation (CV) with 95% confidence intervals [lower, upper] were calculated to quantify relative (ICC) and absolute (TE and CV) reliability and concurrent validity. Relative reliability and agreement of measures were considered poor, fair, and good when corresponding ICC values were < 0.40, 0.40 to < 0.75, and ≥ 0.75 (Rosner, 2015), respectively, and excellent when above 0.90 (Portney, 2020). Absolute reliability and agreement were deemed acceptable when CV values were < 10% (Atkinson & Nevill, 1998); otherwise, they were deemed suboptimal.

The significance level was set at $p \leq 0.05$ for all analyses. Statistical analyses were performed using STATA/IC v.16.1 (StataCorp LP, TX, USA) and Microsoft Excel 2016 (Microsoft Corp., Redmont, WA, USA).

2.4 Results

Characteristics for all players included in the normative section of this study are presented in **Table 1** by position and level. Characteristics for the subset of players involved in the reliability and validity studies are provided as supplementary material (**Table S1**). The frequency of previous muscle tendon unit injuries was greater in forwards than backs (Chi-square $p < 0.001$) and was influenced by level (Fisher's exact $p < 0.001$), with more injuries reported in International-level players (61% yes). International and Super players were older than Provincial and Club ($p \leq 0.001$), as well as heavier than the other levels ($p \leq 0.023$), but of similar height. International players had larger BMI than Provincial and Club ($p \leq 0.018$), as did forwards compared to backs ($p = 0.0248$). Forwards were also taller and heavier than backs (both $p < 0.001$). All other baseline characteristics were similar between playing position and levels.

Table 1. Demographic characteristics of rugby union players by playing level and position. Values are mean ± standard deviation, range (minimum, maximum), and ratios.

Variable	International (n = 29)		Super Rugby (n = 34)		Provincial (n = 36)		Club (n = 21)	
	Forward (n = 19)	Back (n = 10)	Forward (n = 17)	Back (n = 17)	Forward (n = 20)	Back (n = 16)	Forward (n = 10)	Back (n = 11)
Age (years)	27.0 ± 3.3	26.4 ± 3.5	27.3 ± 4.7	24.4 ± 3.1	22.3 ± 2.1	24.2 ± 2.3	20.8 ± 1.4	19.9 ± 1.0
(min, max)	(20.8, 34.0)	(21.7, 32.0)	(20.0, 36.3)	(21.1, 30.4)	(19.6, 27.8)	(20.9, 29.3)	(18.8, 23.4)	(18.4, 21.9)
Height (m)	1.9 ± 0.1	1.8 ± 0.9	1.9 ± 0.1	1.8 ± 0.1	1.9 ± 0.1	1.8 ± 0.1	1.9 ± 0.1	1.8 ± 0.1
(min, max)	(1.8, 2.0)	(1.7, 2.0)	(1.8, 2.0)	(1.7, 1.9)	(1.8, 2.0)	(1.7, 2.0)	(1.7, 2.0)	(1.8, 2.0)
Mass (kg)	118.3 ± 8.5	93.1 ± 11.7	113.9 ± 7.7	94.8 ± 10.2	108.3 ± 8.8	91.1 ± 5.9	108.3 ± 7.3	88.3 ± 8.2
(min, max)	(104.5, 132.0)	(75.3, 110.5)	(103.0, 128.0)	(73.0, 112.0)	(93.0, 124.8)	(81.0, 105.6)	(93.5, 116.1)	(67.6, 99.9)
BMI (kg/m^2)	32.5 ± 2.8	28.1 ± 2.1	31.4 ± 2.5	27.9 ± 1.7	30.5 ± 2.8	27.5 ± 1.4	30.9 ± 3.1	26.1 ± 2.1
(min, max)	(28.9, 38.6)	(25.5, 32.2)	(28.2, 35.7)	(24.9, 32.0)	(27.0, 36.6)	(24.6, 29.9)	(26.9, 38.0)	(22.1, 29.2)
Dominant (right:left)[a]	18:1	9:1	14:3	15:2	18:2	14:2	6:4	10:1
MTU (no:yes)[b]	19:18	17:5	24:12	34:1	34:4	30:3	20:1	22:1

[a] Leg used to kick a ball

[b] Self-reported previous calf muscle or Achilles tendon injury requiring medical care

Abbreviations: BMI, body mass index. MTU, triceps surae muscle-tendon unit

Table 2. Calf muscle test outcomes by position and playing level for dominant and non-dominant legs combined. Values are mean ± standard deviation and range (minimum, maximum).

	International (n = 29)		Super Rugby (n = 34)		Provincial (n = 36)		Club (n = 21)	
Variable	Forward (n = 19)	Back (n = 10)	Forward (n = 17)	Back (n = 17)	Forward (n = 20)	Back (n = 16)	Forward (n = 10)	Back (n = 11)
Eccentric-concentric power								
Bodyweight (W)	732.9 ± 108. 6	602.6 ± 108.7	796.1 ± 126.7	684.4 ± 141.0	675.3 ± 106.4	661.1 ± 107.3	659.0 ± 100.8	619.8 ± 161.9
(min, max)	(519.0, 1007.0)	(395.0, 867.0)	(588.0, 1082.0)	(441.0, 1055.0)	(435.0, 901.0)	(442.0, 1030.0)	(485.0, 870.0)	(396.0, 929.0)
Bodyweight + 35 kg (W)	772.5 ± 136.3	589.2 ± 101.0	757.9 ± 160.2	722.9 ± 173.1	674.4 ± 125.1	672.0 ± 143.4	629.7 ± 149.7	584.7 ± 179.0
(min, max)	(502.0, 1098.0)	(375.0, 784.0)	(451.0, 1145.0)	(429.0, 1174.0)	(435.0, 942.0)	(361.0, 924.0)	(328.0, 909.0)	(334.0, 979.0)
Concentric-eccentric endurance								
Repetitions (n)	20 ± 4	20 ± 4	18 ± 4	22 ± 6	21 ± 6	23 ± 7	18 ± 6	22 ± 7
(min, max)	(12, 32)	(13, 29)	(12, 29)	(9, 32)	(11, 34)	(12, 46)	(7, 29)	(13, 37)
Displacement (cm)	188.9 ± 46.0	185.8 ± 35.8	178.8 ± 39.7	208.7 ± 56.1	177.3 ± 43.1	228.1 ± 60.6	185.8 ± 43.5	212.8 ± 66.7
(min, max)	(118.0, 317.0)	(135.0, 263.0)	(120.0, 287.0)	(115.0, 331.0)	(102.0, 313.0)	(104.0, 353.0)	(88.0, 287.0)	(121.0, 362.0)
Work (J)	2078.5 ± 556.1	1952.1 ± 511.7	1987.6 ± 397.6	1979.1 ± 566.8	1887.4 ± 439.3	2043.9 ± 550.71	1981.7 ± 480.9	1803.2 ± 444.6
(min, max)	(1154.0, 3302.0)	(1020.0, 2903.0)	(1357.0, 2958.0)	(1111.0, 3119.0)	(1170.0, 3122.0)	(889.0, 3360.0)	(936.0, 2822.0)	(1060.0, 2626.0)

2.4.1 Normative outcomes

A summary of the calf muscle test outcomes by position and level is provided in **Table 2**. Results from the GEE analyses for Model A (rugby-related factors) and Model B (rugby-related and clinically relevant factors) are presented in **Table 3**.

Table 3. Summary of the generalised estimation equation analyses for all calf muscle test outcomes. Estimates are presented with their 95% CI [lower, upper][† ‡].

Variable	Estimate [lower, upper]	P-value (< 0.05)
Eccentric-concentric power		
Bodyweight (W)		
Model A (rugby only)		
Intercept	**714.3 [670.3, 758.4]**	**<0.001**
Position		
Backs (Forwards)	-72.8 [-112.2, -33.3]	<0.001
Level		
Super (International)	58.8 [4.0, 113.6]	0.035
Provincial (International)	-8.7 [-63.5, 46.0]	0.755
Club (International)	-33.0 [-94.7, 28.8]	0.295
Provincial (Super)	-67.6 [-118.8, -16.3]	0.010
Club (Super)	-91.8 [-150.4, -33.3]	0.002
Club (Provincial)	-24.3 [-82.9, 34.3]	0.417
Model B (rugby plus others)		
Idem to Model A		
Bodyweight + 35 kg (W)		
Model A (rugby only)		
Intercept	**718.6 [663.1, 774.1]**	**<0.001**
Position		
Backs (Forwards)	-59.3 [-108.1, -10.5]	0.017
Level		
Super (International)	49.0 [-19.2, 117.2]	0.159
Provincial (International)	-15.1 [-83.2, 53.1]	0.665
Club (International)	-77.2 [-153.9, -0.5]	0.049
Provincial (Super)	-64.1 [-127.3, -0.9]	0.047
Club (Super)	-126.2 [-198.4, -54.0]	0.001
Club (Provincial)	-62.2 [-134.4, 10.1]	0.092
Model B (rugby plus others)		
Intercept	**291.8 [24.9, 558.7]**	**0.032**
Level		*(0.026)*
Super (International)	52.3 [-15.1, 119.7]	0.128
Provincial (International)	-4.2 [-72.0, 63.5]	0.903
Club (International)	-57.9 [-135.1, 19.4]	0.142
Provincial (Super)	-56.5 [-118.9, 5.9]	0.076
Club (Super)	-110.1 [-182.3, -38.0]	0.003
Club (Provincial)	-53.6 [-125.3, 18.0]	0.142
BMI	13.3 [4.6, 22.0]	0.003
Concentric-eccentric endurance		
Repetitions (n)		
Model A (rugby only)		
Intercept	**19.4 [18.4, 20.4]**	**<0.001**
Position		
Backs (Forwards)	2.7 [1.2, 4.3]	0.001
Model B (rugby plus others)		
Intercept	**33.1 [25.7, 40.4]**	**<0.001**

MTU		
Yes	-1.4 [-2.4, -0.3]	0.011
BMI	-0.4 [-0.7, -0.2]	0.001
Displacement (cm)		
Model A (rugby only)		
Intercept	**199.9 [187.7, 212.1]**	**<0.001**
Position		
Backs (Forwards)	30.2 [12.3, 48.2]	0.001
Model B (rugby plus others)		
Intercept	**286.5 [203.5, 321.8]**	**<0.001**
Position		
Backs (Forwards)	27.9 [10.1, 45.8]	0.002
Age	-2.5 [-4.9, -0.2]	0.034
Work (J)		
Intercept	**1977.4 [1895.8, 2058.9]**	**<0.001**

Abbreviations: BMI, body mass index. MTU, triceps surae muscle-tendon unit.
† Estimates derive from generalized estimation equation models with forwards and International as reference conditions. Pairwise comparisons derive from marginal linear predictions.
‡ Comparisons are presented as: Comparison (reference). For example, Backs (Forwards) indicate that backs are compared against forwards.

2.4.1.1 Eccentric-concentric bodyweight power test

In the rugby-only model, position and level significantly influenced bodyweight power (**Table 3**). Forwards produced greater power than backs (72.8 W, $p < 0.001$). Pairwise comparisons revealed that Super Rugby athletes were more powerful than International (58.8 W, $p = 0.035$), Provincial (67.6 W, $p = 0.010$), and Club (91.8 W, $p = 0.002$). Adding the clinically relevant factors did not alter the results.

2.4.1.2 Eccentric-concentric weighted power test

Playing position and level significantly influenced weighted power when rugby-related factors were considered in isolation (**Table 3**). Forwards produced greater power than backs (59.27 W, $p = 0.017$). Pairwise comparisons revealed that International and Super Rugby players were more powerful than Club (77.2 W and 126.2 W, $p \leq 0.049$), with Super Rugby also more powerful than Provincial (64.1 W, $p = 0.047$). When adding the clinically relevant factors to the model, position was no longer significant and differences between levels were attenuated, with only Super Rugby remaining significantly more powerful than Club (110.1 W, $p = 0.003$). Each increase in BMI unit was associated with a 13.3 W increase in weighted power output ($p = 0.003$) (**Table 3**).

2.4.1.3 Concentric-eccentric endurance test

When considering rugby-related factors only, backs completed a greater number of repetitions (2.7 repetitions) and total positive displacement (30.2 cm, both $p = 0.001$) than forwards, with no significant effect of level. However, the difference in the number of repetitions between positions was no longer significant when adding clinically relevant factors. A history of prior calf muscle tendon-unit injury and greater BMI negatively affected the number of repetitions completed. Age also influenced total displacement (-2.5 cm for each 1-year change, $p = 0.034$), reducing the positional difference to 27.9 cm ($p = 0.002$) between forwards and backs. Neither the rugby-related nor clinically relevant factors influenced the positive work completed (**Table 3**). The coefficients indicate that rugby athletes on average complete 1977.4 J during the concentric-eccentric endurance test.

2.4.2 Reliability

Outcomes from the test-retest reliability study are summarised in **Table 4**. Reliability of outcomes were fair across measures between the first and second test occasion (ICC 0.70 to 0.75) and good between the second and third test occasion (ICC 0.83 to 0.87). The absolute reliability between the first and second session was suboptimal across measures (CV 11 to 15%), but acceptable between the second and third session (CV < 10%).

Table 4. Comparison of Calf Raise app measures between test-retest occasions. Data are mean ± standard deviations, ranges (minimum, maximum), and statistical estimates with 95% confidence intervals [lower, upper] from 18 participants.

Variable	D1	D2	D3	ICC D2 – D1	ICC D3 – D2	TE D2 – D1	TE D3 – D2	CV (%) D2 – D1	CV (%) D3 – D2
Eccentric-concentric power									
Bodyweight (W)	688.5 ± 152.3	695.6 ± 115.6	684.2 ± 129.0	0.72	0.83	73.4	51.0	10.6	7.4
(min, max), [lower, upper]	(501.9, 1158.0)	(441.8, 1000.1)	(458.4, 1055.7)	[0.51, 0.84]	[0.70, 0.91]	[59.5, 95.7]	[41.2, 66.8]	[8.6, 13.8]	[6.0, 9.7]
Bodyweight + 35 kg (W)	715.8 ± 201.4	704.0 ± 152.6	697.1 ± 146.7	0.70	0.88	100.1	53.2	14.1	7.6
(min, max), [lower, upper]	(435.9, 1340.1)	(361.0, 1038.9)	(453.3, 1105.5)	[0.48, 0.83]	[0.78, 0.94]	[81.2, 131.6]	[43.1, 69.4]	[11.4, 18.4]	[6.2, 9.9]
Concentric-eccentric endurance									
Repetitions (n)	20 ± 5	21 ± 5	20 ± 5	0.75	0.88	2.8	1.8	13.3	8.9
(min, max), [lower, upper]	(11, 31)	(11, 34)	(11, 29)	[0.56, 0.86]	[0.78, 0.94]	[2.2, 3.6]	[1.5, 2.4]	[10.8. 17.3]	[7.2, 11.6]
Displacement (cm)	212.4 ± 53.2	223.7 ± 62.6	206.9 ± 54.8	0.72	0.88	31.3	20.9	14.4	9.7
(min, max), [lower, upper]	(125.0, 353.0)	(104.3, 359.7)	(123.2, 335.5)	[0.52, 0.85]	[0.78, 0.94]	[25.4, 40.9]	[16.9, 27.2]	[11.7, 18.7]	[7.9, 12.6]
Work (J)	2247.4 ± 571.7	2337.8 ± 619.8	2163.8 ± 566.1	0.67	0.87	345.7	219.8	15.1	9.8
(min, max), [lower, upper]	(1345.6, 3509.3)	(1276.7, 3872.2)	(1290.9, 3629.7)	[0.45, 0.82]	[0.76, 0.93]	[280.4, 451.0]	[178.3, 286.7]	[12.2, 19.7]	[7.9, 12.7]

Abbreviations: BW, bodyweight. CV, coefficient of variation. D1, day one. D2, day 2. D3, day 3. ICC, intraclass correlation coefficient. TE, typical error.

2.4.3 Validity

The comparison between Calf Raise app outcomes against laboratory-based outcomes are summarised in **Table 5**. Validity of outcomes across all testing measures were good to excellent when comparing the Calf Raise app against the force plate and 3D motion capture (ICC 0.84 to 1.00). The absolute validity across all testing measures were acceptable when comparing the Calf Raise app against the force plate and 3D motion capture also (CV < 10%).

Table 5. Comparison between Calf Raise app and laboratory measures. Data are mean ± standard deviations, ranges (minimum, maximum), and statistical estimates with 95% confidence intervals [lower, upper] from 20 participants.

Variable	App	Lab	Diff[†]	ICC	TE[†]	CV (%)[†]
Eccentric-concentric bodyweight						
Power app vs. force plate (W)	669.6 ± 121.4	748.1 ± 140.1	78.6 ± 64.1	0.89	45.3	6.4
(min, max), [lower, upper]	(426.0, 965.0)	(473.8, 1044.8)	[58.1, 99.1]	[0.79, 0.94]	[37.1, 58.2]	[5.5, 6.6]
Power app vs. 3D mocap (W)	669.6 ± 121.4	633.6 ± 107.3	-35.9 ± 50.9	0.91	36.0	5.5
(min, max), [lower, upper]	(426.0, 965.0)	(413.1, 886.2)	[-52.2, -19.7]	[0.83, 0.95]	[29.5, 46.2]	[4.5, 7.1]
Eccentric-concentric bodyweight + 35 kg						
Power app vs. force plate (W)	627.2 ± 96.6	619.2 ± 103.3	-7.9 ± 58.5	0.84	41.4	6.6
(min, max), [lower, upper]	(468.0, 839.0)	(411.8, 869.9)	[-26.7, 10.8]	[0.71, 0.91]	[33.9, 53.1]	[5.4, 8.5]
Power app vs. 3D mocap (W)	627.2 ± 96.6	602.8 ± 83.4	-24.4 ± 40.7	0.90	28.8	4.7
(min, max), [lower, upper]	(468.0, 839.0)	(454.9, 814.6)	[-37.4, -11.4]	[0.82, 0.95]	[23.6, 36.9]	[3.8, 6.0]
Concentric-eccentric endurance						
Repetitions (n)	17 ± 4	17 ± 4	0 ± 0	1.00	0.0	0.0
(min, max), [lower, upper]	(9, 23)	(9, 23)	[0, 0]	[--]	[--]	[--]
Displacement (cm)	218.4 ± 46.8	175.0 ± 36.4	-43.4 ± 12.2	0.96	8.6	4.4
(min, max), [lower, upper]	(102.3, 309.8)	(81.7, 238.3)	[-47.3, -39.4]	[0.93, 0.98]	[7.1, 11.1]	[3.6, 5.6]
Work app vs. force plate (J)	2202.1 ± 514.2	1703.8 ± 399.1	-498.3 ± 132.0	0.96	93.3	4.8
(min, max), [lower, upper]	(1242.0, 3484.9)	(955.6, 2725.0)	[-540.5, -456.1]	[0.93, 0.98]	[76.4, 119.8]	[3.9, 6.1]
Work app vs. 3D mocap (J)	2202.1 ± 514.2	1764.8 ± 407.1	-437.3 ± 124.8	0.97	88.2	4.4
(min, max), [lower, upper]	(1242.0, 3484.9)	(991.4, 2801.4)	[-477.2, -397.3]	[0.94, 0.98]	[72.3, 113.3]	[3.6, 5.7]

Abbreviations: BW, bodyweight. CV, coefficient of variation. ICC, intraclass correlation coefficient. Mocap, motion capture. TE, typical error.

[†] Calculated as laboratory measure minus Calf Raise app measure.

2.5 Discussion

We aimed to establish normative values of calf muscle function in uninjured male rugby union athletes in New Zealand, and to determine the reliability and validity of test outcomes. The outcome measures using the Calf Raise application were reliable between raters assessing the same videos, reliable in players between weeks after an initial familiarisation session, and valid when compared to the 3D motion capture system and force plates. Forwards were more powerful than backs, as were Super Rugby players, notably compared against Club and Provincial players. In terms of the concentric-eccentric endurance test, backs outperformed forwards, with no differences between playing levels. When accounting for additional clinically relevant factors, BMI, age, and previous injury explained some of the significant differences observed between positions and levels. This study provides initial benchmark values of calf muscle function for uninjured rugby union athletes in New Zealand. This research is an important step forward considering that previous research on calf muscle function predominantly focused on general population (Hébert-Losier et al., 2011; Hébert-Losier et al., 2017; Lunsford & Perry, 1995) or subgroups of injured individuals (Andreasen et al., 2021; Silbernagel et al., 2006; Silbernagel et al., 2010).

Forwards produced greater amounts of power than backs during both the bodyweight and weighted power tests when not accounting for BMI, with Super Rugby being generally more powerful than the other levels. Super Rugby forwards demonstrated the highest mean power values across groups as shown in **Table 2**. Previous research conducted in New Zealand reported similar findings, with forwards typically being stronger and more powerful than backs and Super Rugby players being more powerful than Provincial and Club (Argus et al., 2009, 2010; Posthumus et al., 2020; Smart et al., 2013). Worth noting is that the addition of clinically relevant factors to our statistical model affected the differences between positions and levels observed for the weighted power outcomes, with BMI significantly influencing power. Specifically, position was no longer significant given that forwards had superior BMI than backs linked to their greater mass. BMI also attenuated differences in weighted power between levels. These results highlight how differences in anthropometric characteristics, such as greater mass in forwards (Zemski, Slater, & Broad, 2015) and higher-level players (Argus et al., 2012; Smart et al., 2013) contribute to positional and level differences in performance metrics underlying their specific on-field requirements.

The eccentric-concentric power developed under load has been shown to be ~22% lower on average in presence of an Achilles tendinopathy compared to the least symptomatic or uninjured leg (Silbernagel et al., 2006). Specifically, power measured using a linear position transducer was reduced when the eccentric-concentric power test was conducted using a standing weight machine under a 33 kg load on the most symptomatic side (Silbernagel et al., 2006). The mean power recorded in the least symptomatic or uninjured leg (384 ± 160 W) in this latter study was considerably lower than our lowest reported mean of 585 ± 179 W assessed at 35 kg using a dumbbell and the Calf Raise application. Although differences in methodology and equipment might have contributed to the 200 W power difference between studies to a certain extent, the magnitude of the difference in weighted power reflects the need for rugby union specific measures rather than reliance on general population outcomes. The mean body mass of participants (80.7 kg) in Silbernagel et al. (2006) study was considerably lower than the mean values of our rugby players across positions and levels (88.4 to 118.4 kg). As noted, even though the two assessment methods differed and should not be considered interchangeable, it is worth noting that both approaches demonstrated comparable test-retest reliability between days. Whilst the relative reliability using the weight machine approach was marginally superior (ICC 0.76 to 0.86) than ours (ICC 0.70 to 0.88), the absolute reliability was lower in the weight machine (CV 15 to 17%) compared to our approach (7 to 14%). Our eccentric-concentric power test outcomes reached good relative (ICC ≥ 0.75) and acceptable absolute (CV < 10%) reliability when comparing second to third test occasions; hence, a familiarisation session prior to conducting these assessments in rugby union players is advised to enhance reliability.

Whilst forwards were more powerful than backs, backs completed approximately 3 more repetitions and covered 30.2 cm more positive displacement than forwards during the concentric-eccentric endurance test when considering rugby-related factors only. A number of studies have used the concentric-eccentric endurance test, although variations in protocol exists (Hébert-Losier et al., 2009a) that are likely to influence outcomes. For the number of repetitions, normative outcomes reported include 20 to 25 in the uninjured leg of patients 2 years post Achilles tendon rupture (Svensson et al., 2019), 24 repetitions across males and females aged 20 to 81 years (Hébert-Losier et al., 2017) and the least symptomatic leg of individuals with Achilles tendinopathy (Silbernagel et al., 2006), 32 to 35 repetitions on the uninvolved side of patients with Achilles tendon ruptures (Silbernagel et al., 2010), and 40 repetitions in uninjured young adults (Hébert-Losier et al., 2011). For the total positive work, the average performance for the non-injured legs of individuals reported are typically around 2000 J when based on heel displacement (Andreasen et al., 2021; Silbernagel et al., 2006; Svensson et al., 2019), which agrees with our outcomes, although mean values of around 3000 J have also been documented (Silbernagel et al., 2010).

The study with the most comparable calf raise endurance test method to ours (i.e., conducted on a step rather than on an incline or from the floor) assessed individuals 2 years post Achilles tendon rupture (Svensson et al., 2019). Their mean outcomes (20 repetitions and 2000 J) on the uninjured legs of the latter individuals are comparable to our findings in rugby union players, which might be somewhat unexpected given the younger age of our cohort, their greater body mass, and their relatively high physical activity levels. Rugby union is a physical high-intensity sport (Nicholas, 1997) that emphasises strength, speed, and power abilities in testing and training (Argus et al., 2009, 2010; Posthumus et al., 2020; Smart et al., 2013). The muscular endurance abilities of players remain largely undocumented in this sport. The current data suggest that although rugby athletes may be more powerful than the general population, their calf muscle endurance are comparable to the general population. Without targeted calf muscle endurance training, male rugby athletes competing in Club to International level rugby on average should complete 20 calf raise repetitions and 2000 J of positive work when assessed on a step.

A history of muscle tendon unit injury and greater BMI negatively affected the number of repetitions completed during endurance testing, with forwards and backs no longer exhibiting differences in this metric. In other words, the greater frequency of muscle tendon unit injuries and BMI in forwards than backs explained the lower number of repetitions detected in forwards. These results support prior research findings that previous calf muscle tendon injuries (Silbernagel et al., 2010; Svensson et al., 2019) and BMI (Hébert-Losier et al., 2017) can have negative impacts on calf muscle endurance. Residual deficits may be important to continue addressing to prevent future calf muscle and tendon injuries in previously injured rugby union athletes (Green & Pizzari, 2017).

2.6 Practical applications

Our findings across the three calf muscle test procedures support previous research, which states that differences in rugby union athletes based on position and level exist, as shown for several physical attributes, including strength and power (Argus et al., 2012; Smart et al., 2013). Worth noting, however, that differences in power were mediated by BMI; thus, anthropometric characteristics underpinned power differences. The frequency of muscle tendon unit injuries and BMI also mediated the number of repetitions completed during endurance testing. The data from this study provide normative calf muscle function values for uninjured male rugby union athletes in New Zealand that accounts for player position and playing level. These data can be used to inform medical teams, coaching staff, strength and condition practitioners, and athletes. Results generated from the test battery used were reliable and valid, with test-retest improving after a familiarisation session. Monitoring calf muscle function regularly can be used to track athletes during rehabilitation and training to inform athlete management. Concurrent monitoring of injury incidence could provide further understanding of injury risk factors and inform prevention strategies. Future studies are needed to establish normative values in female rugby union athletes, as well as rugby sevens given their unique requirements (Austin et al., 2011; Clarke et al., 2017; Clarke et al., 2013; Ross, Gill, & Cronin, 2014).

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Chapter 3 – Final chapter

3.1 Summary

The calf raise test (CRT) is one of the most commonly used tests in clinical practice to assess triceps surae endurance. Normative values in the general population have been established, allowing clinicians to evaluate an individual's outcomes against a set of normative values (Hébert-Losier et al., 2017; Lunsford & Perry, 1995). The test has also been used to inform the clinical management of individuals with Achilles tendinopathies or ruptures (Silbernagel et al., 2006; Silbernagel et al., 2010). Rugby union is the national sport of New Zealand. Soft tissue injuries account for the majority of rugby-related claims received by the Accident Corporation Compensation (i.e., national insurance company in New Zealand), with soft tissue injures to the lower extremity constituting approximately one third of these claims (Quarrie et al., 2020). Injuries to the triceps surae muscles (Green & Pizzari, 2017) and Achilles tendon (Brazier et al., 2019) are of considerable concern in rugby union due to their recurrence and severity. Prior to this Thesis, limited research had addressed what constitutes 'normal' calf muscle function in rugby union players. Therefore, the aim of this Thesis was to establish normative values of calf muscle function in uninjured male rugby union athletes in New Zealand accounting for player position and playing level, while considering age, leg dominance (i.e., foot used to kick a ball), BMI, and previous MTU injury. Secondary aims were to assess the reliability and validity of outcome measures collected using a novel mobile application.

To this end, the findings from Chapter Two from 120 participants assist in establishing baseline values of calf muscle function (endurance and power) for uninjured male rugby union athletes in New Zealand. Forwards generated greater power outcomes than backs during the body weight and weighted power tests, with Super Rugby athletes producing significantly greater weighted power outcomes compared to Provincial and Club levels. When accounting for clinically relevant factors, playing level and BMI significantly influenced weighted power outcomes, with player position being no longer significant. Power was greater as BMI increased. The power tests used in Chapter Two were based on Silbernagel et al. (2006) work conducted in uninjured controls and individuals with Achilles tendinopathy. The mean weighted power (bodyweight + 33 kg) outcomes in Silbernagel et al. (2006) (384 ± 160 W) work was 200 W lower than our lowest recorded mean for our weighted power test (584 ± 179 W) (bodyweight + 35 kg). Differences in test procedures and equipment used may have contributed to the mean difference in power between studies; however, differences between the two populations examined likely explain more of the differences. Indeed, the larger body mass of rugby union players and greater power outputs highlight the need for rugby-specific measures rather than outcomes established from the general population.

Whilst forwards produced superior power outcomes, backs performed more repetitions and total displacement than forwards during the concentric-eccentric endurance test. The addition of clinically relevant factors revealed that previous MTU injuries and BMI significantly and negatively affected the number of repetitions completed (position no longer significant), while playing position and age had significant and negative effects on total displacement. A previous study highlighted that increasing age and previous MTU injuries are predictive indicators of future calf muscle injuries (Green & Pizzari, 2017). Our results add to this research indicating that older age and a history of MTU injuries negatively affect calf muscle endurance outcomes.

There are many studies that have assessed anthropometric characteristics (Brazier et al., 2020; Nicholas, 1997), physical, and physiological attributes (Argus et al., 2012; Smart et al., 2013), and injury risk factors (Brazier et al., 2019; Brooks & Kemp, 2011; Green & Pizzari, 2017) in rugby union athletes. Significant differences between playing positions (e.g., forwards and backs) and levels of professionalism (e.g., International, Super Rugby, Provincial, and Club) have been reported for anthropometric, physical, and physiological attributes (Baker, 2001; Brazier et al., 2020). Higher-level rugby union athletes are generally older, have greater BMI scores, and are heavier compared to athletes competing at lower levels (Argus et al., 2012; Smart et al., 2013). The results from the experimental chapter (Chapter Two) regarding anthropometric characteristics reflect findings from previous research, as International and Super Rugby athletes were older, heavier, and had greater BMI scores compared to Provincial and Club rugby union athletes. In addition, our results highlight how International players and forwards report more previous triceps surae MTU injuries requiring medical attention.

The CRT is one of the most commonly used test in clinical practice, although differences in protocols exist (Hébert-Losier et al., 2009a), which are likely to influence outcomes. A previous study that performed CRT using similar protocols to the one implemented in Chapter Two (i.e., testing conducted on a step instead of the floor) assessed individuals 2 years post Achilles tendon rupture (Svensson et al., 2019). Their participants completed an average of 20 repetitions and 2000 J on their uninjured legs. These findings are comparable to ours, which was somewhat unexpected given the differences in anthropometric characteristics (i.e., age, body mass, and physical activity levels) and athletic status of rugby union players compared to a more general population. Despite similar concentric-eccentric CRT outcomes between the rugby union athletes assessed in Chapter Two and those reported in the literature (Svensson et al., 2019), there are clear differences in the eccentric-concentric power outcomes between rugby union athletes and more general population. These results along with the positional and level differences observed support previous research stating that differences in anthropometric characteristics contribute to positional and level differences in performance (Baker, 2001; Brazier et al., 2020), and that normative outcomes from general populations are unsuitable for athletic ones.

The findings from Chapter Two provide preliminary benchmark values of calf muscle function for uninjured male rugby union athletes in New Zealand. While these results cannot be used to predict future cases of MTU injuries in rugby union athletes without prospective studies, the findings might be useful for detecting power or endurance deficits in the triceps surae muscles and identifying certain risk factors associated with triceps surae MTU injuries. The findings from this Thesis can be used to inform medical teams, coaching staff, strength and condition practitioners, and athletes on the current condition of triceps surae MTU.

3.2 Limitations

One limitation of the experimental chapter (Chapter Two) was that our participant numbers was insufficient to compare triceps surae MTU function across more individualised positions of play in rugby union. While results highlight significant differences in calf muscle testing between forwards and backs across levels of professionalism, we were not able to make a more detailed analysis in terms of all possible positions (i.e., tight-head prop, lock, halfback, outside back) within rugby union.

A second limitation is that testing was conducted only in uninjured rugby union athletes to establish benchmark values reflecting “normal”. Therefore, individuals with a current Achilles tendon or calf muscle injury were excluded. Previous research has demonstrated that a previous Achilles tendon rupture (Brazier et al., 2019) or the presence of an Achilles tendinopathy (Silbernagel et al., 2006) can negatively affect calf muscle function. Hence, including individuals with Achilles tendon or calf muscle injuries would have enhanced the clinical relevance of outcomes specifically for rugby union athletes, but threatened normative values of uninjured players.

Another limitation in the experimental chapter is that female and sevens rugby union athletes were excluded from the study due to low numbers of participants available. Despite having collected preliminary data from male sevens rugby union (n = 17), female rugby union (n = 38), and female sevens rugby union (n = 12), populations were too low to meet the required sample size. Although sevens rugby consists of forwards and backs positions, there are eight less players on the field at once and game times consist of two 7-minute halves compared rather than two 40-

minute halves for rugby union. Differences in anthropometric characteristics and physiological attributes between male and female rugby union athletes are likely greater than those between male rugby union and rugby sevens (Clarke et al., 2017; Sella, McMaster, Beaven, Gill, & Hébert-Losier, 2019). Research findings indicate that male rugby union athletes, particularly at the elite level, have superior anthropometric characteristics (Brazier et al., 2020; Yao et al., 2021) and physiological attributes (e.g., strength, power, maximal speed, and aerobic capacity) (Clarke et al., 2017; Sella et al., 2019; Smart et al., 2013) than female athletes. Based on previous literature highlighting differences in match and player characteristics between fifteens and sevens rugby for male and female athletes (Argus et al., 2012; Clarke et al., 2017; Rienzi, Reilly, & Malkin, 1999; Ross et al., 2014), our findings for normative calf muscle function in male rugby union athletes are likely inappropriate for sevens and female rugby athletes.

3.3 Strengths

The first strength identified in the experimental chapter (Chapter Two) is the considerably large sample size. A total of 130 male rugby union athletes from New Zealand were recruited for the purpose of this study. Despite 10 athletes having to be removed from the recruited cohort due to current or newly sustained injury, our remaining cohort of 120 uninjured male athletes of various positions and levels still provided a large enough sample size to assess triceps surae MTU in rugby union athletes across positions and levels.

A subgroup of 18 rugby union athletes participated in the reliability portion of Chapter Two, whereby they completed an additional two testing sessions spread seven days apart at the same time of day to limit fluctuations in performance. The between-day relative reliability was fair to good across measures (ICC 0.70 to 0.87), and the absolute reliability was acceptable for most measures (CV < 10%), indicating that the test battery was reliable. Improvements in the reliability of measures occurred between the second and third testing sessions. Hence, a familiarisation session prior to calf muscle testing in rugby union athletes is advised to enhance reliability of outcomes.

A subset of 20 rugby union athletes were recruited to perform calf muscle testing to assess the validity of the Calf Raise app against laboratory-based measures given the novelty of the test battery and equipment used. Across all testing measures, the Calf Raise app showed good to excellent reliability against laboratory instruments, with an acceptable level of error (CV ≤ 6.6%).

Another strength of the Thesis is the portability and practicality of the assessment methods. Compared to most assessment tools, the use of the Calf Raise application (Hébert-Losier & Balsalobre-Fernandez, 2020) allows clinicians, medical teams, and coaching staff to conduct testing in both laboratory and field-based environments. Calf muscle testing requires minimal equipment, making testing an easier and more efficient process to conduct when and where convenient.

A final strength of the Thesis is the Calf Raise application's ability to assess calf muscle function and produce both endurance and power components of calf muscle testing. A linear position transducer has been previously used to assess the power and endurance abilities of the calf muscles (Silbernagel et al., 2006). Nonetheless, the mobile application is more accessible, less costly, and allows for faster transition time between test participants. The application is also free to download on the App store and does not require internet to operate.

3.4 Future directions

A previous study has assessed both the power and endurance capacities of calf muscle function in general populations (Silbernagel et al., 2006), while another has assessed the endurance component whilst using a step to conduct testing (Svensson et al., 2019). However, neither study, nor any other, has assessed calf muscle function in rugby union athletes. Our study is the first to assess both the endurance and power capacities of calf muscle function in uninjured male rugby union athletes. As mentioned in the previous Chapters, assessing more than the endurance capacity of calf muscles is recommended in clinical practice (McAuliffe et al., 2019). Given that only male rugby union players were included, future studies should aim to assess calf muscle function specifically in sevens and female rugby players. Prospective studies are still required to determine whether the CRT or power outcomes are useful for predicting injury occurrence and potential risk factors of triceps surae MTU injuries in rugby union. Tracking players over time and their injury incidence would assist in determining whether, for example, low power and/or endurance are risk factors for triceps surae MTU injuries. Finally, given that testing was conducted in non-injured rugby union athletes only, results cannot be generalised to rugby union athletes with current or rehabilitating Achilles tendon or calf muscle injuries. To address this limitation, future research could aim to explore the usefulness of the proposed calf muscle tests to measure the extent of injuries, track rehabilitation progress, and inform return to play.

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Appendix A – Supplementary table

Table S1. Demographic characteristics of rugby union players involved with the reliability and validity sections by playing level and position. Values are mean ± standard deviation, range (minimum, maximum), and ratios.

	Reliability (n = 18)		Validity (n = 20)	
Variable	**Forward (n = 7)**	**Back (n = 11)**	**Forward (n = 13)**	**Back (n = 7)**
Age (years)	21.6 ± 0.9	25.6 ± 4.0	21.2 ± 1.7	20.0 ± 0.6
(min, max)	(20.5, 22.9)	(21.1, 34.4)	(18.9, 24.4)	(19.1, 21.1)
Height (m)	1.9 ± 0.1	1.8 ± 0.1	1.9 ± 0.1	1.8 ± 0.0
(min, max)	(1.8, 2.0)	(1.7, 1.9)	(1.8, 2.0)	(1.8, 1.9)
Mass (kg)	105.7 ± 7.8	93.8 ± 7	111.2 ± 13.3	89.8 ± 8.6
(min, max)	(95.6, 113.6)	(84.0, 105.1)	(94.0, 141.5)	(77.3, 100.2)
BMI (kg/m^2)	30.3 ± 3.3	28.1 ± 1.7	32.1 ± 3.6	27.4 ± 2.6
(min, max)	(26.8, 35.0)	(24.8, 31.1)	(28.6, 38.4)	(24.5, 31.5)
Dominant (right:left)[a]	6:1	10:1	11:2	6:1
MTU (no:yes)[b]	6:1	6:5	10:3	3:4

[a] Leg used to kick a ball
[b] Self-reported previous calf muscle or Achilles tendon injury requiring medical care
Abbreviations: BMI, body mass index. MTU, triceps surae muscle-tendon unit

Appendix B – Ethics approval form

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

Human Research Ethics Committee
Mark Apperley
Telephone: +64 7 838 4528
Email:humanethics@waikato.ac.nz

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

11 March 2020

Dr Kim Hebert-Losier
Te Huataki Waiora School of Health
DHECS
By email: kim.hebert-losier@waikato.ac.nz

Dear Kim

HREC(Health)2020#11 : Investigation of the calf raise test in youth

Thank you for submitting your amended application HREC(Health)2020#11 for ethical approval.

We are now pleased to provide formal approval for your project.

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,

____

Professor Mark Apperley
(Acting) 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)			
RANDOMSATION	☐ R → L	☐ L → R	