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Self-selected and control cadences: Considerations for calf raise test standardisation and interpretation

A thesis
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of the requirements for the degree
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Abstract

Background

The calf raise test (CRT) is an endurance test commonly used to assess triceps surae (TS) muscle tendon unit (MTU) function. The CRT usually involves performing repeated unilateral concentric-eccentric plantar-flexor contractions to fatigue, with repetitions the primary outcome measured. The most common CRT cadence is 60 beats per minute (bpm), though varying cadences are used in the literature (e.g., 30 bpm, 40 bpm, 120 bpm, self-selected, as fast as possible). Recent research reported that changing cadences (30 bpm, 60 bpm, 120 bpm) significantly influenced several CRT outcomes, including total vertical displacement (cm), total work (J), peak height (cm), and peak power (W), but not repetitions. There is speculation that 60 bpm may closely reflect a self-selected cadence, which has not yet been explicitly identified in research. Therefore, the main aim of this thesis was to compare cadences maintained during 10 calf raise repetitions (CR10) and the CRT between three conditions: control (60 bpm), self-selected, and as fast as possible. A secondary aim of this thesis was to explore the influence of cadence on CR10 and CRT outcomes. An additional aim was to explore predictors of sex, body mass index (BMI), and physical activity levels (PAL) as potential influences of CR10 and CRT outcomes, with age and calf muscle training examined as additional potential predictors in the CRT.

Methods

This thesis contains two randomised crossover studies, with repeated measures designs. Study one focused on CR10 and study two on CRT to fatigue. Each experimental study was performed barefoot on the right leg, starting from a foot position of 10° incline (slight dorsiflexion). In study one, 35 healthy participants (16 males, 19 females) aged 19 – 25 years completed the CR10 at three randomised cadence conditions (60 bpm, self-selected, as fast as possible) during a single testing session, 15 minutes apart. In study two, 38 healthy

participants (23 males, 15 females) aged 19 – 43 years completed the CRT to fatigue at three randomised cadence conditions (60 bpm, self-selected, as fast as possible) over three testing sessions, seven days apart. For both experimental studies, 60 bpm was the control condition, going up on the toes and back down to the starting position to the beat of a metronome, up in one beat and down in one beat. The self-selected condition required repetitions be performed at a pace that felt most natural and comfortable, whereas the fast condition required repetitions to be performed as fast as possible. The CR10 and CRT outcomes were recorded using the validated Calf Raise application, tracking vertical displacement of a black circular marker beneath the lateral malleolus. Descriptive statistics of CR10 and CRT outcomes were reported as medians with interquartile ranges [25th, 75th]. Mixed-effect linear models were used to analyse log-transformed CR10 and CRT outcomes, with multilevel mixed-effect Poisson models used for CRT repetitions. Stepwise regressions were used to remove non-significant predictors across models.

Results

In the CR10 experiment, cadence had a significant effect on repetitions per minute, total time, peak power, and displacement variability ($P < 0.001$), but not total work or vertical displacement ($P \leq 0.337$). Median self-selected cadences (75.6 bpm) were 24% faster than 60 bpm, and median as fast as possible cadences (196.8 bpm) were 218% faster than 60 bpm. The fast condition reached the 10 repetitions in less time than self-selected (61%) and 60 bpm (69%), with self-selected completed in 19% less time than 60 bpm. The fast condition exhibited greater displacement variability (53%) and greater peak power (52 – 57%) than the other two conditions, with no significant difference in these outcomes between 60 bpm and self-selected cadence. Self-selected cadence ranges (minimum – maximum) were 48.4 – 129 bpm. Males generated greater peak power and total work than females ($P < 0.001$), with females exhibiting less displacement variability than males ($P < 0.001$). As BMI increased,

so did peak power and total work ($P \leq 0.013$). PAL did not significantly influence CR10 outcomes.

In the CRT experiment, cadence had a significant effect on repetitions per minute, vertical displacement, displacement variability, peak power, total time, and total work ($P \leq 0.011$), but not repetitions ($P = 0.081$). Median self-selected cadences (69.8 bpm) were 14% faster than 60 bpm, and median as fast as possible cadences (109.4 bpm) were 94% faster than 60 bpm. Median self-selected cadences produced less peak power (9%), total time (19%), total work (11%), and displacement variability (17%) compared to 60 bpm, with no significant difference for vertical displacement per repetition. Self-selected cadence ranges (minimum – maximum) were 44.6 – 121.4 bpm. Vertical displacement was greatest in the as fast as possible condition, with displacement variability being 29% greater than self-selected cadences. As fast as possible generated 29% greater peak power than 60 bpm and 42% greater peak power than self-selected cadences. Females generated less peak power and exhibited less vertical displacement, yet achieved greater total test times than males ($P < 0.001$). Individuals with greater BMI completed fewer repetitions and achieved greater peak power ($P < 0.001$). Age and PAL did not significantly influence CRT outcomes, whereas individuals who trained their calf muscles performed greater repetitions, generated greater peak power, had longer total test times, and completed more total work ($P \leq 0.017$) than those who did not.

Summary

Results from the experimental studies show that varying cadences (60 bpm, self-selected, as fast as possible) influenced most CR10 and CRT outcomes. Additionally, sex, BMI and calf muscle training were identified as significant predictors of certain CR10 and CRT outcomes. Furthermore, results show that median self-selected cadences in the CR10 (75.6 bpm) and CRT (69.8 bpm) are greater than, but close to, the commonly used 60 bpm.

However, the range of self-selected cadences in the CR10 and CRT suggest that larger differences in outcomes between conditions may exist at an individual level. Therefore, our findings suggest the continued use of 60 bpm as the test cadence in the CRT to provide standardisation and given its confirmed test-retest reliability until evidence can be provided showing repeatability of self-selected cadences.

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List of Abbreviations

1RM – One repetition maximum

AT – Achilles tendon

BMI – Body mass index

bpm – Beats per minute

BW – Bodyweight

CR10 – 10 calf raise repetitions

CRT – Calf raise test

CV – Coefficient of variation

ICC – Intraclass correlation coefficients

MTU – Muscle tendon unit

PAL – Physical activity level

TS – Triceps surae

Thesis Overview

The main aim of this thesis was to compare cadences maintained during 10 calf raise repetitions (CR10) and the calf raise test (CRT) between three conditions: control (60 bpm), self-selected, and as fast as possible. The secondary aim was to explore the influence of cadence on CR10 and CRT outcomes. An additional aim was to explore predictors of sex, body mass index (BMI), and physical activity levels (PAL) as potential influences of CR10 and CRT outcomes, with age and calf muscle training examined as additional potential predictors in the CRT. This thesis contains four chapters (Figure 1). Chapter one is a literature review on the triceps surae (TS) muscle tendon unit (MTU) and its function, the CRT, how movement cadence influences performance, and cadence considerations. Chapter two is the first experimental study in this thesis, using a randomised crossover trial with a repeated measures design. This study involved 35 participants (16 males, 19 females) completing the CR10 at three randomised cadence conditions (60 bpm, self-selected, and as fast as possible), within a single testing session, 15 minutes apart. Chapter three is the second experimental study of this thesis, using a randomised crossover trial with a repeated measures design. This study involved 38 participants (23 males, 15 females) who completed the fatiguing CRT at three randomised cadence conditions (60 bpm, self-selected and as fast as possible), over three testing sessions, seven days apart. Chapter four is the final chapter that summarises the findings, strengths, limitations, and future research based on the literature review and the two experimental studies (non-fatiguing and fatiguing efforts).

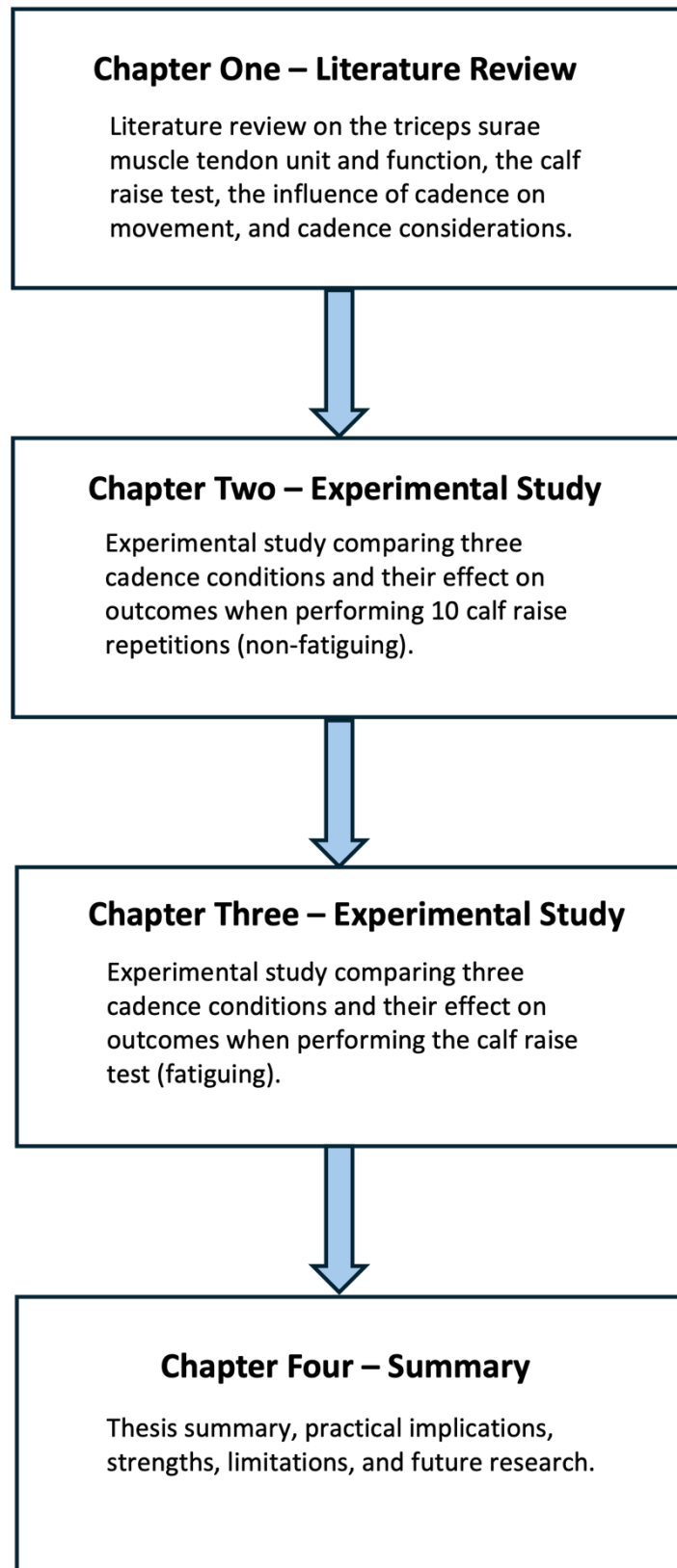


Figure 1. Thesis overview flow diagram

Chapter One – Literature Review

Literature review on the triceps surae muscle tendon unit and function, the calf raise test, the influence of cadence on movement, and cadence considerations.

1.1 Introduction

The main ankle plantar-flexor muscles form the triceps surae (TS) muscle tendon unit (MTU) and comprise of the gastrocnemii (lateral, medial) and soleus muscles, together merging distally at the heel through the Achilles tendon (AT) (Farris & Sawicki, 2012; Mylle et al., 2023). The TS muscles are enduring and are essential to balance; daily functional locomotive movements such as walking, running, and climbing stairs (Farris & Sawicki, 2012; Neptune & Sasaki, 2005; Riener et al., 2002); and sporting movements, including jumping (e.g., hurdles) (Kelly et al., 2025), acceleration (e.g., sprinting) (Pandy et al., 2021), and multidirectional changes in direction (e.g., rugby, football, basketball) (Green & Pizzari, 2017; Marshall, 2014; Soler et al., 2025). To be efficient with functional movements and excel in sport, well-functioning ankle plantar-flexor muscles are required to generate mechanical power and absorb the force produced in each step, stride, or jump (Farris & Sawicki, 2012). Unfortunately, the TS MTU are susceptible to overuse (Chen et al., 2024; Dziekoński, 2025) and acute (Bryan Dixon, 2009; Green et al., 2022; Lantto et al., 2015) injuries. When the ability to move or perform has been lost due to injury, a path of corrective action is needed to restore function (strength and endurance) and performance. A well-known endurance test used within clinical settings to assess and rehabilitate plantar-flexor function is the heel-rise test, also termed the calf raise test (CRT) (Hébert-Losier, Schneiders, et al., 2009; Lunsford & Perry, 1995; Visser et al., 2025). The literature review for this thesis has three main aims: (1) to define the TS MTU and the importance of TS MTU function, (2) to discuss the CRT as a valuable tool in lower limb rehabilitation and strength training, and (3) to explore the self-regulation of pace and how varying CRT cadences could influence CRT outcomes pertinent to rehabilitation and performance.

1.2 The triceps surae muscle-tendon unit

The TS muscles are located on the posterior aspect of the tibia, comprising of two gastrocnemii (lateral gastrocnemius, medial gastrocnemius) and the soleus (Figure 2), commonly known as the ‘calf muscles’ (Farris & Sawicki, 2012; Radice et al., 2017). The gastrocnemii muscles cross two joints (i.e., biarticular muscles spanning both the knee and ankle joints), contributing to knee flexion and ankle plantar-flexion (Kawakami et al., 1998). The gastrocnemii are positioned superficially to the soleus (O'Brien, 2005; Radice et al., 2017). Comparatively, the soleus crosses the ankle joint only (i.e., monoarticular muscle) and thus contributes mainly to ankle plantar-flexion (Kawakami et al., 1998). An additional role of the TS muscles is to aid postural control (Di Giulio et al., 2009; Loram et al., 2005; Schepers et al., 2002; Vandervoort & McComas, 1983). The TS muscles share a common distal insertion at the heel through the AT (O'Brien, 2005; Radice et al., 2017; Spina, 2007), forming the TS MTU (Winnicki et al., 2020). The AT is the longest and one of the strongest tendons in the human body (O'Brien, 2005; Winnicki et al., 2020), recognised for its abilities to store and release elastic energy through the stretch-shortening cycling assisting the TS muscles to reduce the energetic cost of locomotion by approximately 40% (Fletcher & MacIntosh, 2015).

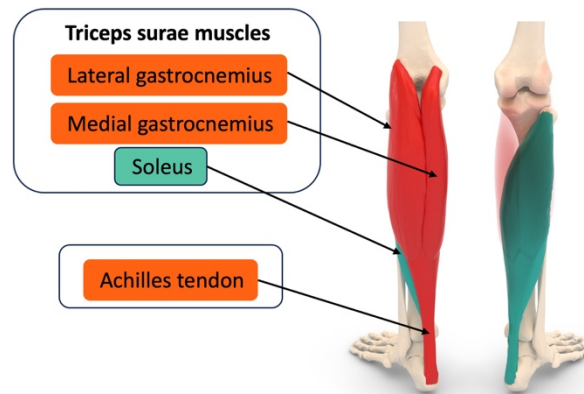


Figure 2. Anatomy of the triceps surae muscle tendon unit [illustration], adapted from 'Wikimedia commons' (BodyParts3D, 2020). CC BY-SA 2.1 JP.

1.2.1 Triceps surae muscle anatomy

The architecture and structure of the gastrocnemii and soleus muscles vary, with each one of the TS muscles having differing muscle fibre properties (Kawakami et al., 1998; Kinugasa et al., 2005), fascicle lengths (Kawakami et al., 1998; Kudo et al., 2015), and contractile behaviours (Vandervoort & McComas, 1983). Hence, each TS muscle uniquely contributes to posture, functional movements, and exercise (Charles et al., 2022; Loram et al., 2005). The gastrocnemii contain approximately 51% fatigue resistant muscle fibres (slow twitch, type I) and approximately 49% power generating muscle fibres (fast-twitch, type II) (Head & Arber, 2013; Johnson et al., 1973; Kinugasa et al., 2005; Spendiff et al., 2002), whereas the soleus predominantly comprises of fatigue resistant muscle fibres at approximately 80 to 90% of slow twitch type 1 fibres (Johnson et al., 1973; Kawakami et al., 1998; Soendenbroe et al., 2026).

Contractile properties of the gastrocnemii and soleus are influenced by their respective muscle fibre compositions (Vandervoort & McComas, 1983), bundled into fascicles (Kawakami et al., 1998). The length of fascicles contribute to the velocity of muscle contractions, range of motion, and how much force the muscle can generate (Arnold & Delp,

2011; Arnold et al., 2013), with force generating capacity being relative to the cross-sectional area of the muscle (Albracht et al., 2008). Behaviour of TS muscle fascicles during shortening, lengthening, and isometric contractions have been studied across literature (Arampatzis et al., 2007; Kawakami et al., 1998; Rana et al., 2013; Reeves & Narici, 2003). Kawakami et al. (1998) reported the average fascicle length of the gastrocnemii and soleus as being longest when the knee is fully extended and the ankle is in a position of dorsiflexion. Out of the TS muscles, the lateral gastrocnemius has longer fascicles capable of greater shortening velocities, and more likely to contribute to greater force in the stretch-shortening cycle during concentric phases of movement (Kawakami et al., 1998). Comparatively, the medial gastrocnemius and soleus have a larger volume of shorter fascicles (Albracht et al., 2008; Kawakami et al., 1998; Kinugasa et al., 2005), with the soleus having a larger physiological cross-sectional area of muscle, increasing the force generating capacity (Albracht et al., 2008). Research (Kinugasa et al., 2005) has shown that activation of cross-sectional muscle mass when performing unilateral standing calf raises is the greatest within the medial gastrocnemius (45.7%), followed by the lateral gastrocnemius (34.9%) and the soleus (34.9%), suggestive that the medial gastrocnemius is an agonist muscle in plantar-flexion during this specific task (Kinugasa et al., 2005). The relationship between fascicle length and velocity has been explored during walking and running through the use of ultrasound (Arnold et al., 2013; Farris & Sawicki, 2012). As velocity increased transitioning from walking to slow running (1.75 m/s to 2.0 m/s), TS muscle fascicle shortening velocity decreased, requiring greater activation of the TS muscles to generate the same amount of force as seen at slower velocities (Arnold et al., 2013), implying that pace influences muscle activation and force production in the TS muscles.

Together, the TS muscles produce approximately 80% of plantar-flexion force (Murray et al., 1976). During walking at 1.5 m/s, modelling indicates the soleus contributes

60% to forward trunk acceleration, whereas the gastrocnemii contributes only 25% (Neptune et al., 2001). Due to differing muscle fibre properties, it could be assumed that the gastrocnemii muscles would be the greatest contributor to movement at higher velocities (Hébert-Losier, Schneiders, et al., 2009). However, Pandy et al. (2021) have shown that during the acceleration phase of sprinting, the average body weight (BW) peak muscle force produced is greater from the soleus (8.4 – 10.7 BW), in comparison to the gastrocnemii (3.5 – 5.5 BW). The greater peak muscle force produced by the soleus during sprinting could be due to the muscle architecture (e.g., larger cross-sectional area, shorter fascicles) (Albracht et al., 2008) combined with the stretch and recoil of the AT, potentially enabling the soleus to shorten more slowly, generating greater forces (Arnold et al., 2013; Monte et al., 2020). Furthermore, peak support force generated in sprinting by the soleus was 1.61 ± 0.18 BW (mean $\pm$ standard deviation), with the gastrocnemii generating the highest propulsive force 0.58 ± 0.08 BW (Pandy et al., 2021), indicating the soleus contributes more to upward support and the gastrocnemii more to forward momentum at higher velocities (Dorn et al., 2012; Pandy et al., 2021). Clearly, movement velocities appear to affect the relative contributions of the TS muscles to plantar-flexion outputs.

1.2.2 Functional importance

Healthy TS MTU function (strength and endurance) is essential for gait, balance, posture, and longevity (Hof et al., 2002; Olewnik et al., 2025; Radice et al., 2017). The gastrocnemii and soleus play an important role contributing to gait cycles, forward propulsion in walking and running (Farris & Sawicki, 2012; Fukunaga et al., 2001; Hof et al., 2002), and in supporting the body through balance and posture (Di Giulio et al., 2009; Loram et al., 2005; Olewnik et al., 2025). The anatomical position of the TS muscles combined with a greater proportion of slower-twitch (type I) muscle fibres in the soleus (Johnson et al., 1973), enable generation of lower intensity force, essential to maintaining an upright position when

standing or walking, with the gastrocnemii acting as a synergistic muscle (Di Giulio et al., 2009; Olewnik et al., 2025). Proprioceptively, when the body sways, a corrective action is required to maintain posture, or movement pace is increased, the gastrocnemii become more active (Di Giulio et al., 2009).

The strong relationships between healthy TS MTU function and the ability to stand upright and to ambulate highlight the importance of assessment and strengthening the TS muscles across population groups, including children (Yocum et al., 2010), older individuals (André et al., 2016; André et al., 2020; Hashish et al., 2015; Maritz & Silbernagel, 2016), and individuals with health conditions, such as chronic venous insufficiency (Uden et al., 2005), stroke (Lee et al., 2017), or peripheral arterial occlusive disease (Monteiro et al., 2013). In populations with health or balance concerns, bilateral calf raises are often used instead of unilateral calf raises in the testing and rehabilitation of the TS muscles (André et al., 2020; Lee et al., 2017; Monteiro et al., 2013) to reduce reliance on single-leg postural abilities and still assess TS muscle endurance.

The process of aging and associated functionality loss is strongly related to living more sedentary lifestyles (Laforest et al., 1990) and loss of muscle mass (Laforest et al., 1990), resulting in reduced lower leg strength and balance (André et al., 2016; Skelton & Beyer, 2003). Reduced walking speeds and limits of stability are associated with increased risk of falls (Rogers et al., 2003), whereas strong plantar-flexor muscles have been linked to having better mobility later in life (André et al., 2020). Several studies have examined the effect and benefit of TS muscle strength and balance training programmes in older populations (65 to 75 years) (André et al., 2020; Ema et al., 2017; Fujiwara et al., 2011). In the study by Fujiwara et al. (2011), performing calf raises daily significantly influenced isometric plantar-flexor strength, increasing by 160 ± 119.8 N, with muscle thickness of the soleus increasing by 2.8 ± 4.3 millimetres over an 8 week period, aiding improvement in

balance. In agreement with increased capabilities, Ema et al. (2017) reported a $36 \pm 37\%$ increase in the rate of plantar-flexion torque development by performing bilateral calf raises three times per week, beneficial to the speed of walking in older populations.

Furthermore, TS muscles are essential for sporting performance with mechanical efficiency of the stretch-shortening cycle, enhanced storage of elastic energy within the TS MTU, and TS muscle strength and endurance (Fletcher & MacIntosh, 2015; Hof et al., 2002; Turner & Jeffreys, 2010) being contributing factors to long distance running, greater speed, acceleration, jumping, and the ability to perform multi-directional activities (Hébert-Losier et al., 2023; Machado et al., 2021; Marshall, 2014). Indeed calf muscle abilities, inclusive of body-weight and weighted calf muscle power (W) and strength endurance shown through total displacement (cm) and total work (J) in the CRT, have been associated with faster 10 m sprint times in rugby union players (Hébert-Losier et al., 2023), underscoring the importance of TS muscles in athletic performance. Unfortunately, there is potential for injury to the TS MTU, especially linked with high intensity sport or with repetitive daily functional loading.

1.2.3 Injuries to the triceps surae muscle tendon unit

The TS MTU are vulnerable to injury in the general population (Heckman et al., 2009) and among athletes (Green & Pizzari, 2017; Hägglund et al., 2013; Lantto et al., 2015). Overuse injuries (e.g., tendinopathies) occur when loading exceeds tissue capacities (Chen et al., 2024; Cook et al., 2002; Dziekoński, 2025; Mahieu et al., 2006), continuously posing challenges to clinicians assessing and treating the TS MTU (Murphy et al., 2022). In addition to tendinopathies, acute and traumatic TS MTU injuries (e.g., AT rupture, gastrocnemius strain, soleus strain) (Bryan Dixon, 2009; Draghi et al., 2021; Green & Pizzari, 2017; Lantto et al., 2015) are common in running, ballet dancing, and multidirectional sports (e.g., football, rugby, basketball) (Green & Pizzari, 2017; Ramkumar et al., 2016; Soler et al., 2025).

Soft tissue injuries to the TS MTU are common, with approximately 13% of all muscle injuries attributed to the TS muscles (Radice et al., 2017). High incidences of calf muscle strains are evident in football (0.84/1000hours of play) and in rugby union, accounting for 3% of injuries per club, per season (Brooks & Kemp, 2011; Green & Pizzari, 2017). Incidence rates of Achilles tendinopathy range from 6% in a life time for the general population and up to 52% within endurance runners (Kujala et al., 2005), with Chen et al. (2024) reporting male runners (5%) had higher incident rate of tendinopathy than female runners (2.8%). In addition to running and team sport, Achilles tendinopathy and soleus strains were the second and third most frequent injuries in elite athletics, averaging 25 days away from sport (Kelly et al., 2022), aligning with Green and Pizzari (2017), highlighting that calf injuries have a relatively long return to sport time. A systematic review (Toohey et al., 2017) reported that index hamstring and quadricep injuries increased risk of subsequent injuries to the calf muscles, meanwhile Orchard (2001) reported an increase risk of calf injury if a previous calf injury had occurred and as age increases, showing that intrinsic factors play a large role in re-injury.

In addition to strains and tendinopathies, AT ruptures are a common, significant injury to the TS MTU in the adult population, with average incidence rates being 8.3 ruptures per 1000 people (Lantto et al., 2015; Marrone et al., 2024; Suchak et al., 2005). Ruptures to the AT are traumatic, often from significant force and can have a lasting impact on function with deficits in the endurance of the TS muscles and tendon elongation reported years after surgical and non-surgical repair (Brorsson et al., 2018; Möller et al., 2002; Olsson et al., 2011; Silbernagel et al., 2012), specifically if treatment phases were not initiated soon enough or the tendon loading was insufficient. When an injury to the lower limb occurs, assessing, monitoring, and enhancing TS MTU function is essential for rehabilitation, resuming normal

activities, and retuning to sports. Therefore, it is appropriate to have tools (e.g., the CRT) to assess TS MTU function in the likelihood that an injury occurs.

1.3 The calf raise test

Originally developed during the 1940s to assess plantar-flexor muscle function during the poliomyelitis epidemic (Lunsford & Perry, 1995), the CRT is a popular tool commonly used within clinical settings (e.g., physiotherapy and strength and conditioning) to assess TS MTU function and capacity before and/or after injury (strength and endurance) (Grävare Silbernagel et al., 2001; Hébert-Losier, Newsham-West, et al., 2009; Kountouris & Cook, 2007; Lunsford & Perry, 1995; Ross et al., 2002) and to guide exercise prescription in a return to sport (Grävare Silbernagel & Crossley, 2015). The CRT usually involves completing a maximal number of repeated unilateral concentric-eccentric contractions of the plantar-flexor muscles in standing from a start position of plantigrade neutral or dorsiflexion (Hébert-Losier, Newsham-West, et al., 2009; Lunsford & Perry, 1995; Ross & Fontenot, 2000; Silbernagel et al., 2010).

Although variable, the protocol to conduct the CRT across published calf raise studies usually involves the following features (Brorsson et al., 2017; Byrne et al., 2017; Franklin et al., 2026; Hébert-Losier et al., 2024; Hébert-Losier, Fernandez, et al., 2025; Visser et al., 2025). To provide support during the CRT, individuals are allowed to place two fingertips per hand, at shoulder height on the wall in front for balance. Individuals remain upright while going up as high as possible on their toes and lowering their heel back to the starting position to the beat of a metronome set at 60 beats per minute (60 bpm), raising in one beat and lowering in one beat. Testing is terminated when the assigned cadence is no longer maintained, calf raise height reduces (more than 50%), the body is propelled forward instead of upward, the testing leg is flexed, balance is lost, or individuals stop due to fatigue (i.e., volitional cessation). One or two warnings is often provided before test cessation. The

repeated concentric-eccentric contractions of the TS muscles during the CRT closely replicate the repeated concentric-eccentric contractions of locomotive movements (e.g., walking, running), therefore providing a functional way to assess the TS MTU performance (Ross & Fontenot, 2000).

1.3.1 Calf raise test repetitions and predictors

Repetitions completed is the most commonly used outcome measure for the CRT (Hébert-Losier, Newsham-West, et al., 2009; Lunsford & Perry, 1995), shown reliable in a range of population groups. Specifically, intraclass coefficients (ICC) show excellent inter-rater, inter-rater, and test-retest reliability ($ICC > 0.90$) for the CRT when used with children (Yocum et al., 2010), excellent test-retest reliability ($ICC \leq 0.96$) with healthy adults (Ross & Fontenot, 2000; Schrefl, 2024), and excellent test-retest reliability ($ICC = 0.90$), inter-rater reliability ($ICC = 0.93$ to 0.96), and good intra-rater agreement ($ICC = 0.79$ to 0.84) with older populations (André et al., 2016). When clinicians select the CRT for assessment of TS MTU function in patients, outcome benchmarks for comparison are essential to progressing rehabilitation, with numerous published studies forming normative data for clinical use (Hébert-Losier, Pandit, et al., 2025; Hébert-Losier et al., 2017; Lunsford & Perry, 1995; Visser et al., 2025).

In the CRT, Lunsford and Perry (1995) recommended that plantar-flexor endurance (repetitions) normative value be 25 repetitions for adults (20 to 59 years), with more recent studies confirming normative repetitions as typically sitting around 20 to 26 for children and teenagers (Hébert-Losier, Pandit, et al., 2025; Mishra et al., 2023; Mishra & Dasgupta, 2024) and 20 to 25 for adults (Hébert-Losier et al., 2017; Visser et al., 2025). However, some CRT studies have reported repetitions ranging from 30 to 40 (Byrne et al., 2017; Ross & Fontenot, 2000; Sara et al., 2021). The established normative values used in clinical settings are based on performance of healthy individuals, therefore, repetition values may not be generalisable

across various populations. While normative values are used in the assessment of TS MTU function, it is important to acknowledge that the number of CRT repetitions an individual completes can be influenced by predictors such as age (Jan et al., 2005), sex (Hébert-Losier et al., 2024; Hébert-Losier et al., 2017; Jan et al., 2005), body mass index (BMI) (Hébert-Losier, Fernandez, et al., 2025; Hébert-Losier et al., 2017; Visser et al., 2025), and physical activity levels (PAL) (Hébert-Losier et al., 2017). Generally, individuals who are younger, male, have a lower BMI, and are more physically active outperform those who are older, female, have a greater BMI, and are less physically active.

Muscle mass reduces and strength declines in individuals across a lifespan (Laforest et al., 1990). Published CRT studies have identified that the number of unilateral repetitions declines with an increase in age (Green et al., 2024; Hashish et al., 2015; Hébert-Losier et al., 2017; Maritz & Silbernagel, 2016; Whyte et al., 2021), in agreement with the reduction in muscle capabilities with age. However, recent studies have not identified age as a predictor of CRT performance (Hébert-Losier, Fernandez, et al., 2025; Monteiro et al., 2017; Visser et al., 2025), potentially influenced by younger participant cohorts with higher PAL, contributing to the change in data produced because studies with older participant cohorts reach well below the normative repetition values (i.e., 10 repetitions) (Whyte et al., 2021).

Furthermore, muscle strength and endurance capabilities can be related to sex, with anatomical (e.g., muscle fibre properties, cross-sectional size) and physiological (e.g., hormones, energy expenditure, motor unit behaviour) differences between males and females, potentially contributing to varying CRT performances (Haizlip et al., 2015; Jan et al., 2005; Landen et al., 2023; Lulic-Kuryllo & Inglis, 2022). In the paper by Visser et al. (2025), it was shown the median unilateral calf raise repetition normative value was 25, however females performed less repetitions (24) than males (26). Comparatively, Monteiro et al. (2017) reported the average bilateral repetition value was 71, yet median repetitions were differed

more substantially between females (56.5) and males (82), with Hébert-Losier et al. (2017) identifying approximately 25% difference in repetitions between sexes.

Differences in repetitions and other CRT outcomes could further be attributed to physical features such as BMI. A negative relationship exists between BMI and CRT repetitions. The greater the BMI, the lesser the amount of repetitions performed (Hébert-Losier, Fernandez, et al., 2025; Hébert-Losier et al., 2022; Hébert-Losier et al., 2017; Visser et al., 2025). Specifically, Hébert-Losier, Fernandez, et al. (2025) reported a 3% decrease in repetitions per 1 unit increase in BMI, in agreement with findings by Visser et al. (2025) showing a small to moderate correlation ($r = -0.28$) between BMI and repetitions. Cesanelli et al. (2025) identified reduced calf raise efficiency with obesity, linking increased TS MTU stiffness and reduced TS strength to greater body mass. BMI becomes an important factor to consider as it impacts daily movements, such as walking (Wearing et al., 2006). Hence, normative CRT repetition values may not apply in clinical practice if BMI is not taken into account.

Although inconsistent, PAL has also been shown to influence CRT repetitions, with lower PAL associated with less repetitions than greater PAL (Hébert-Losier et al., 2017; Visser et al., 2025). This association is expected as a physically active person usually has greater muscle mass, strength, and endurance to perform a greater number of repetitions than a person who is not physically active (Bogdanis, 2012). In contrast, recent research (Hébert-Losier et al., 2024; Hébert-Losier, Fernandez, et al., 2025) identified no association between PAL and CRT repetitions, which could be largely due to both studies having participants who were moderately to highly active. Therefore, those with lower PAL were unaccounted for within these data sets, with results potentially unable to be generalised across all physical capabilities. Completing regular calf muscle training has been found to positively predict CRT repetitions (Green et al., 2024), with those who demonstrate greater PAL potentially

more regularly involved in regular calf training. Consistent with these observations, research has shown that training calf muscles for rehabilitation purposes results in greater CRT repetitions when comparing before and after capabilities (Fujiwara et al., 2011; Karapınar et al., 2025; Maritz & Silbernagel, 2016; Ödemiş et al., 2022). Therefore, training calf muscles regularly appears an important factor to consider in CRT outcomes.

The predictors of age, sex, BMI, and PAL have been shown as influential on CRT repetitions, and are likely predictors of other CRT outcomes, including total work, total time, peak power, peak height, and total vertical displacement. Furthermore, calf training is well documented as increasing calf muscle capacities and is another predictor that should be considered. Consideration of these predictors is important when interpreting CRT results.

1.3.2 Additional calf raise test outcomes

Published research suggests that key CRT outcomes such as total work (J) and peak height (cm) in AT rehabilitation may provide a better insight of TS MTU function over measuring repetitions alone (Byrne et al., 2017; Nordenholm et al., 2022; Silbernagel et al., 2010). The measure of total positive work (concentric phase) encompasses the height of each calf raise and the total number of repetitions completed in consideration of body mass. Total work and peak height can enable detection of reduced TS MTU function as a result of tendon elongation and limited plantar-flexor endurance following AT rupture (Silbernagel et al., 2012). Recently, normative values for total work and peak height have been established in healthy adults for both the dominant leg and non-dominant leg when performing the CRT at 60 bpm on a 10° incline (Visser et al., 2025). The establishment of normative values from uninjured individuals is important as comparisons cannot always be with the contralateral limb in clinic, as an individuals uninjured limb may not have optimal function at time of assessment (Hébert-Losier et al., 2017; O'Neill et al., 2019). However, in uninjured individuals, side-to-side differences in CRT outcomes appear to be of trivial importance.

Visser et al. (2025) reported the median total work and peak height for the dominant leg as 1374 J and 9.3 cm, with the non-dominant leg achieving 1325 J and 9.6 cm. These values were greater in individuals who were male, had lower BMI, and had higher PAL, but not significantly different between legs, in line with previous findings regarding of CRT repetition outcomes (Hébert-Losier et al., 2017). Furthermore, Hébert-Losier, Pandit, et al. (2025) established normative values for total work and peak height at 60 bpm on a 10° incline in children (10 to 17 years), the average total work being 1087.5 J and peak height 9.8 cm. In this study, children who were older, had lower BMI, and were more active exhibited superior CRT outcomes, with no sex or side differences, confirming the side assessed prevents non-clinically meaningful differences in younger, healthy populations.

In addition to repetitions, total work, and peak height, other outcomes measured in the CRT include total time (seconds), peak power (watts), and total vertical displacement (centimetres), with each providing data indicative of TS MTU function (Hébert-Losier et al., 2022; Santos da Silveira et al., 2022; Visser et al., 2025). Total time taken to complete the CRT to fatigue could be indicative of TS muscular endurance (Santos da Silveira et al., 2022), with greater total times associated with more repetitions completed or use of a slower cadence when the pace is uncontrolled. It is possible that peak power as a CRT outcome could be predictive of functional capabilities when CRT cadence is not constrained (Hébert-Losier, Fernandez, et al., 2025), with Nordenholm et al. (2022) establishing that greater peak power at the ankle during walking correlates strongly with CRT repetitions, peak height, and work ($r = 0.62$ to 0.66). Cadence influences total vertical displacement, total work, peak height, and peak power in the CRT (Hébert-Losier, Fernandez, et al., 2025), suggesting that there is potential to develop normative data at varying cadence ranges.

The recording of CRT outcomes other than repetitions has previously required access to expensive technology, inclusive of force plates and 3D motion capture technologies

(Hébert-Losier et al., 2012; Hébert-Losier et al., 2011), classified as the gold standard for the measurement of kinetics (Fernandez et al., 2023). Easier to access technology such as linear encoders have been proven valid with good intra-rater test-retest reliability in measuring CRT outcomes: repetitions (ICC = 0.77), total work (ICC = 0.84), and maximum height (ICC = 0.85) (Byrne et al., 2017; Silbernagel et al., 2010). With advancements in mobile technologies, the Calf Raise application was developed to provide clinicians with an accessible and free to use tool that accurately assesses TS MTU function within clinical settings through the use of computer-vision algorithms (Fernandez et al., 2023).

Scientific research has confirmed the application has excellent intra-rater and inter-rater reliability (ICC $\leq$ 0.949, CV $\leq$ 5.6%) when used with healthy individuals (Fernandez et al., 2023). Good to excellent agreement of derived outcomes against 3D motion and force plates are demonstrated by the application (ICC = 0.84 – 1.00) (Hébert-Losier et al., 2022). When the circular marker for tracking vertical displacement is placed on the lateral malleolus, the application reports excellent concurrent validity for CRT outcomes (ICC = 0.963 – 1.00) (Fernandez et al., 2023). Test-retest reliability for CRT outcomes are good to excellent for total work (ICC = 0.96) (Schrefl, 2024) and peak height (ICC = 0.85) (Byrne et al., 2017) using clinical approaches to measurements, and reported as good for total work (CV < 10%, ICC < 0.87) with CRT familiarisation when using the application (Hébert-Losier et al., 2022). Since development of the application, it has been regularly used across published CRT literature (Franklin et al., 2026; Hébert-Losier et al., 2024; Hébert-Losier, Fernandez, et al., 2025; Hébert-Losier et al., 2023; Hébert-Losier et al., 2022).

A point to consider is that even with the use of valid and reliable tools for measurement of TS MTU function, varying CRT parameters (e.g., foot position, knee position, cadence) can influence CRT outcomes and normative values (Hébert-Losier et al., 2024; Hébert-Losier, Fernandez, et al., 2025; Hébert-Losier et al., 2012), with the potential to

affect how CRT outcomes are interpreted. Variations in CRT parameters and how they potentially impact outcomes are important to consider in research and clinical applications.

1.3.3 Variations in calf raise test parameters

Published systematic reviews clearly indicate how CRT parameters are not universal (Artina et al., 2026; Bohannon, 2022; Hébert-Losier, Newsham-West, et al., 2009; Schrefl et al., 2023), with lack of standardisation contributing to inconsistency across CRT execution, normative values, and data interpretation, making large inferences challenging. Common, yet unstandardised testing parameters for the unilateral CRT include: foot position (e.g., neutral, slight dorsiflexion, forefoot supported), knee position (e.g., flexion, extension), calf raise height (e.g., maximal height, to a target, to a minimum of 5 cm), and cadence (e.g., 30 bpm, 60 bpm, 120 bpm, self-chosen, as fast as possible) (Artina et al., 2026; Green et al., 2024; Hébert-Losier, Newsham-West, et al., 2009; Möller et al., 2005). Systematic reviews have identified gaps within CRT research, creating opportunity for recent published studies to explore and identify the implications of foot position and cadence on CRT outcomes (Hébert-Losier et al., 2024; Hébert-Losier, Fernandez, et al., 2025). The most common starting foot positions (e.g., neutral, slight dorsiflexion, forefoot supported) have been shown to significantly influence the key CRT outcomes of repetitions, peak height, and total work ($P < 0.001$) (Hébert-Losier et al., 2024). Furthermore, cadence (e.g., 30 bpm, 60 bpm, 120 bpm) significantly influenced total vertical displacement, peak height, total work, peak power ($P \leq 0.008$), but not repetitions ($P = 0.200$) (Hébert-Losier, Fernandez, et al., 2025), implying that CRT parameters do matter in the interpretation of the CRT. The test parameter of cadence is the main focus for this thesis.

1.3.4 Cadence as a factor

The most common CRT cadence is 60 bpm, performed to the beat of a metronome (going up on one beat and down on one beat) (Hébert-Losier, Fernandez, et al., 2025; Hébert-

Losier, Newsham-West, et al., 2009), resulting in the completion of 30 repetitions each minute. While 60 bpm is common, varying cadences set to a metronome have been used across literature, including slower cadences of 30 bpm to 40 bpm (Möller et al., 2002; Möller et al., 2005; Rowley et al., 2015) and faster cadences reaching up to 120 bpm (Hébert-Losier et al., 2012; Hébert-Losier et al., 2011). Additionally, unstandardised self-selected (André et al., 2016; Cesanelli et al., 2025; Green et al., 2024; Olsson et al., 2014) and as fast as possible cadences (Monteiro et al., 2017; Monteiro et al., 2013; Santos da Silveira et al., 2022) with no audible cues have been used.

Only recently has the influence of controlled cadence (30 bpm, 60 bpm, 120 bpm) on unilateral CRT outcomes been explored (Hébert-Losier, Fernandez, et al., 2025), with all outcomes collected (total vertical displacement, total work, peak height, peak power) significantly influenced by cadence (all $P < 0.008$), except for repetitions, suggesting cadence matters in CRT metric interpretation. Though self-selected cadences are used, published studies have not identified and reported self-selected CRT cadence ranges. There is limited literature available that provide insight on as fast as possible CRT cadences (Monteiro et al., 2017; Santos da Silveira et al., 2022), with these studies using a bilateral CRT, rather than a unilateral one. Reported average as fast as possible cadences were the equivalent of 137 bpm and 138 bpm (from positions of dorsiflexion and neutral) (Santos da Silveira et al., 2022), aligning with findings of median as fast as possible cadences ranging from 126 to 186 bpm for males, and 116 to 150 bpm for females (Monteiro et al., 2017). Varying age and sex of participant demographics are likely contributors to the range difference in fast cadences. However, these identified fast cadence ranges from bilateral CRT performances still predominantly sit close to or above 120 bpm used in unilateral CRT, placing greater demand on the TS muscles inducing faster muscular fatigue (Santos da Silveira et al., 2022). Though these studies have identified as fast as possible cadences, neither study examined how those

cadences directly affected CRT outcomes, other than total test time and repetitions (Monteiro et al., 2017; Santos da Silveira et al., 2022). Faster self-selected cadences have been associated with shorter total CRT times compared to tests where cadence is externally controlled with a metronome (Monteiro et al., 2017; Santos da Silveira et al., 2022). Furthermore, how cadence affects bilateral CRT repetitions is mixed. Santos da Silveira et al. (2022) reported that healthy adults (18 to 35 years) performed less repetitions at faster cadences, but Monteiro et al. (2017) reported males achieved greater median repetitions (85) at 186 bpm than females (56.5) at 150 bpm, with sex influencing repetitions more than cadence. However, the pace of fast cadences reduced in females with an increase in age (Monteiro et al., 2017), suggesting that sex and age could be a greater influence on repetitions than CRT cadence.

Hébert-Losier, Fernandez, et al. (2025) reported peak height was 5% greater at 60 bpm and 120 bpm compared with 30 bpm, with the slower cadence potentially too slow to illicit the stretch-shortening cycle as efficiently in the concentric phase (Turner & Jeffreys, 2010), resulting in reduced calf raise height. A faster cadence (e.g., 60 bpm, 120 bpm) may be more likely to detect reduced TS muscle function through lower calf raise height, with faster cadences potentially relying more on stored elastic energy for efficient movement. Following AT ruptures, a reduced peak height in the CRT can reflect tendon elongation and signs of reduced plantar-flexor strength (Brorsson et al., 2017; Silbernagel et al., 2012; Zellers et al., 2020). Given that peak power was greatest at 120 bpm (394 W) over slower cadences (30 bpm, 60 bpm), it would suggest performing faster repetitions enabled greater recruitment of fast-twitch (Type II) muscle fibres and greater rates of force development. Though 60 bpm is common, varying standardised cadences for specific purposes in the CRT has potential merit, with slower cadences used post injury, progressing to faster cadences

through rehabilitation to explore power capacity and used in exercise prescription to develop ankle plantar-flexor power.

Furthermore, Hébert-Losier, Fernandez, et al. (2025) reported 60 bpm produced greater overall average total work (1513 J) than 30 bpm (1365 J) and 120 bpm (1327 J), leading them to speculate that 60 bpm may closely reflect a self-selected cadence (Hébert-Losier, Fernandez, et al., 2025), but it is not yet known what pace individuals would self-select when performing the unilateral CRT, or how self-selected cadence would affect CRT outcomes compared to the standard 60 bpm. Given the relatively limited studies on the effect of cadence on the calf raise task, it becomes relevant to consider the influence of cadence in other movements.

1.4 Cadence considerations

Cadence in human movement (e.g., walking, running, weightlifting) and how it influences performance has been considerably researched (Brennan et al., 2017; Dorn et al., 2012; Meireles et al., 2025; Neptune et al., 2008; Nguyen et al., 2026; Teixeira-Salmela et al., 2008; Wilk et al., 2021). A balanced exercise programme manipulates variables, such as the number of repetitions and sets, load, and exercise tempo, to progress specific physiological and neurological adaptations (Hatfield et al., 2006; Headley et al., 2011; Meireles et al., 2025; Morán-Navarro, 2019). The use of tempo (e.g., adjusting movement velocity) as an exercise prescription variable for concentric and eccentric phase of movements can stimulate muscle growth (Wilk et al., 2021), develop power, increase strength (Hatfield et al., 2006), and greater movement speeds are associated with increased muscular power (Meireles et al., 2025). Furthermore, published reviews have outlined increased movement loading (e.g., rate, frequency) as contributing to the development of tendon stiffness in the AT, resulting in better locomotion efficiency and improved rate of force development (Lazarczuk et al., 2022; Merry et al., 2022). However, what cadence calf raise repetitions should be performed at for

TS MTU rehabilitation remains unknown. Considering that the gastrocnemii have more fast-twitch muscle fibres than the more fatigue-resistant soleus (Kinugasa et al., 2005; O'Brien, 2005), performing calf raises at varying cadences may stimulate activation of each TS muscle more specifically. Slower calf raise cadences could increase the time under tension and may be used early in TS MTU rehabilitation or with beginner exercisers to build TS muscles strength to improve muscular endurance (Meireles et al., 2025; Wilk et al., 2021). In contrast, increasing tempo or prescribing faster cadences intentionally and progressively can aid power development, while concurrently increasing TS MTU capacity to perform explosive movements involved in sporting activities (e.g., plyometrics, running) (Baxter, 2021; Fukashiro et al., 2006; Grävare Silbernagel & Crossley, 2015; Hébert-Losier, Fernandez, et al., 2025; Marrone et al., 2024; Schenau et al., 1997).

1.4.1 Cued versus non-cued

The ability for humans to synchronise movement to acoustic stimuli (e.g., metronomes, music) in a phenomenon known as auditory motor synchronisation is well documented in the literature (Bood et al., 2013; Hutchinson & Karageorghis, 2013; Pranjić et al., 2024; Priest & Karageorghis, 2008; Van Dyck et al., 2021; Vanbilsen et al., 2025). More specifically, movement tempo in exercise and rehabilitation tasks coupled with acoustic stimuli has been shown to have a positive influence on repetitive, endurance tasks with greater cadence consistency and time to fatigue in running (Bood et al., 2013; Roerdink et al., 2011; Van Dyck et al., 2021). Furthermore, according to a recent review (Gordon et al., 2024), the use of acoustic stimuli in resistance training has reported greater average one repetition max (1RM) strength adaptations (18 – 41%) than reported at self-selected movement tempos (15 – 35%). Comparatively, the absence of external acoustic stimuli when performing movements (e.g., running, walking) has resulted in individuals fatiguing more

quickly (Bood et al., 2013), and perceiving a higher rate of exertion (Edworthy & Waring, 2006).

While the use of acoustic stimuli has been proven positive in rehabilitation, 1RM strength and running performance, the concept of cued and non-cued performances has only recently been explored in terms of the CRT. Green et al. (2024) explored cued (60 bpm) and non-cued (no audible cue) performances of the unilateral CRT. While self-selected cadence ranges were not explicitly identified, results illustrate that non-cued CRT on average achieved 12 more repetitions than the cued CRT, though results are not clinically comparable as typical CRT protocols (e.g., knee position, calf raise height, cadence) were not instructed or controlled in the non-cued group (Green et al., 2024). Although results are not directly comparable and the study does not examine how non-cued conditions influence CRT outcomes aside from repetitions, it does highlight how varying test conditions (e.g., cued, non-cued) can affect performance.

1.4.2 Self-selecting cadence for an end task versus performing to fatigue

While humans have the ability to self-select movement velocities that are optimal regarding individual energy efficiency (Nguyen et al., 2026; Renfree et al., 2014; Selinger et al., 2015), research suggests humans use decision making theories when self-selecting movement pace accounting for performance time frames (e.g., number of repetitions, endurance based activity) (Elferink-Gemser & Hettinga, 2017; Smits et al., 2014; St. Claire Gibson et al., 2006), motivation levels, and energy output to reduce early exhaustion (Pryor et al., 2020; Smits et al., 2014). In relation to the CRT, it is possible that a self-selected cadence for calf raises could be different when completing 10 repetitions in comparison to performing CRT repetitions to fatigue, with the potential for cadences at 10 repetitions to be faster than those to fatigue. Researchers have speculated that 60 bpm could be close to a self-selected cadence, and shown that 120 bpm is maintainable when performing CRT repetitions to

fatigue (Hébert-Losier, Fernandez, et al., 2025; Santos da Silveira et al., 2022), suggesting self-selected as fast as possible cadences for a specified number of repetitions could be greater than 120 bpm. Lower perceived rates of effort at a non-fatiguing, prespecified number of repetitions may affect how much effort and energy an individual puts into their self-chosen cadences, leading to an all-out pacing strategy (St. Claire Gibson et al., 2006) that increases the likelihood of faster cadences.

1.5 Summary and aim statement

In summary, cadence is an important test parameter to consider in the interpretation of CRT outcomes, and for the prescription of rehabilitation programmes. While speculated that 60 bpm could be close to a self-selected cadence, there is space within current literature to explore what cadence range individuals would self-select or perform as fast as possible in the CRT. Additionally, it remains unknown how CRT outcomes achieved at self-selected and as fast as possible cadences compare to CRT outcomes achieved at the commonly used 60 bpm. The importance of the TS muscles for functional movement, and the human ability to self-select optimal cadence in movement have been well documented, yet no published research has explicitly explored and identified self-selected cadence ranges for the CRT.

Therefore, based on this literature review this thesis completed two experimental studies exploring calf raise cadence. The main aim of study one was to compare cadences maintained during 10 calf raise repetitions (CR10) between three conditions: control (60 bpm), self-selected, and as fast as possible. A secondary aim was to explore the influence of cadence on other relevant CR10 outcomes, being total time, total work, peak power, vertical displacement per repetition, and displacement variability. We hypothesised that self-selected cadences would be faster than 60 bpm but slower than as fast as possible. Furthermore, we hypothesised that faster cadences would produce quicker CR10 completion with greater total work, peak power, vertical displacement, and displacement variability. Additionally, we

aimed to account for BMI, sex, and PAL as potential predictors of CR10 outcomes. The main aim of study two was to compare cadences maintained during the CRT between three conditions: control (60 bpm), self-selected, and as fast as possible. A secondary aim was to explore the influence of cadence on CRT outcomes, being repetitions, total time, total work, peak power, vertical displacement per repetition, and displacement variability. We hypothesised that self-selected cadences would be faster than 60 bpm, and based on the CR10 data, would be 75 bpm or less. Furthermore, we hypothesised that cadence (60 bpm, self-selected pace, and as fast as possible) would influence all CRT outcomes, except repetitions, with faster cadences producing the greatest peak power, vertical displacement, and displacement variability. An additional aim was to explore calf training, age, BMI, sex, and PAL as potential predictors of CRT outcomes. These findings could provide insight on the cadences individuals self-select during non-fatiguing and fatiguing calf raise repetitions, the upper cadence limit in healthy individuals, and how calf raise outcomes of self-selected calf raise repetitions compare with those achieved at 60 bpm.

Chapter Two – Experimental Study

Experimental study comparing three cadence conditions and their effect on outcomes when performing 10 calf raise repetitions (non-fatiguing).

2.1 Introduction

For the majority of the global population, walking is an everyday functional movement. Furthermore, many individuals participate in activities involving explosive movements (e.g., running and jumping), requiring well-functioning triceps surae (TS) muscles to generate force for forward and upward propulsion (Farris & Sawicki, 2012; Jan et al., 2005; Pandey et al., 2021). The TS are the main plantar-flexor muscles at the ankle joint (Machado et al., 2021; Neptune & Sasaki, 2005), comprising of the two gastrocnemii (medial, lateral) and the soleus, merging distally on the heel through the Achilles tendon (AT) to form the TS muscle tendon unit (MTU) (Farris & Sawicki, 2012; Mylly et al., 2023). Like most soft tissue structures, the TS MTU is vulnerable to injury, including overuse injuries to the tendon due to repetitive loading cycles (Chen et al., 2024; Heckman et al., 2009) and acute injuries to the muscles or tendon from sudden accelerations or changes of direction (Bryan Dixon, 2009; Green & Pizzari, 2017; Nielsen et al., 2023).

The calf raise test was developed in the 1940s (Lunsford & Perry, 1995) and is common within clinical settings to assess the strength and endurance of the TS MTU through completion of unilateral repetitive plantar-flexor concentric-eccentric contractions to fatigue (Hébert-Losier, Newsham-West, et al., 2009; Hébert-Losier et al., 2017; Lunsford & Perry, 1995). The number of repetitions completed is the primary clinical outcome used (Hébert-Losier, Newsham-West, et al., 2009; Lunsford & Perry, 1995; Silbernagel et al., 2010); however, published studies (Nordenholm et al., 2022; Silbernagel et al., 2010) have revealed peak height and total work as additional relevant outcomes of TS MTU function that are more sensitive to deficits than repetition count. Though not a typical measure of TS MTU function, peak power has been identified as having an influence on gait functionality (e.g., walking speed and efficiency) (Nordenholm et al., 2022), suggesting that peak power could be an important indicator of TS MTU functional and performance.

Although using a metronome set to 60 bpm to complete 30 repetitions per minute during the calf raise test is common, there is inconsistency across the scientific literature (Hébert-Losier, Fernandez, et al., 2025; Hébert-Losier, Newsham-West, et al., 2009). Calf raise test cadences used include self-selected and as fast as possible without audible guidance (André et al., 2016; Cesanelli et al., 2025; Green et al., 2024; Monteiro et al., 2017; Olsson et al., 2014; Santos da Silveira et al., 2022), in addition to the use of metronomes set to 30 bpm or 40 bpm (Möller et al., 2002; Möller et al., 2005) up to 120 bpm (Hébert-Losier et al., 2012; Hébert-Losier et al., 2011). While there is evidence of how controlled cadences influence unilateral calf raise test outcomes (Hébert-Losier, Fernandez, et al., 2025), it remains largely unknown what cadence individuals self-select when performing calf raise repetitions.

Research has established that individuals have the ability to self-select a movement pace that can enhance endurance activities (e.g., walking, running) while simultaneously reducing energetic costs and regulating muscular work rates (Nguyen et al., 2026; Renfree et al., 2014; Selinger et al., 2015). As the total work generated during a metronome-guided calf raise test was shown greatest at 60 bpm compared to 30 or 120 bpm (Hébert-Losier, Fernandez, et al., 2025), it may be that self-selected cadences are close to 60 bpm during unilateral calf raise repetitions. Data from a published bilateral calf raise study reported average as fast as possible cadences 137 bpm for participants 18 to 35 years of age (Santos da Silveira et al., 2022). In contrast, an earlier study with participants 20 to 59 years of age (Monteiro et al., 2017) reported average as fast as possible cadences as 126 to 186 bpm for males, and lower cadences of 116 to 150 bpm for females. These reported as fast as possible cadences are much higher than the metronome-guided 120 bpm cadence used in some studies (Hébert-Losier, Fernandez, et al., 2025; Hébert-Losier et al., 2012; Hébert-Losier et al., 2011). Bilateral calf raise repetitions are often used in older populations to account for deterioration in balance and TS MTU function with aging (André et al., 2016; André et al.,

2018; Monteiro et al., 2017). Hence, variations in age and physical activity profiles of participants likely explain differences in their ability to maintain high cadences during repetitive calf raise performances. It is possible that as fast as possible cadences will be faster than currently identified in literature when performing 10 repetitions. To date, the upper limit of cadence for performing the calf raise test or calf raise repetitions has not been thoroughly explored. Establishing this upper cadence in uninjured individuals could assist in establishing a normative higher cadence for calf raise repetitions and potentially in identifying limitations in TS MTU mechanical capabilities or ability to efficiently use stored elastic energy in injured groups.

Variations in the calf raise exercise (e.g., isometrics, bilateral, unilateral,) are commonly prescribed as part of TS MTU rehabilitation (Green et al., 2022), with sets of 10 to 15 repetitions often prescribed for hypertrophy (Osborne et al., 2025; Schoenfeld, 2000). A well-rounded exercise programme considers variables such as the number of repetitions and sets, load, and movement tempo (Hatfield et al., 2006; Morán-Navarro, 2019). Research (Hatfield et al., 2006; Meireles et al., 2025; Wilk et al., 2021) clearly illustrates how movement speed can influence exercise outcomes to target individual goals, yet it is unclear what cadence calf raise repetitions should be used for TS MTU rehabilitation. Given that the TS muscles have varying muscle fibre properties, training at different cadences may solicit the TS muscles differently, with the gastrocnemii muscles having a greater proportion of fast-twitch muscle fibres than the more fatigue-resistant soleus muscle (Kinugasa et al., 2005; O'Brien, 2005). Progressively increasing the tempo or adding higher cadence repetitions can assist in developing power, while simultaneously preparing the TS MTU for more explosive movements required in sports (e.g., plyometrics, running) (Fukashiro et al., 2006; Grävare Silbernagel & Crossley, 2015; Hébert-Losier, Fernandez, et al., 2025; Schenau et al., 1997). It is not yet known what calf raise cadence individuals may self-select or are able to maintain

when performed as fast as possible, with implications for exercise prescription and calf muscle testing. Identifying self-selected and the upper cadence limit could be beneficial for informing the prescription of tempo during calf raise exercises for varying stages of TS MTU rehabilitation and strength and conditioning training more broadly.

Physical activity levels (PAL) (Bogdanis, 2012; Visser et al., 2025), sex (Hébert-Losier et al., 2017; Jan et al., 2005), and body mass index (BMI) (Hébert-Losier et al., 2022; Hébert-Losier et al., 2017; Visser et al., 2025) have been shown to influence calf raise test outcomes. Muscle structure differences (e.g., fascicle length, fibre size) between sexes (Blackburn et al., 2006), paired with greater body mass can lead to greater power generation in males (Fukashiro et al., 2006; Hébert-Losier, Fernandez, et al., 2025; Zhou et al., 2017), likely influencing outcomes when calf raises are performed at varying cadences. With this in mind, the primary aim of this study was to compare the cadences maintained during 10 calf raise repetitions (CR10) between three conditions: control (60 bpm), self-selected, and as fast as possible. Non-fatiguing calf raise repetitions were targeted in a first instance for their rehabilitation and training prescription implications, limiting confounding from fatigue. We hypothesised that self-selected cadences would be faster than 60 bpm but slower than as fast as possible. Furthermore, we aimed to explore the influence of cadence on other relevant CR10 outcomes, being total time, total work, peak power, vertical displacement per repetition, and displacement variability. We hypothesised that faster cadences would produce quicker CR10 completion with greater total work, peak power, vertical displacement, and displacement variability. Across analyses, we aimed to account for BMI, sex, and PAL as potential predictors of CR10 outcomes.

2.2 Methods

2.2.1 Sample size

Data from a recent published study identified a *moderate* effect size difference (Cohen's $d = 0.35$) in total work between two CRT cadences: 60 bpm and 120 bpm (Hébert-Losier, Fernandez, et al., 2025). This effect size was used to derive our sample size using G*Power 3.1.9.7 using the repeated measures analysis of variance (ANOVA) for a within-factor study design with sphericity assumed to 1.0. The statistical significance was set to 5%, Cohen's f effect size to 0.18, power to 80%, correlation between measures to 0.70, and group to one with three repeated measures (Hébert-Losier, Pandit, et al., 2025). In accordance with these estimates, a minimum sample size of 32 participants was required.

2.2.2 Study design

A randomised, crossover trial with repeated measures was used to explore the effects of varying cadences (60 bpm, self-selected, and as fast as possible) on the following CR10 outcomes: repetitions per minute (cadence), total time (s), total work (J), peak power (W), vertical displacement per repetition (cm), and displacement variability per repetition (cm). For this purpose, participants were required to perform the unilateral CR10 at three cadences in a single testing session with 15 minutes rest between conditions (Figure 3). All tests were performed barefoot, on the right leg from a 10° incline. Upon arrival, a single researcher involved in the data collection process allocated randomisation to participants. Randomisation of initial participants was based using a 'pick from a hat' approach, with sequence allocation monitored and options reduced for later participants to ensure quasi-equal numbers starting in each condition. Due to the nature of the research, participants and researchers were unable to be blinded. Our study was reported following the extension of randomised crossover trial Consolidated Standards of Reporting Trials (CONSORT) 2025 statement (Hopewell et al., 2025). We pre-registered our study and testing protocols with the

Australian New Zealand Clinical Trials Registry (ANZCTR), registration number ACTRN12625001325493.

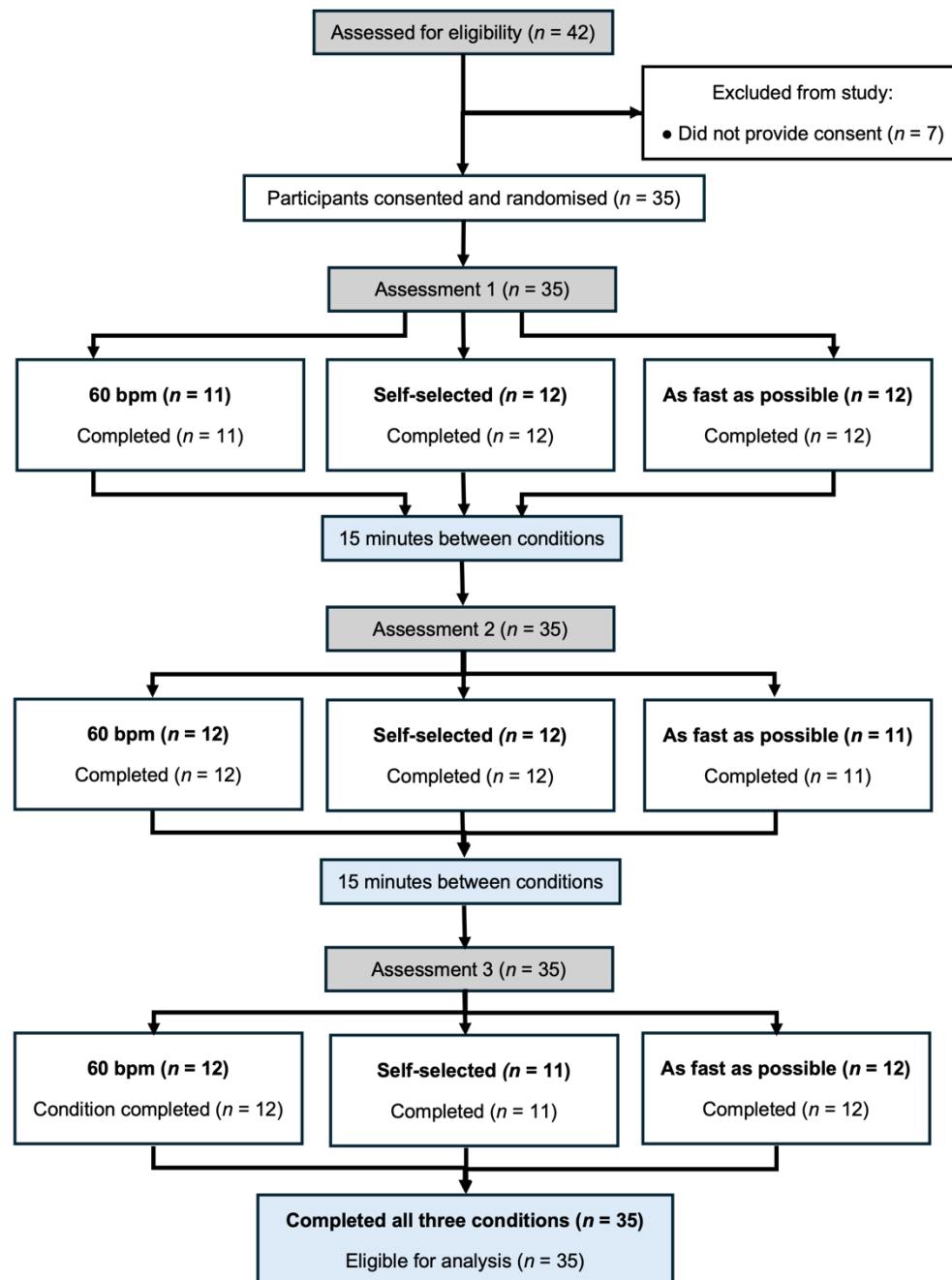


Figure 3. Flow Diagram showing participant condition allocation of randomised crossover trial.

2.2.3 Participants

Staff and students at the University of Waikato in New Zealand were recruited through word of mouth. Individuals over 16 years of age were invited to participate if they were able to perform unilateral calf raises and were in self-disclosed good general health. Individuals were excluded from participation if they had a lower-limb musculoskeletal injury within three months of testing or a history of an AT rupture. This study was granted approval by the Human Research Ethics Committee at the University of Waikato [HREC(HECS)2023#44] and adhered to the Declaration of Helsinki principles (World Medical Association, 2013). Participants were supplied with verbal and written detailed information describing the study aims, benefits (individualised reports), testing process, and potential risks associated with participation (musculoskeletal injury or delayed onset calf muscle soreness). Prior to experimentation, all participants provided written informed consent. All participant data were stored according to data collection policies and research management at the University of Waikato.

To compute the calf raise mechanical work and BMI, body mass (kg) and height (cm) were recorded to the closest 0.01 kg and 1 cm using a scale (Seca model ESE813) and stadiometer (Seca model 0123) before experimentation. Additionally, participants self-completed baseline forms to collect age, sex, injury history, and PAL based on the 6-point Likert scale that took into account the past 12 months (where 1 reflects hardly any physical activity and 6 reflects hard or very hard exercise regularly and several times a week) (Batty, 2000; Grimby et al., 2015; Hébert-Losier et al., 2017; Visser et al., 2025).

2.2.4 CR10 protocol

All experimentations took place in the University of Waikato sports laboratory, providing a well-lit environment with firm flooring, suitable for the placement of a 10° steel

platforms, confirmed using a digital inclinometer. Platforms were positioned 30 cm from the wall to allow fingertip support. Performing the CR10 from a 10° incline (i.e., slight dorsiflexion, Figure 4) was selected as calf raise test outcomes produced from this position are valid and reliable (Byrne et al., 2017; Fernandez et al., 2023; Hébert-Losier et al., 2024) and vertical displacement is greater from this position compared to other foot starting positions (e.g., from a step or a flat surface) (Hébert-Losier et al., 2024). Furthermore, the 10° incline has been used for the calf raise test in clinical settings to manage Achilles tendon injuries (Brorsson et al., 2018; Silbernagel et al., 2006; Silbernagel et al., 2010; Zellers et al., 2020), with a greater range of motion able to be assessed than from the floor, and hence considered more relevant to functional movements (Hébert-Losier et al., 2024; Neptune & Sasaki, 2005).

The CR10 experimental sessions were run by three experienced researchers, each familiar with the CR10 protocol and in assessing physical movement. To prepare for experimentation, participants completed a warm-up barefoot that consisted of 10 bilateral calf raises from the floor, at a self-selected pace. Additionally, participants completed 3 unilateral calf raises barefoot on their right leg on the 10° platform at their allocated cadence condition (i.e., 60 bpm, self-selected, as fast as possible) to ensure proper technique and familiarisation. A rest period of 2-minute was provided between the warm-up and commencement of testing. Before experimentation, participants were provided with written and verbal CR10 instructions, specific to the cadence being assessed. For the control 60 bpm cadence condition, participants were instructed to go up on their toes and return to the starting position following the beat of the metronome (set to 60 bpm), going up in one beat and down in one beat. For the self-selected cadence condition, participants were instructed to perform the CR10 at a pace that felt the most natural and comfortable for them. For the as fast as possible condition, participants were instructed to complete the CR10 as fast as possible. Across all

conditions, participants were instructed to complete their 10 repetitions going up as high as possible on their toes and coming back down to the starting position. For the duration of the CR10, participants maintained full extension of their right knee, with their left knee maintaining 90° flexion, keeping their left foot behind their body. Participants were instructed to place their middle and index fingers on the wall in front of them at shoulder height for balance support. Furthermore, for the duration of the CR10, participants were instructed to remain looking straight ahead and to propel their body upwards, not forwards. Assessors provided participants with verbal encouragement during each CR10 at regular intervals. Failure to maintain correct technique or a loss in balance resulted in termination of the CR10 and repeat of trials after 2 minutes of rest, which was needed on only three occasions.

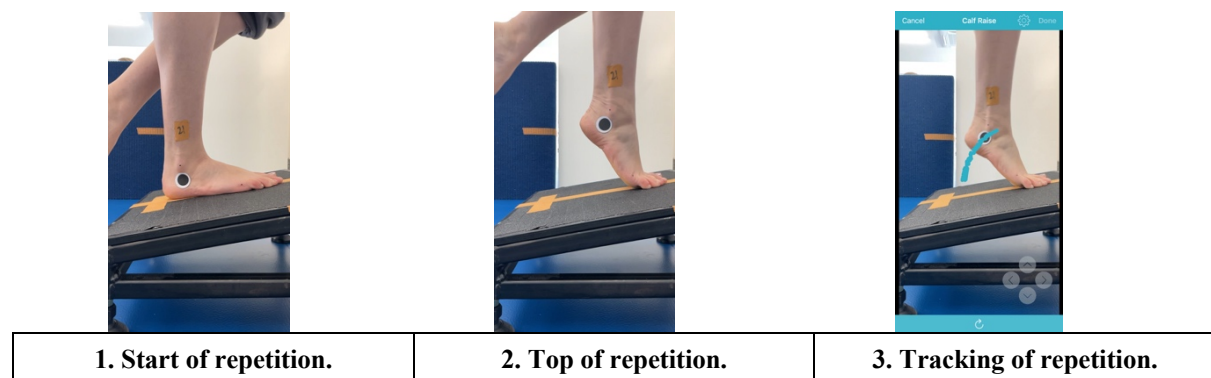


Figure 4. Photographs displaying the positions of a calf raise repetition. The start of each repetition (i.e., slight dorsiflexion) is shown in photograph 1, the top of the calf raise repetition is shown in photograph 2, and the tracking of vertical displacement using the 24 mm black sticker via the Calf Raise application is shown in photograph 3.

2.2.5 Equipment

The CR10 outcomes were recorded using the validated Calf Raise application (version 1.5.1) with a computer algorithm designed to track vertical displacement using a calibrated 24 mm circular sticker positioned underneath the lateral malleolus in line with the

heel on a flat portion of the foot (Fernandez et al., 2023). All CR10 repetitions were recorded in portrait, on Apple iPads running software iOS 17.5.1 (model MPQ13X/A, Apple, Inc), capturing videos at a sampling rate of 60 frames per second. The iPad was positioned on a secure metal stand, 50 cm to the right of the testing foot enabling full coverage of each calf raise repetition (Hébert-Losier, Fernandez, et al., 2025). The application does not compute the number of repetitions per minute, or provide data for each repetition. The raw data curves were exported as text files and imported into Visual3D Professional v2025.09.1 (©HAS-Motion, Kingston, Ontario, Canada) for further processing and to extract cadence (rep/min), total CR10 time (s), total positive work (J), peak power per repetition (W/rep), positive vertical displacement per repetition (cm/rep), and displacement variability (cm) using a custom script. The standard deviation of the positive vertical displacement per repetition was used as indicator of displacement variability. To delineate each repetition, the peak vertical position from each repetition was identified first from the raw data, with the return to the bottom of the raise identified as the instance when velocity reached zero thereafter.

When the application is used with healthy individuals, intraclass correlation coefficients (ICC) and coefficient of variation (CV) demonstrate excellent intra-rater and inter-rater reliability ($ICC \leq 0.949$, $CV \leq 5.6\%$) for calf raise test outcomes for the videos analysed (Fernandez et al., 2023). The application exhibits good to excellent agreement of derived outcomes against gold standard measurements of 3D motion and force plates ($ICC = 0.84$ to 1.00) (Hébert-Losier et al., 2022), with excellent concurrent validity of calf raise test outcomes when the circular marker is placed beneath the lateral malleolus ($ICC = 0.963$ to 1.00) (Fernandez et al., 2023). Test-retest reliability of CRT outcomes are good to excellent for work ($ICC = 0.84$) (Byrne et al., 2017), repetitions ($ICC = 0.91$, $CV \leq 8.7\%$) and peak height ($ICC = 0.93$, $CV \leq 5.7\%$) (Schrefl, 2024). Furthermore, test-rest reliability for

repetitions and total work ($CV < 10\%$, $ICC \leq 0.87$) has been established as good when using the application with familiarity of the calf raise test (Hébert-Losier et al., 2022).

2.2.6 Statistical analysis

Means, standard deviations, minimum-to-maximum ranges, and counts were used to describe participant demographic characteristics. To assess the normality of data distribution, Shapiro-Wilk tests were run prior to statistical analyses on CR10 outcomes. All data were non-normally distributed ($P \leq 0.003$), hence, descriptive statistics were reported as medians with interquartile ranges [25th, 75th]. Prior to inferential analyses, all data were log-transformed to decrease heteroscedasticity and skewness. To analyse log-transformed CR10 outcomes (i.e., repetitions per minute, total time, total work, peak power per repetition, vertical displacement per repetition, and displacement variability), mixed-effects linear regression models applying restricted maximum-likelihood estimation were used. Models explored the main effect of cadence (categorical, 3 levels) on CR10 outcomes, and accounted for sex (categorical, 2 levels), BMI (continuous), and PAL (categorical, 2 levels) as potential predictors. The PAL were reported on a 6-point Likert scale, however due to population distribution these were dichotomised as participants reporting the highest level (hard or very hard exercise regularly and several times a week) and those below this level. Both cadence conditions and predictors were identified as fixed factors, and because our study involved repeated measures, participants were identified as nested random factors with exposure to all three cadence conditions. Estimates from our mixed-effect models are presented as rate ratios. The reference groups were set to 60 bpm for cadence, high for PAL, and male for sex. In stepwise regressions, non-significant predictors were removed from models using the Bayesian information criterion, always maintaining the main effect of cadence within models. Bonferroni-adjusted P -values and 95% confidence intervals [lower, upper] were used in post-hoc comparisons in presence of a main cadence condition. Estimates were exponentiated to

obtain ratios of geometric means for pairwise comparisons, whereas exponentiated coefficients for continuous predictors (i.e., BMI) represent the multiplicative change in geometric mean per unit increase. Stata Statistical Software, version 16.1 (Statacorp LLC, College Station, TX, USA) was used to perform data analysis, with $P < 0.05$ set as statistically significant.

2.3 Results

2.3.1 Participants

Forty-two individuals were recruited, with thirty-five participants (16 males, 19 females) providing consent and completing all cadence conditions (Figure 3). Participant characteristics are described in Table 1.

Table 1. Participant characteristics ($n = 35$)

Participants ($n = 35$)	Male ($n = 16$)	Female ($n = 19$)
Age (years)	20.8 $\pm$ 1.6 (19.2 – 24.7)	20.6 $\pm$ 1.3 (19.3 – 24.0)
Body mass (kg)	79.8 $\pm$ 7.1 (66.3 – 96.1)	68.9 $\pm$ 9.6 (54.8 – 88.8)
Body height (cm)	177.3 $\pm$ 5.5 (166.6 – 188.5)	166.2 $\pm$ 6.7 (150.7 – 180.9)
BMI (kg/m ²)	25.4 $\pm$ 1.5 (23.1 – 27.8)	25.0 $\pm$ 3.2 (19.8 – 31.5)
PAL participant count (0, 3, 4, 5, 6)	1, 0, 0, 3, 12	2, 0, 3, 6, 8

Notes. Values are presented as mean $\pm$ standard deviation (minimum – maximum) and counts.

† Likert scale of PAL: 0 = undisclosed, 3 = light, 4 = moderate 1-2 h, 5 = moderate at least 3 h, 6 = hard or very hard exercise.

Abbreviations: BMI, body mass index; PAL, physical activity levels.

2.3.2 CR10 outcomes

The descriptive summary of CR10 outcomes for each cadence condition is presented in Table 2. The median cadences maintained during the CR10 at 60 bpm, self-selected, and as fast as possible conditions were 61.2 bpm, 75.6 bpm, and 196.8 bpm, respectively. As shown in Table 3, the difference between conditions were significant for all pairwise comparisons ($P < 0.001$), with the as fast as possible cadence being 218% and 157% faster than during 60 bpm and self-selected, and self-selected being 24% faster than 60 bpm. Correspondingly, the CR10 took less time to complete when going as fast as possible compared to self-selected

(61%) and 60 bpm (69%), with self-selected completed in 19% less time than 60 bpm.

Results from the multilevel mixed-effect linear regression models (Table 3) further revealed that cadence condition significantly influenced peak power and displacement variability ($P < 0.001$), but not vertical displacement ($P = 0.337$) and total work ($P = 0.090$). The as fast as possible condition was completed with greater displacement variability (53%) and peak power (52 to 57%) than the two other conditions, with no significant difference in these CR10 outcomes between self-selected and 60 bpm.

Table 2. Descriptive summary of CR10 outcomes by cadence condition from 35 participants.

Outcome	Cadence condition		
	60 bpm	Self-selected	As fast as possible
Cadence (rep/min)	30.6 [30.4, 30.8] (29.8 – 32.6)	37.8 [31.6, 43.6] (24.2 – 64.5)	98.4 [88.2, 108.4] (70.6 – 143.4)
Total time (s)	19.6 [19.5, 19.8]	15.9 [13.8, 19.0]	6.1 [5.5, 6.8]
Total work (J)	732 [600, 792]	730 [639, 781]	665 [562, 810]
Peak power (W/rep)	236 [185, 266]	240 [205, 267]	360 [305, 445]
Vertical displacement (cm/rep)	9.8 [8.9, 10.6]	9.8 [9.0, 10.5]	9.7 [8.5, 10.4]
Displacement variability (cm/rep)	0.44 [0.33, 0.52]	0.47 [0.36, 0.60]	0.69 [0.55, 0.84]

Notes. Values are presented as median with interquartile range [25th, 75th], and (minimum – maximum). Abbreviation: bpm, beats per minute; CR10, 10 calf raise repetitions; rep, repetition.

Table 3. Multi-level mixed effects linear regression models applying restricted maximum-likelihood on log-transformed CR10 outcomes from 35 participants. Models examined the predictors of cadence condition, sex, body mass index, and physical activity levels.

Outcome	Variable	Estimate [‡] [95% CI]	P value
Cadence (rep/min)	<i>Cadence</i>		<0.001*
	Self-selected [†]	1.24 [1.13, 1.36]	<0.001
	As fast as possible [†]	3.18 [2.90, 3.50]	<0.001
	Fast vs self [†]	2.57 [2.34, 2.83]	<0.001
Total time (s)	<i>Cadence</i>		<0.001*
	Self-selected [†]	0.81 [0.74, 0.89]	<0.001
	As fast as possible [†]	0.31 [0.29, 0.35]	<0.001
	Fast vs self [†]	0.39 [0.35, 0.43]	<0.001
Total work (J)	<i>Cadence</i>		0.090
	Self-selected [†]	1.00 [0.96, 1.05]	1.000
	As fast as possible [†]	0.97 [0.92, 1.01]	0.175
	Fast vs self [†]	0.97 [0.92, 1.01]	0.172
	<i>BMI</i>	1.02 [1.00, 1.04]	0.013
	<i>Sex</i> (female)	0.81 [0.73, 0.89]	<0.001
Peak power (W/rep)	<i>Cadence</i>		<0.001*
	Self-selected [†]	1.03 [0.96, 1.12]	0.869
	As fast as possible [†]	1.57 [1.45, 1.70]	<0.001
	Fast vs self [†]	1.52 [1.40, 1.64]	<0.001
	<i>BMI</i>	1.03 [1.02, 1.05]	<0.001
	<i>Sex</i> (female)	0.82 [0.75, 0.90]	<0.001
Vertical displacement (cm/rep)	<i>Cadence</i>		0.337
	Self-selected [†]	1.00 [0.96, 1.05]	1.00
	As fast as possible [†]	0.98 [0.94, 1.02]	0.709
	Fast vs self [†]	0.97 [0.93, 1.02]	0.529
Displacement variability [§] (cm/rep)	<i>Cadence</i>		<0.001*
	Self-selected [†]	1.01 [0.83, 1.22]	1.000
	As fast as possible [†]	1.53 [1.27, 1.86]	<0.001
	Fast vs self [†]	1.53 [1.26, 1.85]	<0.001
	<i>Sex</i> (female)	0.83 [0.70, 1.0]	<0.001

Notes. Reference conditions for cadence and sex; 60 bpm and male, respectively. Statistical significance set at $P < 0.05$. Only significant predictors are reported, non-significant predictors were removed during stepwise regression. *Indicates a statistically significant main effect.

Abbreviations: BMI, body-mass index; CRT, calf raise test.

[†] Bonferroni-adjusted P -values and 95% confidence intervals. [‡] Estimates represent ratios. [§] Reflects the standard deviation of the vertical displacement per repetition.

2.3.3 Predictors

As displayed in Table 3, models established BMI and sex as significant predictors of select CR10 outcomes. BMI significantly influenced peak power and total work ($P \leq 0.013$), with each 1 unit increase in BMI associated with greater total work and peak power by 2% and 3%, respectively. Additionally, there were significant differences between sexes with

males producing 18% greater peak power, generating 19% more total work, and exhibiting 17% greater displacement variability than females ($P < 0.001$). PAL had no significant influence on CR10 outcomes.

2.4 Discussion

This study was designed to compare the cadences maintained during CR10 between three cadence conditions: 60 bpm, self-selected, and as fast as possible. In our population, the median self-selected cadences equalling 75.6 bpm were 24% greater than at 60 bpm, in agreement with our hypothesis that individuals would self-select a cadence faster than 60 bpm but slower than as fast as possible (196.8 bpm). Median as fast as possible cadences were 218% greater than 60 bpm, with the 196.8 bpm median exceeding a recently published study implementing 120 bpm (Hébert-Losier, Fernandez, et al., 2025). Cadence significantly influenced all CR10 outcomes, except for vertical displacement ($P = 0.337$) and total work ($P = 0.090$), with the latter likely due to the task being confined to 10 repetitions and differences in work likely to emerge with an increase in the number of repetitions completed. In partial agreement with our hypothesis, faster cadences were associated with quicker CR10 times, greater peak power, and greater displacement variability between repetitions than identified at self-selected cadences and 60 bpm. Overall, pairwise comparisons of median self-selected cadences (approximately 76 bpm) and 60 bpm established near identical CR10 outcomes, with the only significant difference between conditions being repetitions per minute (i.e., cadence) and total time ($P < 0.001$), both likely explained by completing CR10 at a faster cadence. Of the predictors examined, sex influenced displacement variability, peak power, and total work. Furthermore, in agreement with published calf raise test studies performed to fatigue (Hébert-Losier et al., 2024; Hébert-Losier, Fernandez, et al., 2025; Hébert-Losier et al., 2022; Visser et al., 2025), we observed BMI as a significant predictor of peak power and total work. In contrast to existing literature (Hébert-Losier et al., 2017; Visser et al., 2025),

PAL did not influence CR10 outcomes, which may be the result of assessing only 10 repetitions, combined with the homogeneity of our participants who mostly reported moderate or high PAL on the 6-point Likert Scale (Batty, 2000; Grimby et al., 2015).

The cadence parameter of the calf raise test has been identified as variable across the literature (Bohannon, 2022; Hébert-Losier, Fernandez, et al., 2025; Hébert-Losier, Newsham-West, et al., 2009). Setting a metronome to 60 bpm (30 repetitions per minute) is common, however, cadences range from 30 and 40 bpm (Möller et al., 2002; Möller et al., 2005) to 120 bpm (Hébert-Losier et al., 2011), with studies also using directives to self-select cadence (André et al., 2016; Cesanelli et al., 2025; Green et al., 2024; Olsson et al., 2014) and perform calf raises as fast as possible (Monteiro et al., 2017; Monteiro et al., 2013; Santos da Silveira et al., 2022). Establishing unilateral CR10 self-selected and as fast as possible cadences in comparison to 60 bpm is potentially beneficial for informing exercise prescription. Our study established the median unilateral CR10 cadences for 60 bpm, self-selected, and as fast as possible conditions as 61.2 bpm, 75.6 bpm, and 196.8 bpm, respectively. Median CR10 as fast as possible cadences (approximately 197 bpm) were much faster than average fast cadences reported for fatiguing bilateral calf raises (116 to 186 bpm, 137 bpm) (Monteiro et al., 2017; Santos da Silveira et al., 2022), and faster than recent literature exploring calf raise test outcomes at 120 bpm (Hébert-Losier, Fernandez, et al., 2025). It is likely that self-selected and as fast as possible cadences in the CR10 differ from published studies (Monteiro et al., 2017; Santos da Silveira et al., 2022) as individuals may perceive having a constrained task (e.g., 10 repetitions) as requiring less effort, therefore potentially soliciting faster cadences (St. Claire Gibson et al., 2006). It is not yet determined whether our median CR10 self-chosen cadences are replicable when performed to fatigue.

While median CR10 self-selected cadences were 24% faster than 60 bpm, it is important to highlight that the only CR10 outcomes to significantly differ between these two

conditions where cadence and total time ($P < 0.001$), with non-significant differences in peak power, vertical displacement, displacement variability, and total work. However, minimum and maximum ranges for self-selected cadence (48.4 bpm – 129 bpm) compared with 60 bpm (59.6 bpm – 65.2 bpm) show a considerable range in the former, suggesting that meaningful, and potentially significant differences could exist in CR10 outcomes between self-selected and 60 bpm on an individual level. The range of self-selected cadences could be driven by what individuals perceived self-selected to be, potentially opting to move at a faster pace because there was a specific end-task (e.g., 10 repetitions) (Smits et al., 2014; St. Claire Gibson et al., 2006), in addition to differences in metabolic efficiency, muscle fibre properties, and MTU stiffness (Cesanelli et al., 2025; Haizlip et al., 2015). Although, research has suggested individuals can reliably self-select cadences and intensities that optimise their physical capabilities (Hamlyn-Williams et al., 2014; Nguyen et al., 2026; Tucker, 2009), the considerable observed range in self-selected cadence suggests that the standardised 60 bpm may be better for standardisation between individuals.

Repetitions are the primary outcome measured for TS MTU function assessment in the calf raise test (Hébert-Losier, Schneiders, et al., 2009; Lunsford & Perry, 1995; Silbernagel et al., 2010; Visser et al., 2025). However, as our study standardised the number of repetitions, we explored how cadence acutely influences other CR10 outcomes in a non-fatigued state: total time, total work, peak power, vertical displacement, and displacement variability. The importance of vertical displacement and total work as measurements to assess TS MTU function has been suggested across literature (Cramer et al., 2022; Nordenholm et al., 2022; Silbernagel et al., 2010). As anticipated, cadence did not significantly influence total work ($P = 0.090$), likely explained by all three cadence conditions completing 10 repetitions. In contrast to our expectations and to previous literature (Hébert-Losier, Fernandez, et al., 2025), cadence did not influence vertical displacement ($P = 0.337$). It is

possible that the slower cadence (30 bpm) used in the previous study influenced differences in vertical displacement due to reduced stretch-shortening contributions. Additionally test-retest reliability of vertical displacement is 6.6% (Byrne et al., 2017), indicating the 5% difference identified may not be meaningful (Hébert-Losier, Fernandez, et al., 2025). In contrast, we analysed 60 bpm, median self-selected (75.6 bpm), and median as fast as possible cadences (196.8 bpm), suggesting cadences were fast enough to enable greater contributions of the stretch-shortening cycle and enhanced mechanical efficiency during the concentric phase of the calf raise (Harrison et al., 2004; Schenau et al., 1997). While total work and vertical displacement were not significantly influenced by cadence, it is worth noting the minimum and maximum ranges for self-selected (48.4 bpm - 129 bpm) and as fast as possible conditions (141.2 bpm - 286.8 bpm) would likely influence outcomes on an individual level, though our study was not designed to explore cadences across minimum and maximum ranges or individual responses.

Though not typical measurements of TS MTU function, CR10 outcomes displacement variability and peak power were influenced by cadence and may be useful indicators of functional performance. Displacement variability at the fastest condition was 53% greater than at self-selected and 60 bpm cadences. While repetitions were standardised in the CR10, as fast as possible cadences may have been too fast to control, leading to height variability between repetitions with additional neuromuscular control requirements used to coordinate acceleration, deceleration, and change of direction (Mulla & Keir, 2023; Zajac, 1993). Additionally, a greater perceived effort may have been associated with the fast condition, potentially contributing to displacement variability between repetitions (Smits et al., 2014). An interesting point to consider is acoustic stimuli (e.g., metronome) was used to control cadence at 60 bpm, not self-selected or as fast as possible cadences. Research (Bood et al., 2013; Roerdink et al., 2011; Van Dyck et al., 2021) has illustrated that humans are able to

better maintain pace and move more efficiently when performing with acoustic stimuli. While no significant differences in displacement variability were identified between self-selected cadences and 60 bpm in the CR10, the difference in displacement variability between cadences may be greater when performing more calf raise repetitions.

As expected, with an increase in cadence, peak power at the fast condition was 57% greater than 60 bpm and 52% greater than self-selected cadences for 10 repetitions. Our results align with a recent study where 120 bpm produced 13% greater power than 60 bpm when performing fatiguing calf raise tests (Hébert-Losier, Fernandez, et al., 2025). It is likely greater variations in peak power exist in our study due to participants reaching faster cadences, with median fast cadences reaching approximately 197 bpm, and range (minimum – maximum) from 141.2 bpm – 286.8 bpm. Greater peak power at the ankle when walking has been shown to correlate highly to greater repetitions ($r = 0.64$), vertical displacement ($r = 0.62$), and total work ($r = 0.66$) in the calf raise test (Nordenholm et al., 2022), suggestive that ankle peak power can be predictive of TS MTU function and performance (e.g., gait speed and efficiency). Muscle fibre properties vary between the gastrocnemii (fast twitch and slow twitch mix) (Head & Arber, 2013; Spendiff et al., 2002) and the soleus (predominantly slow twitch) (Kawakami et al., 1998), with research establishing cadence can influence peak power (Hébert-Losier, Fernandez, et al., 2025) implying varying muscle fibres are activated at different cadences. The use of cadence to inform exercise prescription (e.g., for training or rehabilitation) could provide clinical practitioners and exercise physiologists with insight for the development of the TS MTU, tailored to the individual. More specifically, to achieve hypertrophy and develop muscular endurance (Wilk et al., 2021), slower cadences such as self-selected or 60 bpm could be prescribed for calf raise repetitions, but faster cadences to develop muscular power and the stretch-shortening cycle (Meireles et al., 2025; Schenau et

al., 1997; Wilk et al., 2021) and to progressively overload the AT when returning to sport from injury (Grävare Silbernagel & Crossley, 2015; Morán-Navarro, 2019).

We observed a significant difference between sexes, with males producing 17% more displacement variability per repetition, 18% greater peak power, and 19% greater total work than females. Our results align with recent comparisons of 30, 60, and 120 bpm where males produced 29% greater power and 30% greater total work than females (Hébert-Losier, Fernandez, et al., 2025). Greater peak power and total work are likely explained by body mass differences between sexes, with males being 13.7% heavier than females in our cohort. Additionally, differences in physiological (hormones, metabolism, chromosomes), anatomical (muscle fibre properties), and physical (BMI) features exist between males and females (Haizlip et al., 2015; Jan et al., 2005; Landen et al., 2023), which could potentially contribute to difference in CR10 outcomes. The average BMI in our cohort was 25.4 kg/m² (males) and 25.0 kg/m² (females), with estimates showing a 1 unit increase in BMI increases peak power by 3% and increases total work by 2%. Estimates are in partial alignment with a previous calf raise test study (Hébert-Losier, Fernandez, et al., 2025) where BMI was established to have an influence on peak power, but contrastingly also on vertical displacement likely due to their population having a greater average BMI (29.1 kg/m²) and contrasting 30 bpm to 60 bpm (Hébert-Losier, Fernandez, et al., 2025). As indicated, the 30 bpm may have been too slow to reach greater calf raise heights with limited stretch-shortening cycle contributions. Though sex did not significantly influence cadence, females maintaining 17% less displacement variability than males could potentially be explained by differing motor unit firing patterns between sexes (Lulic-Kuryllo & Inglis, 2022), but would require a more detailed investigation using electromyography.

2.4.1 Limitations

The main limitation of our study was that we only examined 10 calf raise repetitions, not repetitions to fatigue. Examining a constrained number of repetitions was deliberate as it allowed assessment of three cadences in a relatively short amount of time, not requiring the assessment of calf raise repetitions between days or extended rest periods to account for fatigue. The data that we have collected and analysed can provide insight to what cadences individuals may self-select or perform as fast as possible, but it remains unknown whether the self-selected cadences would be the same when performed to fatigue. When performing movements, humans are efficient at selecting paces that will optimise their performance while experiencing the least amount of perceived discomfort (Smits et al., 2014). It is possible that as participants were only required to complete 10 repetitions at each assigned cadence condition, they may have performed repetitions at a faster pace than to fatigue because they had a known endpoint to the task (St. Claire Gibson et al., 2006). A second limitation lies within our cohort of participants who self-disclosed being free of lower limb injury and no history of AT ruptures. Changes to TS MTU structure and function following injury are well documented in the literature (Brorsson et al., 2018; Brorsson et al., 2017; Nielsen et al., 2023; Silbernagel et al., 2012). It is possible that individuals with a history of, or a current TS MTU injury, may produce different cadences in the self-selected and as fast as possible CR10.

2.4.2 Practical applications and future research

Our study demonstrated that median self-selected cadences (approximately 76 bpm) for the unilateral CR10 are faster than the commonly used 60 bpm cadence, with statistical significance only evident in CR10 outcomes related to repetitions per minute and total time. While there are likely no meaningful differences on average in prescribing 60 bpm over median self-selected cadences in the CR10 for rehabilitation or training, the minimum and maximum range of cadences that people self-select (48.4 bpm – 129 bpm) at an individual level is considerably large, suggesting that using 60 bpm to maintain standardisation could be preferential. Though self-selected cadences are deemed more natural, whether the CR10 cadences would be replicable in calf raise tests performed to fatigue is unknown. Further studies are required to explore self-selected and as fast as possible cadences in the calf raise test to fatigue before making recommendations for exercise prescription greater than 10 repetitions and assessment of TS MTU endurance. The clear difference in peak power generated by faster cadences compared with 60 bpm and self-selected cadences highlights the potential to use faster calf raises cadences in later stage rehabilitation and for training. A recent study (Hébert-Losier et al., 2023) has established a relationship between calf muscle abilities and sprint performance, with further research highlighting the influence of calf training on calf raise test outcomes (Karapınar et al., 2025). Given that different muscle fibre properties can be developed through varying velocities (Spendiff et al., 2002), it would be of interest to explore calf muscle training as a predictor of cadence and calf raise test outcomes.

2.4.3 Conclusion

In conclusion, cadence significantly influenced CR10 outcomes displacement variability, peak power, and total time, but not vertical displacement or total work. Sex was a significant predictor of displacement variability, peak power, and total work, whereas BMI was a significant predictor of peak power and total work. Our study identified median self-

selected cadences (75.6 bpm) were higher than the commonly used 60 bpm in CR10, though no significant differences were detected in outcomes between conditions, except for total time. Acknowledgement of cadence, sex, and BMI are of importance when interpreting CR10 outcomes to guide exercise prescription. Whether self-selected and as fast as possible cadences identified in our population would apply to different populations (e.g., injured and older individuals) or when performing calf raises to fatigue is not known. To inform exercise prescription and clinical recommendations, further studies are needed to establish self-selected and as fast as possible cadences in a fatiguing calf raise test and varied populations.

Chapter Three – Experimental Study

Experimental study comparing three cadence conditions and their effect on outcomes when performing the calf raise test (fatiguing).

3.1 Introduction

The triceps surae (TS) muscle tendon unit (MTU) is comprised of the medial gastrocnemius, lateral gastrocnemius, and soleus, merging distally on the calcaneus through the Achilles tendon (AT) (Farris & Sawicki, 2012; Mylly et al., 2023). The TS MTU are the main ankle plantar-flexor muscles, important for everyday functional activities such as walking, running, and climbing stairs (Crotty et al., 2024; Farris & Sawicki, 2012; Jan et al., 2005; Pandey et al., 2021), as well as for sporting activities like jumping, accelerating, decelerating, and changing direction (Flavell et al., 2013; Green & Pizzari, 2017; Lantto et al., 2015). Unfortunately, the TS MTU is susceptible to injuries, including overuse (e.g., tendinopathies) (Chen et al., 2024; Dziekoński, 2025; Heckman et al., 2009) and acute (e.g., Achilles tendon ruptures, medial gastrocnemius strains, soleus strains) (Bryan Dixon, 2009; Green et al., 2022; Kelly et al., 2025; Lantto et al., 2015) injuries, affecting both the general population and athletes.

The calf raise test (CRT) is one of the most common tools used to assess TS MTU function. The test involves repetitive unilateral concentric-eccentric plantar-flexor contractions (Hébert-Losier, Newsham-West, et al., 2009; Hébert-Losier et al., 2017; Lunsford & Perry, 1995), with bilateral CRT sometimes used in older populations (André et al., 2016; André et al., 2018; Monteiro et al., 2017). Repetitions completed are the primary CRT outcome used in clinical settings to measure TS muscular strength and endurance (Hébert-Losier, Newsham-West, et al., 2009; Lunsford & Perry, 1995; Silbernagel et al., 2010); however, research (Nordenholm et al., 2022; Silbernagel et al., 2010) suggests that other CRT outcomes, such as peak height and total work, are more sensitive in identifying deficits in TS MTU function than repetitions alone. Additionally, peak power TS ability has been reported as a predictor of functional movement (e.g., walking speed) (Nordenholm et al., 2022). Although the CRT is most commonly performed following the beat of a

metronome set to 60 beats per minute (bpm), resulting in completing 30 repetitions per minute, variations in cadence used for the CRT exist (e.g., 30 bpm, 120pm, self-selected with no audible cues) (Hébert-Losier, Newsham-West, et al., 2009; Hébert-Losier, Schneiders, et al., 2009; Nordenholm et al., 2022). Peak power increases as CRT cadence increases (Hébert-Losier, Fernandez, et al., 2025), suggesting it may be a relevant measure of CRT performance, especially when the test is performed without a metronome (Cesanelli et al., 2025; Green et al., 2024; Monteiro et al., 2017; Monteiro et al., 2013; Santos da Silveira et al., 2022). Cadence does not only affect CRT peak power, but also other CRT outcomes. Although the number of repetitions was found to not significantly differ between three cadences in a recent study (Hébert-Losier, Fernandez, et al., 2025), 60 bpm resulted in the greatest total work, 120 bpm involved the greatest peak height, and 30 bpm was associated with the lowest peak height.

Humans often self-select a movement velocity for optimisation (Nguyen et al., 2026; Renfree et al., 2014; Selinger et al., 2015). The fact that 60 bpm resulted in the greatest mechanical work could be linked with the speed being close to self-selected cadences. This speculation aligns with self-selected cadences of non-fatiguing unilateral 10 calf raise repetitions (CR10) from our pilot study (75.6 bpm). However, self-selected movement speeds may well differ when individuals are faced with a fatiguing rather than on-fatiguing task. Data from a published bilateral calf raise study (Santos da Silveira et al., 2022) reported average fast cadences of 137 bpm, in agreement with an earlier study (Monteiro et al., 2017) showing bilateral calf raises were performed as fast as possible by individuals (aged 20 to 59 years) with cadences ranging from 126 to 186 bpm in males, with a lower range of cadences in females of 116 to 150 bpm. In contrast, the median fast cadence by individuals (aged 19 to 25 years) from our non-fatiguing CR10 study was faster, reaching approximately 197 bpm. Varying participant demographics combined with fatiguing and non-fatiguing repetitions

could explain the difference in published cadence data and our CR10 study. As fast as possible cadences would likely be slower than those from CR10 if performed to fatigue.

Performing the CRT at faster speeds than 60 bpm may be valuable from a rehabilitation and training perspective, specifically in a sporting context. Muscle fibre properties vary within the TS muscles, with the gastrocnemii (greater fast-twitch proportion) contributing more to speed and power (Hébert-Losier, Schneiders, et al., 2009; O'Brien, 2005), and the soleus (greater slow-twitch proportion) contributing more to endurance (Hébert-Losier, Schneiders, et al., 2009; Kinugasa et al., 2005). Indeed, calf muscle power has been strongly related to sprint performance (Hébert-Losier et al., 2023), with the TS contributing to greater stride length in locomotive movements when increasing velocity (Dorn et al., 2012). However, as velocity at the ankle plantar-flexors increases, the TS fascicles shorten more quickly, decreasing their ability to produce high forces over longer periods of time (Neptune & Sasaki, 2005). The tempo in which movement (e.g., lifting weights) is performed can target specific goals, with power being developed through performing faster repetitions (Meireles et al., 2025). Progression to faster CRT cadences could potentially aid the development of power, and appropriately load the TS MTU in preparation for more demanding activities and returning to sport post-injury (Fukashiro et al., 2006; Grävare Silbernagel & Crossley, 2015; Hébert-Losier, Fernandez, et al., 2025; Schenau et al., 1997). Although 120 bpm has been used in the literature, bilateral CRT performances indicate the range of as fast as possible speeds are much higher (116 – 186 bpm) (Monteiro et al., 2017; Santos da Silveira et al., 2022). It is unclear how fast individuals can perform repeated unilateral calf raise repetitions to fatigue, which would be useful in guiding calf raise prescription and determining upper cadence limits for the CRT. In addition, it may be an interesting diagnostic tool, whereby individuals with a slower maximal calf raise cadence

may present deficits in TS MTU function, particularly in their ability to use stored elastic energy and the stretch-shortening cycle.

Several factors have been shown to influence CRT outcomes, including sex (Hébert-Losier et al., 2017; Jan et al., 2005), physical activity levels (PAL) (Bogdanis, 2012), and body mass index (BMI) (Hébert-Losier et al., 2022; Hébert-Losier et al., 2017). Differences in muscle architectural structure (Blackburn et al., 2006) and body mass (Fukashiro et al., 2006) between sexes are likely to influence repetitions and peak power at varying cadences (Hébert-Losier, Fernandez, et al., 2025). Additionally, a significant relationship between plantar-flexor strength and 10 m sprint times has been identified (Hébert-Losier et al., 2023), leading to the theory that those who train calf muscles might have the potential to perform faster self-selected cadences and produce greater CRT outcomes than those who do not train their calf muscles (Fujiwara et al., 2011; Green et al., 2024; Karapınar et al., 2025; Ödemiş et al., 2022). Therefore, the main aim of our study was to compare cadences maintained during the CRT between three conditions: control (60 bpm), self-selected, and as fast as possible. A secondary aim was to explore the influence of cadence on CRT outcomes, being repetitions, total time, total work, peak power, vertical displacement per repetition, and displacement variability. We hypothesised that self-selected cadences would be faster than 60 bpm, and based on the CR10 data, would be 75 bpm or less. Furthermore, we hypothesised that cadence (60 bpm, self-selected pace, and as fast as possible) would influence all CRT outcomes, except repetitions, with faster cadences producing the greatest peak power, vertical displacement, and displacement variability. An additional aim was to explore calf training, BMI, sex, age and PAL as potential predictors of CRT outcomes.

3.2 Methods

3.2.1 Sample size

Published data from a recent study identified a *moderate* effect size difference (Cohen's d 0.35) in total work between the most common CRT cadence of 60 bpm and a faster cadence of 120 bpm (Hébert-Losier, Fernandez, et al., 2025). Hence, our sample size was derived using G*Power 3.1.9.7 and the repeated measures analysis of variance (ANOVA) within-factor design, setting the Cohen's f effect size to 0.18, group to one with three repeated measures, power to 20%, statistical significance to 5%, correlation between measures to 0.70 (Hébert-Losier, Pandit, et al., 2025), and sphericity assumed to 1.0. Based on these estimates, a sample of 32 participants was required, but a minimum of 36 was targeted to account for 10% of missing data.

3.2.2 Study design

A randomised, crossover study with repeated measures was used to explore how varying cadences (i.e., 60 bpm, self-selected, and as fast as possible) influence the following CRT outcomes: number of repetitions, repetitions per minute (cadence), total positive work (J), positive vertical displacement per repetition (cm), displacement variability per repetition (cm), and peak power per repetition (W). To achieve this goal, participants were required to attend three separate testing sessions, 7 days apart (Figure 5). At each session, CRT performance was assessed under one of the three cadence conditions. A single researcher (NG) involved in the data collection process allocated randomisation upon arrival to participants. Participants and researchers were unable to be blinded due to the nature of the research task. When participants returned for their second and third testing sessions, they were asked if they felt any residual muscle soreness from their previous testing session (yes/no). If any muscle soreness was reported, the plan was to delay testing an additional week. However, no participants disclosed residual soreness. We accounted for BMI, sex, age,

PAL based on a 6-point Likert scale (Batty, 2000; Grimby et al., 2015; Hébert-Losier et al., 2017; Visser et al., 2025), and current calf training (yes/no) as potential predictors in our analyses. We reported our study following the extension of randomised crossover trial Consolidated Standards of Reporting Trials (CONSORT) 2025 statement (Hopewell et al., 2025). Our study and testing protocols were pre-registered with the Australian New Zealand Clinical Trials Registry (ANZCTR), registration number ACTRN12625001325493.

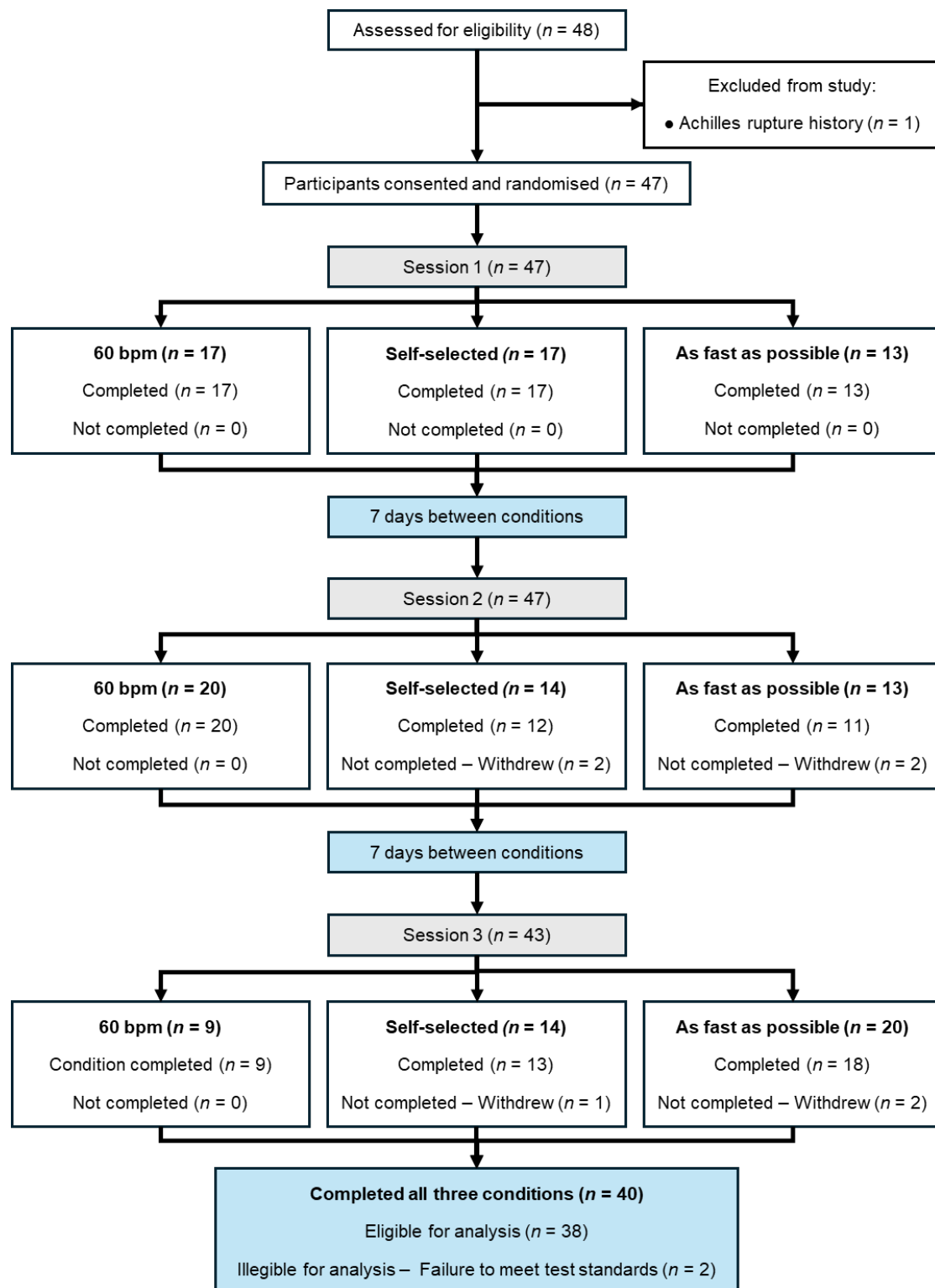


Figure 5. Flow diagram of participant flow through the randomised crossover trial.

3.2.3 Participants

We recruited healthy individuals who were students, staff, or visitors at the University of Waikato or members of a local Hamilton gym facility through word of mouth. Individuals were required to be 16 years of age or older, able to perform single leg calf raises, and in self-reported good health to participate. Individuals were excluded if they had experienced a lower-limb musculoskeletal injury within three months of testing or had a history of an AT rupture. Approval to conduct this study was granted by the Human Research Ethics Committee at the University of Waikato [HREC(HECS)2025#09] before participant recruitment. Our study adhered to the Declaration of Helsinki principles (World Medical Association, 2013). Participants were provided detailed verbal and written information describing the study aims, procedures, benefits (individualised reports), and potential risks associated with participation (delayed onset calf muscle soreness or musculoskeletal injury from physical activity participation). All participants provided informed, written consent prior to study commencement. Participant confidentiality was maintained using a coding system, with research data stored in line with University of Waikato policies for data collection and the management of research.

At the first testing session, participants completed a baseline questionnaire to gather information regarding age, sex, injury history, and PAL based on a Saltin-Grimby adapted 6-point Likert scale that considered the past 12 months (where 1 reflects hardly any physical activity and 6 reflects hard or very hard exercise regularly and several times a week) (Batty, 2000; Grimby et al., 2015; Grimby & Frändin, 2018; Hébert-Losier et al., 2017; Visser et al., 2025). Participants were further asked ‘Do you regularly strength train your calf muscles?’ to explore whether regular calf training was a predictor of CRT outcomes. A digital scale (Seca, model 813) and stadiometer (Seca, model 0123) were then used to record participant baseline

body mass and height, to the nearest 0.01 kg and 0.1 cm, respectively. Participant mass was recorded at each session to ensure appropriate CRT mechanical work computation.

3.2.4 CRT protocol

All sessions were conducted in either the University of Waikato sports laboratory or in a local, private gym facility. Each testing location provided a well-lit environment, with a firm, level surface suitable for the placement of the 10° incline steel platform used during the CRT, verified using a digital inclinometer. All unilateral CRT trials were conducted barefoot, on the right leg, from the 10° inclined steel platform (i.e., starting from a position of dorsiflexion, Figure 6). A 10° incline was selected as outcomes from this foot starting position are valid and reliable (Byrne et al., 2017; Fernandez et al., 2023; Hébert-Losier et al., 2024). The position involves greater vertical displacement compared to starting from a step or flat surface (Hébert-Losier et al., 2024), with the larger range of motion deemed more functionally relevant to day-to-day movements (i.e., walking, running, climbing stairs) (Hébert-Losier et al., 2024; Neptune & Sasaki, 2005) and the clinical management of Achilles tendon injuries (Silbernagel et al., 2006; Silbernagel et al., 2010; Zellers et al., 2020).

Three researchers trained in CRT methodologies completed assessments. These researchers were all sport scientists, strength and conditioning coaches, and/or qualified physiotherapists with a minimum 5 years of experience in assessing human movement. In preparation for the CRT, participants completed a warmup comprising of 10 bilateral calf raises from the floor, at a self-selected pace. Participants completed a further 3 practice unilateral repetitions of their specific CRT cadence condition (i.e., to a digital metronome set at 60 bpm, a self-selected pace, or as fast as possible). A rest period of two-minutes in quiet stance was provided between the warmup and commencement of the CRT.

Prior to experimentation, assessors provided standardised written and verbal cadence instructions to each participant, corresponding to their testing condition. For the 60 bpm condition (i.e., 30 repetitions per minute), participants were asked to go up on their toes and back down to the starting position following the beat of the metronome, going up in one beat and down in one beat. For the self-selected condition, participants were asked to select a pace that felt the most natural and most comfortable to them. For the fast condition, participants were asked to perform the task as fast as possible. For each cadence condition, participants were instructed to go up as high as possible on their toes and to come back down to the starting position (i.e., repeated concentric and eccentric plantar-flexor contractions), for as many repetitions as possible. Participants maintained their right knee straight during the CRT and their left knee at 90° flexion with their left foot behind their body. For balance and support, participants were instructed to place their middle and index fingers on the wall in front of them, at shoulder height. Participants were asked to look straight ahead and to propel their body upwards, not forwards. During each CRT, assessors provided regular, positive verbal encouragement. Participants were provided one technique prompt if deviating, and the CRT was terminated if participants could not correct on the subsequent raise. Specifically, CRT was terminated when participants were unable to maintain their assigned cadence, started to propel their body forward rather than upward, reduced their maximal height by 50% or more, flexed their tested knee, used compensatory strategies (e.g., hip thrusting), lost balance, or stopped volitionally due to fatigue.

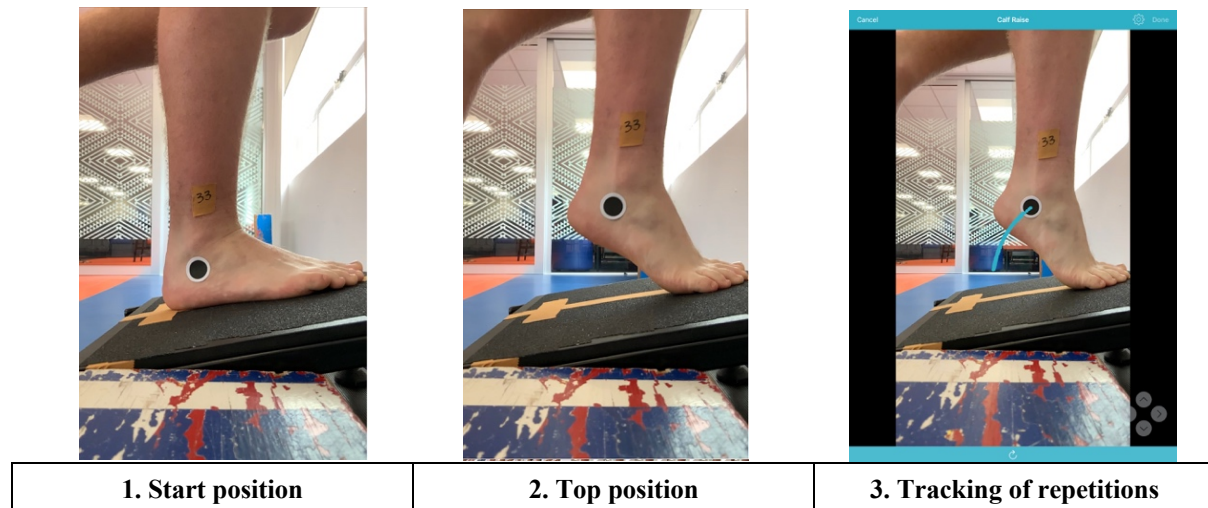


Figure 6. Photographs demonstrating the positions of the calf raise test, starting from a position of dorsiflexion on a 10° incline steel platform. Photograph (1) demonstrates the starting position, photograph (2) demonstrates the top position of each repetition, and photograph (3) demonstrates the Calf Raise application tracking the vertical displacement of the 24 mm round black sticker positioned below the lateral malleolus.

3.2.5 Equipment

The CRT outcomes were recorded using the validated Calf Raise application (version 1.5.1) installed on an Apple iPad running iOS 17.5.1 (model MPQ13X/A, Apple, Inc) (Fernandez et al., 2023; Hébert-Losier, Fernandez, et al., 2025). A sampling rate of 60 frames per second captured the CRT videos in portrait orientation. The iPad was positioned on a secure metal stand, 50 cm to the right of the testing foot to capture the entire calf raise movement. The application uses a computer vision algorithm designed to track the vertical displacement of a circular marker. Prior to testing, a 24 mm black circular sticker was placed inside a 32 mm white one (to ensure colour contrast) below the lateral malleolus on a flat portion of the foot (Figure 2). The 24 mm circular sticker was used as known calibration target within the application prior to deriving CRT outcomes, and the body mass of participants on the day of testing was entered to enable calculation of work (J) and power (W)

from the vertical position curve (Fernandez et al., 2023; Hébert-Losier, Fernandez, et al., 2025). Since the application does not provide data for each repetition or allow computation of cadence, the raw vertical position, power, and work data curves were exported as text files and imported into Visual3D Professional v2025.09.1 (©HAS-Motion, Kingston, Ontario, Canada). A custom script was developed to automatically extract the following variables for analysis: cadence, number of repetition (n), positive vertical displacement per repetition (cm), displacement variability per repetition (cm), peak power per repetitions (W), total CRT time (s), and total positive work (J). To delineate each repetition, peak height from the raw data were identified first, with the return to the bottom of each raise identified as the instance when velocity reached zero thereafter.

Intraclass correlation coefficients (ICC) and coefficient of variation (CV) indicate excellent intra-rater and inter-rater reliability ($ICC \leq 0.949$, $CV \leq 5.6\%$) when using the application with healthy individuals (Fernandez et al., 2023). The application demonstrates good to excellent agreement of derived outcomes against 3D motion and force plates ($ICC = 0.84 - 1.00$) (Hébert-Losier et al., 2022) and excellent concurrent validity for CRT outcomes when the circular marker is places on the lateral malleolus ($ICC = 0.963 - 1.00$) (Fernandez et al., 2023). Test-retest reliability for CRT outcomes are excellent for repetitions ($ICC = 0.96$) (Hébert-Losier et al., 2017), good for work ($ICC = 0.84$) and peak height ($ICC = 0.85$) (Byrne et al., 2017), and good for repetitions and total work ($CV < 10\%$, $ICC \leq 0.87$) derived from the application with CRT familiarisation (Hébert-Losier et al., 2022).

3.2.6 Statistical analysis

Participant demographic characteristics were described using means, standard deviations, minimum-to-maximum ranges, and counts. Prior to statistical analyses on CRT outcomes, Shapiro-Wilk tests were used to check for normality of data distribution. Since all data were non-normally distributed ($P \leq 0.003$), descriptive statistics of CRT outcomes were

reported as medians with interquartile ranges [25th, 75th] and data were log-transformed (except for repetition) to decrease heteroscedasticity and skewness prior to inferential analyses. Multilevel, mixed-effects Poisson regression was used to analyse the repetition outcome, whereas linear regression models applying restricted maximum-likelihood estimation were used to analyse the remaining log-transformed CRT outcomes (i.e., cadence, displacement per repetition, displacement variability per repetition, peak power per repetition, total time, and total work). The model explored the main effect of cadence (categorical, 3 levels) on outcomes, and accounted for sex (categorical, 2 levels), BMI (continuous), age (continuous), PAL (categorical, 2 levels), and current calf training (categorical, 2 levels) as potential predictors. Although PAL were gathered on a 6-point Likert scale, these were dichotomised as participants reporting the highest level (hard or very hard exercise regularly and several times a week) and those below this level due to population distribution. In our model, cadence condition and predictors were entered as fixed factors, but participants were entered as nested random factors due to our study involving repeated measures and being exposed to all three cadence conditions. Estimates from our mixed-effect models are presented as rate ratios. Reference groups were set to 60 bpm for cadence condition, male for sex, most active for PAL, and yes for current calf training. Stepwise regressions were used to remove non-significant predictors, and verified using the Bayesian information criterion, always maintaining the main effect of cadence within models. In post-hoc comparisons between cadence conditions, 95% confidence intervals [lower, upper] and alpha levels set to $P < 0.05$ were Bonferroni adjusted. Estimates were exponentiated to obtain ratios of geometric means for pairwise comparisons, whereas exponentiated coefficients for continuous predictors (i.e., BMI) represent the multiplicative change in geometric mean of the outcome per unit increase in the predictor. Data analyses

were performed using Stata Statistical Software, version 16.1 (Statacorp LLC, College Station, TX, USA), with $P < 0.05$ set as statistically significant.

3.3 Results

3.3.1 Participants

Forty-seven participants were recruited. Seven were unable to complete all three conditions, and two participant datasets were excluded due to incorrect technique (Figure 5). Thirty-eight participants completed the three conditions (23 males, 15 females, Table 4), with no missing data for CRT outcomes or predictor variables. Participants' characteristics are described in Table 4.

Table 4. Characteristics of participants ($n = 38$)

Characteristic	Males ($n = 23$)	Females ($n = 15$)
Age (years)	22.2 ± 5.5 (19.2 – 41.8)	24.5 ± 7.9 (19.0 – 43.4)
Body mass (kg)	81.6 ± 13.1 (64.6 – 109.2)	64.6 ± 9.0 (52.8 – 84.6)
Body height (cm)	179.0 ± 7.8 (163 – 196)	167.3 ± 6.1 (157 – 179)
Body mass index (kg/m^2)	25.4 ± 3.5 (20.9 – 34.2)	23.3 ± 2.7 (19.5 – 28.7)
Current calf training (yes, no)	13, 10	3, 12
PAL participant count (3, 4, 5, 6)	1, 2, 5, 15	0, 2, 6, 7

Notes. Values are presented as mean $\pm$ standard deviation (minimum – maximum) and counts.

Likert scale of PAL: 3 = light; 4 = moderate 1-2 h; 5 = moderate at least 3 h; 6 = hard or very hard several times a week.

Abbreviations: BMI, body mass index; PAL, physical activity level.

3.3.2 CRT outcomes

A descriptive summary of CRT outcomes for each cadence condition is presented in Table 5. The median cadences held at 60 bpm, self-selected, and as fast as possible were 60.2 bpm, 69.8 bpm, and 109.4 bpm. Results from the multilevel mixed-effect Poisson and linear regression models are shown in Table 6, with cadence being 14% and 94% greater under the self-selected and as fast as possible conditions than 60 bpm, with a 70% difference between the latter two (all $P \leq 0.002$). Models revealed that cadence significantly influenced all CRT outcomes ($P \leq 0.011$), except for repetitions ($P = 0.081$). Post-hoc comparisons revealed the as fast as possible condition compared to 60 bpm involved significantly lesser repetitions (11%), total work (8%), and total time (55%), but greater peak power (29%), vertical

displacement per repetition (7%), and displacement variability per repetition (7%). The self-selected condition produced lower peak power (9%), total time (19%), total work (11%), and displacement variability (17%) compared to 60 bpm, with no significant difference for vertical displacement per repetition.

Table 5. Descriptive summary of calf raise test outcomes by cadence condition from participants ($n = 38$).

Outcome	Cadence condition		
	60 bpm	Self-selected	As fast as possible
Cadence (rep/min)	30.1 [30.0, 30.3] (29.3 – 31.0)	34.9 [29.0, 39.7] (22.3 – 60.7)	54.7 [48.4, 73.6] (36.3 – 112.5)
Repetitions (n)	21 [19, 25]	20 [18, 23]	18.5 [15, 23]
Vertical displacement (cm/rep)	9.4 [8.9, 10.0]	9.1 [8.5, 9.7]	10.0 [9.3, 11.0]
Displacement variability (cm/rep)	0.81 [0.62, 0.97]	0.65 [0.55, 0.82]	0.82 [0.71, 0.93]
Peak power (W/rep)	247 [203, 297]	229 [178, 261]	317 [238, 368]
Total time (s)	41.9 [37.0, 49.6]	34.9 [28.3, 41.3]	19.3 [15.0, 24.1]
Total work (J)	1488 [1311, 1769]	1369 [1180, 1537]	1397 [1114, 1633]

Notes. Values are presented as median with interquartile range [25th, 75th], and (minimum – maximum).
Abbreviation: bpm, beats per minute; rep, repetition.

Table 6. Results from the multilevel mixed-effect Poisson (for repetitions) and linear regression models applying restricted maximum-likelihood on log-transformed (for the other calf raise test outcomes) from participants ($n = 38$). Models considered cadence condition, sex, body mass index, physical activity levels, and current calf training.

Outcome	Variable	Estimate [‡] [95% CI]	<i>P</i> value
Cadence (rep/min)	<i>Cadence</i>		<0.001*
	Self-selected [†]	1.14 [1.04, 1.26]	0.002
	As fast as possible [†]	1.94 [1.77, 2.13]	<0.001
	Fast vs self [†]	1.70 [1.54, 1.86]	<0.001
Repetitions (<i>n</i>)	<i>Cadence</i>		0.081
	Self-selected [†]	0.94 [0.84, 1.06]	0.698
	As fast as possible [†]	0.89 [0.79, 1.01]	0.075
	Fast vs self [†]	0.95 [0.84, 1.10]	0.883
	<i>BMI</i>	0.96 [0.95, 0.98]	<0.001
	<i>Calf training</i> (no)	0.82 [0.72, 0.92]	<0.001
Displacement per repetition (cm)	<i>Cadence</i>		<0.001*
	Self-selected [†]	0.97 [0.94, 1.01]	0.213
	As fast as possible [†]	1.07 [1.03, 1.11]	<0.001
	Fast vs self [†]	1.10 [1.06, 1.14]	<0.001
Displacement variability [§] (cm)	<i>Cadence</i>		<0.001*
	Self-selected [†]	0.83 [0.71, 0.96]	0.007
	As fast as possible [†]	1.07 [0.92, 1.24]	0.859
	Fast vs self [†]	1.29 [1.11, 1.50]	<0.001
	<i>Sex</i> (female)	0.85 [0.73, 0.98]	<0.001
Peak power per repetition (W)	<i>Cadence</i>		<0.001*
	Self-selected [†]	0.91 [0.85, 0.98]	0.009
	As fast as possible [†]	1.29 [1.20, 1.39]	<0.001
	Fast vs self [†]	1.42 [1.32, 1.52]	<0.001
	<i>BMI</i>	1.03 [1.01, 1.05]	<0.001
	<i>Sex</i> (female)	0.78 [0.69, 0.88]	<0.001
Total time (s)	<i>Cadence</i>		<0.001*
	Self-selected [†]	0.81 [0.72, 0.92]	<0.001
	As fast as possible [†]	0.45 [0.40, 0.51]	<0.001
	Fast vs self [†]	0.55 [0.49, 0.62]	<0.001
	<i>Sex</i> (female)	1.22 [1.07, 1.38]	<0.001
	<i>Calf training</i> (no)	0.88 [0.78, 1.00]	<0.001
Total work (J)	<i>Cadence</i>		0.011*
	Self-selected [†]	0.89 [0.81, 0.98]	0.011
	As fast as possible [†]	0.92 [0.84, 1.01]	0.092
	Fast vs self [†]	1.03 [0.94, 1.13]	1.000
	<i>Calf training</i> (no)	0.73 [0.64, 0.84]	<0.001

Notes. Reference conditions for cadence, sex, and current calf training are 60 bpm, male, and yes, respectively. Statistical significance set at $P < 0.05$. * indicates a significant main effect of cadence. Only significant predictors are reported in the table, with non-significant predictors removed during stepwise regression.

Abbreviations: BMI, body-mass index; CRT, calf raise test.

[†]Bonferroni-adjusted *P* values and 95% confidence intervals. [‡]Estimates represent ratios. [§]Reflects the standard deviation of displacement per repetition.

3.3.3 Predictors

As shown in Table 6, models established BMI had a significant influence on the number of repetitions and peak power ($P < 0.001$). For each 1 unit increase in BMI, the models estimate 4% fewer repetitions and 3% greater peak power. Furthermore, sex significantly influenced peak power, displacement variability, and total time, with females producing 22% less peak power than males and exhibiting 15% lower displacement variability per repetition than males ($P < 0.001$), but achieving a 22% greater total time than males ($P < 0.001$). Participating in calf training significantly influenced all CRT outcomes ($P \leq 0.017$), except for displacement per repetition, displacement variability, and cadence. Calf training increased peak power, total time, and total work by 13%, 22%, and 27%, respectively. Age and PAL did not significantly influence any of the CRT outcomes.

3.4 Discussion

In our population, the median self-selected cadence was 69.8 bpm, which was 14% faster than the commonly used CRT cadence of 60 bpm. Our findings agree with our hypothesis that self-selected CRT cadence would be faster than 60 bpm, with the median being less than 75 bpm. Even the as fast as possible cadence was less than 120 bpm, with the median self-selected value being 109.4 bpm, indicating that setting the cadence at the 120 bpm value may be too fast for most individuals. As anticipated, cadence significantly influenced all CRT outcomes, except for repetitions. Faster cadences, which would involve faster TS muscle shortening velocities (Farris & Sawicki, 2012; Neptune & Sasaki, 2005), produced greater peak power and involved shorter test times. The latter observation is consistent with the completion of similar total repetitions than at the other cadences, but at a faster pace. The fastest cadence was linked with greater vertical displacement than the other cadences, as well as greater variability than self-selected. Of the predictors examined, sex influenced peak power, displacement variability, and total time. Consistent with previous

studies (Hébert-Losier et al., 2024; Hébert-Losier, Fernandez, et al., 2025; Hébert-Losier et al., 2022; Visser et al., 2025), we observed that BMI influenced repetitions and peak power. Calf training positively influenced repetitions, peak power, total time, and total work, in agreement with established relationships between plantar-flexor strength and function (Alonso-Fernandez et al., 2020; Fujiwara et al., 2011; Hébert-Losier et al., 2023; Karapınar et al., 2025; Ödemiş et al., 2022; Pandey et al., 2021). In contrast, age and physical activity levels categorised using a 6-point Likert scale (Batty, 2000; Grimby et al., 2015) did not significantly influence CRT outcomes, which may be due to the homogeneity of participants (19 – 43 years), and mostly reporting moderate or greater PAL. While time and cost effective, the Saltin-Grimby physical activity scale has demonstrated validity; however, evidence is strongest for the original 4-point version, with more limited validation for the later 6-point adaptations (Beldo et al., 2022; Grimby et al., 2015; Grimby & Frändin, 2018).

Cadence has been identified as a variable CRT parameter across clinical and research settings (Bohannon, 2022; Hébert-Losier, Fernandez, et al., 2025; Hébert-Losier, Newsham-West, et al., 2009). Although 60 bpm is the most common, multiple cadences are implemented, ranging from 30 bpm and 40 bpm (Möller et al., 2002; Möller et al., 2005) to 120 bpm (Hébert-Losier et al., 2012; Hébert-Losier et al., 2011) and unstandardised self-selected (André et al., 2016; Cesanelli et al., 2025; Green et al., 2024; Olsson et al., 2014) and as fast as possible (Monteiro et al., 2017; Monteiro et al., 2013; Santos da Silveira et al., 2022). In our study, we showed that median unilateral CRT cadences maintained in the 60 bpm, self-selected, and as fast as possible conditions were 60.2 bpm, 69.8 bpm, and 109.4 bpm, respectively. In contrast, our CR10 study resulted in slightly higher median self-selected (75.6 bpm) and as fast as possible (196.8 bpm) cadences, potentially explained by participants performing only 10 repetitions, compared to our study performing repetitions to fatigue. The median as fast as possible cadence was 109.4 bpm to fatigue; contrastingly,

bilateral CRT performed as fast possible to fatigue by a similar demographic reached average cadences of approximately 137 bpm (Santos da Silveira et al., 2022), with median fast cadence ranges of 116 to 186 bpm identified in earlier research (Monteiro et al., 2017). These central tendencies suggest that a unilateral CRT cadence of 120 bpm may be too fast for the average individual. To explore and justify a potential standardised CRT cadence over self-selected, it is worth noting how close CRT outcomes of a median self-selected cadence (69.8 bpm) are to those at 60 bpm. While 60 bpm yielded 9% greater peak power, 11% greater total work, and 17% greater variability in displacement per repetition than self-selected cadences, vertical displacement per repetition showed no significant difference ($P = 0.213$). However, minimum and maximum ranges for self-selected cadence (44.6 bpm – 121.4 bpm) compared with 60 bpm (58.6 bpm – 62 bpm) show a considerable cadence range exists, suggesting that potentially greater differences could exist in CRT outcomes between self-selected and 60 bpm on an individual level. Research indicates that individuals have the ability to self-regulate cadences that are optimal and reproduce physical outcomes based on self-selected intensities (Hamlyn-Williams et al., 2014; Nguyen et al., 2026; Tucker, 2009). However, in the context of the CRT, the repeatability of a self-selected cadence on different testing occasions is not guaranteed and may negatively affect test-retest reliability. Therefore, further studies are needed to explore the test-retest reliability of self-selected CRT cadences.

Cadence did not significantly influence repetitions, with the median being 20 repetitions across cadence conditions. This result is comparable to a recent study finding no significant differences in CRT repetitions between three cadence conditions (30, 60, 120 bpm) (Hébert-Losier, Fernandez, et al., 2025). Overall, our median number of repetitions is lower than the reported normative values for unilateral CRT repetitions of 25 (Visser et al., 2025), which could be a result of higher participant BMI (Hébert-Losier et al., 2022). Given that total work reflects muscular endurance, accounting for both repetitions and vertical

displacement (Fernandez et al., 2023; Silbernagel et al., 2010; Silbernagel et al., 2012), it could be suggested that 60 bpm is more optimal compared to self-selected as it maximises the work outcome. The 11% difference in total work at 60 bpm could be explained by performing the CRT to the beat of a metronome, compared with no audible cues for the self-selected and as fast as possible conditions. The auditory motor synchronisation between movement and acoustic stimuli (e.g., music, metronomes) for performance and rehabilitation has been well documented across the literature (Bood et al., 2013; Hutchinson & Karageorghis, 2013; Pranjić et al., 2024; Priest & Karageorghis, 2008; Van Dyck et al., 2021; Vanbilsen et al., 2025). Coupling the movement tempo in exercise and rehabilitation tasks with acoustic stimuli has been shown to positively influence repetitive endurance tasks (Bood et al., 2013; Roerdink et al., 2011; Van Dyck et al., 2021). Comparatively, performing movements (e.g., running, walking) with no external acoustic stimuli results in individuals perceiving a higher rate of exertion (Edworthy & Waring, 2006), thus fatiguing earlier (Bood et al., 2013). It is possible that setting a metronome to the median self-selected cadence (approximately 70 bpm) could lead to an increase in repetitions and total work compared to the CRT with a metronome set to 60 bpm. Although the 11% difference total work (119 J) between conditions was significant, this difference may not be clinically meaningful, with test-retest change in total work being 10.6% (Hébert-Losier et al., 2022). Future research is needed to determine the effect of acoustic stimuli on CRT outcomes as well as what magnitude of change in work is clinically meaningful.

As one would expect, due to an increase in velocity, the as fast as possible condition produced 42% greater peak power than self-selected cadences and 29% more than at 60 bpm. Results align with previous research where 120 bpm produced 22% and 13% greater power than 30 bpm and 60 bpm, respectively (Hébert-Losier, Fernandez, et al., 2025). Peak power can be predictive of TS MTU functional performance, with greater ankle peak power

correlating to greater CRT repetitions and increased gait speed and efficiency (Nordenholm et al., 2022). The gastrocnemii contain both slow-twitch (type I, fatigue resistant) and fast-twitch (type II, power generating) muscle fibres (Head & Arber, 2013; Spendiff et al., 2002), in comparison to the soleus that contains a greater proportion of slow twitch muscle fibres (Kawakami et al., 1998). Given cadence affects peak power, varying cadences could be used to detect and improve specific deficits. Slower cadences (i.e., 60 bpm or self-selected) could be used for hypertrophy (Wilk et al., 2021) to develop endurance, and faster cadences (i.e., as fast as possible) could be used to develop stretch-shortening cycle capabilities and muscular power (Schenau et al., 1997; Wilk et al., 2021). Cadence could become a factor of importance when using the CRT during different stages of TS MTU rehabilitation. Appropriate loading and progressions during AT rehabilitation aids return to sport and reduce rate of injury recurrence (Grävare Silbernagel & Crossley, 2015).

Although cadence was identified as significantly influencing peak vertical displacement ($P < 0.001$), the difference in displacement between cadences may not be clinically meaningful. The median vertical displacement (10 cm) at the maximal cadence was 10% and 7% higher than the self-selected and 60 bpm cadences, respectively. At faster cadences, the contribution of the stretch-shortening cycle would be higher in the concentric phase of the CRT, likely producing greater vertical displacement (Hébert-Losier, Fernandez, et al., 2025; Kubo et al., 1999). Though we studied an injury-free population, tendon elongation and reduced plantar-flexor strength, common following AT ruptures, can be detected by lesser vertical displacement in clinical settings (Cramer et al., 2022; Hoeffner et al., 2024; Silbernagel et al., 2010; Silbernagel et al., 2012). It is worth noting cadence significantly influenced displacement variability per repetition. We expected greater variability during the as fast as possible condition, which was validated only when compared to the self-selected (69.8 bpm) condition ($P < 0.001$). Displacement variability was 29%

greater in the as fast as possible condition and 17% greater in the metronome-controlled 60 bpm condition compared to the self-selected cadence condition. It is possible that individuals were able to better self-regulate their movements (Edwards & Polman, 2013; Elferink-Gemser & Hettinga, 2017; Smits et al., 2014) in the self-selected condition, presenting as less displacement variability between repetitions. The assumption was that displacement per repetition would remain near identical at 60 bpm with the use of acoustic stimuli (e.g., metronome) to enhance performance (Bood et al., 2013; Pranjic et al., 2024), however it is possible greater displacement variability occurred at 60 bpm as individuals were required to operate at a cadence different to their naturally preferred ones and synchronisation with the beat was lost. Participants might also have been trying to coordinate their movements to the beat, increasing the mental load. In contrast, high displacement variability evident in the fast condition is likely due to faster cadences being more difficult to control. Further investigation is needed to examine whether differences in vertical displacement variability still exist when the CRT is performed at a metronome-paced 60 bpm and 70 bpm.

We identified regular calf training as a significant predictor of CRT repetitions, peak power, total time, and total work. Regular calf training produced 18% more repetitions, 13% greater peak power, 12% more total time and 27% greater total work than those who did not train calves. Our results align with existing published studies (Alonso-Fernandez et al., 2020; Fujiwara et al., 2011; Green et al., 2024; Karapinar et al., 2025; Ödemiş et al., 2022) that have established calf muscle training influences CRT outcomes. Given the established relationship between 10 m sprint times and calf-muscle abilities (Hébert-Losier et al., 2023) and the TS MTU contribution to torque generation at the ankle (Pandy et al., 2021), increasing calf muscle size and strength through training would presumably contribute to the production of greater peak power when performing CRT repetitions as fast as possible. Similarly, calf training could potentially predict cadences selected, however results did not

support these speculations. That being said, we had an imbalanced cohort with participants training calf muscles (16), being less than those who did not train (22). While outside of the scope of this research, it would be interesting to explore if training calf muscles leads to self-selecting a faster CRT cadence with sufficient sample sizes, an important factor to consider when interpreting CRT results.

Furthermore, we identified significant differences between sexes, with females maintaining 22% greater total time than males, yet producing 22% less peak power and 15% less displacement variability than males. Anatomical (muscle fibre properties, cross-sectional size) and physiological (hormones, energy expenditure) exist between males and females, likely contributing to the differences in CRT performance (Haizlip et al., 2015; Jan et al., 2005; Landen et al., 2023). Additionally, physical differences (BMI) between sexes may further contribute to difference in CRT outcomes, in our study the average BMI were 25.4 kg/m² and 23.3 kg/m² for males and females, respectively. As BMI increased by 1 unit, our models indicate repetitions decreased by 4% and peak power increased by 3%, aligning with previous literature establishing BMI to have a negative relationship with CRT repetitions (Hébert-Losier, Fernandez, et al., 2025; Hébert-Losier et al., 2017; Visser et al., 2025). Interestingly, females maintained greater total time with less displacement variability, potentially influenced by motor unit recruitment differences between sexes (Lulic-Kuryllo & Inglis, 2022), and the potential for greater fatiguability of muscular contractions to occur in males, compared to females (Hunter, 2009; Hunter, 2014). However, this study was not powered to detect repetition fatiguability between sexes.

3.4.1 Limitations

Limitations exist within our study. Firstly, our findings are based on a sample of healthy, injury-free, young adults. As aging occurs, the ability to activate muscle changes, strength levels reduce, and recovery slows due to reduced collagen levels (Gräware

Silbernagel & Crossley, 2015; Kjaer, 2004). Furthermore, individuals with a history of TS MTU injury have a change in muscle structure (Nielsen et al., 2023), and tendon elongation is common after an AT rupture (Hoeffner et al., 2024; Silbernagel et al., 2010; Silbernagel et al., 2012). Elongated AT have a lower rate of force development at the ankle, which negatively impacts performance abilities (e.g., jumping, running) (Nicholson et al., 2020; Silbernagel et al., 2012), hence, elastic energy storage is potentially impaired due to tendon structural changes (Nicholson et al., 2020; Nilsson-Helander et al., 2008). It is possible that an older demographic and those with lower limb injury pathologies may self-select a slower CRT cadence and not achieve as high cadences when asked to go as fast as possible, therefore limiting the generalisability in clinical settings and across varying populations. Additionally, our findings are applied to unilateral CRT, it is not known if the self-selected and as fast as possible cadences identified would be the same in a bilateral CRT. We did not examine muscle activation, fatigue, and fibre lengths or tendon changes using technologies such as electromyography and ultrasound. Examining the TS MTU in more depth could have provided further mechanistic insight into muscle activation and fatigue at varying cadences.

3.4.2 Practical applications and future research

Our results illustrate significant differences between CRT outcomes (displacement variability, peak power, total time, total work) produced at 60 bpm and median self-selected cadences (69.8 bpm). While there are likely no meaningful differences in using 60 bpm over median self-selected cadences (approximately 70 bpm) in the CRT for repetitions, vertical displacement, and total work, the minimum and maximum range of cadences that people self-select (44.6 bpm – 121.4 bpm) at an individual level is quite substantial. Though more natural, it is not known whether self-selected CRT cadences could be replicated in subsequent testing. Standardising the CRT cadence could produce greater consistency in detection of deficits and improvements in calf muscle function, potentially improving test-retest reliability

in clinical settings. Further studies are required to explore the repeatability of self-selected cadences and to compare CRT outcomes at 60 bpm and 70 bpm before making clinical recommendations regarding optimal CRT cadences. Greater peak power derived from faster cadences creates opportunity to explore future research on the CRT as a training or preseason tool. Performing the CRT at cadences aligning with paces seen in sporting movements and linked with TS MTU injuries (e.g., running, change of direction), could contribute meaningfully to injury prevention within sport.

3.4.3 Conclusion

In conclusion, varying CRT cadences significantly influenced displacement per repetition, displacement variability per repetition, peak power, total time, and total work, but not repetitions. Calf training was a significant predictor of repetitions, peak power, total time, and total work, with sex being a significant predictor of displacement variability, peak power and total time. Additionally, BMI was a significant predictor of peak power and repetitions. Consideration of cadence and predictors such as calf training, sex, and BMI are important when interpreting CRT outcomes. Overall, our findings have highlighted that 60 bpm is close to median self-selected cadences (69.8 bpm), although potentially not clinically meaningful differences were detected in total work between conditions, as within test-retest errors reported elsewhere. To provide evidence-based clinical recommendations on the optimal CRT cadence for rehabilitation, further research is needed to explore the test-retest reliability of using self-selected cadences over 60 bpm and experimentation with rehabilitating populations. Faster CRT cadences could be prescribed in later stage TS MTU rehabilitation and may aid the development of greater peak power and recruitment of fast-twitch muscle fibres, to progressively load the MTU in preparation for sport.

Chapter Four – Summary

Thesis summary, practical implications, strengths, limitations, and future research.

4.1 Summary

The TS muscles (i.e., gastrocnemii, soleus) are the main ankle plantar-flexor muscles (Machado et al., 2021; Neptune & Sasaki, 2005) that merge distally on the heel through the Achilles tendon (AT) to form the TS MTU (Farris & Sawicki, 2012; Mylly et al., 2023). The TS MTU is essential to everyday functional movements (e.g., walking, running), and are susceptible to injury (Chen et al., 2024; Green & Pizzari, 2017; Heckman et al., 2009). The CRT is an endurance test commonly used in clinical settings to assess TS MTU function through repetitive unilateral concentric-eccentric TS muscle contractions to fatigue (Hébert-Losier, Schneiders, et al., 2009; Lunsford & Perry, 1995). The most common cadence of the CRT is 60 beats per minute (bpm), however the parameter of cadence is not universal (Hébert-Losier, Schneiders, et al., 2009), with metronome-controlled cadences ranging from 30 bpm to 120 bpm used across literature (Hébert-Losier et al., 2012; Hébert-Losier et al., 2011; Möller et al., 2002; Möller et al., 2005), and self-selected and as fast as possible without audible cues also employed (André et al., 2016; Cesanelli et al., 2025; Green et al., 2024; Monteiro et al., 2017; Monteiro et al., 2013; Santos da Silveira et al., 2022). Recent unilateral CRT research (Hébert-Losier, Fernandez, et al., 2025) has illustrated how varying cadences (30 bpm, 60 bpm, 120 bpm) significantly influenced all CRT outcomes (total vertical displacement, total work, peak height, peak power) ($P \leq 0.008$), except for repetitions ($P = 0.200$), with earlier research (Monteiro et al., 2017; Santos da Silveira et al., 2022) identifying self-selected fast cadences as being faster than 120 bpm in the bilateral CRT. However, no published studies have identified self-selected and as fast as possible cadence ranges for non-fatiguing and fatiguing calf raise repetitions, and subsequently compared how those cadences influenced outcomes against 60 bpm.

The main aim of this thesis was to compare cadences maintained during 10 calf raise repetitions (CR10) and the CRT at three conditions (60 bpm, self-selected, as fast as possible). The secondary aim was to explore the influence of cadence on CR10 and CRT outcomes. Furthermore, we aimed to explore how predictors of sex, body mass index (BMI), and physical activity levels (PAL) influenced CR10 and CRT outcomes, with additional predictors of age and calf muscle training examined in fatiguing repetitions.

This thesis includes two experimental studies. In study one (chapter two), 35 participants performed the CR10 at three cadence conditions (60 bpm, self-selected, as fast as possible), in a single testing session, 15 minutes apart. In study two (chapter three), 38 participants performed the CRT to fatigue at three cadence conditions (60 bpm, self-selected, as fast as possible), over three testing sessions, seven days apart. There were 19 females in the study one (54% of the cohort), and 15 females in study two (39% of the cohort).

In study one there was a significant difference between cadence conditions, median as fast as possible cadences (196.8 bpm) were 218% greater than 60 bpm, and median self-selected cadences (75.6 bpm) were 24% greater than 60 bpm when performing non-fatiguing repetitions. In the CR10, cadence conditions significantly influenced the following outcomes: repetitions per minute, total time, peak power, displacement variability ($P < 0.001$), but not total work or vertical displacement ($P \leq 0.337$). Similarly in study two there was a significant difference between cadence conditions, median as fast as possible cadences (109.4 bpm) were 94% greater than 60 bpm, with median self-selected cadences (69.8 bpm) being 14% greater than 60 bpm when performing to fatigue. In the CRT, cadence conditions significantly influenced the following outcomes: repetitions per minute, vertical displacement, displacement variability, peak power, total time and total work ($P < 0.001$), but not repetitions ($P = 0.081$). The median number of repetitions, considering all conditions, was 20 [17, 23].

Post-hoc comparisons from the CRT showed 60 bpm reached 8-11% greater total work than median self-selected (69.8 bpm) and as fast as possible (109.4 bpm) cadences, with the as fast as possible condition reaching 7% and 10% greater vertical displacement than 60 bpm and self-selected, respectively. Given that total work encompasses repetitions and vertical displacement, research has suggested that total work assesses TS MTU function better than repetitions alone and is an important outcome for test interpretation (Fernandez et al., 2023; Silbernagel et al., 2010; Silbernagel et al., 2012). The 11% difference in total work (119 J) between 60 bpm and self-selected cadences may not be clinically meaningful at a group level, with test-retest change in total work being 10.6% (Hébert-Losier et al., 2022). However, at an individual level when considering the range (minimum – maximum) of self-selected cadences reached, meaningful differences in total work may exist. Comparatively, no significant differences in total work were identified between 60 bpm and median self-selected cadences (75.6 bpm) in the CR10, potentially explained by performing only 10 repetitions. Peak power and displacement variability were greatest in the as fast as possible condition, reaching 52-57% greater peak power and 53% greater displacement variability than the slower conditions in the CR10. Similarly, in the CRT the as fast as possible condition generated 29% and 42% greater peak power, with 7% and 29% greater displacement variability than 60 bpm and self-selected cadences, respectively.

As speculated in earlier research (Hébert-Losier, Fernandez, et al., 2025), median self-selected cadences were relatively close to 60 bpm in the CR10 (75.6 bpm) and the CRT (69.8 bpm). However, it is important to acknowledge that the minimum and maximum self-selected cadence ranges were considerably broad in both the CR10 (48.4 – 129 bpm) and the CRT (44.6 – 121.4 bpm), suggesting that 60 bpm may not adequately reflect self-selection and be too fast or too slow for some individuals. While there may not be clinically meaningful difference between using 60 bpm and self-selected cadences on CRT outcomes at a group

level, the range of self-selected cadences suggest CRT outcomes may differ more between individuals.

Significant differences were identified between sexes in both experimental studies, with females achieving 18% less peak power, generating 19% less total work, and exhibiting 17% less displacement variability than males in the CR10 ($P < 0.001$). Our models showed BMI significantly influenced outcomes. As BMI increased by 1 unit, total work increased by 2% and peak power increased by 3% in the CR10. Similar influences of predictors were seen in the CRT, with females achieving 22% less peak power, exhibiting 15% less displacement variability, yet achieving a 22% greater total time than males ($P < 0.001$). With every 1 unit increase in BMI, there was a 3% increase in peak power and a 4% decrease in repetitions in the CRT. PAL did not significantly influence outcomes in either experimental study, likely due to the moderate to high activity levels of participants. Additionally, age did not influence CRT outcomes, likely due to the age range (19 – 43 years) of our participants. Our studies agree with previous calf raise studies reporting sex and BMI as significant predictors (Hébert-Losier, Fernandez, et al., 2025; Hébert-Losier et al., 2017; Visser et al., 2025), highlighting the importance of accounting for sex and BMI when interpreting test outcomes. Furthermore, we identified that training calf muscles involved 18% greater repetitions, and increased peak power by 13%, total time by 22%, and total work by 27% during the CRT. Thus, calf muscle training becomes an important factor when assessing individuals.

4.1.1 Practical implications

The findings in this thesis can be used to justify the current selection of 60 bpm as the CRT cadence. While median self-selected cadences of the CR10 (75.6 bpm) and CRT (69.8 bpm) were close to 60 bpm, they present much greater variability between individuals, ranging from 48.4 bpm to 129 bpm for CR10 and 44.6 bpm to 121.4 bpm for CRT. Though self-selecting a cadence is potentially more natural, recommending self-selected CRT

cadences over 60 bpm in clinical settings cannot be made until further research into cadence and CRT outcome repeatability has been conducted. Therefore, data from our experimental studies suggest the continued use of 60 bpm assists in standardising the CRT, enabling greater inferences between studies and likely enhancing test-retest reliability between initial TS MTU assessment and subsequent testing.

Furthermore, our findings can be used to inform exercise prescription in training and rehabilitation, with exercise physiologists and clinicians (e.g., physiotherapists) benefiting from our data. We have shown that performing non-fatiguing and fatiguing calf raises as fast as possible produces 57% and 29% greater peak power than 60 bpm, respectively. As TS MTU rehabilitation progresses, calf raises could be prescribed at faster cadences to develop muscular power, enhance stretch-shortening cycle capabilities, recruit fast-twitch muscle fibres, and to prepare the TS MTU for more explosive movements (e.g., running, plyometrics) in a return to sport (Grävare Silbernagel & Crossley, 2015; Schenau et al., 1997; Wilk et al., 2021). A point to consider in the context of sport, training calf muscles at cadences similar to the pace of play may additionally contribute to injury prevention.

4.1.2 Strengths

A primary strength of the experimental studies in this thesis is the study design. Both study one and study two were randomised crossover trials with a repeated measures design, therefore enabling sample sizes of 35 to 38 participants being sufficiently powered to detect a *small* effect size (Cohen's f 0.18) difference between conditions. Sample sizes were comparable with recent published research examining CRT cadence (Hébert-Losier, Fernandez, et al., 2025). Furthermore, the repeated measures design meant each participant acted as their own control, reducing within-subject variability.

A second strength is in the tools used to collect and assess our data in both experimental studies. The validated Calf Raise application was used to track vertical displacement of each calf raise repetition using a calibrated 24 mm circular sticker positioned underneath the lateral malleolus in line with the heel on a flat portion of the foot (Fernandez et al., 2023). The application demonstrates excellent intra-rater and inter-rater reliability ($ICC \leq 0.949$, $CV \leq 5.6\%$) for CRT for videos analysed (Fernandez et al., 2023), with good to excellent agreement of derived outcomes when compared to gold standard measurements of 3D motion and force plates ($ICC = 0.84$ to 1.00) (Fernandez et al., 2023; Hébert-Losier et al., 2022). While the application did not compute repetitions per minute or data for each repetition, the raw data curves from the Calf Raise application were exported to Visual3D Professional v2025.09.1 (©HAS-Motion, Kingston, Ontario, Canada) for additional processing. The Calf Raise application is a free resource, easily accessible for use in clinical settings.

An additional strength is the statistical analyses performed on data collected. Before statistical analysis, Shapiro-wilks tests were run to check for normality of data. Both sets of data from our experimental data were not normally distributed, thus data were log transformed (except for repetitions in study two where Poisson regression was used) to reduce heteroscedasticity and skewness prior to inferential analyses. Our analyses accounted for sex, BMI, and physical activity levels as potential predictors of CR10 and CRT outcomes, with age and calf muscle training additional potential predictors of CRT outcomes. Accounting for such predictors provided more robust confounding control, enabling greater detection of true effects present in our models.

4.1.3 Limitations

One of the main limitations to the CR10 and CRT studies is the homogeneity of the population studied. Participants were healthy, injury-free, and relatively young with

moderate-to-high PAL based on the Likert scale used. While our results can be generalised to similar populations, what self-selected and fast cadences are reached and how these cadences influence CRT and CR10 outcomes may differ in individuals who are aging, have greater BMI, present with lower PAL, and are currently injured or have a history of TS MTU injury. Therefore, when interpreting calf raise outcomes against our findings, age, BMI, PAL, and injury status must be taken into consideration.

A second limitation is that calf raises (CR10, CRT) were performed starting from a foot position of slight dorsiflexion (10° incline). As with cadence, foot position is a CRT parameter that has been identified as important, yet variable across published reviews (Artina et al., 2026; Hébert-Losier, Newsham-West, et al., 2009; Hébert-Losier, Schneiders, et al., 2009). The decision to start from a 10° incline in our experimental studies was based on published research (Hébert-Losier et al., 2024), where it was reported that vertical displacement was greater from a position of dorsiflexion in comparison to starting from a step and the floor. Furthermore, starting from a 10° incline has been shown to be valid and reliable (Byrne et al., 2017; Fernandez et al., 2023; Hébert-Losier et al., 2024). It is not known whether self-selected and as fast as possible cadences identified in our studies would differ when calf raises are performed from a step or the floor. Therefore, our results may not be directly comparable or generalisable to tests performed with differing foot positions.

Another limitation is that we did not use technology such as electromyography and ultrasound to examine muscle activation, fatigue, or changes in muscle fibre lengths during calf raise repetitions. Examining the TS MTU in greater depth to gain mechanistic insight of how cadence influenced muscle activation and fatigue could have further strengthened our studies, however access to such technology is not cost effective or readily available.

Lastly, research has shown that individuals have the ability to self-select optimal cadences and reproduce said cadences upon repeated efforts (Nguyen et al., 2026; Selinger et al., 2015). However, our experimental studies did not explore whether self-selected or as fast as possible cadences were reproducible on subsequent attempts. Instructing the use of self-selected cadences over metronome-controlled cadences in the CRT without evidence confirming cadence reproducibility could reduce test-retest reliability and create outcomes less comparable between individuals.

4.1.4 Future Research

The experimental studies in this thesis are the first to explore self-selected and as fast as possible cadence ranges for non-fatiguing and fatiguing calf raise repetitions, and to compare their CR10 and CRT outcomes to those achieved at 60 bpm. Future research could build on our findings that reported median self-selected cadences of the CR10 (75.6 bpm) and CRT (69.8 bpm) as being close to the commonly used 60 bpm. Given the considerable minimum to maximum ranges of self-selected cadences in the CR10 (48.4 bpm – 129 bpm) and the CRT (44.6 bpm – 121.4 bpm), the use of a metronome could standardise the CRT by enabling greater test-retest reliability and consistency for between subject comparisons. Therefore, it could be worthwhile to explore how CRT outcomes differ between 60 bpm and 70 bpm to provide evidence for suggested clinical use. Furthermore, future research could explore the test-retest reliability of self-selected and as fast as possible cadences in the CRT, examining whether cadences could be replicated on subsequent attempts, thus potentially providing evidence for the use of self-selected cadences in clinical settings. Lastly, future research could address some of the limitations to our experimental studies inclusive of exploring self-selected cadences from different foot starting positions and participants of varying demographics to establish if our results can be further generalised.

4.1.5 Conclusion

Overall, this thesis provides evidence that varying cadences (60 bpm, self-selected, as fast as possible) influenced most CR10 and CRT outcomes. In addition, sex, BMI and calf muscle training were identified as significant predictors of certain CR10 and CRT outcomes. Accounting for such predictors is important when interpreting calf raise outcomes. Median self-selected cadences were 75.6 bpm (CR10) and 69.8 bpm (CRT), close to the commonly used 60 bpm. Additionally median as fast as possible cadences were 196.8 bpm (CR10) and 109.4 bpm (CRT), indicating that 120 bpm may be too fast for fatiguing repetitions in some individuals. Although the significant differences identified between 60 bpm and self-selected cadence may not be clinically meaningful, the range in self-selected cadences and absence of reliability data rather favour the continued use of 60 bpm in clinical settings for standardisation.

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Appendices

Appendix A: HECS ethics approval (CR10)

The University of Waikato
Private Bag 3105
Hamilton, New Zealand, 3240
0800 WAIKATO (924 528)

HECS Human Ethics Committee
Brett Langley
Telephone +64 77 838 4060
Heecs-ethics@waikato.ac.nz



THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

27 July 2023

Kim Hebert-Losier
Steve Finlayson
Anna Butcher

Re: HECS Ethics Approval of Application HREC(HECS)2023#44 "Calf raise cadence in humans"

Dear Kim:

Thank you for submitting your amended application HREC(HECS)2023#44 for ethical approval.

We are pleased to provide formal approval for your project, including the following activities:

- Recruitment of approximately 42 physically active and healthy male and female (>16 years of age) participants for a study that aims to determine the preferred cadence and quickest cadence when performing calf raises and how the metrics of these compare to calf raises performed at 60 bpm.
- Have participants complete a baseline data collection form.
- Have participants complete sets of calf raisers in which they will be asked to go up and down on their toes 10 times on a small incline on one leg. This will be repeated three times at different rates with 5 minute rest periods between.
- In total, the entire session should take no more than 20-30 minutes to complete.

Please contact the committee by email (hecs-ethics@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.

Kind regards,

Brett Langley, PhD
Chairperson
HECS Human Ethics Committee
University of Waikato

Appendix B: Participant consent form (CR10)

Consent Form for Participants

Title – Calf raise test protocol variations

I have read the Participant Information Sheet for this study and have had the details of 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 question or to refuse to do any particular activity.*
- *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.*

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 to Use Images and Videos (Optional)

I agree to my images and videos being used in their original (unaltered) form for publication, scientific presentation, and/or education purposes. I understand that anonymity cannot be preserved.

	Participant:	Researcher:
Signature		
:	_____	_____
Name:	_____	_____
Date:	_____	_____

Appendix C: Participant data collection form (CR10)

Participant Data Collection Sheet		 THE UNIVERSITY OF WAIKATO <i>Te Whare Wānanga o Waikato</i>	
GENERAL			
ID number			
NAME			
DATE OF BIRTH (dd/mm/yyyy)			
SEX (please tick)	☐ MALE ☐ FEMALE ☐ OTHER: _____		
FOOTEDNESS (foot used to kick a ball)	☐ RIGHT ☐ LEFT		
ETHNICITY			
SPORT			
What sport do you play?			
What level do you play?	☐ school ☐ club ☐ national ☐ other _____		
How many times a week do you play?			
How many hours a week do you play?			
How many years have you been playing?			
During the past 12 months, how much do you move or exert yourself physically during leisure/play time (overall)? ☐ Hardly no physical activity (reading, watching TV, using the computer) ☐ Mostly sitting, sometimes walk, easy tasks/play ☐ Light physical activity for about 2 – 4 hours a week, like fishing, walking, dancing ☐ Moderate exercise 1 – 2 hours a week, like jogging, swimming, gymnastics ☐ Moderate exercise at least 3 hours a week, like jogging, swimming, gymnastics ☐ Hard or very hard exercise regularly and several times a week, during which the physical exercise is great, like jogging, rugby, football			
INJURIES			
Are you in good general health?	☐ YES ☐ NO		
Do you have any current or recent injuries (3 months)? Please provide detail (e.g., right Achilles tendon)	☐ YES ☐ NO		
Have you suffered any injuries in the past? Please provide detail (e.g., right ACL tear 2015)	☐ YES ☐ NO		
PHYSICAL ACTIVITY IN THE LAST 7 DAYS			
During the past 7 days , please tell us how much time you have spent in each category of activity. Vigorous physical activities require hard physical effort and make you breathe much harder than normal. Moderate activities take moderate physical effort or make you breathe somewhat harder than normal. Walking includes at work, school, and home, walking from place to place, and any other walking that you have done for recreation, sport, exercise. Sitting includes time spent sitting at work, at school and at home, while doing some course work and leisure/play time. This may include time spent sitting at a desk, visiting friends, reading, or sitting or lying down to watch TV.			
Vigorous	_____ days per week	_____ minutes per day	
Moderate	_____ days per week	_____ minutes per day	
Walking	_____ days per week	_____ minutes per day	
Sitting	_____ days per week	_____ hours per day	

Appendix D: HECS Ethics approval (CRT)

The University of Waikato
Private Bag 3105
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0800 WAIKATO (924 528)

HECS Human Ethics Committee
Brett Langley
Telephone +64 77 838 4060
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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

26 March 2025

**Kim Hebert-Losier
Ben Bidois
Ryan Hood
Christiaan Cumming
Charlotte Scheffler
Noelle Gutry**

Re: HECS Ethics Approval of Application HREC(HECS)2025#09 “Calf raise test protocol variations”

Dear Kim:

Thank you for submitting your amended application HREC(HECS)2025#09 for ethical approval.

We are pleased to provide formal approval for your project, including the following activities:

- Recruitment of approximately 92 participants for a study that assess the influence of variations in calf raise test parameters, including cadence, height, and footwear, on calf raise test outcomes.
- Have participants complete a baseline questionnaire that asks general biographical information, sport and exercise participation, and prior injuries.
- Have participants go up and down on their toes on a small incline on one leg under three conditions on three different days: 1) at self-selected pace; 2) as fast as possible; and 3) at a set pace.
- Have participants go up and down on their toes on a small incline on one leg under three conditions on three different days: 1) going as high as possible up on toes; and 2) going as high as possible on toes, reaching for a target.
- Have participants go up and down on their toes on a small incline on one leg under two conditions on three different days: 1) with footwear; and 2) barefoot.

Please contact the committee by email (hecs-ethics@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.

Kind regards,

**Brett Langley, PhD
Chairperson
HECS Human Ethics Committee
University of Waikato**

Appendix E: Participant consent form (CRT)

Consent Form for Participants

Title – Calf raise test protocol variations

I have read the Participant Information Sheet for this study and have had the details of 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 question or to refuse to do any particular activity.*
- *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.*

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 to Use Images and Videos (Optional)

I agree to my images and videos being used in their original (unaltered) form for publication, scientific presentation, and/or education purposes. I understand that anonymity cannot be preserved.

	Participant:	Researcher:
Signature		
:	_____	_____
Name:	_____	_____
Date:	_____	_____

Appendix F: Participant data collection form (CRT)

 THE UNIVERSITY OF SYDNEY	
Participant Data Collection Sheet	
ID number	
NAME	
DATE OF BIRTH (dd /mm/yyyy)	
SEX (please tick)	☐ MALE ☐ FEMALE
FOOTEDNESS (foot used to kick a ball)	☐ RIGHT ☐ LEFT
ETHNICITY	
EMAIL (for post-study report)	
What sport do you play?	
What level do you play?	☐ school ☐ club ☐ national ☐ other _____
How many times a week do you play?	
How many hours a week do you play?	
How many years have you been playing?	
During the past 12 months, how much do you move or exert yourself physically during leisure/play time (overall)? ☐ Hardly no physical activity (reading, watching TV, using the computer) ☐ Mostly sitting, sometimes walk, easy tasks/play ☐ Light physical activity for about 2 – 4 hours a week, like fishing, talking, dancing ☐ Moderate exercise 1 – 2 hours a week, like jogging, swimming, gymnastics ☐ Moderate exercise at least 3 hours a week, like jogging, swimming, gymnastics ☐ Hard or very hard exercise regularly and several times a week, during which the physical exercise is great, like jogging, rugby, football	
Are you in good general health?	☐ YES ☐ NO
Do you have any current or recent injuries (3 months)? Please provide detail (e.g., right Achilles tendon)	☐ YES ☐ NO
Have you suffered any injuries in the past? Please provide detail (e.g., right ACL tear 2015)	☐ YES ☐ NO
Do you regularly strength train your calf muscle?	☐ YES ☐ NO
If yes, what do you do? (frequency, exercises, sets, reps)	Times a week _____ Exercises _____ Sets _____ Reps _____
Anthropometrics	Height (cm) _____ Mass (kg) _____
Order of conditions	
Gear ratio of foot	_____ 5 th metatarsal to ankle _____ ankle to achilles tendon