Scientific Investigation of the Calf Raise Test Using the Calf Raise Mobile Application to Inform Test Administration and Interpretation

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Abstract

The Calf Raise Test (CRT) is a widely used functional assessment of triceps surae muscle-tendon unit function. While it exhibits acceptable reliability, administration inconsistencies and test parameter variations likely contribute to observed normative value discrepancies in the literature. Additionally, devices employed in research for standardisation and quantification of outcomes beyond the number of repetitions are often inaccessible in clinics. This Thesis addresses these gaps by conducting an evidence-based assessment of the CRT and examining how changes in test parameters affect outcomes. The overarching aims of this Thesis were to: (1) develop a valid and reliable method to assess the CRT in clinical practice that provides research-grade outcomes, and (2) examine the influence of changing CRT parameters on outcomes and triceps surae muscle function. To achieve these ~~overarching~~ aims, two literature reviews and three experimental studies were conducted.

The first literature review, aligned with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, provides an overview of CRT devices used in research. Thirty-five studies were included, identifying seven CRT devices. The linear encoder emerged as the most used, quantifying all three main CRT outcomes (repetitions, peak height, and total work). However, its limited clinical use is attributed to hardware costs and need for programming skills.

Chapter 3 introduces the Calf Raise application (CR_{app}), a smartphone application designed to aid standardise CRT procedures and automate outcomes. Thirteen individuals underwent single-leg CRT on both legs across three occasions. CR_{app} outcomes (i.e., repetitions, total work, total height,

peak height, fatigue index, and peak power) were validated against 3D motion capture and force plate data, demonstrating excellent concurrent validity and agreement levels. The CR_{app} proved valid, reliable, and suitable for both research and clinical practice.

Chapter 4 explores the impact of varying ankle starting positions on CRT outcomes in 49 healthy individuals, accounting for gender, age, body mass index (BMI), and physical activity levels. Participants performed single-leg CRT in three randomised conditions on three occasions: flat (0°), incline (10° dorsiflexion), and step (full dorsiflexion). Analysis of CR_{app} data indicate significant effects of ankle starting position on all CRT outcomes, emphasising the importance of ankle start position for CRT administration and interpreting test outcomes.

Chapter 5 investigates the effects of varying cadence on CRT outcomes in 36 healthy individuals, considering gender, age, BMI, and physical activity levels. Participants performed single-leg CRT in three randomised conditions on three occasions: 30, 60, and 120 beats per minute. Significant cadence effects were observed on CR_{app} outcomes, hence this study confirmed that cadence does matter when administering the CRT and interpreting its outcomes.

Chapter 6, a systematic review following PRISMA guidelines, examines changes in standing CRT parameters on triceps surae surface electromyography (EMG) activity and fatigue measures. Seven studies were included, indicating increased activity in medial gastrocnemius increased with feet externally rotated, knees straight, and added load; lateral gastrocnemius with feet internally rotated, knees straight, and added load; and soleus with knees bent, whole-body vibration, and added load.

These findings can inform evidence-based practices, though further training studies are recommended.

Overall, this Thesis introduces the CR_{app}, an innovative, valid, and reliable method of quantifying key CRT outcomes. Also, this Thesis provides a better understanding of the influence of varying CRT parameters on outcomes. The evidence-base generated from this Thesis may be used to inform best practice use and interpretation of the CRT and guide future research.

Dedication

This Thesis is dedicated to my Lord and Saviour, Jesus Christ, with whom all things are possible.

And to my grandparents, Emiliana and Ricardo Fernandez and to my dad, Victor Fernandez.

Your love, wisdom, and faith have always been my source of strength.

I would not be the person I am today without your love and guidance.

I love you all deeply.

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3D MOCAP	Three-dimensional motion capture
AMES	Ankle Measure for Endurance and Strength
ATP	Adenosine triphosphate
ATR	Achilles tendon rupture
BMI	Body mass index
bpm	Beats per minute
CI	Confidence interval
CR_{app}	Calf Raise application
CRT	Calf raise test
CV	Coefficient of variations
DOMs	Delayed onset muscle soreness
DVT	Deep vein thrombosis
EMG	Electromyography
ICC	Intraclass correlation coefficient
iEMG	Integrated electromyography
iOS	iPhone operating system
IPAQ	International Physical Activity Questionnaire
LG	Lateral gastrocnemius
MF	Median frequency
MF-NS	Median frequency-normalised slope
MG	Medial gastrocnemius
MTU	Muscle-tendon unit
NOS	Newcastle-Ottawa Scale
NR	Not reported

PFP	Patellofemoral pain
PICOS	Population, Intervention, Comparison, Outcomes and Study
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-analyses
QUIPS	QUality Assessment in Prognostic Studies
RMS	Root mean square
ROB	Risk of bias
SSC	Stretch-shortening cycle
SD	Standard deviation
SEM	Standard error of measurement
SENIAM	Surface Electromyography for the Non-Invasive Assessment of Muscle
SOL	Soleus

Research outputs arising from this doctoral thesis

Peer-reviewed manuscripts

- Fernandez, M. R., Athens, J., Balsalobre-Fernandez, C., Kubo, M., & Hébert-Losier, K. (2023). Concurrent validity and reliability of a mobile iOS application used to assess calf raise test kinematics. *Musculoskeletal Science & Practice*, *63*, 102711. https://doi.org/10.1016/j.msksp.2022.102711.

- Fernandez, M. R., & Hébert-Losier, K. (2023). Devices to measure calf raise test outcomes: A narrative review. *Physiotherapy research international: the journal for researchers and clinicians in physical therapy*, *28*(4), e2039. https://doi.org/10.1002/pri.2039.

- Fernandez, M. R., Athens, J., O Neill, S., Kubo, M., & Hébert-Losier, K. (2023). Effects of ankle starting position on calf raise test outcomes: Position does matter. *Under Review*

- Fernandez, M. R., Athens, J., O Neill, S., Kubo, M., & Hébert-Losier, K. (2023). Effects of cadence on calf raise test outcomes: Cadence does matter. *Under Review*

- Fernandez, M. R., Athens, J., Kubo, M., & Hébert-Losier, K. (2023). Triceps surae muscle activity and fatigue during standing single leg calf raises: A systematic review. *Under Review*

Peer-reviewed conference abstracts

Hébert-Losier, K., Fernandez, M. R., Athens, J., Kubo, M., Balsalobre-Fernandez, C. Validation of the calf raise application. *12th Australasian Biomechanics Conference (ABC12) 2021 Conference, Online Conference, 6 – 7 December 2021*

Fernandez, M. R., Athens, J., Balsalobre-Fernandez, C., Kubo, M., & Hébert-Losier, K. Concurrent validity and reliability of a mobile iOS application used to assess calf raise test kinematics. *29th Congress of International Society of Biomechanics (ISB)*, 30 July – 3 August 2023.

Chapter 1

Introduction

1.1 Introduction

In rehabilitation and sports medicine clinical practice, as well as in research, it is common to use functional assessment or outcome measure to evaluate neuromuscular (Medijainen et al., 2015) and musculoskeletal (Manske & Reiman, 2013) performance. These tests measure an individual's ability to perform a functional task, such as jumping, running, and sit-to-stand for the lower limbs; and grasping, reaching, or throwing for the upper limbs. The outcomes or data collected from these tests can help clinicians and researchers identify impairments, such as muscle weaknesses or restrictions in motion, related to pathological conditions affecting the neuromuscular and musculoskeletal system. Further, outcomes from these tests can be used to assess the risk of injury in specific functional tasks or sports (Blackburn & Guido, 2013) and can aid in directing rehabilitation goals and monitoring rehabilitation progress.

The calf raise test (CRT) is one of the most widely used functional tests of triceps surae muscle-tendon unit (MTU) function (i.e., strength and endurance) in clinical practice and research. It is considered a manual muscle test of the plantarflexors (Hislop & Montgomery, 1996). Other test methods such as handheld or isokinetic dynamometry or force places can also be used to assess calf muscle strength and power (Ercan et al., 2019; Mentiplay et al., 2015), but these approaches are less practical than manual muscle testing. The triceps surae MTU is one of the main contributors to mechanical work during human locomotion, as shown for walking (McCarthy et al., 2006) and running (Machado et al., 2021). The CRT demonstrates acceptable reliability (Byrne et al., 2017; Hébert-Losier et al., 2017; Ross & Fontenot, 2000), but a systematic review (K. Hébert-Losier et al., 2009) identified inconsistent description of its parameters, implementation of its testing protocol, and normative values, which can limit cross-study inferences. Variations in calf raise parameters include different starting ankle positions (K. Hébert-Losier et al., 2009; Kim Hébert-Losier et al., 2009), foot positions (e.g., foot in external rotation vs foot in internal rotation) (Akuzawa et al., 2017; Marcori et al., 2017; Riemann et al., 2011), knee positions (e.g., knee extension vs knee flexion) (Hébert-Losier et al., 2012a, 2012b), amount of additional load (Kinugasa & Akima, 2005), integration of whole-body vibration (Robbins & Goss-Sampson, 2013), footwear conditions (e.g., barefoot, with standard shoes, or with own shoes), and cadence (K. Hébert-Losier et al., 2009; Kim Hébert-Losier et al., 2009; Möller et al., 2002), which can all potentially influence muscle activation and therefore calf raise test outcomes. Furthermore, all these variations in test parameters may influence outcomes and contribute to the variations in normative values (i.e., averages of 16 to 73 repetitions in healthy adults) observed in the literature (Table 1).

This Thesis addresses this gap by conducting an evidence-based assessment of the CRT and examining how changing test parameters influence outcomes to help guide clinicians and researchers in the use and interpretation of the CRT.

Table 1. Reported calf raise test parameters and outcomes in healthy adults from a selection of published articles (*n* = 13).

Authors (year of publication) **Country**	**Participants**	**CRT parameters**	**Outcomes (mean ± SD)**
Byrne et al. (2017) UK	**Sample**: 38 healthy individuals (18 males, 20 females) **Age:** 22.7 ± 3.1 y **Height:** 173 ± 10 cm **Mass**: 74.9 ± 15.1 kg	**Ankle starting position:** 10° DF incline **Knee starting position:** Extension **Pace:** 30 calf raises/min (60 bpm) **Calf raise height:** As high as possible **Balance support:** Fingertips **Termination criteria:** Inability to keep the pace, inability to maintain full extension, using more than fingertip support, volitional fatigue	**Number of repetitions (*n*)** Left: 32.6 ± 11.4 Right: 34.7 ± 12.1 **Peak height (cm)** Left: 13.5 ± 2.1 Right: 13.6 ± 1.8 **Work (J)** Left: 2436 ± 908 Right: 2583 ± 863
Chitre and Prabhu (2017) India	**Sample**: 80 healthy individuals *Age range: 20-30* **Height**: NR **Mass:** NR *Age range: 31-40* **Height**: NR **Mass:** NR	**Ankle starting position:** Flat **Knee starting position:** Extension **Pace:** 30 calf raises/min (60 bpm) **Calf raise height:** As high as possible **Balance support:** 1 finger on a wall **Termination criteria:** Plantarflexion angle reduces to less than 50-75% of the initial angle, loss of balance, inability to maintain knee extension, volitional fatigue	*Age range: 20-30* **Number of repetitions (*n*)** 31.85 ± 9.09 *Age range: 31-40* **Number of repetitions (*n*)** 27.9 ± 5.45

Hébert-Losier et al. (2017) Sweden	**Sample**: 32 healthy individuals (22 males, 10 females) **Age:** 28± 8 y **Height:** NR **Mass**: NR	**Ankle starting position:** 10° DF incline **Knee starting position:** Extension **Pace:** 30 calf raises/min (60 bpm) **Calf raise height:** As high as possible **Balance support:** Fingertips **Termination criteria:** Inability to keep the pace, inability to maintain full extension, inability to maintain trunk position, using more than fingertip support; volitional fatigue	**Number of repetitions (*n*)** *Age: 20* Male Left: 37.4 Right: 37.5 Female Left: 29.6 Right: 30.7 *Age: 30* Male Left: 32.7 Right: 33.0 Female Left: 26.8 Right: 28.0 *Age: 40* Male Left: 28.1 Right: 28.5 Female Left: 24.0 Right: 25.3
Hébert-Losier and Holmberg (2013a) Sweden	**Sample**: 48 healthy individuals *Males* **Sample:** 28 males **Age:** 38 ± 12 y **Height:** 169 ± 7 cm **Mass**: 82 ± 9 kg *Females* **Sample:** 20 females **Age:** 41 ± 11 y **Height:** 169 ± 8 cm **Mass**: 69 ± 9 kg	**Ankle starting position:** ~5° DF incline **Knee starting position:** Extension and 45° flexion **Pace:** 60 calf raises/min (120 bpm) **Calf raise height:** As high as possible **Balance support:** 2% body weight on a horizontal bar suspended in front **Termination criteria:** Inability to keep the pace, more than 2% body weight for support volitional fatigue	*Knee extension* **Number of repetitions (*n*)** 37 ± 13 **Peak height (cm)** 11.6 ± 2.3 *45° knee flexion* **Number of repetitions (*n*)** 40 ± 17 **Peak height (cm)** 10.7 ± 2.7

Hébert-Losier et al. (2012b) New Zealand	**Sample:** 48 healthy individuals *Younger males* **Sample:** 12 males **Age:** 22.4 ± 1.8 y **Height:** 177.4 ± 5.6 cm **Mass**: 71.7 ± 10.2 kg *Younger females* **Sample:** 12 females **Age:** 22.7 ± 2.0 y **Height:** 165.1 ± 4.2 cm **Mass:** 61.1 ± 10.7 kg **Middle aged:** 12 males **Age**: 41.1 ± 3.1 y **Height:** 177.7 ± 5.6 cm **Mass:** 81.7 ± 14.9 kg **Middle aged:** 12 females **Age:** 41.5 ± 3.4 y **Height**: 166.5 ± 8.1 cm **Mass:** 66.6 ± 10.3 kg	**Ankle starting position:** Flat **Knee starting position:** Extension and 45° knee flexion **Pace:** 60 calf raises/min (120 bpm) **Calf raise height:** as high as possible **Balance support:** 2% body weight on a horizontal bar suspended in front **Termination criteria:** inability to keep the pace, support was used to assist performance, calf raise height threshold was not reached, volitional fatigue	*Knee extension* **Number of repetitions (*n*)** 45.1 *45° knee flexion* **Number of repetitions (*n*)** 48. 4
Jan et al. (2005) Taiwan	**Sample:** 60 healthy individuals 30 males **Age:** 29.0 ± 4.8 y **Height:** 169.7 ± 6.1 cm **Mass**: 69.7 ± 8.0 kg 30 females **Age:** 30.3 ± 4.9 y **Height:** 160.5 ± 3.9 cm **Mass**: 52.4 ± 5.5 kg	**Ankle starting position:** Flat **Knee starting position:** Extension **Pace:** 30 calf raises/min (60 bpm) **Calf raise height:** as high as possible **Balance support:** fingertips; permitted to gently put 1 or 2 fingers on the examiner's shoulders **Termination criteria:** inability to maintain full knee extension, using more than fingertip support, overpressure on the examiner's shoulders volitional fatigue	**Number of repetitions (*n*)** *Age: 21-40* Male: 22.1 Female: 16.1
Lunsford and Perry (1995) USA	**Sample**: 203 healthy individuals (122 males, 81 females) *Males*	**Ankle starting position:** Flat **Knee starting position:** Extension **Pace:** 30 calf raises/min (one heel-rise every 2 seconds)	**Number of repetitions (*n*)** Male: 27.8 ± 11.5 Female: 28.4 ± 9.8

	Sample: 122 males **Age:** 34.7 ± 8.5 y **Height:** 178.9 ± 7.9 cm **Mass**: 79.7 ± 11.5 kg *Females* **Sample:** 81 females **Age:** 29.3 ± 5 y **Height:** 164.8 ± 6 cm **Mass**: 60 ± 8.6 kg	**Calf raise height:** As high as possible **Balance support:** Touch the examiner with a single finger **Termination criteria:** Leaned or pushed down on the examiner, inability to maintain full knee extension, plantarflexion range of motion decreased by more than 50% of the starting range of motion, volitional fatigue, or requested to stop	
Möller et al. (2005) Canada	**Sample**: 10 healthy males **Age:** 37 y, range: 31-43 **Height:** 184 cm, range: 172-195 **Mass**: 88 kg, range: 75-98	**Ankle starting position:** Flat **Knee starting position:** Extension **Pace:** 20 calf raises/min (40 bpm) **Calf raise height:** 5 cm (predetermined height using a CRT measuring device-Haberometer) **Balance support:** Fingers on a wall **Termination criteria:** Volitional fatigue	**Number of repetitions (*n*)** Left: 28.05 ± 5.15 Right: 29.80 ± 6.15
Österberg et al. (1998) Sweden	**Sample**: 10 healthy women. **Age:** 24 ± 3 y **Height:** 167 ± 4 cm **Mass**: 67 ± 8 kg	**Ankle starting position:** 10° DF incline **Knee starting position:** Extension **Pace:** 46 calf raises/min (92 bpm) **Calf raise height:** As high as possible **Balance support:** Fingertips on the wall **Termination criteria:** Volitional fatigue	**Number of repetitions (*n*)** 36 ± 2 **Work (J)** Eccentric phase: 6624 ± 467 Concentric phase: 6631 ± 472
Pereira et al. (2010) Brazil	**Sample**: 22 healthy individuals (14 males, 8 females) **Age:** 21 ± 1 y **Height:** 171 ± 2 cm **Mass**: 65 ± 2 kg	**Ankle starting position:** Flat **Knee starting position:** Extension **Pace:** 23 calf raises/min (46 bpm) **Calf raise height:** 5 cm (predetermined height using a CRT measuring device-Haberometer) **Balance support:** One hand flat on a wall **Termination criteria:** Inability to keep the pace (in three calf raise attempts), could no longer achieve the	**Number of repetitions (*n*)** 73 ± 42

		predetermined height in three sequential calf raise attempts, volitional fatigue	
Sara et al. (2021) USA	**Sample**: 28 healthy individuals *14 males* **Age:** 21.5 ± 8 y **Height**: 181 ± 8 cm **Mass:** 79.4 ± 10.3 kg *14 females* **Age:** 21.1 ± 9 y **Height**: 1.66 ± 0.07 cm **Mass:** 64.0 ± 10.8 kg	**Ankle starting position:** Flat **Knee starting position:** Extension **Pace:** 30 calf raises/min (60 bpm) **Calf raise height:** As high as possible. Dorsal part of the foot contact with the horizontal target plate (custom-made CRT device) **Balance support:** NR **Termination criteria:** Volitional fatigue (two consecutive missed contact with the horizontal target plate (custom-made CRT device)	**Number of repetitions (*n*)** Male: 32.6 ± 6.9 Female: 39.4 ± 14.8
Sman et al. (2014) Australia	**Sample**: 40 healthy individuals (21 males,19 females) **Age:** 24 ± 6.2 y **Height:** 174 ± 12.3 cm **Mass**: 68 ± 9.3 kg	**Ankle starting position:** Flat **Knee starting position:** Extension **Pace:** 23 calf raises/min (46 bpm) **Calf raise height:** As high as possible, clearing the band from the CRT measuring device (AMES) **Balance support:** Fingertips of one hand on the wall **Termination criteria:** Could no longer achieve the maximal rise (clear the elastic band), placed too much weight on the wall, inability to maintain full knee extension, volitional fatigue, or requested to stop	**Number of repetitions (*n*)** 23 ± 13.3
Zellers et al. (2017) USA	**Sample**: 20 healthy individuals *Non-dancers* 2 males, 8 females **Age:** Range: 16 to 35 y **Height:** NR **Mass**: NR *Ballet dancers* 2 males, 8 females	**Ankle starting position:** 10° DF incline **Knee starting position:** Extension **Pace:** 30 calf raises/min (60 bpm) **Calf raise height:** As high as possible **Balance support:** 2 fingertips on the wall **Termination criteria:** Inability to maintain pace, inability to maintain heel rise height of less than 2cm, inability to maintain full knee flexion, volitional fatigue	*Non-dancers* **Number of repetitions (*n*)** 32.5 ± 8.29 **Peak height (cm)** 13.3 ± 1.8 **Work (J)** 2241 ± 786 *Ballet dancers* **Number of repetitions (*n*)** 19.7 ± 3.6

	Age: Range 16 to 35 y **Height:** NR **Mass**: NR		**Peak height (cm)** 16.5 ± 0.75 **Work (J)** 1643 ± 492

Note: bpm, beats per minute; CRT, calf raise test; DF, dorsiflexion; NR, not reported.

This first chapter of this Thesis provides a background on the triceps surae MTU anatomy and function, as well as the CRT and its use in clinical practice and research. This overview provides a foundation and basis for this Thesis, and leads to establishing its aims, framework, and significance.

1.2 Background

1.2.1 Triceps surae muscle-tendon unit

The triceps surae (TS) consist of the soleus (SOL), medial gastrocnemius (MG), and lateral gastrocnemius (LG) muscles that share a common insertion into the calcaneus via the Achilles tendon (Standring, 2016). The triceps surae muscles account for 80% of plantarflexion torque (Murray et al., 1976). There are numerous intrinsic and extrinsic foot muscles that contribute to foot stability and function during weight-bearing activities. These muscles include the tibialis posterior, peroneus longus, and flexor digitorum longus, all of which are essential and synergistic muscles that contribute to foot flexibility, foot rigidity, and propulsion during gait (Akuzawa et al., 2017). Tibialis posterior and peroneus longus are also involved in foot stabilization and have synergistic functions and control the subtalar joint during gait acting as supinators and pronators (Akuzawa et al., 2017; Murley et al., 2009). These muscles can be activated during calf raises to various extents (Bellew et al., 2010; Kulig et al., 2004), with the plantarflexors remaining the main contributors.

Together with the Achilles tendon, the triceps surae muscles form the triceps surae MTU (Lehr et al., 2021). The triceps surae MTU acts as a spring, storing and releasing elastic energy that reduces the metabolic cost during locomotion and increases the efficiency of muscle contraction. The MTU stiffness increases with locomotion speed, allowing for enhanced storage and release of energy, enabling the body to move more efficiently, and reducing fatigue (Komi, 1984, 2000). The MG and LG muscles have approximately an equal proportion of Type

I (slow-twitch, fatigue-resistant fibres) and Type II (fast-twitch, fatigue sensitive, force and power generating fibres) muscle fibres (Edgerton et al., 1975; Johnson et al., 1973), with MG containing approximately 6% more Type II muscle fibres than LG. In contrast, the SOL has a greater proportion of Type I (>75%) than Type II fibres (Edgerton et al., 1975; Johnson et al., 1973). These muscle fibre types rely on different energy systems and hence respond differently to muscle contraction types and velocities (Plotkin et al., 2021; Qaisar et al., 2016). Type I fibres use aerobic metabolism, which synthesises adenosine triphosphate (ATP) more slowly, but can maintain contractions for longer periods. In contrast, Type II fibres synthesise ATP more rapidly using anaerobic or glycolytic metabolism. Type II fibres lead to more powerful contractions and are recruited during short, intense bursts of activity. However, these fibres quickly deplete their energy supply, leading to fatigue. Type I fibres are more resistant to fatigue and are recruited during long, steady contractions (Baker et al., 2010; Scott et al., 2001). From a functional perspective, Type I fibres are more involved during endurance activities like running and cycling (Bergh et al., 1978). Type II fibres are further recruited during short bursts of high-intensity activities like sprinting (Trappe et al., 2015) or weightlifting (Serrano et al., 2019). Thus, SOL is more suited to endurance activities (Bohm et al., 2021), whereas MG and LG are more suited for strength- and power-based activities (Plotkin et al., 2021). Furthermore, the difference in muscle fibre composition may explain why MG and LG fatigue more quickly than SOL during repetitive tasks.

The triceps surae muscles also have unique muscle architectural properties. The muscle architecture refers to the arrangement of muscle fibres within a muscle, which determines muscle function and performance (Lieber & Fridén, 2000; Maganaris et al., 1998). These architectural properties include fibre length, pennation angle, and physiological cross-sectional area (Charles et al., 2022; Kawakami, 2012). When the knee is in full extension, and the ankle joint is at 15°, LG has the longest fascicle length, followed by MG and SOL (Kawakami et al., 1998). As the ankle joint angle increases from -15° to 30°, MG has a larger pennation angle followed by LG and SOL (Maganaris et al., 1998). SOL is a mono-articular ankle plantarflexor that spans the ankle joint only, while the gastrocnemii muscles are bi-articular and cross both the knee and ankle joints (Kawakami et al., 1998; Suzuki et al., 2014). These configurations affect how they function with changes in knee and ankle joint angles (Kim & Jeon, 2016; Landin et al., 2016), as alterations in joint angles affect both the moment arm and length of the muscle (Winters & Kleweno, 1993). Changes in the knee angle may result in significant changes to the plantarflexion torque of the gastrocnemii muscles in particular (Landin et al., 2015), with a lesser effect on SOL. The biarticulate gastrocnemii muscles become actively insufficient at extreme knee flexion angles (Landin et al., 2015) and contribute to plantarflexion torque to a lesser extent in these extreme knee flexion positions (Landin et al., 2016). In contrast, with the knee extended and the ankle dorsiflexed, the gastrocnemii muscles are in a lengthened position and can generate maximum plantarflexion torque (Landin et al., 2015).

1.2.2 Calf raise test

The CRT (also known as the heel rise test or heel raise test) was introduced in the 1940s to assess the plantarflexors strength and endurance in poliomyelitis patients (Beasley, 1961). It is now widely used in sports medicine (Hébert-Losier et al., 2022; Madeley et al., 2007), orthopaedics (Silbernagel et al., 2010; Van Cant et al., 2017), patients with cardiovascular conditions (Haber et al., 2004; Kröönström et al., 2014), neurology (Krautwurst et al., 2016; Svantesson, Osterberg, Grimby, et al., 1998), paediatrics (Mishra et al., 2022), and gerontology (André et al., 2020; André et al., 2016) to evaluate the strength and endurance of the triceps surae MTU. The standing CRT involves repeated concentric and eccentric contractions of the plantarflexors in unilateral stance performed to volitional exhaustion. In clinical practice, the number of calf raise repetitions completed is recorded as the primary test outcome (Beasley, 1961; Lunsford & Perry, 1995). Other CRT outcomes that are measured and reported in the literature are peak height (i.e., maximum displacement of the heel during calf raises) and total work (i.e., the total positive displacement of the heel times an individual's body weight) (Andreasen et al., 2020; Byrne et al., 2017; Silbernagel et al., 2010; Svantesson, Osterberg, Thomeé, et al., 1998), as shown in Table 1. These three outcomes are used to quantify triceps surae MTU function, monitor ankle and foot rehabilitation progress, and evaluate the effectiveness of rehabilitation management (Aufwerber et al., 2022; Häggmark et al., 1986; J. A. Zellers et al., 2020).

Clinically, the CRT is typically administered without a measuring device and relies solely on counting the number of repetitions performed. In research, to minimise methodological error and enhance standardisation of test parameters, the CRT is administered using custom-made devices, like the Haberometer, or laboratory-based equipment, such as motion capture systems and force plates (Figure 1). The use of laboratory-based equipment in particular enables the quantification of other CRT outcomes, namely peak height and total work. Measuring all three outcomes is a major advantage and provides a more comprehensive and objective assessment of ankle function. The number of repetitions provides an indicator of endurance that is easy to quantify clinically, and is determined by contractile tissue and muscle endurance metabolism (Holloszy, 1967). Peak height moreover reflects the tendon and muscle fibre length (Baxter et al., 2018). Total work further reflects the muscle endurance metabolism and provides a more scientifically rigorous and accurate indication of endurance than repetitions as it considers the vertical displacement of each repetition and body mass of individuals (Andreasen et al., 2020; Byrne et al., 2017; Silbernagel et al., 2010). However, the devices used in research are not yet commonly integrated in clinical settings possibly due to complexity in set-up, high costs, low accessibility, or requirements of specific knowledge on how to operate the equipment. Figure 1 illustrates the reported devices for monitoring CRT outcomes.

As noted above in the 1.1 Introduction section, there is no uniform description of CRT parameters, test protocol, or thresholds for interpreting test outcomes (Hébert-Losier et al., 2009). Table 1 presents some of the common CRT parameters reported in the literature. Noteworthy are differences in ankle starting position and cadence. Furthermore, there is no easily accessible objective means of quantifying all CRT outcomes (i.e., repetitions, peak height, and total work) that can be applied in both research and clinical settings. This lack of standardisation and objective quantification of outcomes is a potential contributing factor to the range of norms reported for the CRT (Hébert-Losier et al., 2009). Furthermore, changes in test parameters can influence the amount of muscle activity during the CRT, as shown for changes in knee flexion angle (Hébert-Losier et al., 2012a). Changing other parameters of the CRT could potentially affect MG, LG, and SOL contributions to the task.

In addition, differences in the demographic characteristics of participants can affect normative values for the CRT. It has been reported that CRT performance varies between genders (André et al., 2016; Hébert-Losier et al., 2017; Jan et al., 2005; Mishra et al., 2022; Monteiro et al., 2017), where males typically outperform females. Furthermore, CRT performance is reported to decrease with an increase in age (André et al., 2016; Hébert-Losier et al., 2017; Jan et al., 2005; Mishra et al., 2022; Monteiro et al., 2017), an increase in body mass index (BMI) (Hébert-Losier et al., 2017; Monteiro et al., 2017), and lower physical activity levels (Hébert-Losier et al., 2017; Monteiro et al., 2017). In most CRT studies, predictors are not considered during the analysis or interpretation of results.

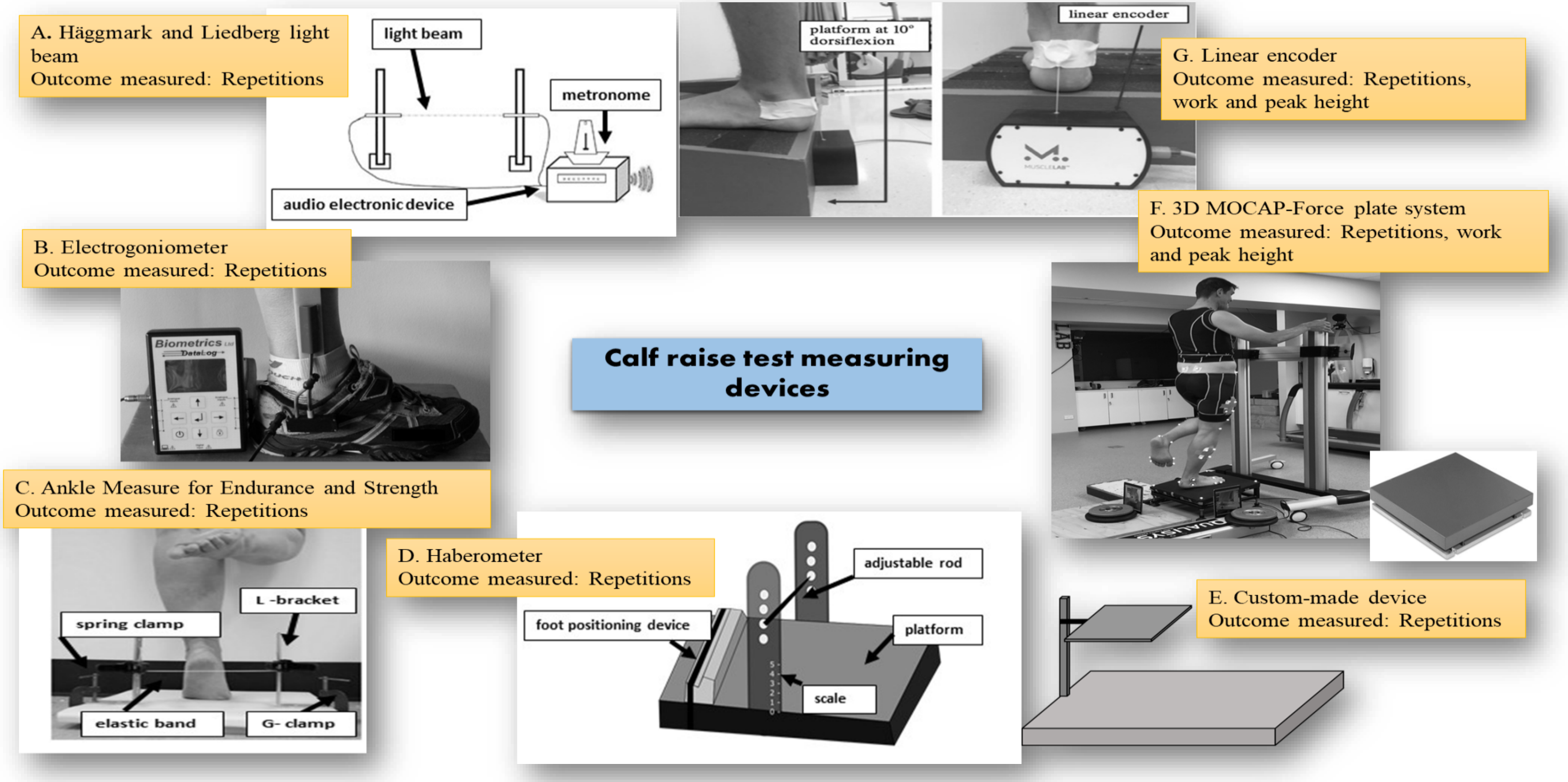

Figure 1. Calf raise test measuring devices used in the scientific literature.

(A) Häggmark et al. (1986), (B) van der Linden et al. (2018), (C) Sman et al. (2014), (D) Haber et al. (2004), (E) Sara et al. (2021), (F) Hébert-Losier and Holmberg (2013a), (G) Arch et al. (2018). Abbreviations: 3D MOCAP, three-dimensional motion capture. Photos used with copyright permission (Appendix A).

1.3 The rise of mobile health technologies

In recent years, advances in smartphone technology have led to a growing number of commercially available smartphone and tablet applications (i.e., “apps”), facilitating the collection of physiological (Sánchez Rodríguez et al., 2018) and biomechanical (Mousavi et al., 2020; Peart et al., 2019; Silva et al., 2021) variables without the need for additional equipment. Typically, smartphones and tablets contain microphones, cameras, light sensors, accelerometers, gyroscopes, inclinometers, and magnetometers as part of their hardware capabilities (Majumder & Deen, 2019). These hardware components can be combined with software applications to facilitate the measurement of various parameters. In several situations, smartphone and tablet applications have been demonstrated to be valid and reliable for assessing biomechanical variables for different tasks, including sit-to-stand (Ruiz-Cárdenas et al., 2018), standing posture (Timurtaş et al., 2022), active and passive joint ranges of motion (Nuhmani et al., 2021), and walking gait (Christensen et al., 2022). These advancements provide an opportunity for clinicians to quantify functional assessments in a more objective manner.

Indeed, with the advent of mobile applications, the integration of technology into science and clinical practice will become increasingly important for rehabilitation management in the years to come. It is believed that patients and clients will become more engaged in rehabilitation management due to moving towards a “smart” healthcare system (Merolli et al., 2021). Practitioners can evaluate clients remotely and provide real-time feedback, reducing the need to conduct costly and time-consuming laboratory assessments (Silva et al., 2015). Moreover, mobile applications are playing an increasingly important role in self-management and remote management of individuals, which is revolutionising the way practitioners measure and monitor performance (Escriche-Escuder et al., 2020; Landers & Ellis, 2020). By using this digitally enhanced approach to healthcare, individuals can engage in a more interactive and quantitative manner with their health and well-being (Dicianno et al., 2015; Merolli et al., 2021; Ventola, 2014).

Although mobile applications have the potential to offer significant benefits in healthcare, systematic reviews have reported that few of the available health-related applications have undergone a thorough validation process (de la Vega & Miró, 2014; Llorens-Vernet & Miró, 2020). This lack of validation could lead to inaccurate use of results to inform practice, affecting clinical evaluations and management plans. Furthermore, scientifically validated applications may not be publicly available, limiting large-scale clinical uptake. Hence, any new applications being made available to the public should undergo validation assessment before being promoted for use to inform practice.

1.4 Thesis aims

The inexistence of a clinically accessible CRT measuring device and incomplete understanding of the effects of variations in the CRT protocol on outcomes and triceps surae muscle function highlight the value of further exploring this topic. Therefore, the overarching aims of this Thesis were to: (1) develop a valid and reliable method to assess the CRT in clinical practice that provides research-grade outcomes, and (2) examine the influence of changing CRT parameters on key test outcomes and triceps surae muscle function to guide exercise prescription and interpretation of the CRT outcomes. To achieve these overarching aims, two literature reviews and three experimental studies were conducted. As part of this Thesis, a smartphone application called the Calf Raise (CR_{app}) was developed to assist in automating CRT outcomes and standardising testing procedures, with its reliability and validity assessed in *Chapter 2*.

The overarching aim of this Thesis was achieved through the following specific aims of each Chapter:

1. To provide an overview of the CRT devices used in the scientific literature to measure CRT outcomes, namely the number of repetitions, peak height, and total work performed. This review focused on the design, reliability, concurrent validity, and perceived strengths and limitations of the existing CRT devices for clinical use. *(Chapter 2)*
2. To validate use of the CR_{app} in healthy individuals by examining its concurrent validity and agreement levels against laboratory-based equipment and establish its intra- and inter-rater reliability. *(Chapter 3)*
3. To examine the influence of ankle starting position on single-leg CRT outcomes, namely the number of repetitions, total vertical displacement, peak height, and total work. The goal was to compare the three most common ankle starting positions used the conduct the CRT: flat (0^{o}), incline (10^{o} dorsiflexion), and step (full dorsiflexion). *(Chapter 4)*
4. To determine the effect of cadence on single-leg CRT outcomes, namely the number of repetitions, total vertical displacement, peak height, total work performed, and peak power. The goal was to compare the three cadences: 30, 60, and 120 bpm. *(Chapter 5)*
5. To investigate the potential influence of select predictors on single-leg CRT outcomes as a secondary aim; namely age, gender, BMI, and level of physical activity. *(Chapters 4 and 5)*
6. To systematically review the electromyography (EMG) literature examining how variations in standing CRT or calf raise exercise parameters influence MG, LG, and SOL muscle activity and fatigue parameters in healthy individuals. *(Chapter 6)*

The following hypotheses were tested:

1. The CR_{app} exhibits good-to-excellent validity and agreement against laboratory-based equipment and good-to-excellent intra- and inter-rater reliability. *(Chapter 3)*
2. Performing the CRT on a step leads to lesser repetitions than performed on an incline followed by from flat (i.e., floor) due to greater ranges of ankle motion. *(Chapter 4)*
3. A faster CRT cadence results in greater peak power, but lower number of repetitions, total distance, and total work than a slower CRT cadence due to faster muscle shortening velocities being more fatigable. *(Chapter 5)*
4. Participant demographics will affect CRT outcomes. Males will perform better than females, and CRT outcomes will decrease with an increase in age, an increase in BMI, and a decrease in physical activity levels. *(Chapter 4 and Chapter 5)*

1.5 Thesis framework

Although each Chapter has specific aims and hypotheses, the overall aim of the Thesis is to provide empirical support for the use of the CR_{app} and evidence-based understanding of how variations in CRT parameters influence outcomes and triceps surae muscle function to guide prescription and interpretation of the CRT. The Thesis structure is presented in Figure 2.

This Thesis provides an overview of triceps surae MTU anatomy and function, as well as the CRT *(Chapter 1)* and a review of the literature on the devices used in research to quantify CRT performance *(Chapter 2)*. The evaluation and implementation phase of this Thesis consists of three experimental studies. The first study presents the validity and reliability of the Calf Raise iOS mobile application in measuring CRT outcomes in healthy individuals *(Chapter 3)*. The two other experimental studies examine the effect of ankle starting position (*Chapter 4*) and cadence (*Chapter 5*), two vital CRT parameters, on test outcomes. These studies also consider how select predictors (age, gender, BMI, and level of physical activity) potentially influence CRT outcomes. Lastly, a systematic review that synthesises literature on how changes in calf raise parameters affect the muscle activity and fatigue of the triceps surae recorded using electromyography is presented *(Chapter 6)*. The final chapter synthesises the main findings of this Thesis, highlights its strengths and limitations, addresses clinical implications, and proposes directions for future research *(Chapter 7)*.

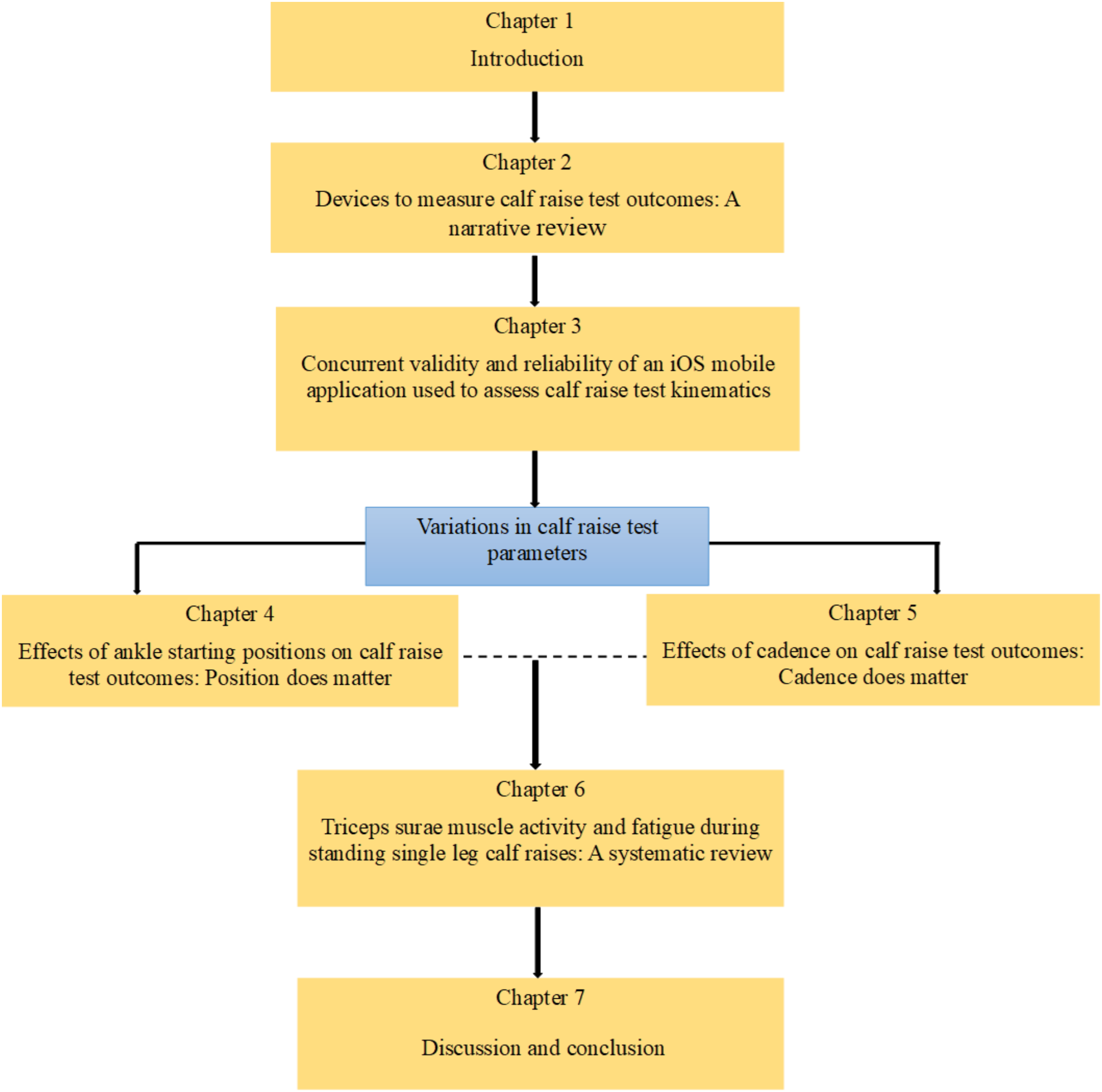

Figure 2. Thesis structure.

1.6 Thesis significance

This Thesis was designed to achieve the following significance:

1. By automating testing procedures, the CR_{app} should enable objective quantification of CRT outcomes and enhance standardisation of testing procedures in clinics and research. By having a more objective means of quantifying performance in practice, the information can be used to set specific patient or client objectives, as well as assess the effectiveness of rehabilitation programmes.
2. By having a clear understanding of how test parameters affect CRT outcomes, clinicians and researchers are better able to accurately interpret test outcomes. In addition, this understanding might be helpful as a tool for prescribing exercises and monitoring rehabilitation progress.
3. Understanding the effects of demographic characteristics, such as age, gender, BMI, and physical activity level, on CRT outcomes will assist in test interpretation. Consequently, this information can be used to inform clinical decision-making and guide individualised rehabilitation programmes.
4. This Thesis can be used as a reference in using the CR_{app} in future research studies, including replication studies, and documentation of normative values for different age groups or conditions.
5. The outlined Thesis research will contribute to the evidence-based knowledge on the CRT and CRT implementation.

Chapter 2

Devices to measure calf raise test outcomes: A narrative review

Fernandez, M. R., & Hébert-Losier, K. (2023). Devices to measure calf raise test outcomes: A narrative review. *Physiotherapy Research International : The Journal for Researchers and Clinicians in Physical Therapy*, *28*(4), e2039. https://doi.org/10.1002/pri.2039.

Prelude: A brief overview of the devices used to measure CRT outcomes is provided in the background of this Thesis. This Chapter provides a more comprehensive and systematic overview of the CRT devices used to quantify CRT outcomes, such as the number of repetitions, peak height, and total work performed. This Chapter focuses on the design, reliability, concurrent validity, and perceived strengths and limitations of these devices for clinical use.

2.1 Introduction

The unilateral CRT is a clinical tool that assesses triceps surae MTU function (K. Hébert-Losier et al., 2009). The test requires individuals to go up on their toes and back down as many times as possible standing on one leg and therefore requires repetitive concentric-eccentric actions of the ankle plantarflexors until volitional cessation. Clinicians document the total number of repetitions achieved as the primary outcome (K. Hébert-Losier et al., 2009; Lunsford & Perry, 1995; Ross & Fontenot, 2000). The CRT is therefore considered a clinical-friendly method to assess calf MTU function that requires neither specialised equipment nor much time or space, which is advantageous for field-based and in-clinic testing (André et al., 2016; Haber et al., 2004). The CRT is used across disciplines, such as paediatrics (Maurer et al., 2007), cardiology (Monteiro et al., 2013), neurology (Svantesson, Osterberg, Grimby, et al., 1998), orthopaedics (J. A. Zellers et al., 2020), and gerontology (André et al., 2018). However, according to Sman et al. (2014), using a standardised CRT device and protocol across individuals would be ideal for monitoring and replicating test outcomes. In science, researchers commonly use devices to assist in standardising the test protocol and quantify additional outcomes other than the number of repetitions completed (Cibulka et al., 2017; Pereira et al., 2010; Van Cant et al., 2017).

Indeed, aside from the number of calf raises performed, other CRT measures are considered key outcomes and indicators of function; for example, total (concentric) work and maximum calf raise height during the CRT are markers of functional recovery post Achilles tendon rupture (ATR) (Byrne et al., 2017; Silbernagel et al., 2010; J. A. Zellers et al., 2020) More specifically, the amount of work completed during the CRT has been shown to be a more sensitive metric in the presence of ATR than the number of repetitions (Silbernagel et al., 2010), where work is computed considering calf raise height and body mass displaced during repetitions. Given that work considers the positive displacement of each repetition during the CRT, this measure is deemed scientifically more rigorous and accurate than the number of repetitions to quantify calf MTU endurance (Byrne et al., 2017). In terms of peak height during the CRT, this measure expressed as a ratio of the involved to uninvolved limb (i.e., limb symmetry index) at 6-months post ATR predicted patient-reported symptoms and physical activity levels at 12-months as quantified using the Achilles tendon Total Rupture Score (Olsson et al., 2014). Furthermore, both total work and peak height during the CRT have been identified as more sensitive metrics of residual impairments than the total number of repetitions at 6- and 12-months post ATR. Specifically, repetitions identified the percentage of patients with normal function (defined as the limb symmetry index reaching 90% or higher) as 38% and 63% at 6- and 12-months, respectively. Comparatively, these figures based on the limb symmetry index were 9% and 23% when considering total work, and 6% and 22% when considering peak height (Silbernagel et al., 2010).

Hence, total work and peak height during the CRT are deemed important measures of calf MTU function (A. Nordenholm et al., 2022; J. A. Zellers et al., 2020). These CRT metrics cannot be quantified clinically without a device. However, clinicians still typically only count the number of repetitions as the primary outcome. This narrative review aimed to provide an overview of the CRT devices used in the scientific literature to measure CRT outcomes, namely the number of repetitions, peak height, and total work performed. This review focused on the design, reliability, concurrent validity, and perceived strengths and limitations of these devices for clinical use. It is anticipated that this narrative review provides practitioners a clear understanding of CRT devices potentially available to them for quantifying outcomes.

2.2 Methods

2.2.1 Search strategy

Even though a narrative review was planned, a systematic process aligning with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Page et al., 2021) was applied. A systematic electronic search was conducted on April 9^{th}, 2022, in the following databases: Cochrane, PubMed®, Scopus, Sports Medicine & Education Index, and SPORTDiscus. The search term used were "calf raise", "heel raise", "heel rise", "test$", and "eval$". The Boolean operators "OR" and "AND" were used to combine the search terms. When available, search limiters applied included peer-reviewed journal articles, English language, and human. The searches implemented for each database are provided in the supplementary materials (Appendix B). References of all studies meeting inclusion were screened to identify additional relevant studies that might have been missed.

The search results were imported into Endnote 20 (Clarivate Analytics, Boston, USA). After removing duplicates, all titles and abstracts were transferred to Rayyan (Qatar Computing Research Institute, Qatar), a free web application for systematic reviews (Ouzzani et al., 2016). In Rayyan, titles and abstracts were screened against the inclusion criteria. The inclusion criteria were scientific peer-reviewed original research of any analytical study design (i.e., observational or experimental) as defined by the Oxford Centre for Evidence-Based Medicine (i) published in English; (ii) that used the unilateral CRT (i.e., repeated concentric-eccentric plantar-flexor actions in unilateral stance to volitional cessation or performed to fatigue); and (iii) measured CRT outcomes using equipment (e.g., motion capture system, force plate, linear encoder, custom devices, or any other device). Exclusion criteria were: (i) editorials, commentaries, discussion papers, conference abstracts, and reviews; (ii) studies that did not describe their methods; and (iii) studies where unilateral CRT outcomes to volitional cessation were not assessed. All studies that met inclusion were retrieved in full text, and their eligibility criteria were assessed. A single reviewer (RF) conducted all the screening, which was verified by a second reviewer (KHL).

2.2.2 Data extraction and synthesis

Relevant information was extracted from each included paper in a custom-made Excel (Microsoft Office, Microsoft, Redmond, WA, USA) data extraction form. The following data were extracted from each study: authors, publication year, study location (based on where data were collected when stated explicitly or institutional ethics approval), study aims, participant characteristics (i.e., healthy, or pathologic population, age, gender, body mass, and height), CRT device, and CRT outcomes (i.e., number of repetitions, peak height, and work). In addition, data on the reliability of the identified CRT devices (i.e., test-retest, intra-rater, and inter-rater) and their concurrent validity (i.e., agreement of outcomes between devices) were extracted. Any stated strengths and limitations of devices were also extracted. A single reviewer (RF) extracted all data, and a second reviewer (KHL) verified the completeness of extraction.

Data are summarised using tables for the characteristics of the reviewed studies, reliability and concurrent validity properties, and perceived strengths and limitations of the CRT devices for clinical use. The reliability and concurrent validity of devices were deemed excellent, good, moderate, and poor when corresponding intraclass correlation (ICC) values were >0.90, >0.75 to 0.90, between 0.50 and 0.75, and <0.50 (Portney, 2020). Additionally, it was possible to group CRT devices under thematic headings; and therefore, devices are presented thematically using a narrative synthesis format. No risk of bias assessment was undertaken as it was not relevant to the aims of this review.

2.3 Results

2.3.1 Selection of studies and study characteristics

Figure 3 presents a flowchart of the screening and selection processes. Thirty-five articles met inclusion and were included in the narrative synthesis. The individual study characteristics are presented in Table 2.

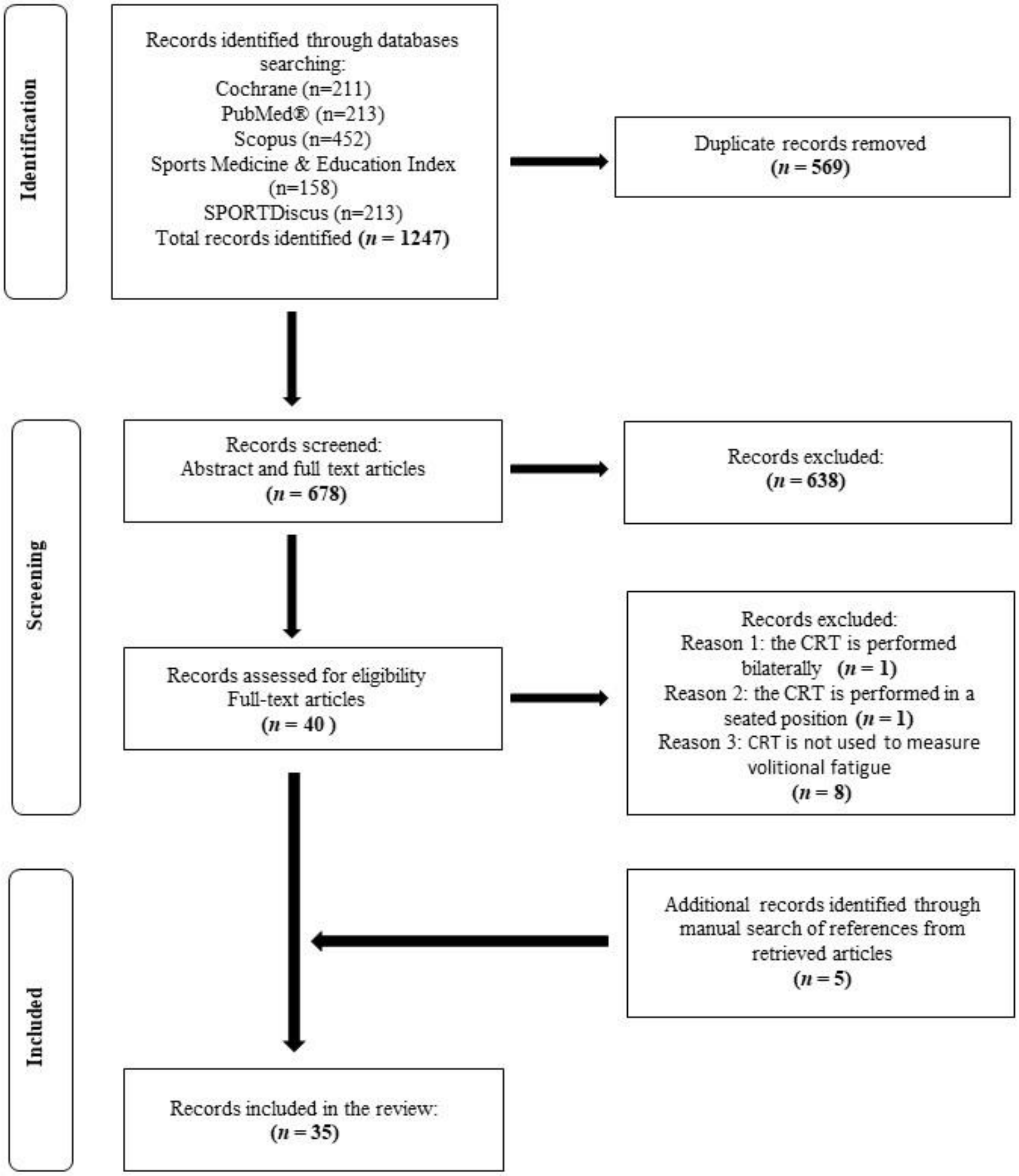

Figure 3. Flowchart of the search strategy and selection process.

Table 2. Summary of articles reviewed (*n* = 35).

Authors (year of publication) Country	Purpose	Participants	Device	CRT outcomes
Andreasen et al. (2020) Denmark	To evaluate the concurrent validity of the heel-rise work test performed with use of the heel as surrogate for centre of body mass.	**Sample**: 45 patients with ATR (36 males, 9 females) **Age:** 41 ± 9 y **Height:** NR **Mass**: NR	Linear encoder Laboratory-based equipment (3D MOCAP)	Work
Arch et al. (2018) USA	To evaluate the relationship between gait and clinical measures of plantarflexors function for individuals with no neuromuscular injuries or diseases.	**Sample**: 24 healthy (15 males, 9 females) **Age:** 43.6 ± 24.5 y **Height:** 1.74 ± 0.08 m **Mass**: 78.7 ± 11.8 kg	Linear encoders	Number of repetitions
Brorsson et al. (2021) Sweden	To evaluate the possible differences in foot structure between the injured and the healthy limb and between treatment groups six years after an ATR.	**Sample**: 90 patients with ATR *Surgery* **Sample:** 36 males, 9 females **Age:** 50 ± 9 y **Height:** NR **Mass:** NR *Non-surgery* **Sample:** 39 males, 6 females **Age:** 48 ± 9 y **Height:** NR **Mass:** NR	Linear encoder	Number of repetitions Peak height Work
Brorsson et al. (2018) Sweden	To evaluate calf muscle performance and patient reported outcomes at least 5 years after an ATR in patients included in a prospective, randomised controlled trial.	**Sample:** 66 patients with ATR (53 males, 13 females) **Age:** 50 ± 8.5 y **Height:** 178 ± 9.7 cm **Mass**: 85.9 ± 13.5 kg	Linear encoder	Number of repetitions Peak height
Brorsson et al. (2017) Sweden	To explore differences in ankle biomechanics, calf muscle recovery, tendon length, and	**Sample:** 34 patients with ATR	Linear encoder	Number of repetitions Peak height

	patient-reported outcome measurements at a mean of 6 years after ATR between two groups with less than 15% and greater than 30% differences in heel-rise height at 1-year follow-up, respectively.	*ATR <15% difference in heel-rise height* **Sample:** 15 males, 2 females **Age:** 40 ± 5 y **Height:** NR **Mass:** NR *ATR >30% difference in heel-rise height* **Sample:** 16 males, 1 female **Age:** 56 ± 9 y **Height:** NR **Mass:** NR		
Byrne et al. (2017) UK	To measure and compare the intrarater test-retest reliability and measurement agreement of the three heel rise endurance test outcome measures in healthy adult during a standardised and computerised heel rise endurance test employing a linear displacement sensor.	**Sample**: 38 healthy individuals (18 males, 20 females) **Age:** 22.7 ± 3.13 y **Height:** 1.73 ± 0.104 m **Mass**: 74.9 ± 15.1 kg	Linear encoder	Number of repetitions Peak height Work
DeWolf et al. (2018) USA	To objectively compare musculoskeletal attributes of pre pointe and recently en pointe ballet dancers to identify differences between those cohorts and secondarily to investigate ant relationships between the resulting quantitative measures and a qualitative pointe success appraisal completed by each dancer's experienced ballet teacher.	**Sample**: 49 healthy females *Pre-pointe* **Sample:** 28 females **Age:** 10.21 ± 1.17 y **Height:** 124.05 ± 13.45 cm **Mass:** 39.13 ± 13.18 kg *Pointe* **Sample:** 21 females **Age:** 11.42 ± 0.81 y **Height:** 136.91 ± 16.04 cm **Mass:** 40.79 ± 8.77 kg	AMES	Number of repetitions

Haber et al. (2004) Canada	To assess the reliability of a protocol using an apparatus specifically designed to standardise the standing heel rise test for triceps surae muscle fatigability on a healthy group of subjects without a current injury.	*Short term test-retest group* (30 minutes) and *Intermediate term group* (48 hours) **Sample:** 40 healthy individuals (19 males, 21 females) **Age:** 24 y (range 17-63) **Height:** NR **Mass**: NR *Long term test-retest group* (7 days) **Sample:** 38 patients with deep vein thrombosis (21 males, 16 females); unaffected side tested **Age:** 51 y (range 25-76) **Height:** NR **Mass**: NR	Haberometer	Number of repetitions
Häggmark et al. (1986) Sweden	To compare the muscle function in a group of patients with ATR treated with surgery versus a group of patients treated non-operatively with a follow up time of three to five years.	*Surgical ATR group* (10 males, 5 females) **Age:** 35. 5 y (range 23-59) **Height:** NR **Mass**: NR *Non- surgical ATR group* (6 males, 2 females) **Age:** 34. 9 y (range 25-55) **Height:** NR **Mass**: NR	Häggmark and Liedberg light beam electronic device	Work
Hamrin et al. (2020) Sweden	To determine patient-related and treatment related predictors of superior and inferior function in sport and recreational activities 1 year after an ATR.	**Sample**: 285 patients with ATR (238 males, 47 females) **Age:** 40.0 ± 8.4 y **Height:** 178.4 ± 8.3 cm **Mass**: 83.3 ± 13.1 kg	Linear encoder	Number of repetitions Peak height Work
Hébert-Losier et al. (2012b) New Zealand	To investigate with surface EMG the influence of knee flexion angles on the soleus, medial gastrocnemius, and	**Sample:** 48 healthy individuals *Younger males* **Sample:** 12 males	Laboratory-based equipment (3D MOCAP)	Number of repetitions Peak height Work

	lateral gastrocnemius fatigue during the maximal numbers of unilateral heel raises.	**Age:** 22.4 ± 1.8 y **Height:** 177.4 ± 5.6 cm **Mass**: 71.7 ± 10.2 kg *Younger females* **Sample:** 12 females **Age:** 22.7 ± 2.0 y **Height:** 165.1 ± 4.2 cm **Mass:** 61.1 ± 10.7 kg *Middle aged males* **Sample:** 12 males **Age**: 41.1 ± 3.1 y **Height:** 177.7 ± 5.6 cm **Mass:** 81.7 ± 14.9 kg *Middle aged females* **Sample:** 12 females **Age:** 41.5 ± 3.4 y **Height**: 166.5 ± 8.1 cm **Mass:** 66.6 ± 10.3 kg		
Hébert-Losier et al. (2011) New Zealand	To provide an estimate of the ability of a healthy population to maintain 0° and a 30° knee flexion angle during knee extension heel raise test and knee flexion heel raise test, by investigating the average knee angle maintained and the absolute angular error in knee flexion position during the two versions.	**Sample**: 17 healthy individuals (9 males, 8 females) **Age:** 25.6 ± 4.6 y **Height:** 172.4 ± 9.3 cm **Mass**: 71.1 ± 10.0 kg	Laboratory-based equipment (3D MOCAP)	Number of repetitions Peak height
Hébert-Losier and Holmberg (2013a) Sweden	To characterise and compare the biomechanics and clinical outcomes of the single legged heel raise test performed on an incline with the knee straight and	**Sample**: 48 healthy individuals *Males* **Sample:** 28 males **Age:** 38 ± 12 y	Laboratory-based equipment (3D MOCAP and force plate)	Number of repetitions Peak height

	bent while considering age and sex as cofounders.	**Height:** 169 ± 7 cm **Mass**: 82 ± 9 kg *Females* **Sample:** 20 females **Age:** 41 ± 11 y **Height:** 169 ± 8 cm **Mass**: 69 ± 9 kg		
Jan et al. (2005) Taiwan	To investigate the number of repetitions of the one-leg heel-rise test required for normal plantar-flexor strength in different groups of subjects categorized by age and sex.	**Sample:** 180 healthy individuals *Males 21-40 y* **Sample**: 30 males **Age**: 29.0 ± 4.8 y **Height**: 169.7 ± 6.1 cm **Mass**: 69.7 ± 8.0 kg *Males 41-60 y* **Sample**: 30 males **Age**: 50.2 ± 4.9 y **Height**: 167.2 ± 5.4 cm **Mass**: 67.0 ± 8.0 kg *Males 61-80* **Sample**: 30 males **Age**: 69.0 ± 4.0 y **Height**: 166.3 ± 5.4 cm **Mass**: 66.5 ± 6.5 kg *Females 21-40 y* **Sample**: 30 females **Age**: 30.3 ± 4.9 y **Height**: 160.5 ± 3.9 cm **Mass**: 52.4 ± 5.5 kg *Females 41-60 y* **Sample**: 30 females	Electrogoniometer	Number of repetitions

		Age: 49.9 ± 1.0 y **Height**: 157.0 ± 6.0 cm **Mass**: 57.9 ± 9.2 kg *Females 61-80* **Sample**: 30 females **Age**: 69.1 ± 4.1 y **Height**: 154.9 ± 5.2 cm **Mass**: 58.8 ± 5.5 kg		
Lunsford and Perry (1995) USA	To further refine the standing heel-rise test by assessing the number of heel-rises that can be accomplished by both male and female.	**Sample**: 203 healthy individuals (122 males, 81 females) *Males* **Sample:** 122 males **Age:** 34.7 ± 8.5 y **Height:** 178.9 ± 7.9 cm **Mass**: 79.7 ± 11.5 kg *Females* **Sample:** 81 females **Age:** 29.3 ± 5 y **Height:** 164.8 ± 6 cm **Mass:** 60 ± 8.6 kg	Electrogoniometer	Number of repetitions
Möller et al. (2005) Canada	To evaluate the test-retest intra tester reliability of isokinetic measurements in three different positions for ankle plantarflexion and dorsi flexion torque production and to evaluate calf muscle endurance with a standardised heel raise test.	**Sample**: 10 healthy males **Age:** 37 y, range: 31-43 **Height:** 184 cm, range: 172-195 **Mass**: 88 kg, range: 75-98	Häggmark and Liedberg light beam electronic device (modified)	Number of repetitions
Nawoczenski et al. (2016) USA	To investigate muscle performance (ankle plantarflexion power and endurance) during functional tasks and patient-reported outcomes following an isolated	**Sample:** 24 participants *Gastrocnemius recession group* 8 males, 6 females **Age:** 52.8 ± 7.9 y **Height:** 1.7 ± 0.7 m	Laboratory-based equipment (3D MOCAP and force plate)	Work

	gastrocnemius recession for individuals with recalcitrant Achilles tendinopathy and an isolated gastrocnemius contracture.	**Mass**: 92.3 ± 15.5 kg *Control group* **Sample**: 5 males, 5 females **Age:** 53.3 ± 3.3 y **Height:** 1.7 ± 1.0 m **Mass**: 84.0 ± 16.1 kg		
A. Nordenholm et al. (2022) Sweden	To evaluate the one-year postoperative outcomes in patients with chronic ATR using a comprehensive battery including several validated tests.	**Sample**: 22 patients with ATR (14 males, 8 females) **Age:** 61 ± 15 y **Height:** 173 ± 9 cm **Mass**: 85 ± 15 kg	Linear encoder	Number of repetitions Peak height Work
Olsson et al. (2014) Sweden	To investigate predictors of both symptomatic and functional outcomes for both symptoms and function after ATR.	**Sample**: 93 patients with ATR (79 males, 14 females) **Age:** 39.7 ± 9.3 y **Height:** 179 ± 8 cm **Mass**: 84 ± 12 kg	Linear encoder	Peak height
Österberg et al. (1998) Sweden	To measure the torque influencing the ankle joint during a standing heel rise test from force plate to calculate work during the test.	**Sample**: 10 healthy males **Age:** 25 ± 3 y **Height:** 179 ± 3 cm **Mass**: 76 ± 7 kg	Laboratory-based equipment (force plate) Electrogoniometer	Number of repetitions Work
Pereira et al. (2010) Brazil	To investigate the amplitude and sub-100 Hz frequency content of surface EMG signals obtained from several muscles during the lowering and raising phases of a heel-raise task performed until failure.	**Sample**: 22 healthy individuals (14 males, 8 females) **Age:** 21 ± 1 y **Height:** 171 ± 2 cm **Mass**: 65 ± 2 kg	Haberometer	Number of repetitions
Sara et al. (2021) USA	To determine (1) associations between standing heel rise test repetitions and measures of maximal plantarflexionplantarflexion strength, assessed as baseline maximal voluntary isometric	**Sample**: 28 healthy individuals *14 males* **Age:** 21.5 ± 8 y **Height**: 1.81 ± 0.08 m **Mass:** 79.4 ± 10.3 kg	Custom-made device	Number of repetitions

	contraction, (2) associations between standing heel rise test repetitions and the reduction in maximum voluntary isometric contraction following the standing heel rise test, and (3) whether sex differences exist in performance of the standing heel rise test.	*14 females* **Age:** 21.1 ± 9 y **Height**: 1.66 ± 0.07 cm **Mass:** 64.0 ± 10.8 kg		
Silbernagel et al. (2006) USA	To evaluate if Achilles tendinopathy caused functional deficits on the injured side compared with the non-injured side in patients.	**Sample**: 42 patients with Achilles tendinopathy (23 males, 19 females) **Age:** 26 ± 8 y **Height:** 178 ± 8 cm **Mass**: 74.9 ± 15.1 kg	Linear encoder	Number of repetitions Work
Silbernagel et al. (2010) USA	To examine this heel-rise test (that evaluates the height of each heel-rise along the number of repetitions) to evaluate its validity and ability to detect differences in outcome and to compare this test to the test that will be only measures of ankle range of motion and patient-reported outcome.	**Sample**: 78 patients with ATR (65 males, 13 females) **Age:** 42 ± 9 y **Height**: 178 ± 9 cm **Mass:** 85 ± 13 kg	Linear encoder	Number of repetitions Peak height Work
Silbernagel et al. (2012) USA	To evaluate if differences in heel rise height are associated with differences in Achilles tendon length after an ATR.	**Sample**: 18 participants *Controls* 7 males, 3 females **Age:** 28 ± 8 y **Height:** 177 ± 13 cm **Mass**: 73 ± 16 kg *Acute complete ATR* 5 males3 females **Age:** 46 ± 13 y **Height:** 176 ± 7.7 cm	Linear encoder	Number of repetitions Peak height

		Mass: 83 ± 13 kg		
Silbernagel et al. (2015) USA	To evaluate whether there are any differences in outcome between men and women after an acute ATR.	**Sample:** 182 patients with ATR *Surgical* **Sample:** 76 males, 18 females **Age:** 40 ± 10 y **Height:** NR **Mass:** NR *Nonsurgical* **Sample:** 76 males, 12 females **Age:** 39 ± 14 y **Height:** NR **Mass:** NR	Linear encoder	Peak height Work
Sman et al. (2014) Australia	To document the construction and reliability of the AMES device.	**Sample**: 40 healthy individuals (21 males,19 females) **Age:** 24 ± 6.2 y **Height:** 174 ± 12.3 cm **Mass**: 68 ± 9.3 kg	AMES	Number of repetitions
Österberg et al. (1998) Sweden	To investigate the fatigue process of the gastrocnemius and soleus muscles separately in a standard heel rise test.	**Sample**: 10 healthy women. **Age:** 24 ± 3 y **Height:** 167 ± 4 cm **Mass**: 67 ± 8 kg	Electrogoniometer	Number of repetitions Work
Svantesson, Osterberg, Grimby, et al. (1998) Sweden	To investigate the fatigue process in the triceps surae during the heel-rise test (eccentric and concentric phases) in comparison with a walking test and muscle strength.	**Sample:** 16 males *Hemiparesis* **Sample:** 8 males **Age:** 57 ± 4 y **Height:** NR **Mass**: 82 ± 10 kg *Reference (Healthy)* **Sample:** 8 males **Age:** 59 ± 3 y **Height:** NR **Mass**: 82 ± 14 kg	Electrogoniometer	Number of repetitions Work

Svensson et al. (2019) Denmark	To examine muscle function, muscle architecture, and tendon length in persons who reported that they experience a functional deficit more than 2 years after an ATR.	**Sample**: 12 patients with ATR (8 males, 3 females) **Age:** 51 ± 12 y **Height:** 178 ± 10 cm **Mass**: 90 ± 19 kg	Linear encoder	Number of repetitions Peak height Work
Tengman et al. (2015) Sweden	To evaluate muscle fatigue and determine whether fatigue could be detected with a limited number of heel rises after total ATR.	**Sample**: 52 patients with ATR (46 males,6 females) **Age:** 47.8 ± 10.2 y **Height:** NR **Mass**: NR	Laboratory-based equipment (3D MOCAP and force plate)	Number of repetitions Peak height Work
Van Cant et al. (2017) Belgium	To evaluate hip abductor, trunk extensor, and ankle plantarflexors endurance in females and without patellofemoral pain, using clinical tests.	**Sample:** 96 females *Patellofemoral pain* 20 females **Age:** 21.1 ± 2.6 y **Height:** 162.1 ± 5.8 cm **Mass**: 55.9 ± 7.4 kg *Controls* 76 females **Age:** 20.5 ± 2.8 y **Height:** 165.5 ± 5.8 cm **Mass**: 58.3 ± 7.4 kg	AMES	Number of repetitions
Westin et al. (2018) Sweden	To perform a long-term follow-up of patients with an Achilles tendon re-rupture using established outcome measurements for tendon structure, lower extremity function and symptoms, and to compare the results with those for the uninjured side.	**Sample**: 391 patients with ATR (326 males, 65 females) **Age:** 40.4 ± 8.7 y **Height:** 178.5 ± 8.6 cm **Mass**: 83.7 ± 13.1 kg	Linear encoder	Number of repetitions Peak height Work
Zellers et al. (2017) USA	To describe the Achilles tendon structure and plantarflexors function of classical ballet dancers compared to non-	**Sample**: 20 healthy individuals *Non-dancers* 2 males, 8 females	Linear encoder	Number of repetitions Peak height Work

	dancers using established, clinical Achilles tendon examination methods.	**Age:** Range: 16 to 35 y **Height:** NR **Mass**: NR *Ballet dancers* 2 males, 8 females **Age:** Range 16 to 35 y **Height:** NR **Mass**: NR		
Zellers et al. (2018) USA	To determine the strength of the relationship of the Achilles tendon resting angle in both knee extended and knee flexed positions with tendon length measured using ultrasound as a validation study; and to identify the relationship between the Achilles tendon resting angle with tendon material properties and patient functional performance to better understand its clinical utility.	**Sample**: 42 patients with ATR (34 males, 8 females) **Age:** 45.9 ± 16.2 y **Height:** NR **Mass**: NR	Linear encoder	Work
J. A. Zellers et al. (2020) USA	To investigate the relationship between early tendon morphology and mechanical properties to long-term function on heel-rise and jumping tests in individuals after ATR.	**Sample**: 22 patients with ATR (17 males, 5 females) **Age:** 40 ± 11 y **Height:** NR **Mass**: NR	Linear encoder	Peak height Work

Note: 3D MOCAP, three-dimensional motion capture; AMES, Ankle Measure for Endurance and Strength; ATR, Achilles tendon rupture; EMG, electromyography; NR, not reported.

2.3.2 Calf raise test measuring devices

It was possible to thematically group CRT devices into seven categories: Häggmark and Liedberg's light beam electronic device; electrogoniometer; laboratory-based devices – three-dimensional (3D) motion capture and force plate (used separately or together); Haberometer, linear encoder; Ankle Measure for Endurance and Strength (AMES); and a custom-made device. The timeline of first use of these devices in the scientific literature are presented in Figure 4. Furthermore, the reliability and concurrent validity of the CRT devices are summarised in Table 3, and their perceived strengths and limitations from a clinical perspective are outlined in Table 4.

Of all the measuring devices, the linear encoder was used most frequently in studies (*n* = 18, 51.4%) (Andreasen et al., 2020; Arch et al., 2018; Brorsson et al., 2021; Brorsson et al., 2018; Brorsson et al., 2017; Byrne et al., 2017; Hamrin et al., 2020; A. Nordenholm et al., 2022; Olsson et al., 2014; Silbernagel et al., 2015; Silbernagel et al., 2006; Silbernagel et al., 2010; Silbernagel et al., 2012; Svensson et al., 2019; Westin et al., 2018; Zellers et al., 2018; J. A. Zellers et al., 2020; Zellers et al., 2017), followed by 3D motion capture with (*n* = 4, 11.4%) (Hébert-Losier et al., 2011; Hébert-Losier & Holmberg, 2013a ; Nawoczenski et al., 2016; Tengman et al., 2015) or without (*n* = 2, 5.7%) (Hébert-Losier et al., 2011; Hébert-Losier et al., 2012b) force plate. Four studies (11.4%) used the electrogoniometer alone (Jan et al., 2005; Lunsford & Perry, 1995; Österberg et al., 1998; Svantesson, Osterberg, Grimby, et al., 1998) three studies (8.5%), used the AMES (DeWolf et al., 2018; Sman et al., 2014 ; Van Cant et al., 2017), and two studies (5.7% each) used the Häggmark and Liedberg light beam electronic device (Häggmark et al., 1986; Möller et al., 2005) and Haberometer (Haber et al., 2004; Pereira et al., 2010). Finally, one study (2.9% each) used the force plate with an electrogoniometer (Österberg et al., 1998), 3D motion capture with a linear encoder (Andreasen et al., 2020), and a custom made CRT device (Sara et al., 2021), as reported in Table 2. These devices were used most often in studies to examine Achilles tendon pathologies (*n* = 18, 50%) (Andreasen et al., 2020; Brorsson et al., 2021; Brorsson et al., 2018; Brorsson et al., 2017; Häggmark et al., 1986; Hamrin et al., 2020; Nawoczenski et al., 2016; A. Nordenholm et al., 2022; Olsson et al., 2014; Silbernagel et al., 2015; Silbernagel et al., 2006; Silbernagel et al., 2010; Silbernagel et al., 2012; Svensson et al., 2019; Tengman et al., 2015; Westin et al., 2018; Zellers et al., 2018; J. A. Zellers et al., 2020) and healthy populations (*n* = 17, 47.2%) (Arch et al., 2018; Byrne et al., 2017; DeWolf et al., 2018; Haber et al., 2004; Hébert-Losier et al., 2011; Hébert-Losier & Holmberg, 2013b; Hébert-Losier et al., 2012b; Jan et al., 2005; Lunsford & Perry, 1995; Möller et al., 2005; Österberg et al., 1998; Pereira et al., 2010; Sara et al., 2021; Sman et al., 2014; Svantesson, Osterberg, Grimby, et al., 1998; Svantesson, Osterberg, Thomeé, et al., 1998; Zellers et al., 2017), but in one study each (2.9%) for specific musculoskeletal [patellofemoral pain (Van Cant et al., 2017)] or medical [stroke (Svantesson, Osterberg, Grimby, et al., 1998) and deep vein thrombosis (Haber et al., 2004)] conditions.

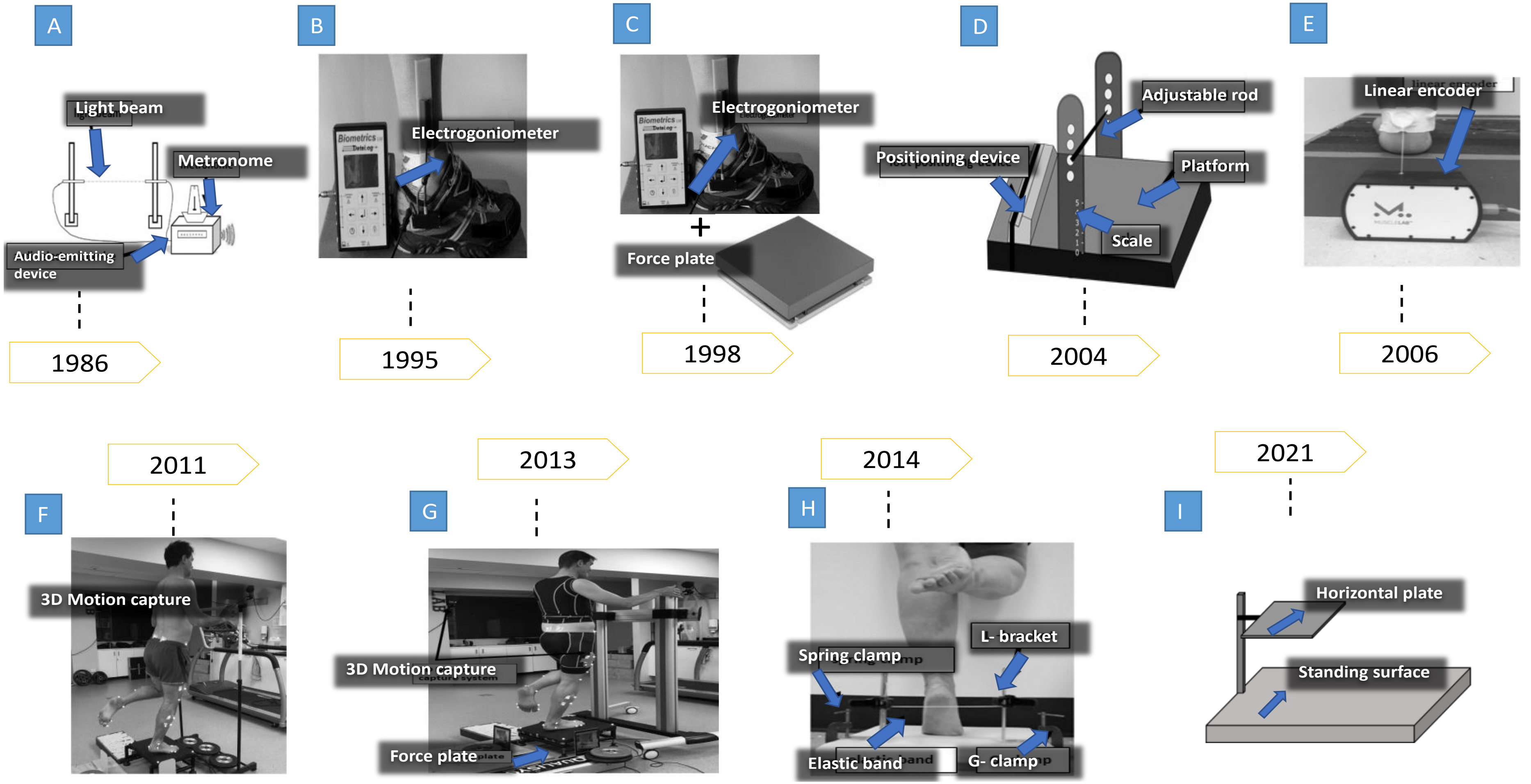

Figure 4. Timeline of when various calf raise test devices were first used in the scientific literature.
(A) Häggmark and Liedberg light beam electronic device Häggmark et al. (1986), (B) Electrogoniometer van der Linden et al. (2018), (C) Electrogoniometer and force plate Österberg et al. (1998), (D) Haberometer Haber et al. (2004), (E) Linear encoder Arch et al. (2018), (F) 3D motion capture system Hébert-Losier et al. (2011), (G) 3D motion capture and force plate Hébert-Losier and Holmberg (2013a), (H) Ankle Measure for Endurance and Strength Sman et al. (2014), (I) Custom-made CRT device Sara et al. (2021).

Table 3. Summary of reported reliability or concurrent validity of calf raise test devices.

Authors (year of publication) CRT devices	Participants	Reliability or concurrent validity of outcomes	Interpretation*
Andreasen et al. (2020) Linear encoder 3D MOCAP	Patients with acute Achilles tendon rupture (*n* = 45, 36 males and 9 females)	**Total work measurement error (%)** *Linear encoder heel vs MOCAP heel* Injured side = 1.5 % (p = 0.163) Non-injured side = 2.9 % (p < 0.0001) *Linear encoder heel vs MOCAP pelvis* Injured side = 21% (p < 0.0001) Non-injured side = 24.7% (p < 0.0001) **Total work concurrent validity (linear regression slope [95%CI])** *Linear encoder heel vs MOCAP heel* Injured side = 0.95 [0.91, 1.00] Non-injured side = 1.00 [0.98, 1.03] *Lienar encoder heel vs MOCAP pelvis* Injured side = 0.79 [0.70, 0.87] Non-injured side = 0.92 [0.86, 0.97] **Limb symmetry index (linear regression slope [95% CI])** *Linear encoder heel vs MOCAP heel* 0.98 [0.92; 1.02] *Linear encoder heel vs MOCAP pelvis* 1.03 [0.90, 1.09]	The CRT performed using the heel as a surrogate for centre of body mass overestimates the total work by 21.0–24.7% versus the gold standard (MOCAP pelvis) but can precisely detect the relative difference between limbs. Using the heel is considered valid for assessing relative differences between limbs.
Byrne et al. (2017) Linear encoder	Healthy individuals (*n* = 38, 18 males, 20 females)	**Test-retest reliability (average 9 days)** *Number of repetitions (n)* ICC = 0.77 SEM = 6.7 CV = 13.9% -	**Based on the ICC estimates** Linear encoder has “good” test-retest reliability for measuring number of repetitions, work, and peak height when tested in healthy individuals.

		Work (J) ICC = 0.84 SEM = 419 CV = 13.1% *Peak height (cm)* ICC = 0.85 SEM = 0.8 CV = 6.6%	
Haber et al. (2004) Haberometer	Healthy individuals (*n* = 40, 19 males, 21 females) Patients with deep vein thrombosis (*n* = 38, 21 males, 16 females)	**Short term test-retest reliability (30 minutes)** *Number of repetitions (n)* $ICC_{2,1}$ = 0.85 SEM = 2.3 CV = 9% **Intermediate term test-retest reliability (48 hours)** *Number of repetitions (n)* $ICC_{2,1}$ = 0.79 SEM = 3.1 CV = 9% **Long term test-retest reliability (7 days)** *Number of repetitions (n)* $ICC_{2,1}$ = 0.88 SEM = 3.4 CV = 15%	**Based on the ICC estimates** Haberometer has “good” short, intermediate, and long-term test-retest reliability for measuring the number of repetitions when tested in healthy individuals and uninjured side of patients with deep vein thrombosis.
Möller et al. (2005) Häggmark and Liedberg light beam electronic device (modified)	Healthy individuals (*n* = 10 males)	**Test-retest reliability (5 to 7 days)** *Number of repetitions (n) right side* Difference in mean (right) = 1.2 Limits of agreement = -15.3, 17.7 ICC = 0.84	**Based on the ICC estimates** Häggmark and Liedberg light beam electronic device (modified) has “good” test-retest reliability for measuring number of repetitions when tested in healthy individuals.

		CV = 19.1% *Number of repetitions (n) left side* Difference in mean (left) = 1.7 Limits of agreement = -8.9, 12.3 ICC = 0.78 CV = 13.5%	
Sman et al. (2014) Ankle Measure for Endurance and Strength	Healthy individuals (*n* = 40, 21 males, 19 females)	**Inter-rater reliability** *Number of repetitions (n)* $ICC_{2,1}$ = 0.97 SEM = 10.4	**Based on the ICC estimates** AMES has "excellent" inter-rater reliability for measuring number of repetitions when the CRT is assessed simultaneously by two examiners when tested in healthy individuals.

Note: 3D MOCAP, three-dimensional motion capture; AMES, Ankle Measure for Endurance and Strength; CI, confidence interval; CRT, calf raise test; CV, coefficient of variation; ICC, intraclass correlation; SEM, standard error of the mean.; *Reliability and concurrent validity "excellent", "good", "moderate", and "poor" when corresponding ICC was >0.90, >0.75 to 0.90, between 0.50 and 0.75, and <0.50 (Portney, 2020).

Table 4. Perceived strengths and limitations of the various calf raise test devices for use in clinical practice.

Devices	Strengths	Limitations	Outcomes measured	Clinical friendliness*
Häggmark and Liedberg light beam electronic device	Simple Portable Good test-retest reliability (healthy) Used in ATR and healthy	Requires electricity Set height of 5 cm Used to record repetitions only Not commercially available	Repetitions	2
Electrogoniometer	Simple Portable Used in stroke and healthy	Requires electricity Requires specific hardware and software	Repetitions Work	2
Haberometer	Simple Portable Good test-retest reliability (healthy) Used in DVT and healthy	Requires electricity Set height of 5 cm Rod over foot may affect balance Used to record repetitions only Not commercially available, but it can be setup	Repetitions	1
Linear encoder	Relatively simple Relatively portable Measures three CRT outcomes Good test-retest reliability Most frequently used Valid versus 3D MOCAP Used in ATR, AT, and healthy	Medium cost Requires electricity Requires specific hardware and software Requires programming	Repetitions Peak height Work	2
Laboratory-based equipment (3D MOCAP and force plate)	Measures three CRT outcomes Gold standard for measuring biomechanical variables related to the CRT High accuracy Used in ATR and healthy Can be used to record other biomechanical measure	High cost Requires electricity Requires specific hardware and software Requires programming Requires user expertise Time consuming to set-up	Repetitions Peak height Work	3
Ankle Measure for Endurance and Strength	Simple Portable Low-cost Adjustable height Excellent inter-rater reliability (healthy) Used in PFP and healthy	Used to record repetitions only Not commercially available, but it can be setup	Repetitions	1
Custom-made CRT	Simple Portable Low-cost Adjustable height Used in healthy	Used to record repetitions only Not commercially available No studies on reliability and validity findings	Repetitions	2

Note: *Rank-ordered from most (1) to least (3) clinical-friendly. *Abbreviations:* 3D MOCAP, three-dimensional motion capture; ATR, Achilles tendon rupture; CRT, calf raise test; DVT, deep vein thrombosis; PFP, patellofemoral pain. Clinical friendliness score is based on ease of use of the device, cost-effectiveness, and accessibility.

2.3.2.1 Häggmark and Liedberg's light beam electronic device

In 1986, Häggmark and Liedberg reported using a light beam electronic device for measuring fatigue resistance in the calf muscles in ATR individuals (Häggmark et al., 1986). Specifically, they constructed a device with a light beam attached to vertical rods at a fixed height of 5 cm (Figure 4). Participants needed to lift their heels over the light beam to the sound of a metronome that controlled and monitored pace. When the 5 cm heel target was reached, the device emitted an audible signal to assist the researchers track the number of repetitions. Möller et al. (2005) developed a modified version of this device and tested it in healthy individuals, adding a foot block to prevent the foot from sliding during testing and to enhance participant safety (Möller et al., 2005). The test-retest reliability of the main outcome (i.e., number of repetitions) was good when performed a week later in healthy individual (Möller et al., 2005) (Table 3). One limitation of this device is that it requires electricity to function, which makes using the device in remote areas or in field settings challenging (Möller et al., 2005; Sman et al., 2014). Furthermore, this device is not available for purchase, and only monitors the number of repetitions.

2.3.2.2 Electrogoniometer

Researchers and clinics use electrogoniometers to measure joint movement (Bronner et al., 2010; Shamsi et al., 2019). A sensor is positioned over the joint centre of rotation. In comparison to motion analysis, the electrogoniometer has a high level of reliability and validity (Bronner et al., 2010).

The electrogoniometer was first used by Lunsford and Perry (1995) during the CRT in healthy individuals to determine criterion for normal CRT performance. The recorded plantar-flexion ankle measurements were used to quantify the number of repetitions, as well as to determine when the test should end based on the ankle plantar-flexion range of motion decreasing by more than 50% from the initial range (Lunsford & Perry, 1995). Jan et al. (2005) used the device in a similar fashion, also to establish normative values for different ages and genders.

Studies in 1998 used electrogoniometers during the CRT in healthy individuals (Österberg et al., 1998; Svantesson, Osterberg, Grimby, et al., 1998) and stroke patients (Svantesson, Osterberg, Grimby, et al., 1998). These studies used an electrogoniometer to determine the concentric and eccentric parts of the calf raise motion and inform electromyographic analysis. Furthermore, total (concentric) work was calculated using the mass of individuals, gravitational acceleration constant, length of the foot between the axis of rotation of the ankle and metatarsophalangeal joints, and angular velocity (Österberg et al., 1998; Svantesson, Osterberg, Grimby, et al., 1998).

The main advantage of electrogoniometers over standard goniometers is their increased precision of joint angle measurements (Bronner et al., 2010). Furthermore, the voltage signals recorded during dynamic motion can be immediately transferred to a computer (Österberg et al., 1998) or data logger (Bronner et al., 2010) and provide joint displacement data in real-time to inform CRT termination (e.g., 50% of ankle plantar-flexion range of motion). Although it is more expensive than a standard goniometer, electrogonimoters are still a low-cost alternative to 3D motion capture systems. To apply this device to the CRT, however, requires a certain amount of programming to compute work, as well as the recording of foot length for work computation.

2.3.2.3 Laboratory-based devices: Three-dimensional motion capture and force plate

Three-dimensional (3D) motion capture systems (Jakob et al., 2021) and force plates (Peterson Silveira et al., 2017) are considered the gold standards for collecting biomechanical data in laboratory settings (Figure 4). Österberg et al. (1998) were the first to use a force plate during the CRT alongside an electrogoniometer to quantify torque and work during the test in healthy individuals, while Hébert-Losier et al. were the first to use 3D motion capture in isolation (Hébert-Losier et al., 2011) and together with a force plate (Hébert-Losier & Holmberg, 2013a) to quantify CRT outcomes in healthy individuals. The main advantages of these devices are their high accuracy in quantifying biomechanical measures and ability to calculate other metrics than those traditionally reported for the CRT, such as joint angles and torques. Force plates also provide an actual force measure, which can be used to calculate work as a product of (actual) force and displacement rather than a (fixed) force based on the mass of individuals and gravitational acceleration constant. Although motion capture systems and force plates are common in research and have been used to assess CRT outcomes in healthy individuals (Hébert-Losier et al., 2011; Hébert-Losier & Holmberg, 2013a) as well in patients with ATR (Andreasen et al., 2020; Nawoczenski et al., 2016; Tengman et al., 2015), these devices have limited application in day-to-day clinical practice because of their high costs, limited availability, and time-consuming setup requirements (Schurr et al., 2017).

2.3.2.4 Haberometer

To aid in CRT standardisation, Haber et al. (2004) developed the Haberometer (Figure 4), a simple portable device that measures the number of repetitions. The Haberometer is similar to the Häggmark and Liedberg light beam electronic device but does not rely on electric components. The Haberometer consists of two vertical rods that set the height of calf raise repetitions to 5 cm and a horizontal block that prevents the foot from sliding forward, which are all attached to a base platform (Haber et al., 2004). The device was used in both healthy individuals (Haber et al., 2004; Pereira et al., 2010) and those with deep vein thrombosis (Pereira et al., 2010).

The Haberometer demonstrated good short, medium, and long-term test-retest reliability for quantifying the number of repetitions based on ICC measures (Table 3). Haber et al. (2004) recommended the device for clinics and research because of its simplicity and its reliable outcomes. However, one of the perceived drawback of the device is the rod placement over the foot, which may compromise safety if a loss of balance occurs during testing (Haber et al., 2004). Furthermore, this device is not available for purchase and only monitors the number of repetitions.

2.3.2.5 Linear encoder

Silbernagel et al. (2006) were the first researchers to introduce the use of a linear encoder for measuring CRT outcomes, which was in ATR patients. The linear encoder (Figure 4) contains a spring-loaded displacement sensor which is attached to the heel and tracks vertical displacement over time. The linear displacement data can be used to calculate work and velocity. Typically, the linear encoder is used to measure the three main CRT outcomes: number of repetitions, peak height, and total work (Byrne et al., 2017; Silbernagel et al., 2010). These linear encoder-derived outcomes have shown good test-retest reliability (Byrne et al., 2017) (Table 3). Furthermore, outcomes from the linear encoder are the only ones which have been validated against 3D motion capture, with the work from the linear encoder almost perfectly correlated to the work from a 3D marker placed on the heel (Andreasen et al., 2020). Since linear encoders can provide the three main outcomes of repetitions, peak height, and work; these devices have been used the most in research to monitor CRT outcomes in healthy individuals (Arch et al., 2018; Byrne et al., 2017; Zellers et al., 2017) and patients with Achilles tendon pathologies (Andreasen et al., 2020; Brorsson et al., 2016; Brorsson et al., 2021; Brorsson et al., 2018; Brorsson et al., 2017; Hamrin et al., 2020; A. Nordenholm et al., 2022; Olsson et al., 2014; Silbernagel et al., 2015; Silbernagel et al., 2006; Silbernagel et al., 2010; Silbernagel et al., 2012; Svensson et al., 2019; Westin et al., 2018; Zellers et al., 2018; J. A. Zellers et al., 2020).

Although CRT outcomes derived from linear encoders provide meaningful information on ankle plantarflexion function that can assist in assessment and management of individuals (Byrne et al., 2017), the associated cost with purchasing linear encoder hardware and software prohibits their clinical use. Nonetheless, linear encoders are more affordable than 3D motion capture or force plate systems and considered a good option for research-compatible outcomes at a modest cost.

2.3.2.6 Ankle Measure for Endurance and Strength

Sman et al. (2014) introduced the AMES to address some of the shortcomings of other CRT devices that were used to date, such as the need for electric current, computers, specialised software, or specialised hardware (e.g., light beams and linear encoders). The AMES (Figure 4) consists of a platform, two blocks, two L-shaped brackets, and an elastic band. The elastic band is attached horizontally to the brackets using two spring clamps on either side. In addition, the elastic band height is fully adjustable. To track the number of repetitions, individuals place their heels on the elastic band between the brackets and raise the heel as high as possible during testing (Sman et al., 2014). Hence, the height of the calf raise can be individually set and is not fixed to a certain threshold, like 5 cm. The AMES was originally tested in healthy individuals

(Sman et al., 2014), and later used in patients with patellofemoral pain (Van Cant et al., 2017) as well as in youth ballet dancers (DeWolf et al., 2018).

The AMES presented excellent inter-rater reliability for the number of repetitions completed (Table 3) when simultaneously assessed by two examiners (Sman et al., 2014). Sman et al. (2014) advanced the AMES was ideal for assessing CRT outcomes in clinical and research settings due to its simplicity. The authors recommended further modifications to the AMES to ensure safety while using the apparatus, such as replacing the L-shaped brackets with curved brackets and adding a foot fixation to minimise foot slippage during testing, which could affect the CRT outcome (Sman et al., 2014). Noteworthy is that this device is not available for purchase and only monitors the number of repetitions.

2.3.2.7 Custom-made device

Sara et al. (2021) investigated the correlation between the number of repetitions performed during the CRT and maximal plantar-flexor strength in males and females. A custom-made CRT device was used to aid in standardising the test. The device (Figure 4) consists of a horizontal plate affixed above a standing surface by an upright support bar. This horizontal plate acts as a visual and tactile guide that is adjusted (vertical and anteroposterior) to the dorsal ankle crease at the end-range of a maximal single-leg calf raise. Conceptually, this device is similar to the AMES device. Although the device is easy to use, portable, and simple, there are no existing studies to support its validity and reliability, the device only monitors the number of repetitions, and it is not available for purchase.

2.4 Discussion

In clinical practice and research, the CRT is used to assess the strength-endurance of the triceps surae muscles (Lunsford & Perry, 1995; Österberg et al., 1998). Despite being considered a reliable and valid clinical tool, there are concerns regarding the standardisation of its protocols (K. Hébert-Losier et al., 2009; Sman et al., 2014) and that key clinical parameters are omitted when only counting the number of repetitions (Byrne et al., 2017). To address these shortcomings, a range of devices have been developed and used to standardise and objectivise CRT performance. This review critically appraised 35 relevant studies that used measuring devices to evaluate CRT outcomes in healthy individuals as well as those with medical conditions to inform evidence-based practice. Among the 35 studies included, the Haberometer, AMES, and custom-made devices were considered the most clinical-friendly, but these only recorded the number of repetitions. The laboratory-based 3D motion capture and force plate systems are considered to provide the greatest precision of measurement and offer the advantage of quantifying the three main CRT outcomes but are the least clinical-friendly and most costly devices. The Häggmark and Liedberg light beam electronic device, electrogoniometer, and linear encoder were all considered as moderately clinically friendly from a practical and cost perspective, with the linear encoder being the most often used in the scientific literature and the only device reported to quantify the three main outcomes. As such, the linear encoder method appears to offer the best compromise for clinicians seeking research-grade outcomes for the CRT at a modest cost.

Although the number of calf raises performed is the primary test outcome evaluated in clinics Österberg et al. (1998), suggested assessing calf raise height during the test as shorter height ranges could lead to more repetitions since less work is required per repetition. Furthermore, it is noteworthy from a clinical perspective that the number of repetitions and height are related to different physiological and structural factors (Svensson et al., 2019). The number of repetitions is determined by contractile tissue and muscle endurance metabolism (Holloszy, 1967), while the height of the calf raise is moreover determined by tendon and muscle fiber length (Baxter et al., 2018). These triceps surae muscle properties can all affect the total work performed during the CRT as both the number of repetitions and height are used to compute work (Österberg et al., 1998). Furthermore, research supports that peak height and work are more sensitive metrics in presence of pathology and functional deficits (Baxter et al., 2018; Svensson et al., 2019; J. A. Zellers et al., 2020). For these reasons, several researchers have advocated using peak height and work in addition to the number of repetitions as objective measures of triceps surae MTU function during the CRT (Byrne et al., 2017; Fernandez et al., 2022; Silbernagel et al., 2006). Of the seven thematically grouped devices sourced from the literature, only the linear encoder and laboratory-based 3D motion capture and force plate systems had been used to quantify all three CRT outcomes. Of the two methods, the linear encoder is the most affordable option for clinical use and clinically based research. Indeed, the linear encoder was the most frequent device used in the scientific literature likely due to its ability to provide reliable (Byrne et al., 2017) research-grade outcomes (Andreasen et al., 2020) at a moderate financial cost compared to 3D motion and force plate systems. This device, however, still requires specialised software and knowledge to extract data, making the linear encoder less suitable for everyday clinical applications and explaining its lack of general uptake from a clinical standpoint.

The Haberometer, AMES, and custom-made device were considered as the most clinically friendly CRT devices (Table 4), followed by Häggmark and Liedberg’s light beam electronic device because of their simplicity, portability, affordability, and no requirement of specialised hardware or software. These devices can assist in standardising CRT parameters, with the

Haberometer and AMES shown reliable for measuring the number of repetitions (Haber et al., 2004; Möller et al., 2005; Sman et al., 2014). Though none of the reviewed literature sought to quantify the work performed when using these devices; because of the fixed calf raise height, the work completed can be calculated based on the number of repetitions, known calf raise height, and mass of individuals similar to the work computations used for the linear encoder, electrogoniometer, and motion capture systems. The one drawback, however, is that peak height during each raise is not quantified and the proposed work computations from the set height would therefore underestimate the actual work performed. Furthermore, these devices are not readily available for purchase, again limiting their widespread uptake in clinical practice.

This literature has a few limitations to acknowledge. First, this review focused on the single-leg CRT performed to fatigue, and did not consider other variations of this task, such as when calf raises are done bilaterally or for a set duration (André et al., 2016; Aruje Zahid et al., 2022). Different devices have been used for these task variations, including an overhead bar to set calf raise height (André et al., 2016) and inertial measurement units (Aruje Zahid et al., 2022), which could be applicable to the single-leg CRT. The former method would have similar strengths and limitations than the Haberometer or AMES, whereas the latter still needs development and validation for the single-leg CRT. This review also focused on the CRT devices and their design, reliability, concurrent validity, and perceived strengths and limitations for clinical use, not on other psychometric properties of the assessment procedures, such as responsiveness of outcomes, sensitivity, or specificity. Despite our narrative review following a rigorous and systematic process in accordance with the PRISMA guidelines, no critical appraisal of the included studies was undertaken due to the varied methods used in the studies. Furthermore, no risk of bias assessment was completed as it was not relevant to the review aims. Therefore, this review was limited to a narrative synthesis of the findings and conclusions drawn from the studies included. Nonetheless, this approach was deemed suitable for the aims of the review and to provide a comprehensive overview of the current CRT devices used, their strengths, and their limitations.

2.5 Conclusion

This review provides clinicians and researchers insight into what devices have been used to assess the CRT, and the strengths and limitations of these devices. The use of devices for the CRT has a dual purpose: to enhance standardisation of procedures and to further objective CRT outcomes beyond the number of repetitions. The linear encoder offers the best compromise for clinicians seeking research-grade outcomes for the CRT at a modest cost.

Chapter 3

Concurrent validity and reliability of a mobile iOS application to assess calf raise test kinematics

Fernandez, M. R., Athens, J., Balsalobre-Fernandez, C., Kubo, M., & Hébert-Losier, K. (2023). Concurrent validity and reliability of a mobile iOS application used to assess calf raise test kinematics. *Musculoskeletal Science & Practice*, *63*, 102711. https://doi.org/10.1016/j.msksp.2022.102711

Prelude: The previous Chapter identified a series of devices that can be used to standardise and quantify CRT outcomes. However, few of these devices were clinically accessible or measured key CRT outcomes other than the number of repetitions. Advances in computer vision technology has led to iOS mobile applications that provide low-cost research-grade alternatives for clinicians and researchers to quantify test outcomes, including for the CRT. This Chapter introduces the Calf Raise application and aims to determine its concurrent validity and agreement levels against laboratory-based equipment. It also establishes its intra- and inter-rater reliability.

3.1 Introduction

The CRT is used to assess triceps surae (or "calf") MTU properties in research and practice, notably endurance (Kim Hébert-Losier et al., 2009). The CRT involves repetitive plantarflexors concentric-eccentric contractions in unilateral stance until fatigue. The number of repetitions completed to exhaustion is used as primary outcome (K. Hébert-Losier et al., 2009), with gender, age, physical activity level, and body mass index influencing outcomes (Hébert-Losier et al., 2017). Clinicians administer this test in injury assessment and management, including for monitoring Achilles tendinopathy (Murphy et al., 2018; Silbernagel et al., 2006) Achilles tendon rupture (Saarensilta et al., 2022; Silbernagel et al., 2012; Van Vulpen et al., 2013) or triceps surae strain conditions (Green & Pizzari, 2017). The test is also used in children (Yocum et al., 2010), older individuals (André et al., 2018), and athletes (Greisberg et al., 2019; Nunes et al., 2019).

In clinic, the number of repetitions is the primary outcome used to quantify CRT performance, given the lack of tools to further objectivise performance. However, studies suggest that measuring calf raise height alongside total repetitions is crucial when using the CRT as measure of plantarflexion endurance (Tengman et al., 2015). Most studies using the CRT not only report total repetitions but also total work and peak height in both healthy (Byrne et al., 2017; Hébert-Losier et al., 2012b) and various clinical populations (Silbernagel et al., 2010; Jennifer A. Zellers et al., 2020). In patients with Achilles tendon ruptures (Silbernagel et al., 2012) or Achilles tendinopathies (Silbernagel et al., 2006), the total positive work is a more sensitive measure for detecting differences between the injured and uninjured sides than the total repetitions (Silbernagel et al., 2010). Work and peak height (but not repetitions) have also demonstrated significant positive associations with the Achilles tendon rupture score six months post-surgery (Byrne et al., 2017; Olsson et al., 2011) highlighting how work and peak height during the CRT can be important clinical measures. Furthermore, the CRT has been administered at different paces (K. Hébert-Losier et al., 2009),which would affect calf raise power. In presence of Achilles tendinopathy, calf muscle power is lower than in healthy controls (Silbernagel et al., 2006). Hence, monitoring power could be clinically meaningful.

To assess outcomes other than the number of repetitions, motion capture and force plate technologies are used in research (Hébert-Losier et al., 2012b) and accepted as gold standard for recording kinematics and kinetics. However, these devices are expensive, and the analysis and interpretation are complex, which is not ideal clinically. Although using a linear encoder to track heel displacement during the CRT is clinically more affordable, valid, and presents good reliability in measuring CRT outcomes (Byrne et al., 2017; Silbernagel et al., 2010), mobile applications are playing an increasingly important role in self and remote management. Mobile technology advancements have resulted in inexpensive evidence-based smartphone or tablet-based tools of high clinical value and research potential (Peart et al., 2019).

The above considered, our team developed the Calf Raise application (CR_{app}) for Apple iPhone operating system (iOS) users to facilitate the objective quantification, the replication of laboratory-based metrics otherwise difficult to measure in clinics, and the standardization of the CRT. The CR_{app} uses computer-vision algorithms to track a circular marker placed on an individual's foot from videos. Although this algorithm has been shown valid and reliable for tracking barbell motion during weightlifting when compared to 3D motion capture (Balsalobre-Fernández C et al., 2020), the use of this algorithm applied to the CRT has not yet been validated.

Therefore, we aimed to validate use of CR_{app} in healthy individuals by examining its concurrent validity and agreement levels against laboratory-based equipment and establish its intra- and inter-rater reliability. Based on the previous validation work of the tracking algorithm (Balsalobre-Fernández C et al., 2020), we hypothesized that the CR_{app} would exhibit good-to-excellent validity and reliability.

3.2 Materials and methods

3.2.1 Participants

A priori sample size calculations indicated that a sample size of 12 participants was needed based on the ability to detect a good correlation (i.e., 0.75) (Portney, 2020) between CR_{app} and laboratory measures with alpha set at 0.05 and power set at 0.80. As each participant would was expected to perform the CRT protocol on both legs and three conditions (explained under CRT protocol below), each participant would contribute six video files per marker for concurrent validity assessment (i.e., 72 paired comparisons). Using intraclass correlation coefficient (ICC), this sample would be sufficient when setting the minimal acceptable concurrent validity level between CR_{app} and laboratory measures (i.e., two samples) at 0.75 and expected validity level at 0.865 with alpha set at 0.05 and power set at 0.80 to validate the concurrent validity (Borg et al., 2022).

Thirteen healthy individuals [mean (standard deviation) age: 38 (10) years, height: 175.33 (8.94) cm, mass: 82.90 (21.12) kg for 6 males; age: 34 (7) years, height: 161.71 (6.18) cm, mass: 57.13 (8.28) kg for 7 females] participated in this study voluntarily. Physical activity levels were low for three, moderate for three, and high for seven participants based on the self-administered short-form International Physical Activity Questionnaire (IPAQ) (Craig et al., 2003). Participants were recruited from the local community via online and poster advertisements. Participants were eligible if they were 16 to 50 years old, could follow simple instructions, and were able to perform repeated single-leg calf raises. Participants were excluded if they had any prior or current injury or condition preventing proper CRT execution. The decision to exclude clinical or pathological populations was made *a priori* given that the clinical status of individuals should not affect the validity (CR_{app} vs laboratory) or reliability (intra and inter rater) of the CR_{app}. Hence, data from healthy individuals would be sufficient for the purpose of validating the functionality of the CR_{app}. The Human Research Ethics Committee of the University of Waikato granted ethical approved to conduct this observational cross-sectional validation study (HREC2020#11) which followed the Declaration of Helsinki. Prior to participation, participants received verbal and written information about the study and signed an informed consent document. Participants were advised of the potential risks, which included delayed onset muscle soreness (DOMs). All data were collected within a three-month period.

3.2.2 Calf raise test protocol

The CRT was performed on three testing occasions in various conditions (flat (Hébert-Losier et al., 2012b), 10 degrees incline (Byrne et al., 2017; Silbernagel et al., 2010) and edge of step (Svensson et al., 2019) to reflect how the CRT is commonly implemented. Hence, each individual contributed multiple unique CRT performances to the final dataset. Steel platforms with four feet were purposefully designed for this study to fit on top our laboratory force plate and to keep the placement of the CR_{app} recording device consistent across the three conditions. Four to seven days separated the testing sessions to minimize residual fatigue or DOMs from prior sessions. A licensed physiotherapist (RF) administered all procedures. Prior to testing, baseline measures were recorded. Mass was recorded using a zeroed force plate (AMTI AccuGait Optimized, Advanced Mechanical Technology Incorporated, Watertown, MA).

Participants then completed a standardized warm-up that consisted of performing 10 double-leg calf raises on a 10° incline guided by a 60 bpm metronome, going up on one beat and down on one beat.

Prior to CRT experimentation, participants were provided with verbal and written instructions. Participants were asked to stand on one leg with the knee straight on one of three platforms (flat, 10 degrees incline, step) placed on a force plate. The order of platforms was randomised across the three sessions. The non-tested leg was bent to 90 degrees knee flexion with the foot behind participants. Participants were instructed to perform a maximal number of repetitions on either the right or left leg allocated randomly. Testing was repeated on the alternate leg after 5 min of rest. Participants were allowed to place two fingertips per hand at shoulder height against a support for balance and instructed to go as high as possible and to lower the heel back to the starting position on each repetition. Calf raises were performed at a rate of 30 per minute guided by a 60 bpm metronome, going up on one beat and down on one beat. The test was terminated when participants could not complete an additional repetition, stopped due to fatigue (i.e., volitional cessation), were unable to keep the pace, flexed the knee on their tested leg, moved the body forwards rather than upwards, or used more than their fingertips for balance. These CRT parameters were selected as the most common in research (K. Hébert-Losier et al., 2009).

Round black stickers of 24 mm in diameter were placed on the feet (one immediately below the lateral malleolus and one on the heel) to enable tracking within the CR_{app} (Figure 5). The two marker locations were collected to confirm validity of tracking from both lateral and posterior views. During testing, videos of the foot were recorded using the CR_{app} installed on two iPad Air 2 devices (Apple, Inc., Cupertino, CA, USA) running iOS 14.1. Devices were placed 30 cm to the side of and behind participants, level with the markers, and stabilised on a frame. This 30 cm distance was selected as it permitted to capture the entire movement of the marker during calf raise repetitions. Simultaneously, retroreflective markers of 12.5 mm in diameter were placed in the centre of the round stickers to collect 3D motion using an 8-camera Oqus 700 3D motion capture system sampling at 60 Hz and the Qualisys Track Manager (v.2019.1.4000, Qualisys AB, Gothenburg, Sweden). Ground reaction forces were recorded using the AMTI force plate at twice the 3D motion frequency (i.e., 120 Hz).

A validated Perceived Recovery Status Scale (Laurent et al., 2011) monitored recovery between trials. Recovery time was extended if 8 (*well recovered*) was not reached. Furthermore, participants completed an 100 mm visual analogue pain scale 24, 48, and 72 hours post-testing to monitor DOMs. On average, corresponding values were 1.04 (1.85), 1.31 (2.23), and 0.94 (2.11) mm. No participant was still experiencing DOMs when reporting for subsequent sessions.

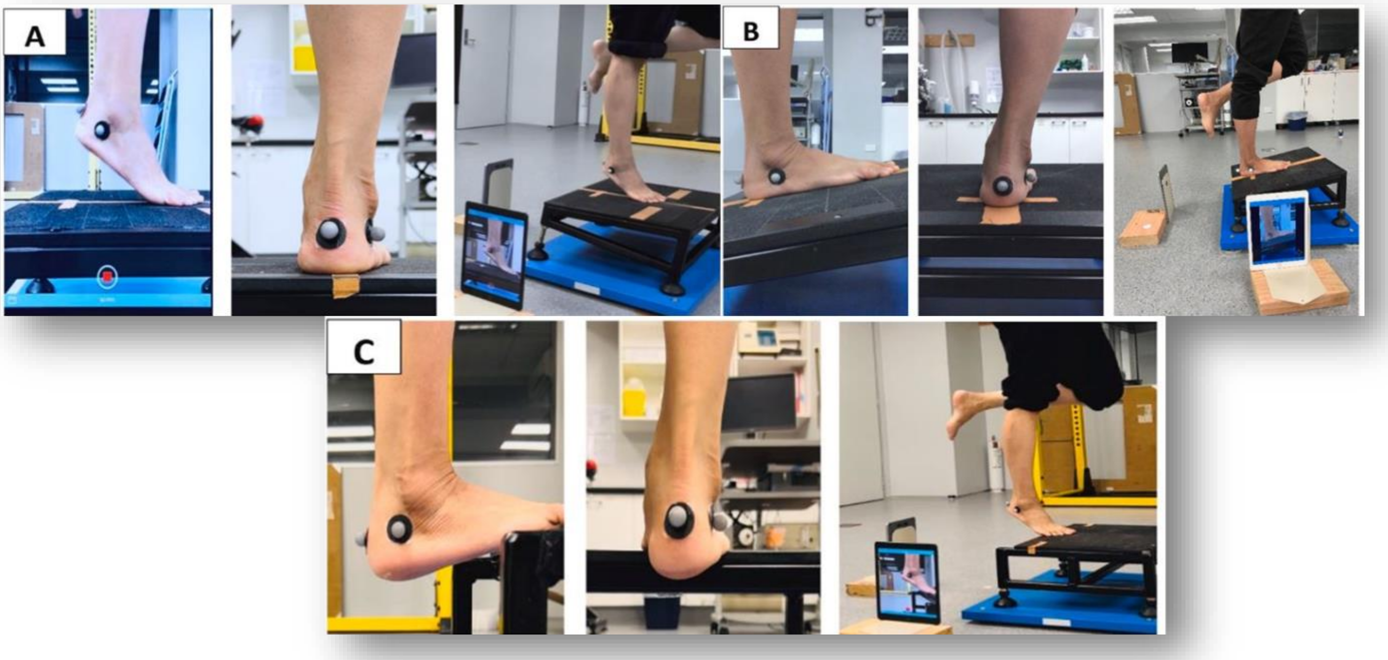

Figure 5. Marker placement below the lateral malleolus (left image) and on the heel (middle image). The black round sticker of 24 mm in diameter and retroreflective marker of 12.5 mm in diameter enabled tracking within the Calf Raise application and Qualisys 3D motion capture system, respectively. The placement of the two iPad devices positioned 30 cm from the markers is also shown (right image).

3.2.3 Data processing

The CR_{app} uses a previously validated computer-vision algorithm that enables image-processing features to track the 2D path of selected objects in video footage (Balsalobre-Fernández C et al., 2020). Specifically, The CR_{app} was designed for this study using a set of custom computer-vision algorithms using Apple's Vision framework to automatically track the vertical position of a circular marker placed on the foot at 60 Hz using Xcode 12 for macOS Catalina 10.15 and the Swift 4 programming language with iOS 14 SDK (Apple Inc., USA). To calibrate the application, the CR_{app} user must adjust the size of a scalable circle and position it around the circular adhesive marker of known diameter (in this case, 24 mm) in the first video frame. At the end of the automatic video processing, the CR_{app} user also identifies the start of the first calf raise repetition, first peak, last peak, and end of the last calf raise repetition from the vertical position curve. From this curve, where the initial marker position in the first video frame defines a vertical position of zero, the number of repetitions (n), peak vertical displacement (cm), and total positive vertical displacement (d, cm) are extracted. A fatigue index (%) is computed as:

$$Fatigue\ index = \frac{|1^{st}\ \text{peak height} - \text{last peak height}|}{1^{st}\ \text{peak height}}\ x\ 100$$

Prior to data extraction, the mass of individuals recorded on the day is entered to enable positive work (J) computation as:

$$Work = F_g \times d$$

where F_g is computed as body mass times gravitational acceleration ($g = 9.81$ m/s^2). Total negative work is also computed based on the total negative vertical displacement. Finally, peak positive and negative power (W) are extracted from the power curve generated using:

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

where $\Delta time$ is based on the sampling frequency (i.e., 0.0167 s at 60 Hz).

The raw data collected using the Qualisys Track Manager were processed using Visual3D Professional (v.2021.01.1, C-Motion Inc., Germantown, Maryland, USA). Any marker data gaps up to 6 frames were interpolated using a third-order polynomial fit algorithm. A fourth-order low-pass Butterworth filter with a 15 Hz cut-off frequency was applied to the force data. From the marker position curve, repetitions, peak displacement, total positive displacement, fatigue index, total positive and negative work, and peak positive and negative power were extracted using the same approach as for the CR$_{app}$. Work and power curves were also generated using the vertical ground reaction force and marker displacement data rather than using a fixed force (F_g).

To examine intra- and inter-rater reliability, three novice CR$_{app}$ users were randomly selected to extract the CR$_{app}$ based-outcome measures from an existing internal database of 106 videos. Users were familiar with the CRT and had one-on-one training on how to use the CR$_{app}$ with one of the developers (KHL). Each user had to calibrate the application and subsequently identify the start of the calf raise repetition, first peak, last peak, and end of the last calf raise repetition. Each rater analysed the 106 videos three times each, 7 days apart. A previous reliability study involving data from raters using a similar iOS mobile application (Balsalobre-

Fernández et al., 2017) reported ICC levels of 0.941. Setting the minimal acceptable reliability at 0.90, and expected reliability at 0.94 yields a required sample size of 83 when setting power at 80% and significance level at 5% (Borg et al., 2022). Hence, the reliability portion of the study was deemed sufficiently powered. Raters did not have access to their previous analyses or the analyses from the other raters.

3.2.4 Statistical analysis

Two datasets were used for statistical analysis: one from the lateral malleolus and another from the heel marker. For descriptive statistics, we report mean (SD) values.

3.2.4.1 Validity

We used the intraclass correlation coefficient ($ICC_{3,k}$) with 95% confidence interval [upper, lower] based on a two-way mixed effects, consistency, and mean of *k* measurements model (Koo & Li, 2016; Perinetti, 2018) to assess concurrent validity of the CR_{app} against laboratory-based measures. Based on common thresholds (Portney, 2020), relative agreement between methods was deemed excellent, good, fair, and poor when corresponding ICC values were > 0.90, >0.75, between 0.50 and 0.75, and <0.50. Absolute agreement was examined using standard errors of the mean measurement (SEM) to describe the variation in native units, and coefficient of variations (CV) to express the typical variation as a percentage (Atkinson G & Nevill A, 1998; Hopkins, 2000), CV <10% was considered acceptable (Atkinson G & Nevill A, 1998). Further, Bland-Altman plots and 95% limits of agreement were constructed using the MethodCompare-R package to assess possible bias and homoscedasticity/heteroscedasticity of data (Atkinson G & Nevill A, 1998; Taffé et al., 2019). To visually evaluate the performance of the CR_{app} against laboratory-based systems, precision plots were constructed (Taffé, 2020).

3.2.4.2 Reliability

Intra- and inter-rater reliability were assessed in a similar manner, but used an $ICC_{3,1}$ two-way mixed effect, absolute agreement, and single-rater measurement model (Koo & Li, 2016; Perinetti, 2018) for intra-rater, and an $ICC_{2,1}$ two-way random effect, absolute agreement, and single-rater measurement model for inter-rater. All statistical analyses were performed using R Statistical Software (v.4.0.5, https://www.R-project.org).

3.3 Results

Descriptive data and concurrent validity analysis results are presented in Table 5 and Table 6, respectively. Differential and proportional biases between the two measurement methods are reported in Table 7, with precision plots shown in Figures 6 and 7.

3.3.1 Validity

The $ICC_{3,k}$ results presented in Table 5 indicate excellent agreement for all lateral malleolus outcomes (range: 0.963 to 1.00), and good-to-excellent agreement at the heel (range: 0.878 to 1.00). The absolute CV across outcomes for the lateral malleolus was 5.8 (3.9) %, and for the heel was 9.6 (7.9) %. CV values were lowest for both markers for repetitions (0%) and highest for the fatigue index (15.3% lateral malleolus and 33.3% heel). Relative agreement was acceptable across measures (CV <10%), except for the fatigue index for both markers and positive peak power derived from the force plate for the heel.

Bland-Altman plots were heteroscedastic for all outcomes (see Appendices C1 to C2). Therefore, limits of agreement were calculated based on log-transformed data. The small differences in the two measurements indicate good agreement between systems as reflected in the narrow confidence intervals of the estimated proportional bias (Table 7). Further, the precision plots (Figures 6 and 7) show that after removing the observed biases, the CR_{app} is as precise as the laboratory-based systems for all outcomes for both markers, except for peak displacement derived from the heel.

3.3.2 Reliability

The CR_{app} showed excellent intra-rater reliability (rater one: $ICC_{3,1} \geq 0.985$, absolute CV ≤ 3.7%; rater two: $ICC_{3,1} \geq 0.995$, absolute CV ≤ 1.9%; rater three: $ICC_{3,1} \geq 0.970$, absolute CV ≤ 5.0%), and inter-rater reliability (day one: $ICC_{2,1} \geq 0.951$, absolute CV ≤ 5.6%; day two: $ICC_{2,1} \geq 0.950$, absolute CV ≤ 5.6%; day three: $ICC_{2,1} \geq 0.949$, absolute CV ≤ 5.6%). Complete reliability data are presented as supplementary material (Appendices C3-C8).

Table 5. Calf Raise application and laboratory-based data collected during the calf raise test from the lateral malleolus and heel markers. Values are means (standard deviations)**.**

Outcome measure	**Lateral malleolus**		**Heel**	
	CR_{app}	Laboratory	CR_{app}	Laboratory
Repetition (*n*)	30 (9)	30 (9)	30 (9)	30 (9)
Total vertical displacement (cm)	274.80 (101.01)	280.68 (99.53)	345.28 (127.2)1	387.54 (135.51)
Peak height (cm)	9.88 (1.60)	9.76 (1.61)	11.71 (1.84)	13.54 (1.98)
Fatigue index (%)	14.8 (12.4)	14.9 (12.9)	10.2 (10.2)	12.8 (11.2)
Total positive work (J) (FP)	1812.27 (766.94)	1707.96 (653.76)	2289.37 (982.98)	2375.38 (897.81)
Total positive work (J) (marker)	1812.27 (766.94)	1851.41 (756.08)	2289.37 (982.98)	2562.51 (1033.06)
Total negative work (J) (FP)	-1794.39 (769.62)	-1729.98 (682.36)	-2268.26 (991.85)	-2401.59 (934.59)
Total negative work (J) (marker)	-1794.39 (769.62)	-1853.35 (755.96)	-2268.26 (991.85)	-2563.75 91031.67)
Peak positive power (W) (FP)	241.79 (87.75)	232.83 (77.67)	324.41 (131.59)	319.9 (110.1)
Peak positive power (W) (marker)	241.79 (87.75)	236.97 (83.59)	324.41 (131.59)	321.95 (118.89)
Peak negative power (W) (FP)	-211.67 (70.74)	-209.41 (76.69)	-295.22 (110.6)	-286.03 (109.74)
Peak negative power (W) (marker)	-211.67 (70.74)	-215.15 (70.86)	-295.22 (110.6)	-288.8 (99.23)

Note. Data from $n = 77$ data files per marker from calf raise tests performed in three conditions (floor, 10° incline, and edge of step).

Abbreviations: CR_{app}, Calf Raise application; FP, force plate.

Table 6. Concurrent validity analyses between the Calf Raise application and laboratory-based data for the lateral malleolus and heel markers. Statistical values are presented with 95% confidence interval [lower, upper].

Outcome measure	**Lateral malleolus**			**Heel**		
	ICC	SEM (raw units)	CV (%)	ICC	SEM (raw units)	CV (%)
Repetition (*n*)	1.0	0	0	1.000	0	0
Total vertical displacement (cm)	0.996 [0.995, 0.998]	8.46 [6.97, 9.96]	3.1 [2.5, 3.6]	0.976 [0.965, 0.984]	28.34 [22.22, 34.45]	7.7 [6.0, 9.4]
Peak height (cm)	0.963 [0.946, 0.975]	0.43 [0.35, 0.51]	4.4 [3.6, 5.1]	0.878 [0.821, 0.916]	0.89 [0.71, 1.07]	7.1 [5.6, 8.5]
Fatigue index (%)	0.984 [0.976, 0.989]	2.27 [1.89, 2.65]	15.3 [12.7, 17.9]	0.932 [0.900, 0.953]	3.83 [3.25, 4.41]	33.3 [28.2, 38.3]
Total positive work (J) (FP)	0.985 [0.978 0.990]	122.18 [97.10, 147.27]	6.9 [5.5, 8.4]	0.977 [0.966, 0.984]	201.31 [167.28, 235.35]	8.6 [7.1, 10.1]
Total positive work (J) (marker)	0.998 [0.996, 0.998]	53.73 [44.19, 63.27]	2.9 [2.4, 3.5]	0.985 [0.978, 0.990]	173.52 [135.90, 211.14]	7.2 [5.6, 8.7]
Total negative work (J) (FP)	0.991 [0.987, 0.994]	98.23 [79.42, 117.16]	5.6 [4.5, 6.7]	0.980 [0.971, 0.986]	191.47 [158.06, 224.87]	8.2 [6.8, 9.6]
Total negative work (J) (marker)	0.997 [0.996, 0.998]	59.10 [48.12, 70.08]	3.2 [2.6, 3.8]	0.985 [0.978, 0.990]	173.96 [135.94, 211.99]	7.2 [5.6, 8.8]
Peak positive power (W) (FP)	0.969 [0.955, 0.979]	20.33 [16.62, 24.04]	8.6 [7.0, 10.1]	0.954 [0.933, 0.969]	36.00 [30.01, 42.00]	11.2 [9.3, 13.0]
Peak positive power (W) (marker)	0.992 [0.988, 0.994]	10.99 [9.13, 12.85]	4.6 [3.8, 5.4]	0.971 [0.957, 0.980]	29.97 [24.91, 35.02]	9.3 [7.7, 10.8]
Peak negative power (W) (FP)	0.971 [0.957, 0.980]	17.6 [14.64, 20.57]	8.4 [7.0, 9.9]	0.977 [0.967, 0.984]	23.20 [19.97, 26.44]	8.0 [6.9, 9.1]
Peak negative power (W) (marker)	0.977 [0.967, 0.984]	14.95 [12.34, 17.55]	7.0 [5.8, 8.2]	0.981 [0.972, 0.987]	20.41 [17.46, 23.36]	7.0 [6.0. 8.0]

Note. Number of paired comparisons *n* = 77 per marker from calf raise tests performed in three conditions (floor, 10° incline, and edge of step).

Abbreviations: CR_{app}, Calf Raise application; CV, coefficient of variation; ICC, intraclass correlation coefficient; FP, force plate; SEM, standard error of the mean measurement

Table 7. Differential and proportional bias with corresponding 95% confidence interval [lower, upper] between the Calf Raise application and laboratory-based data from the lateral malleolus and heel markers.

Outcome measure	**Lateral malleolus**		**Heel**	
	Differential bias (raw units)	Proportional bias	Differential bias (raw units)	Proportional bias
Repetition (*n*)	0	0	0	0
Total vertical displacement (cm)	-20.99 [-62.14, 20.16]	1.07 [0.93, 1.21]	-13.87 [-74.95, 47.20]	0.94 [0.79, 1.09]
Peak height (cm)	-0.20 [-1.90, 1.50]	1.03 [0.86, 1,21]	1.38 [-2.23, 5.00]	0.76 [0.50, 1.03]
Fatigue index (%)	-11.8 [-23.7, 0.1]	2.20 [1.24, 317]	-1.9 [-11.0, 7.1]	1.17 [0.33, 2.02]
Total positive work (J) (FP)	-211.68 [-471.34, 47.99]	1.20 [1.05, 1.34]	-275.77 [-640.53, 88.90]	1.09 [0.94, 1.24]
Total positive work (J) (marker)	-138.23 [-380.51, 104.05]	1.07 [0.94, 1.19]	-150.83 [-499.01, 197.35]	0.96 [0.83, 1.09]
Total negative work (J) (FP)	194.10 [-60.06, 448.27]	1.16 [1.02, 1.30]	235.81 [-133.04, 604.67]	1.05 [0.91, 1.20]
Total negative work (J) (marker)	159.82 [-86.62, 406.26]	1.07 [0.94, 1.19]	191.38 [-163.80, 546.57]	0.97 [0.84, 1.10]
Peak positive power (W) (FP)	-17.56 [-57.54, 22.42]	1.13 [0.96, 1.29]	-43.76 [-103.82, 16.30]	1.16 [0.98, 1.35]
Peak positive power (W) (marker)	-16.96 [-54.19, 20.28]	1.11 [0.96, 1.26]	-28.58 [-85.88, 28.72]	1.11 [0.94, 1.29]
Peak negative power (W) (FP)	-17.11 [-47.47, 13.25]	0.94 [0.80, 1.08]	5.44 [-36.94, 47.81]	1.07 [0.92, 1.21]
Peak negative power (W) (marker)	12.06 [-21.85, 45.96]	1.05 [0.90, 1.21]	39.86 [-6.15, 85.86]	1.17 [1.02, 1.33]

Note. Number of paired comparisons *n* = 77 per marker from calf raise tests performed in three conditions (floor, 10° incline, and edge of step).

Abbreviation: FP, force plate.

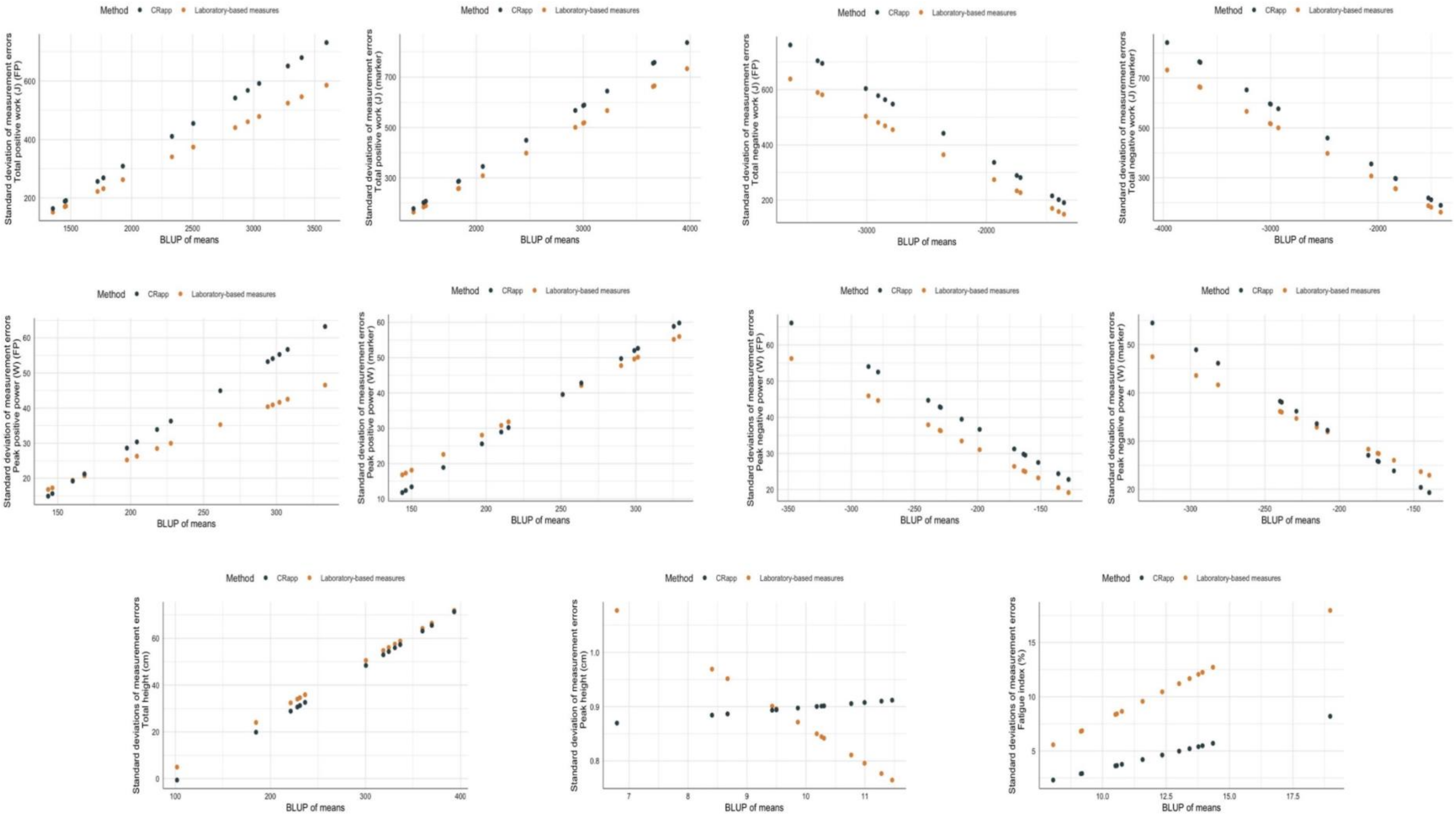

Figure 6. Precision plots for the lateral malleolus marker showing the precision (i.e., standard deviation of the measurement error) of each measuring system. *Abbreviations*: BLUP, best linear unbiased predictor; CR$_{app}$, Calf Raise application; FP, force plate.

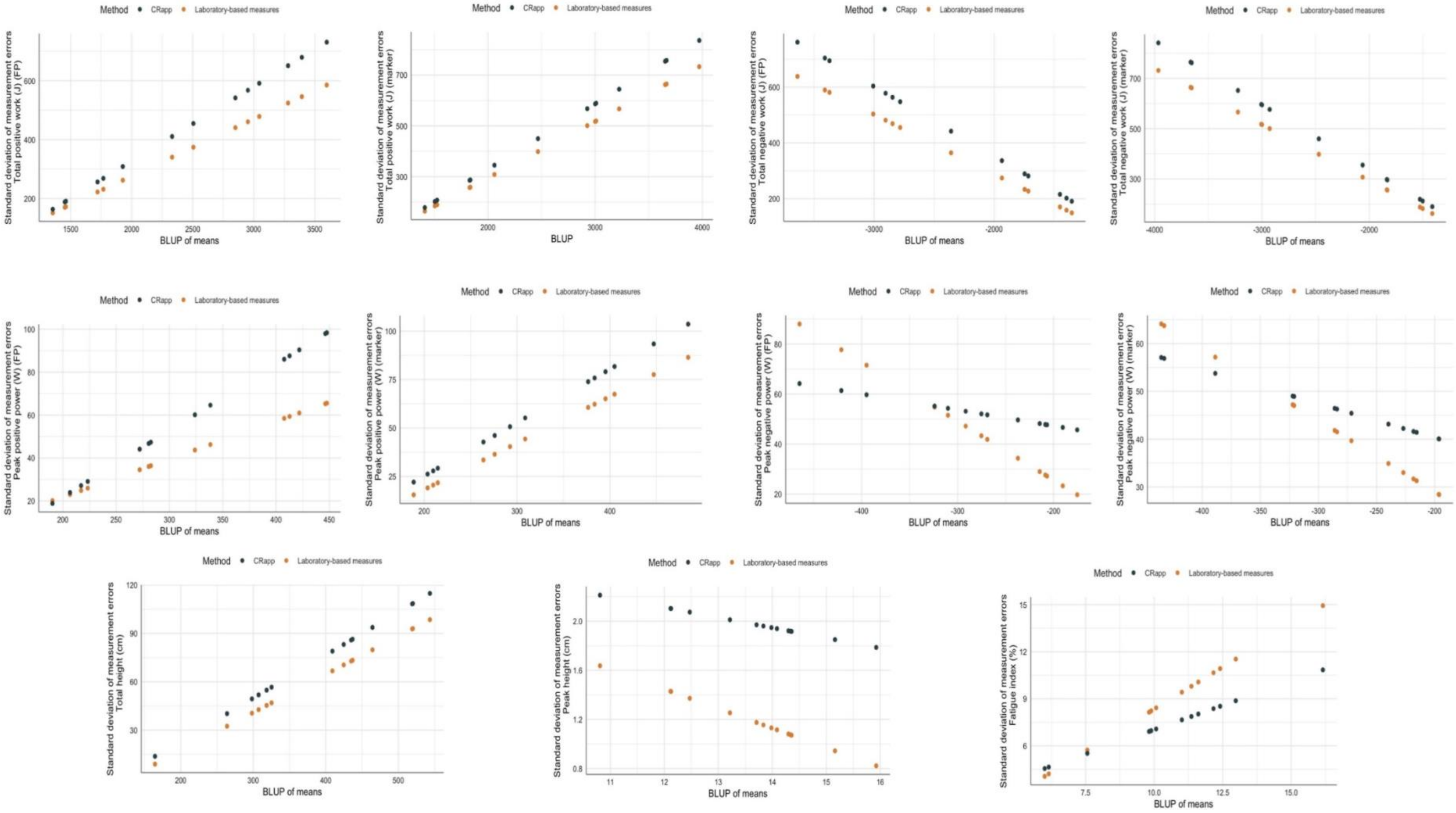

Figure 7. Precision plots for the heel marker showing the precision (i.e., standard deviation of the measurement error) of each measuring system. *Abbreviations*: BLUP, best linear unbiased predictor; CR$_{app}$, Calf Raise application; FP, force plate.

3.4 Discussion

We aimed to determine the concurrent validity and rater reliability of a computer-vision-based mobile application to quantify CRT outcomes. Our results show that the agreement between the CR_{app} and laboratory-based measures are excellent for the lateral malleolus ($ICC_{3,k} \geq 0.963$) and good-to-excellent for the heel ($ICC_{3,k} \geq 0.878$) markers across outcomes based on ICC values. The absolute agreement across measures based on the typical errors was acceptable ($CV < 10\%$) except for the fatigue index and peak positive power for the heel marker. Bland-Altman plots showed variances of measurement errors across outcomes. Thus, results from Bland-Altman plots can be misleading and unreliable to determine the true measurement agreement between methods due to heteroscedasticity (Taffé, 2020). Hence, we constructed precision plots to visually and clinically appraise the performance of the recalibrated (i.e., bias corrected values or adjustments made to data to account for systematic errors or biases in measurements or observations) CR_{app}, using the MethodCompare statistical function in R (Taffé et al., 2019). These plots indicate the CR_{app} is precise when compared to laboratory-based systems following recalibration except for peak displacement from the heel marker. Lastly, reliability of CR_{app} measures were excellent within ($ICC_{3,1} \geq 0.970$, $CV \leq 5.0\%$) and between ($ICC_{2,1} \geq 0.949$, $CV \leq 5.6\%$) novice users. Together, these results confirm the CR_{app} is valid and reliable for measuring CRT outcomes in healthy adults. The application can be used as a tool to objectivise CRT outcomes in research and clinic with confidence.

To our knowledge, this is the first study to evaluate the psychometric properties of a mobile application to quantify CRT outcomes. Our validity findings are slightly superior to those reported for a mobile application implementing the same computer-vision algorithm to track 2D motion of a barbell trajectory during weightlifting (Balsalobre-Fernández C et al., 2020).

In the aforementioned study, the agreement between the mobile application and 3D motion capture system was good-to-excellent for peak vertical, forward, and backward displacement and peak vertical velocity (ICC 0.838 to 0.944), whereas our ICC values were at least 0.963 and 0.878 for the lateral malleolus and heel markers, respectively. This comparison highlights the importance of conducting validity studies that are specific to the intended use of novel mobile applications.

The absolute measurement error of CR_{app} outcomes was, on average, larger for the heel (mean CV 9.6%) than the lateral malleolus (mean CV 5.8%) marker. The movement of the heel away from the camera linked with the rotational movement of the ankle during the CRT likely explains the larger differences between CR_{app} and laboratory-based measures for the heel compared to the lateral malleolus marker, which could be exacerbated in presence of hindfoot deformity. Indeed, the movement of the lateral malleolus marker is more in plane with the initial calibration image. Thus, although both markers are susceptible to parallax errors due to the inherent limitations linked with image processing of 2D videos (Martin et al., 2020), the likelihood of out-of-plane motion is greater and more systematic for the heel marker. This parallax error would be greatest at the end of plantarflexion range, or at the peak height of the calf raise. This inaccurate assessment of the peak height explains the poorer precision plots for the peak displacement outcome at the heel and large discrepancy in fatigue index between the CR_{app} and motion capture data for the heel marker (33.3%) since the fatigue index is derived from peak displacement measures. Hence, we recommend using the CR_{app} with a marker placed on the side of the foot immediately below the lateral malleolus rather than on the heel for more accurate data.

Three-dimensional motion capture and force plate systems are considered gold standard for measuring kinematics and kinetics (Moore & Willy, 2019). Since these two systems use different base units and algorithms to calculate work and power CRT outcomes, it is reasonable to expect that the outcomes derived from these systems might differ and affect validity and accuracy of CR_{app} measures. Indeed, the CR_{app} and 3D motion capture systems use a fixed force based on an individual's mass and gravitational constant when computing work and power, whereas the force plate provides an actual force measure. In our study, outcomes derived from 3D motion capture were more comparable to CR_{app} outcomes than the force plate derived ones. The CR_{app} uses a computer-vision motion analysis-based algorithm, which is more comparable to the 3D motion capture system, extracting data from sequential images to quantify movement. In other words, the CR_{app} and 3D motion capture system both track displacement data to measure outcomes. Our measurement error of 2.9% between the CR_{app} and 3D motion capture for total positive work from the lateral malleolus marker is similar to the 2.9% measurement error found when comparing total work derived from a linear encoder fixed to the heel compared to 3D motion capture (Andreasen et al., 2020). Together, these results suggest the CR_{app} has comparable validity and accuracy to a linear encoder for quantifying CRT outcomes. The linear encoder is often used in research to measure CRT outcomes (Byrne et al., 2017; Silbernagel et al., 2010), and our findings indicate that the CR_{app} could be a suitable mobile alternative, although a direct comparison of both devices would be needed to confirm this proposition.

The main limitation of our study is the inclusion of only healthy adult-age individuals to assess CR_{app} validity and reliability, whereas the CRT is used across a range of populations from paediatrics (Yocum et al., 2010) to older adults (André et al., 2018) and athletes (Greisberg et al., 2019), and is most relevant in clinical populations (Cibulka et al., 2017; Silbernagel et al., 2006; Silbernagel et al., 2012; Svantesson, Osterberg, Grimby, et al., 1998; Van Vulpen et al., 2013). However, the clinical status or population examine should not affect the validity and reliability of the CR_{app} if similar procedures and set-ups are used.

3.5 Conclusion

In conclusion, our study demonstrates that the CR_{app} is valid and reliable for measuring key CRT outcomes in healthy adults. The marker placed below the lateral malleolus demonstrates superior agreement to laboratory-based measures due to lower parallax errors than a marker placed on the heel. Therefore, placing a marker on the side rather than the posterior aspect of the foot is recommended. The fatigue index was the least valid measure from the CR_{app} and should therefore be used with caution. The CR_{app} can now be used to establish empirically based normative values across populations and used to inform clinical care.

Chapter 4

Effects of ankle starting position on calf raise test outcomes: Position does matter

Fernandez, M. R., Athens, J., O Neill, S., Kubo, M., & Hébert-Losier, K. (2023). Effects of ankle starting position on calf raise test outcomes: Position does matter. *Under Review*

Prelude: In the previous Chapter, the CR_{app} was shown to be valid and reliable for quantifying key CRT outcomes (i.e., the number of repetitions, total displacement, peak height, positive and negative total work, and positive and negative peak power). Therefore, the CR_{app} could be used in the following experimental chapters to examine the influence of varying CRT protocols on outcomes. This Chapter investigates the effects of varying ankle starting positions [i.e., flat (0^{o}), incline (10^{o} dorsiflexion), and step (full dorsiflexion)] on CRT outcomes using the valid and reliable CR_{app}, while accounting for predictors linked with participant characteristics.

4.1 Introduction

The CRT, also known as the heel-raise test or heel-rise test, was introduced in the 1940s as a clinical method for measuring triceps surae muscle function (i.e., strength and endurance) (Lunsford & Perry, 1995; Ross & Fontenot, 2000; Silbernagel et al., 2010). The CRT remains a standard assessment tool in clinical practice and research (K. Hébert-Losier et al., 2009) and is used to assess functional abilities in varied populations, including children (Maurer et al., 2007), the elderly (André et al., 2016), and individuals with musculoskeletal (Lee et al., 2021; Van Cant et al., 2017) and medical (Haber et al., 2004; Monteiro et al., 2013; Svantesson, Osterberg, Grimby, et al., 1998) conditions. The CRT involves standing on one leg and performing repeated concentric and eccentric plantarflexion contractions while maintaining a straight knee. The contractions are repeated to volitional cessation, with the number of repetitions performed recorded as the primary outcome (Lunsford & Perry, 1995). Other CRT metrics, such as peak height and work, are considered key objective outcomes of the triceps surae MTU function in Achilles tendon rupture rehabilitation and research (Byrne et al., 2017; Olsson et al., 2014; Silbernagel et al., 2010). These metrics are deemed more sensitive in detecting functional impairments in ATR than the number of repetitions completed.(Byrne et al., 2017; Silbernagel et al., 2010).

Despites its common use, there is no consensus protocol used in the literature when administering the CRT (K. Hébert-Losier et al., 2009) and the majority of studies only report the number of repetitions completed. As a result of inconsistent protocols and test parameters, normative values for CRT outcomes vary across studies (Hébert-Losier et al., 2017; Jan et al., 2005; Lunsford & Perry, 1995). Consequently, clinicians and researchers may have difficulty interpreting test results and deciding on what parameters to implement in practice. Hence, it is imperative to understand how changes in parameters affect CRT outcomes to promote evidence-based practice. Studies have reported that varying CRT parameters can affect triceps muscle activity (Hébert-Losier et al., 2012a) and fatigue (Hébert-Losier et al., 2012b). For instance, changing the knee flexion angle during the CRT can increase or decrease the relative contributions of the soleus (SOL), medial gastrocnemius (MG), and lateral gastrocnemius (LG) muscles. However, this parameter has a limited effect on the number of repetitions achieved (Hébert-Losier et al., 2012a).

Another CRT parameter that varies in practice and research is the ankle starting position (K. Hébert-Losier et al., 2009; Kim Hébert-Losier et al., 2009). The CRT has been performed from plantigrade (0°) from a flat surface (Flanagan et al., 2005; Hébert-Losier et al., 2012a), 10° dorsiflexion with an incline platform (Brorsson et al., 2018; Byrne et al., 2017), or near maximal dorsiflexion with the forefoot on the edge of a step (Silbernagel et al., 2006). Due to the length-tension relationship, these variations are expected to alter TS muscle force production (Hali et al., 2021; Maganaris, 2003), with an increase in plantarflexion force as dorsiflexion range increases (Sale et al., 1982). This change might result in a greater number of repetitions. Conversely, the increased range of motion with increased dorsiflexion may cause earlier TS muscle fatigue due to greater mechanical work (Enoka, 2002), leading to fewer repetitions. Hence, CRT outcomes may differ depending on ankle starting positioning.

Therefore, this study aimed to examine the influence of ankle starting position on CRT outcomes, namely the number of repetitions, total vertical displacement, peak height, and total work. The goal was to compare the three most common ankle starting positions used the conduct the CRT: flat (0°), incline (10° dorsiflexion), and step (full dorsiflexion). Due to the increased range of motion and mechanical work required per repetition when dorsiflexion is increased, we hypothesised lesser repetitions in step than incline than flat conditions. Given that CRT performance has been reported to differ between genders (André et al., 2016; Hébert-Losier et al., 2017; Jan et al., 2005; Mishra et al., 2022; Monteiro et al., 2017) and decrease with age (André et al., 2016; Hébert-Losier et al., 2017; Jan et al., 2005; Mishra et al., 2022; Monteiro et al., 2017), BMI (Hébert-Losier et al., 2017; Monteiro et al., 2017), and lower physical activity levels (André et al., 2016; Hébert-Losier et al., 2017; Monteiro et al., 2017), a secondary objective was to investigate the potential influence of these predictors on CRT outcomes.

4.2 Methods

4.2.1 Sample size

Based on one-sample comparison of means and setting the minimal detectable change between ankle starting positions to six repetitions based on test-retest data (Olsson et al., 2014), the estimated required sample size was of 43 to attain 90% power at a 5% level of significance assuming a mean and standard deviation of 32 ± 12 repetitions (Olsson et al., 2014). To account for 10% of missing data, 48 participants were targeted.

4.2.2 Study design

A randomised crossover study with repeated measures was used to examine the effect of varying ankle starting position (i.e., flat, incline, and step) on the following CRT outcomes: number of repetitions, total vertical displacement, peak height, and total work. We also considered the following predictors in the analysis: age, gender, BMI, and physical activity levels based on (IPAQ) short form scores (Lee et al., 2011).

4.2.3 Participants

Through targeted online distribution lists and word-of-mouth, we recruited 49 healthy individuals from the local University campus. Participants had to be at least 16 years old, able to follow simple instructions, and able to perform repeated single-leg calf raises. We excluded participants with injuries, previous ATR, or conditions that would interfere with CRT performance. Before participation, participants were informed verbally and in writing about the study and potential risks involved with participation, such as DOMS. All participants then signed an informed consent document. The Human Research Ethics Committee of the University of Waikato approved this study (HREC2020#11), which followed the Declaration of Helsinki. Any personally identifiable information obtained from participants was coded to preserve anonymity and confidentiality. All data were stored in keeping with university policies on data protection and research governance.

Prior to testing, baseline measurements (i.e., age, gender, height, and body mass) were recorded, and participants completed a self-administered IPAQ short form questionnaire to classify their physical activity levels as low, moderate, or high (Lee et al., 2011). Furthermore, participants were asked, “Which foot do you use to kick a ball?” to determine their leg dominance (van Melick et al., 2017).

4.2.4 Calf raise test protocol

Prior to testing, baseline measurements (i.e., age, gender, height, and body mass) were recorded, and participants completed a self-administered IPAQ short form questionnaire to classify their physical activity levels as low, moderate, or high (Lee et al., 2011). Furthermore, participants were asked, “Which foot do you use to kick a ball?” to determine their leg dominance (van Melick et al., 2017).

All CRT were performed barefoot on either the dominant or non-dominant leg of participants (allocated at random upon arrival for testing). The CRT was conducted three times on three separate occasions in one of the following randomised conditions: flat, incline (10° dorsiflexion), and step (full dorsiflexion). Individuals completed the three test occasions on the same leg that had been allocated to them at random. Test sessions were separated by seven days to minimise residual fatigue and DOMS. Trained physiotherapists conducted all the tests in a university movement laboratory. To warm-up, participants performed 10 double-leg calf raises from the ground at 60 bpm (30 raises per minute), guided by a metronome. Participants then completed three single-leg repetitions on their allocated condition for a given session to ensure the CRT condition was performed appropriately. Two-minute rest was provided after the warm-up before formal experimentation.

Written and verbal instructions were provided to participants before CRT experimentation. Participants stood on one leg with the knee straight on one of three platforms, either flat (0° dorsiflexion), incline (10° dorsiflexion), or step (full dorsiflexion), as shown in Figure 8. Participants were instructed to bend their non-tested leg to 90° knee flexion with their foot behind them. They were allowed to place two fingertips of each hand on the wall in front of them at shoulder height to assist with balance during testing. They were instructed to perform as many calf raises as possible whilst going up as high as possible, returning back to the starting position for each repetition, and keeping the knee of the test leg straight. Each participant performed the test at a frequency of 30 calf raises per minute, guided by a metronome set to 60 bpm. Verbal encouragement was provided at regular intervals throughout the test. Finally, the CRT was stopped when participants could not maintain the pace, bent their test leg knee, moved forward rather than upward, applied more than their fingertips to maintain balance, or stopped due to fatigue (i.e., volitional cessation).

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4.2.4.1 Measurement device

The CRT outcomes were recorded using the CR_{app} (Hébert-Losier & Balsalobre-Fernández, 2020) that uses computer-vision algorithms to track the vertical displacement of a marker placed on the foot (Fernandez et al., 2022; Hébert-Losier & Balsalobre-Fernández, 2020; Hébert-Losier et al., 2022). During testing, the CR_{app} was used to record videos at a sampling rate of 60 Hz on one iPad Air device with iOS 14.1 (Apple, Inc., Cupertino, CA, USA). The iPad was positioned 30 cm from the side of the tested foot of participants, which enabled the entire movement to be captured, and secured using a metal stand. To track the vertical displacement during the CRT, a round black sticker sized 24 mm was placed below the lateral malleolus. The test setup is illustrated in Figure 8.

To derive CRT outcomes, the body mass of individuals recorded on the day of testing was entered into the application and the application was calibrated to the 24 mm round sticker. The computer-vision algorithms then track the vertical displacement of the marker over time from the video recordings, where the initial marker position in the first video frame defines a vertical position of zero. From the position curve, the following outcomes are extracted: number of repetitions (n); peak height (cm) defined as the maximum height of a single repetition from the initial position; total vertical displacement (cm) defined as the sum of all positive displacement, and total work (J) computed as the product of body mass, gravitational acceleration ($9.81\ m/s^2$), and total vertical displacement.

The application has demonstrated good-to-excellent validity of CRT outcomes (i.e., repetitions, peak height, total vertical displacement, and total work) against 3D motion capture and force plate (intraclass correlation coefficient ≥ 0.963, coefficient of variation ≤ 6.9%) (Fernandez et al., 2022; Hébert-Losier et al., 2022). The CR_{app} also demonstrates good-to-excellent inter-rater, intra-rater, and test-retest reliability (Fernandez et al., 2022; Hébert-Losier et al., 2022).

4.2.5 Statistical analyses

We used mixed-effects models (i.e., Poisson for repetitions and linear models for peak height, total vertical displacement, and total work) to examine the effect of ankle starting position on CRT outcomes, accounting for age, gender, BMI, and physical activity levels. Further, upon checking the normality and heteroscedasticity of data, all continuous outcomes were log-transformed to decrease the observed heteroscedasticity. Hence, the estimates from the linear mixed-effects models represent rate ratios.

In our models, participants were treated as nested random factors to deal with the mixed effects sampling scheme generated by individuals being exposed to all three ankle starting positions. In addition, age, gender, BMI, and physical activity levels were entered as fixed factors. Thus, our model included both fixed and random effects. As a reference for comparison, the flat starting position was used to compare the effects of incline and step positions on CRT outcomes. Furthermore, the reference group for gender was set to male.

The mixed-effects models were able to address incomplete data. The mixed-effects framework accommodates for this variability by incorporating random effects, which allows for estimation and consideration of within-subject differences in spite of varying completion rates across conditions or missing data.

In stepwise regression, non-significant predictors were sequentially removed from the initial model using the Bayesian information criterion except for ankle starting position. In all cases, 95% confidence intervals [lower, upper] and p-values were adjusted with the multivariate t-test distribution in post-hoc comparisons. The alpha level for all statistical analyses was set a priori to $p < 0.05$. All data were processed and analysed using R Core Team (2021) version 4.1.1 (2021-08-10) (Team, 2021), and the *lme4* R package for mixed-effects models analyses (Douglas Bates, 2015).

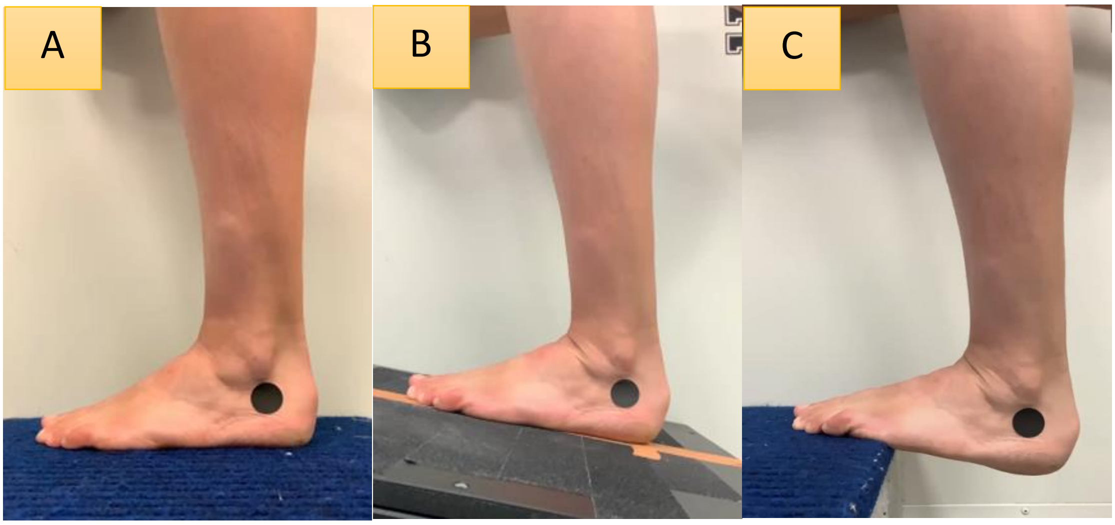

Figure 8. CRT experimental set-up.
A. Flat (0° dorsiflexion); B. Incline (10° dorsiflexion); C. Step (full dorsiflexion).

4.3 Results

4.3.1 Participants

All forty-nine recruited participants participated in the study (29 females and 20 males) and were aged 19 to 41 years. Their demographic data are presented in Table 8. The physical level scores ranged from moderate to high, with no participant presenting with a low level of physical activity. None of the participants were experiencing DOMS on their test leg when reporting for their subsequent experimental session. All participants completed at least two of the three testing sessions, but not all completed all three conditions (Table 9). All available data were analysed.

Table 8. Demographic characteristics of the 49 participants as mean ± standard deviation.

Participants Characteristics	Male	Female	All
	n = 20	n = 29	n = 49
Age (y)	20 ± 2	22 ± 5	21 ± 4
Height (cm)	182 ± 8	168 ± 6	174 ± 10
Mass (kg)	89 ± 21	69 ± 10	77 ± 18
BMI (kg.m^{-2})	27 ± 5	24 ± 3	25 ± 4
IPAQ (Mod: High)	4:16	8:19	12:35

Abbreviation: BMI, body mass index; IPAQ, International Physical Activity Questionnaire; Mod, moderate.

4.3.2 Calf raise test outcomes

Table 9 presents the CRT outcomes as means and standard deviations for each ankle starting position. Results from the mixed-effects models are shown in Table 10, with ankle starting position influencing the four CRT outcomes ($p < 0.001$). Post-hoc comparisons are summarised in Table 11 and revealed that all paired comparisons were statistically significant ($p \leq 0.023$). Finally, Figure 9 illustrates the effects of the three ankle starting positions and predictors on the CRT outcomes.

Table 9. Descriptive summary of calf raise test outcomes as means ± standard deviation by ankle starting position from 49 participants.

Outcomes	Flat (0°)	Incline (10°DF)	Step (Full DF)
	n = 43	n = 48	n = 46
Repetitions (n)	28 ± 8	22 ± 7	18 ± 8
Total vertical displacement (cm)	229 ± 70	211 ± 70	159 ± 80
Peak height (cm)	9.14 ± 1.18	10.86 ± 1.36	8.44 ± 1.87
Total work (J)	1706 ± 608	1571 ± 599	1165 ± 572

Note. Not all 49 participants completed the three ankle starting positions, as indicates the *n* presented under each position.
Abbreviation: DF, dorsiflexion.

The number of repetitions completed was significantly greater in the flat ankle starting position, followed by the incline and step positions (Table 10, Figure 9A). In addition, males performed more repetitions than females ($p = 0.021$), as did individuals with lower BMI ($p = 0.002$) (Table 10, Figure 9A).

Similar to the number of repetitions, total vertical displacement and total work were significantly greater in flat followed by incline and step ($p < 0.023$, Table 10, Figure 9B, D). Moreover, males performed more work than females (Table 10, Figure 9D). Ankle starting position also significantly influenced peak height, with the greatest height seen in incline followed by flat and step ($p \leq 0.002$, Table 10, Figure 9C).

4.3.3 Predictors

Gender and BMI significantly influenced the number of repetitions. Gender also influenced the total work performed (Table 10, Figure 9A, D).

However, gender had no significant effect on peak height ($p = 0.200$) and total vertical displacement ($p = 0.050$). Further, BMI did not significantly influence the total vertical displacement ($p = 0.056$), peak height ($p = 0.835$), and total work ($p = 0.259$).

Finally, age and physical activity levels did not significantly influence CRT outcomes. Consequently, these predictors were dropped from the models during the stepwise regression.

Table 10. Mixed-effects models that considered ankle starting position, age, gender, BMI, and physical activity levels on CRT outcomes.

CRT outcomes	Variables	Estimates* [95% CI]	*p*-value
Repetitions (*n*)	*Positions*		<0.001
	Flat (0°)	-	
	Incline (10°DF)	0.77 [0.70, 0.83]	
	Step (Full DF)	0.61 [0.56, 0.67]	
	Gender		0.021
	Male	-	
	Female	0.83 [0.71, 0.97]	
	BMI	0.97 [0.95, 0.99]	0.002
Total vertical displacement (cm)	*Positions*		<0.001
	Flat (0°)	-	
	Incline (10°DF)	0.88 [0.81, 096]	
	Step (Full DF)	0.61 [0.56, 0.67]	
Peak height (cm)	*Positions*		<0.001
	Flat (0°)	-	
	Incline (10°DF)	4.96 [3.16, 7.81]	
	Step (Full DF)	0.45 [0.29, 0.72]	
Total work (J)	*Positions*		<0.001
	Flat (0°)	-	
	Incline (10°DF)	0.88 [0.81, 0.97]	
	Step (Full DF)	0.62 [0.57, 0.82]	
	Gender		<0.001
	Male	-	
	Female	0.68 [0.57, 0.82]	

Note. Reference indicated with hyphen (-); BMI = body mass index; CI = confidence interval; CRT = calf raise test; DF = dorsiflexion. *Estimates represent rate ratios; 95% CI for position are adjusted using multivariate t-test distribution.

Table 11. Mixed-effects models post-hoc comparisons for the ankle starting position.

CRT outcomes	Variables Comparison / Reference	Estimates* [95% CI]	*p*-value
Repetitions (*n*)	*Positions*		
	Incline (10°DF) / Flat (0°)	0.77 [0.69, 0.85]	<0.001
	Step (Full DF) / Flat (0°)	0.61 [0.55, 0.69]	<0.001
	Step (Full DF) / Incline (10°DF)	0.80 [0.72, 0.90]	<0.001
Total displacement (cm)	*Positions*		
	Incline (10°DF) / Flat (0°)	0.88 [0.79, 0.98]	0.014
	Step (Full DF) / Flat (0°)	0.61 [0.55, 0.68]	<0.001
	Step (Full DF) / Incline (10°DF)	0.70 [0.63, 0.77]	<0.001
Peak height (cm)	*Positions*		
	Incline (10°DF) / Flat (0°)	1.18 [1.10, 1.26]	<0.001
	Step (Full DF) / Flat (0°)	0.90 [0.84, 0.97]	0.002
	Step (Full DF) / Incline (10°DF)	0.77 [0.72, 0.82]	<0.001
Total work (J)	*Positions*		
	Incline (10°DF) / Flat (0°)	0.88 [0.79, 0.99]	0.023
	Step (Full DF) / Flat (0°)	0.62 [0.56, 0.69]	<0.001
	Step (Full DF) / Incline (10°DF)	0.70 [0.63, 0.78]	<0.001

Note. CI = confidence interval; CRT = Calf raise test; DF = dorsiflexion.
*Estimates represent rate ratios. 95% CI and *p* values are adjusted using multivariate t-test distribution.

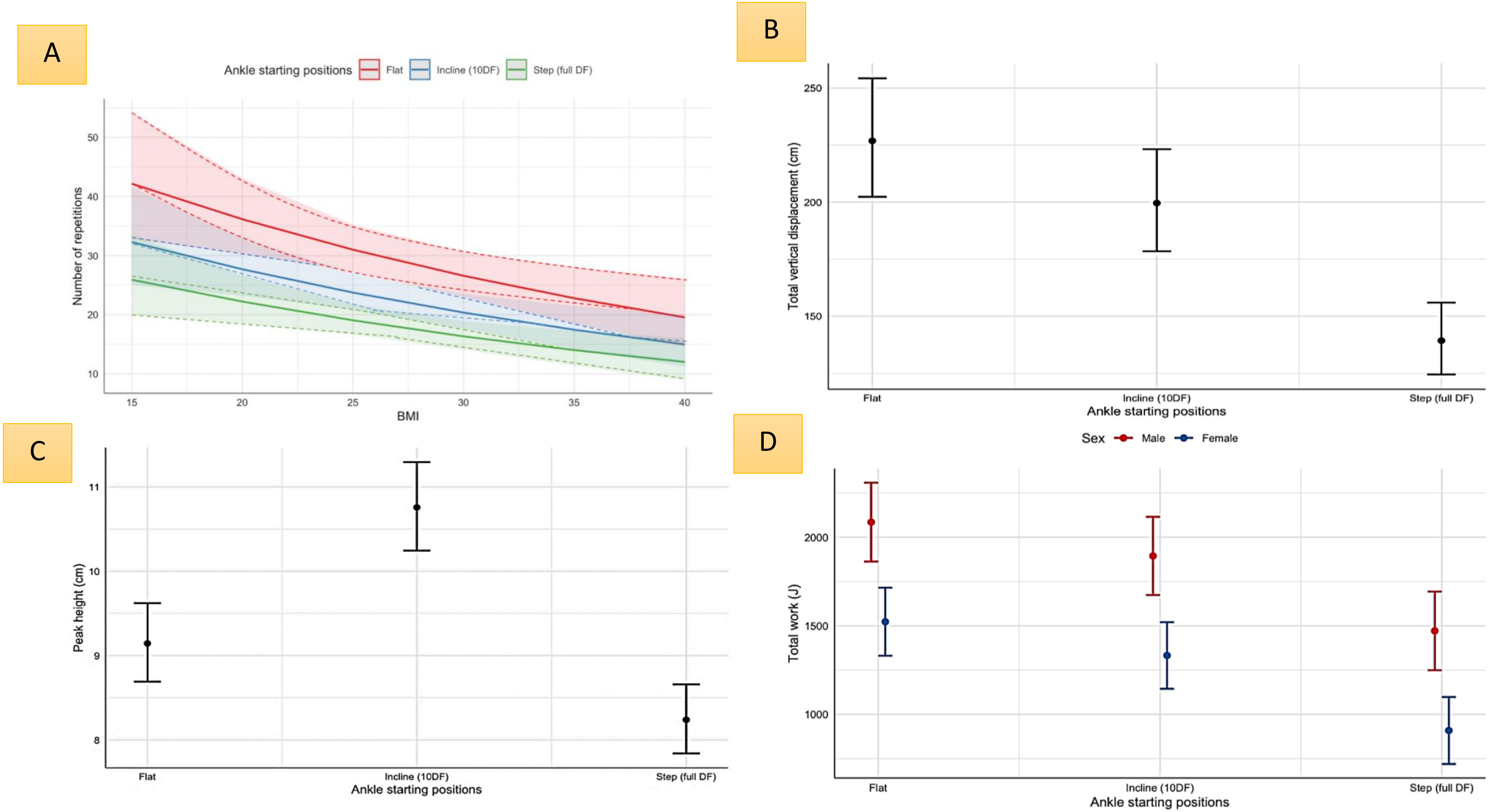

Figure 9. Figures illustrating the effects of the three ankle starting positions on calf raise test outcomes. A. Number of repetitions, B. Total vertical displacement, C. Peak height, and D. Total work. Data are presented as linear graphs or dot plots with mean and standard deviation values. DF = dorsiflexion.

4.4 Discussion

This study is the first of its kind, comparing CRT outcomes between the three most common ankle starting positions used for this test. This study clearly illustrates differences in CRT outcomes between the three test positions, thus supporting the hypothesis that altering ankle position affects the number of repetitions, total vertical displacement, peak height, and total work. In addition, gender and BMI significantly affected the number of repetitions and total work performed in the CRT, whereas age and physical activity level did not influence any of the CRT outcomes in our population.

The ankle position is one of many CRT parameters identified as variable in research and clinical settings, with the plantigrade (flat) ankle position being the most common, followed by the 10° dorsiflexion (incline) position (Hébert-Losier et al., 2009). Although these ankle starting positions are common, no previous studies have directly compared CRT outcomes between positions. Our results support that changing ankle starting position significantly influences CRT outcomes, which might partly explain the variable normative values reported in the literature with regards to the number of repetitions (Bohannon, 2022) given the lack of use of a standardised protocol (Hébert-Losier et al., 2009). Indeed, performing the CRT from plantigrade (flat) (Jan et al., 2005; Lunsford & Perry, 1995) and 10° dorsiflexion (incline) (Hébert-Losier et al., 2017) positions have both been used to establish normative values.

To explore the effect of ankle starting position, we adopted commonly used test parameters, i.e., knee starting position, extension; calf raise height, as high as possible; balance, fingertip support; pace, set at 30 raises per minute (guided by a 60 bpm metronome); and test termination criteria (e.g., volitional exhaustion, pace not maintained, supporting knee flexed, forward lean) (K. Hébert-Losier et al., 2009). Overall, our study indicates that performing the CRT on the flat will yield a superior number of repetitions, with 23% and 39% more repetitions compared to on a 10° incline or with the forefoot on the edge of a step, respectively. These differences should be considered when administering the CRT, contrasting clinical outcomes to normative values, and comparing literature using different protocols.

We also found that ankle starting position influenced other CRT outcomes than repetitions (i.e., peak height, total vertical displacement, and total work), which were measured using a valid and reliable iOS mobile application (Fernandez et al., 2022). Although the primary outcome evaluated in clinics is the number of repetitions performed, Svantesson, Osterberg, Thomeé, et al. (1998) suggested to also assess calf raise height since shorter heights could lead to a greater number of repetitions as less work is required per repetition due to a lesser range. Additionally, from a clinical perspective, it is noteworthy that the number of repetitions and peak height CRT outcomes are associated with different physiological and structural factors (Svensson et al., 2019). Contractile tissue and muscle endurance metabolism determine the number of repetitions (Holloszy, 1967), while tendon length moreover determines peak height (Baxter et al., 2018). All these triceps surae MTU properties influence the total vertical displacement and work performed (Silbernagel et al., 2010; Svantesson, Osterberg, Thomeé, et al., 1998).

Furthermore, research supports that peak height and work are more sensitive outcomes than repetitions in presence of pathology and functional deficits (Baxter et al., 2018; Svensson et al., 2019; Zellers et al., 2018; J. A. Zellers et al., 2020). Overall, our study indicates that performing the CRT on the flat yields a superior total vertical displacement and work, with 12% and 38-39% greater values than when completed on a 10° incline or with the forefoot on the edge of a step, respectively. Peak height, however, was the greatest on the 10° incline, being 18% and 15% greater than from flat or step conditions. Again, these discrepancies in outcomes highlight how test protocol can affect outcomes, which warrant clinical and research consideration.

Repetitions, total vertical displacement, and total work were the greatest in the plantigrade (flat) ankle starting position, and the lowest from the step. Although our study did not measure muscle fibre length using ultrasound, ankle torque, or muscle activity using EMG, changes in ankle position have been shown to affect muscle length and torque values due to the length-tension relationship (Cresswell et al., 1995; Sale et al., 1982), as well as triceps surae EMG (Sale et al., 1982). Sale et al. (1982) reported that increasing ankle dorsiflexion lengthens the triceps surae muscles and increases plantarflexion torque, which could presumably increase the number of repetitions, total vertical displacement, and work outcomes from the CRT performed on an incline or step compared to flat**.** However, increasing ankle range of motion during plantarflexion efforts also increases the contraction time and EMG activation of the triceps surae muscles (Sale et al., 1982)**,** thus potentially leading to an earlier onset of muscle fatigue and CRT termination.

Further, when standing on a flat surface, calf raises are arguably performed in a more habitual manner in that the movement pattern resembles walking on a level surface (Meinders et al., 1998). An inclined surface and a step, on the other hand, require greater ranges of motion and stabilisation throughout that range, with greater work demands (McIntosh et al., 2006) and activation (Lichtwark & Wilson, 2006) of the triceps surae muscles. Furthermore, the CRT was executed to the same pace across ankle positions in our study. The time during which the heel was in contact with a supporting surface between repetitions was greatest in the flat condition, followed by the incline condition. In the step condition, the heel was never in contact with a supporting surface; hence, the muscles were presumably always contracted and the time under tension was greatest. All these factors could explain the quicker muscle fatigue in the incline and step conditions, resulting in lower CRT outcomes in comparison to the flat condition.

Presumably, peak height should have been greatest in the step condition due to an increased range of plantarflexion motion, which was not the case. This finding is likely due to participants not going through the entire range of available motion despite instructions at the start as well as during the CRT. As the CR_{app} takes the marker position in the first video frame as defining a vertical position of zero, the 10° incline condition often resulted in a greater range of calf raise motion and peak height than the step condition as the ankle was visibly in greater dorsiflexion. Furthermore, participants had a tactile end point to return to in the incline condition compared to the step condition, encouraging them to return to a dorsiflexed position. Range of motion during testing was not actively monitored as part of this investigation, which could have confirmed these observations.

Previously reported data (Jan et al., 2005; Möller et al., 2005; Sman et al., 2014) on repetitions performed from a plantigrade (flat) ankle position are consistent with our results (i.e., means around 28 repetitions), but no data for the other CRT outcomes (peak height, total vertical displacement, and total work) are available for comparison. For the incline (10° dorsiflexion) and step positions, our means are within range of previously published studies (Byrne et al., 2017; Hébert-Losier et al., 2022; Hébert-Losier et al., 2017; Silbernagel et al., 2006; Svantesson, Osterberg, Thomeé, et al., 1998), with some expected variations linked with differences in sampled population, CRT protocol, and measuring device. For instance, the mean work completed in a cohort of rugby players from a step condition was almost double compared to ours (Hébert-Losier et al., 2022), which can be explained in large part due to differences in body mass. This difference between populations emphasises the importance of population-specific normative data to inform practice.

Furthermore, despite our efforts to standardise the test protocol and replicate those commonly used in the literature, differences in pace or cadence (Haber et al., 2004; Lunsford & Perry, 1995; Möller et al., 2005; Österberg et al., 1998), could also explain variance in CRT outcomes when contrasting studies (Kudo et al., 2015). In addition, most studies use a linear encoder to track heel displacement when quantifying CRT outcomes (Byrne et al., 2017; Silbernagel et al., 2010). We used the CR_{app} with a marker placed below the lateral malleolus rather than at the heel, like the linear encoder. This lateral marker placement was selected despite potential differences in outcome with a heel marker placement as the lateral malleolus marker is less prone to perspective errors and has been shown more valid compared to laboratory-based systems (Fernandez et al., 2022).

Females performed fewer repetitions than males (17%), as did individuals with a greater BMI. This gender difference is in line with previous studies (Jan et al., 2005) and general physiology, wherein females exhibit lower strength levels, cross-sectional area of the triceps surae muscles, and plantarflexor torque than males (Ema et al., 2020b; Handelsman et al., 2018; Jan et al., 2005; Sepic et al., 1986). However, some studies (Sara et al., 2021; Sman et al., 2014) found no gender-specific differences in the number of repetitions performed during the CRT, and that the 17% difference between genders we found reflects a 3 to 5 repetition difference. It is debatable whether this difference is clinically meaningful given that six repetitions typically defines the minimal detectable change based on test-retest data (Hébert-Losier et al., 2017). In line with a prior study (Hébert-Losier et al., 2022), we also found that BMI affected the number of repetitions, wherein a one unit increase in BMI resulted in a 3% decrease in repetition.

Individuals with an increased BMI are at a biomechanical disadvantage during the CRT due to the need to support additional body mass against gravity, which may lead to earlier triceps surae muscle fatigue. These findings align with research indicating poorer musculoskeletal (Jiang et al., 2012), fitness (Joshi et al., 2012), and muscular endurance (Mayer et al., 2012) outcomes in individuals with greater BMI. However, BMI did not affect the total work outcome likely due to body mass being accounted for in the work computations. In contrast to prior studies finding differences in the number of repetitions (Hébert-Losier et al., 2012a; Hébert-Losier et al., 2017; Jan et al., 2005; Sara et al., 2021), physical activity levels and age did not influence any of CRT outcomes.

Our population had a relatively narrow age range and were all engaged in moderate-to-high levels of physical activity; hence, this homogeneity would have reduced data variability and potentially affected our results. This homogeneous nature of our population may limit the generalisability of our results to a broader population. As exploring the potential influence of predictors on CRT outcomes was a secondary objective to examining the effect of ankle position, we included these predictors as confounding variables. We did not specifically design the study to examine the effects of predictors on CRT outcomes. Hence, this study was powered to detect significant differences in CRT outcomes between ankle starting positions.

Our study has limitations. First, the findings are based on a sample of healthy young adults, which limits their generalisability to clinical and other populations. Nevertheless, this study provides a starting point for further research into the effects of ankle starting position on CRT outcomes, with implications for individuals with weakness. Further, the step condition was meant to involve full dorsiflexion range, with participants not reaching full dorsiflexion based on our video observations. We did not standardise or quantify each participant's full range of motion or monitor range of motion during testing. Hence, we cannot define how much dorsiflexion affects CRT performance. Finally, we can only make inferences to muscle activity, fatigue levels, and muscle fibre length as EMG and ultrasound were not used.

Based on our findings, the following recommendations are made for research and clinical application. The CRT can be performed from three ankle starting positions, and each position influences the test outcomes (e.g., expect the least number of repetitions in CRT from a step, and the greatest from flat). To provide evidence-based practice in terms of clinical decision-making, future research is recommended to examine the effects of varying CRT ankle starting positions in pathological and other populations, such as paediatric and elderly. It is pertinent to consider the type of injury and phase of rehabilitation when administering the CRT (i.e., insertional versus mid-portion Achilles tendinopathy or early-stage versus late-stage post-ATR) and choosing the ankle start position, as there are different loads and shears applied to the Achilles tendon. Finally, interpretation of CRT outcomes should also consider other predictors, such as gender and BMI.

4.5 Conclusion

Significant differences between the three most common ankle starting positions of the CRT were found in the number of repetitions, peak height, total vertical displacement, and total amount of work. Among the predictors, gender and BMI significantly influence the number of repetitions and total work, whereas age and physical activity levels did not. The latter result might have stemmed from the homogeneity of participants. The effect of varying ankle position on CRT outcomes can inform ankle functional assessments, progress monitoring, and rehabilitation management. Interpretation of CRT outcomes and between-study comparisons need to consider these factors.

Chapter 5

Effects of cadence on calf raise test outcome: Cadence does matter

Fernandez, M. R., Athens, J., O Neill, S., Kubo, M., & Hébert-Losier, K. (2023). Effects of cadence on calf raise test outcomes: Cadence does matter. *Under Review*

Prelude: The previous Chapter showed that varying ankle starting positions significantly influenced CRT outcomes. Gender and BMI also significantly affected outcomes. Using the validated and reliable CR_{app}, this Chapter now seeks to examine how CRT cadence influences outcomes. Specifically, this Chapter investigates the effects of varying cadence (i.e., 30, 60, and 120 bpm) on CRT outcomes, while accounting for predictors linked with participant characteristics.

5.1 Introduction

The triceps surae MTU is composed of three muscles (MG, LG, SOL) connected distally by a single long viscoelastic compliant tendon (the Achilles tendon) (Lehr et al., 2021). Both MG and LG are bi-articular muscles that act on both knee and ankle joints. These muscles contain approximately equal proportions of Type I (slow-twitch, fatigue-resistant) and Type II (fast-twitch, force and power generating, fatigue-sensitive) muscle fibres (Spendiff et al., 2002). On the other hand, SOL is mono-articular and acts only at the ankle joint and contains a greater proportion of Type I (>75%) than Type II fibres (Johnson et al., 1973; Kawakami et al., 1998). The triceps surae MTU is a key contributor to human movement (e.g., walking, running, and jumping) (Hof et al., 2002; Machado et al., 2021). Aside from its force-transmitting role, the Achilles tendon stores and releases elastic energy, sparing the muscles' work and thus conserving metabolic energy (Monteiro et al., 2020). In the presence of pathologies, such as Achilles tendinopathies (Silbernagel et al., 2006), Achilles ruptures (Möller et al., 2002), or triceps surae muscle strains (Bryan Dixon, 2009), daily functional activities and athletic performances (Gallo et al., 2012) are compromised.

The CRT is a widely accepted clinical tool that assesses triceps surae MTU function. This test consists of repeated concentric–eccentric plantarflexors contractions in unilateral stance performed to volitional cessation. The number of calf raise repetitions is recorded as the primary clinical outcome (K. Hébert-Losier et al., 2009; Silbernagel et al., 2010). One naturally occurring MTU function is the stretch-shortening cycle (SCC) whereby an eccentric contraction precedes a concentric one (Komi, 2000), which ultimately enhances contractile performance (Seiberl et al., 2021). The lengthening of the triceps surae MTU during the eccentric phase of the SSC facilitates force production during the subsequent concentric phase, with the resulting force output depending on the velocity and coupling times between the eccentric and concentric actions (Komi, 2000; Svantesson & Grimby, 1995). More explicitly, faster speeds and shorter coupling times in SSC actions generally result in greater concentric force and better muscle performance (Seiberl et al., 2021). However, faster contractile shortening velocities performed repeatedly are more fatigable than slower ones; hence, velocity of movement can affect muscle fatigue (Spendiff et al., 2002). It is therefore likely that a change in calf raise cadence or pace may affect CRT outcomes.

Although the CRT is a reliable assessment tool (Hébert-Losier et al., 2017; Möller et al., 2005; Ross & Fontenot, 2000), a previous literature review (K. Hébert-Losier et al., 2009) has identified that CRT parameters vary considerably when administered. Thus, determining the most appropriate parameters for addressing specific test objectives and interpreting test outcomes can be challenging clinically. The most used cadence in the literature to pace CRT repetitions is 60 bpm, but ranges from 40 to 120 beats per minute (bpm) (K. Hébert-Losier et al., 2009; Kim Hébert-Losier et al., 2009; Möller et al., 2002). These cadences result in performing 20 to 60 calf raise repetitions per minute during the CRT (K. Hébert-Losier et al., 2009; Kim Hébert-Losier et al., 2009; Möller et al., 2002). In walking, varying cadences has been shown to affect triceps surae MTU and gastrocnemius muscle mechanics (Brennan et al., 2017). Specifically, MG fascicles shortened more quickly at cadences slower than preferred, but not at higher cadences despite greater muscle activation. It was proposed that MG shortening work and cumulative activation costs were greater at cadences slower and higher than preferred, respectively (Brennan et al., 2017). It remains unknown how cadence influences CRT outcomes (i.e., repetitions, total vertical displacement, total work, peak height, and peak power) as no comparisons have been published to date.

Although there are no studies on the effect of cadence on unilateral calf raise performances, a prior study has examined its effects on bilateral calf raises to fatigue (da Silveira et al., 2022). Performing the CRT standing on both legs at 60 repetitions per minute versus at a self-selected (as fast as possible, 69 repetitions per minute) cadence led to comparable numbers of repetitions being performed despite higher heart rates at the faster cadence (da Silveira et al., 2022). The lack of difference in CRT outcomes might be due to the small difference in cadences between conditions (i.e., 9 repetitions per minute), as well as the focus on the number of repetitions that primarily reflects the endurance ability of the triceps surae muscles. From a clinical perspective, endurance, power, and work metrics all represent muscle performance. Since larger variations in CRT cadence are used in the literature and in clinical practice (K. Hébert-Losier et al., 2009; Kim Hébert-Losier et al., 2009; Möller et al., 2002), it becomes important to examine how a spectrum of cadence affects unilateral CRT outcomes, notably repetitions, total vertical displacement, total work, peak height, and peak power.

Furthermore, studies (Hébert-Losier et al., 2017; Jan et al., 2005) have shown that the number of repetitions performed during CRT varies between genders based on differences in muscle cross-sectional area and fibre type composition (Haizlip et al., 2015; Zhou et al., 2017), with a lower number of repetitions generally seen in females. In addition, other predictors, such as body mass index (BMI) (Hébert-Losier et al., 2022; Hébert-Losier et al., 2017), have been shown to influence CRT outcomes; specifically, repetitions decrease as BMI increases. BMI may also affect work and power as these variables are directly related to load during dynamic tasks (Farris & Sawicki, 2012; Rivière et al., 2020). Moreover, a previous study reported that increased age and lower levels of physical activity negatively affected CRT repetitions (Hébert-Losier et al., 2017). As muscle strength and fatigue are generally related to age (Ema et al., 2020a) and physical activity participation (Bogdanis, 2012), these variables might potentially affect other CRT outcomes.

Therefore, our main aim was to determine the effect of cadence (i.e., 30, 60, and 120 bpm) on unilateral CRT outcomes. We hypothesised that a faster cadence would result in greater peak power during the unilateral CRT, but lower number of repetitions, total distance, and work due to faster muscle shortening velocities being more fatigable. The peak height of repetitions should remain unaffected by cadence. As a secondary aim, we also examined the effect of age, gender, BMI, and level of physical activity on CRT outcomes.

5.2 Methods

5.2.1 Sample size

Based on one-sample comparison of means and setting the minimal detectable change between cadence conditions to six repetitions based on test-retest data (Olsson et al., 2014), the estimated required sample size was of 32 to attain 80% power at a 5% level of significance (mean = 32 repetitions, standard deviation = 12 repetitions). To account for 10% of missing data, 35 participants were targeted.

5.2.2 Study design

A randomised crossover study with repeated measures was used to examine the effect of varying cadence (i.e., 30, 60, and 120 bpm) on CRT outcomes: number of repetitions, total vertical displacement, total work, peak height, and peak power. Predictors such as age, gender, BMI, and physical activity levels based on IPAQ short form (Lee et al., 2011) scores were also considered in the analysis.

5.2.3 Participants

We recruited 36 healthy individuals from the local community using targeted online distribution lists and word of mouth. Participants had to be at least 16 years old, able to follow instructions, and able to perform repeated unilateral calf raises. Participants with injuries and or conditions that could interfere with CRT performance were excluded. The objectives and methods of the study, as well as the possible risks (e.g., delayed onset muscle soreness), were thoroughly explained to participants prior to participation. Following that, participants signed an informed consent form. The Human Research Ethics Committee of the University of Waikato approved this study (HREC2020#11), which followed the Declaration of Helsinki guidelines. Anonymity and confidentiality were maintained by coding any personally identifiable information obtained from participants. All data were stored in compliance with university policies on data protection and research governance.

Baseline measures (i.e., age, gender, height, and mass) and a self-administered IPAQ short-form questionnaire were collected prior to testing (Lee et al., 2011). Based on answers to the IPAQ, participants were categorised as having low, moderate, or high levels of physical activity. In addition, participants were asked, “Which foot do you use to kick the ball?” to determine leg dominance (van Melick et al., 2017).

5.2.4 Calf raise test protocol

The CRT was performed barefoot on a 10° inclined custom-made steel platform three times on three separate occasions in one of the following randomised test conditions: 30, 60 and 120 bpm. These cadences would correspond to completing 15, 30, and 60 full calf raise repetitions per minute as participants were going up in one metronome beat, and down in one metronome beat. All CRT for a given individual were administered either on the dominant or non-dominant leg. The test side was allocated to each participant in a counterbalanced randomised order. To minimise residual fatigue and delayed onset muscle soreness, tests were separated by seven days. Upon reporting for testing on the second and third occasions, participants were asked whether they were experiencing calf muscle soreness from the prior session.

A single trained researcher administered all tests either at our institution's biomechanics laboratory or at the home of participants based on their preference. All testing was performed in the same location for a given individual, and in a well-lit environment. The platform was placed on a firm level surface. As part of the warm-up, participants performed ten bilateral calf raises from the ground at a self-selected cadence. Participants then performed three unilateral calf raises on the 10° incline following the beat of a metronome in accordance with their assigned cadence condition for that day to ensure they were performing the task appropriately. Participants rested two-minutes after the warm-up before formal experimentation.

Written and verbal instructions were provided to participants before data collection. Participants stood barefoot on one leg on the 10° platform with the knee straight prior to completing the test. Participants were required to follow the beat of a metronome set at one of three different cadences (i.e., 30, 60 and 120 bpm), going up in one beat and down in one beat. During the CRT, participants maintained the test leg fully extended, and the contralateral leg bent to 90° knee flexion with the foot behind them. We instructed participants to perform as many repetitions as possible and to go as high as possible, returning the foot to the initial position for each repetition. Participants were allowed to place two fingertips per hand at shoulder height against the wall for balance. Throughout the test, the researcher provided regular and consistent verbal encouragement. Finally, the test was ceased if participants failed to maintain the CRT pace, flexed their test leg, moved forwards instead of upwards, used more than two fingertips for balance support, or stopped due to fatigue (i.e., volitional cessation). One warning was provided to re-establish correct form before test cessation.

5.2.4.1 Measurement device

The CRT outcomes were recorded using the Calf Raise application ($CR_{app)}$ (version 1.5.1) (Hébert-Losier & Balsalobre-Fernández, 2020) that uses computer-vision algorithms to track the vertical displacement of a marker placed on the foot (Fernandez et al., 2022; Hébert-Losier & Balsalobre-Fernández, 2020; Hébert-Losier et al., 2022). During testing, the application was used to record videos at a sampling rate of 60 frames per second on one iPad Air device with iOS 14.1 (model A1822, Apple, Inc., Cupertino, CA, USA). The iPad was positioned 30 cm from the side of the tested foot of participants and secured using a metal stand. To track the vertical displacement during the CRT, a round black sticker sized 24 mm was placed below the lateral malleolus. The test setup is illustrated in Figure 10.

To derive CRT outcomes, the application was first calibrated to the 24 mm round sticker. From the position curve, where the initial marker position in the first video frame defines a vertical position of zero (i.e., heel in contact with the platform), the following measures are extracted: number of repetitions (*n*); peak vertical displacement (cm) defined as the maximum height of any one of the calf raise repetitions; and total vertical displacement (*d*, cm) computed as the sum of all total positive vertical displacement. Before data extraction, the mass of individuals recorded on the testing day was entered into the application to calculate the total positive work (J) as the product of F_g (body mass multiplied by gravitational acceleration, 9.81 m/s^2) and total vertical displacement (*d*). Finally, peak power (W) was extracted from the power curve generated using:

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

where $\Delta time$ is based on the sampling frequency (i.e., 0.0167 s at 60 frames per second).

The application has demonstrated excellent validity for all CRT outcomes (repetitions, total vertical displacement, total work, peak height, and peak power) derived from a lateral marker position against 3D motion capture and force plate data (intra-class correlation, ICC: 0.963 to 1.00; coefficient of variation, CV: 0 to 8.6%) (Fernandez et al., 2022; Hébert-Losier et al., 2022). The application also demonstrates excellent intra-rater (ICC: 0.983 to 1.000, CV: 0.0 to 3.5%), excellent inter-rater (ICC: 0.977 to 0.997, CV: 1.6 to 3.9%), and good to excellent test-retest (ICC: 0.87 to 0.96, CV: 6.5 to 9.8%) reliability for these outcomes (Fernandez et al., 2022; Hébert-Losier et al., 2022; Hébert-Losier et al., 2017).

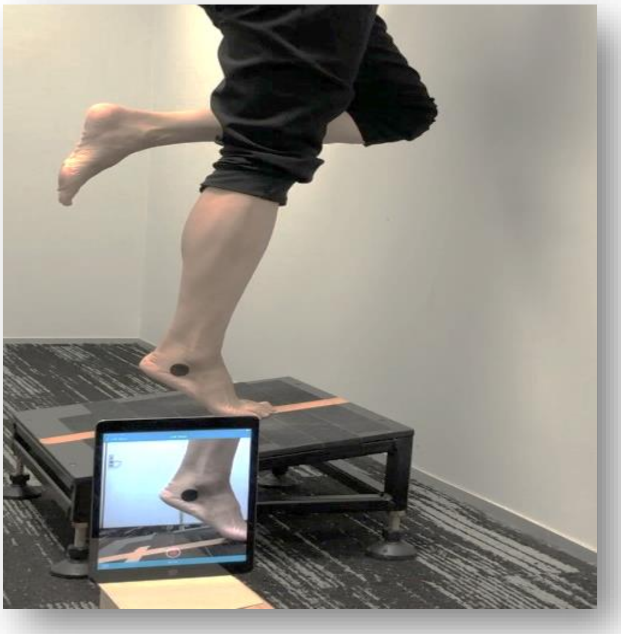

Figure 10. Calf raise test experimental set-up.

5.2.5 Statistical analyses

We used linear mixed-effects models (i.e., Poisson for repetitions and linear models for total vertical displacement, total work, peak height, and peak power) to examine the effect of cadence on CRT outcomes, accounting for age, BMI, gender, and physical activity level. Further, upon checking the normality and heteroscedasticity of data, all continuous outcomes were log-transformed to decrease the observed heteroscedasticity. Hence, the estimates from the linear mixed-effects models represent rate ratios.

In our models, participants were treated as nested random factors to deal with the mixed-effects sampling scheme generated by individuals being exposed to all three different cadences. In addition, CRT cadence, age, BMI, gender, and physical activity level based on IPAQ scores were entered as fixed factors. Thus, our model included both fixed and random effects. As a reference point of comparison, the 60 bpm (30 repetitions per minute) cadence condition was used to compare the effects of 30 and 120 bpm on CRT outcomes. Furthermore, the reference group for gender was set to male and activity level to high.

In stepwise regression, non-significant predictors were sequentially removed from the initial model using the Bayesian information criterion except for the cadence. In all cases, 95% confidence intervals (CI) and *p*-values were adjusted with the multivariate t-test distribution. The alpha level for all statistical analyses was set a priori to $p < 0.05$. Data were processed and analysed using R (2021) version 4.1.1 (2021-08-10), and linear mixed effects analyses were performed using the *lme4* R package.

5.3 Results

5.3.1 Participants

Thirty-six participants completed the study (18 women and 18 men), with a mean age of 29 ± 9 years. The physical activity levels of participants were moderate or high, with no participant presenting with a low level of physical activity. None of the participants were experiencing calf muscle soreness on their test leg when reporting for their experimental sessions. Demographic information is presented in Table 12.

Table 12. Demographic characteristics of participants as mean ± standard deviation.

Characteristics	Male (*n* = 18)	Female (*n* = 18)	All (*n* = 36)
Age (y)	28 ± 9	30 ± 10	29 ± 9
Height (cm)	178 ± 9	164 ± 16	171 ± 11
Mass (kg)	97 ± 73	73 ± 15	85 ± 19
BMI (kg.m^{-2})	30.4 ± 27.2	27.2 ± 4.9	28.8 ± 4.5
Physical activity level[a] (Mod: High)	17:1	10:8	27:9

Note: [a]International Physical Activity Questionnaire short form categories expressed as a ratio (Mod: High). Mod, moderate.

5.3.2 CRT outcomes

CRT outcomes for each cadence condition are summarised in Table 13. Results from the mixed-effects models are shown in Table 14. On average, participants completed 16 to 18 repetitions across the three cadence conditions. The mixed-effects model analyses revealed that cadence significantly influenced total vertical displacement, total work, peak height, and peak power CRT outcomes (all $p \leq 0.008$, Table 3), but not the number of repetitions ($p = 0.200$, Table 14).

Post-hoc analyses are summarised in Table 14, and Figure 11 shows the effects of the three cadence conditions and other factors on CRT outcomes. Post-hoc analysis (Table 15) revealed that CRT performed at 60 bpm resulted in significantly greater total vertical displacement and work than the slower (30 bpm) and faster (120 bpm) cadences, with no significant difference between the latter two cadences. In addition, peak height was significantly greater in the 60 and 120 bpm conditions than at 30 bpm. Finally, peak power was significantly greater at 120 bpm than 30 and 60 bpm, with the difference in peak power not reaching significance between the slower two cadences ($p = 0.080$).

5.3.3 Predictors

Gender, BMI, age, and physical activity level

Mixed-effect models revealed a significant difference in the total work (Figure 11D) and peak power (Figure 11E) between males and females, where males outperformed females by ~30% ($p < 0.001$, Table 14). In contrast, there were no significant differences in repetitions ($p = 0.410$), total vertical displacement ($p = 0.114$), and peak height ($p = 0.112$) between males and females.

Moreover, BMI significantly influenced the number of repetitions ($p = 0.007$, Figure 11A), total vertical displacement ($p = 0.003$, Table 3, Figure 11B), and peak power ($p = 0.005$, Figure 11E) generated in the CRT (Table 14**).** Results indicate that as BMI increased, repetitions and total vertical displacement declined, whereas peak power increased. In contrast, BMI did not significantly affect peak height ($p = 0.082$) and total work ($p = 0.725$). Finally, age and physical activity levels did not significantly influence any of the CRT outcomes.

Table 13. Means ± standard deviation of Calf Raise Test outcomes across all three cadences from 36 participants.

CRT outcomes	**Cadence (bpm)**[a]		
	30	**60**	**120**
Number of repetitions (*n*)	16 ± 6	18 ± 6	17 ± 7
Total vertical displacement (cm)	167 ± 69	187 ± 65	163 ± 69
Total work (J)	1365 ± 570	1513 ± 511	1327 ± 545
Peak height (cm)	11.37 ± 1.65	12.00 ± 1.88	11.96 ± 2.03
Peak power (W)	328 ± 126	351 ± 131	394 ± 141

Note: [a]Cadence followed during the test, raising in one beat and lowering in one beat. CRT, Calf Raise Test.

Table 14. Mixed-effects models that considered Calf Raise Test cadence, age, gender, body mass index, and physical activity levels on Calf Raise Test outcomes**.**

CRT outcomes	**Variables**	**Estimate**[b] **[95% CI]**	***p*-value**
Number of repetitions (*n*)	*Cadence*[a]		0.200
	30	0.90 [0.80, 1.01]	
	60	-	
	120	0.93 [0.83, 1.04]	
	BMI	0.97 [0.95, 0.99]	0.008[†]
Total vertical displacement (cm)	*Cadence*[a]		0.007[†]
	30	0.87 [0.78, 0.97]	
	60	-	
	120	0.85 [0.77, 0.95]	
	BMI	0.97 [0.95, 0.99]	0.003[†]
Total work (J)	*Cadence*[a]		0.006[†]
	30	0.87 [0.78, 0.97]	
	60	-	
	120	0.85 [0.76, 0.95]	
	Gender		<0.001[†]
	Male	-	
	Female	0.70 [0.57, 0.85]	
Peak height (cm)	*Cadence*[a]		0.008[†]
	30	0.95 [0.92, 0.98]	
	60	-	
	120	1.00 [0.96, 1.03]	
Peak power (W)	*Cadence*[a]		<0.001[†]
	30	0.93 [0.86, 0.99]	
	60	-	
	120	1.13 [1.05, 1.21]	
	BMI	1.03 [1.01, 1.05]	0.005[†]
	Gender		<0.001[†]
	Male	-	
	Female	0.71 [0.60, 0.84]	

Note: [a]Cadence followed during the test, raising in one beat and lowering in one beat. [b]Estimates represent rate ratios. 95% CI for cadence are adjusted using multivariate t-test distribution. [†]Indicates significance ($p < 0.05$). Reference indicated with hyphen (-). BMI, body mass index; CI, confidence interval; CRT, calf raise test.

Table 15. Mixed-effects models post-hoc comparisons for the three Calf Raise Test cadences.

CRT outcomes	**Variables Comparison/Reference**	**Estimate[b] [95% CI]**	***p*-value**
Number of repetitions (*n*)	*Cadence*[a]		
	30/60	0.90 [0.79, 1.03]	0.152
	120/60	0.93 [0.81, 1.06]	0.380
	120/30	1.03 [0.90, 1.18]	0.857
Total vertical displacement (cm)	*Cadence*[a]		
	30/60	0.87 [0.76, 0.99]	0.033†
	120/60	0.85 [0.75, 0.97]	0.014†
	120/30	0.98 [0.86, 1.12]	0.946
Total work (J)	*Cadence*[a]		
	30/60	0.87 [0.76, 0.99]	0.031†
	120/60	0.85 [0.75, 0.97]	0.012†
	120/30	0.98 [0.86, 1.12]	0.932
Peak height (cm)	*Cadence*[a]		
	30/60	0.95 [0.91, 0.99]	0.019†
	120/60	1.00 [0.95, 1.04]	0.981
	120/30	1.05 [1.00, 1.10]	0.031†
Peak power (W)	*Cadence*[a]		
	30/60	0.93 [0.85, 1.01]	0.080
	120/60	1.13 [1.04, 1.23]	0.003†
	120/30	1.22 [1.12, 1.32]	<0.001†

Note. [a]Cadence followed during the test, raising in one beat and lowering in one beat. [b]Estimates represent rate ratios. 95% CI for cadence are adjusted using multivariate t-test distribution. †Indicates significance ($p < 0.05$). CI, confidence interval; CRT, Calf Raise Test.

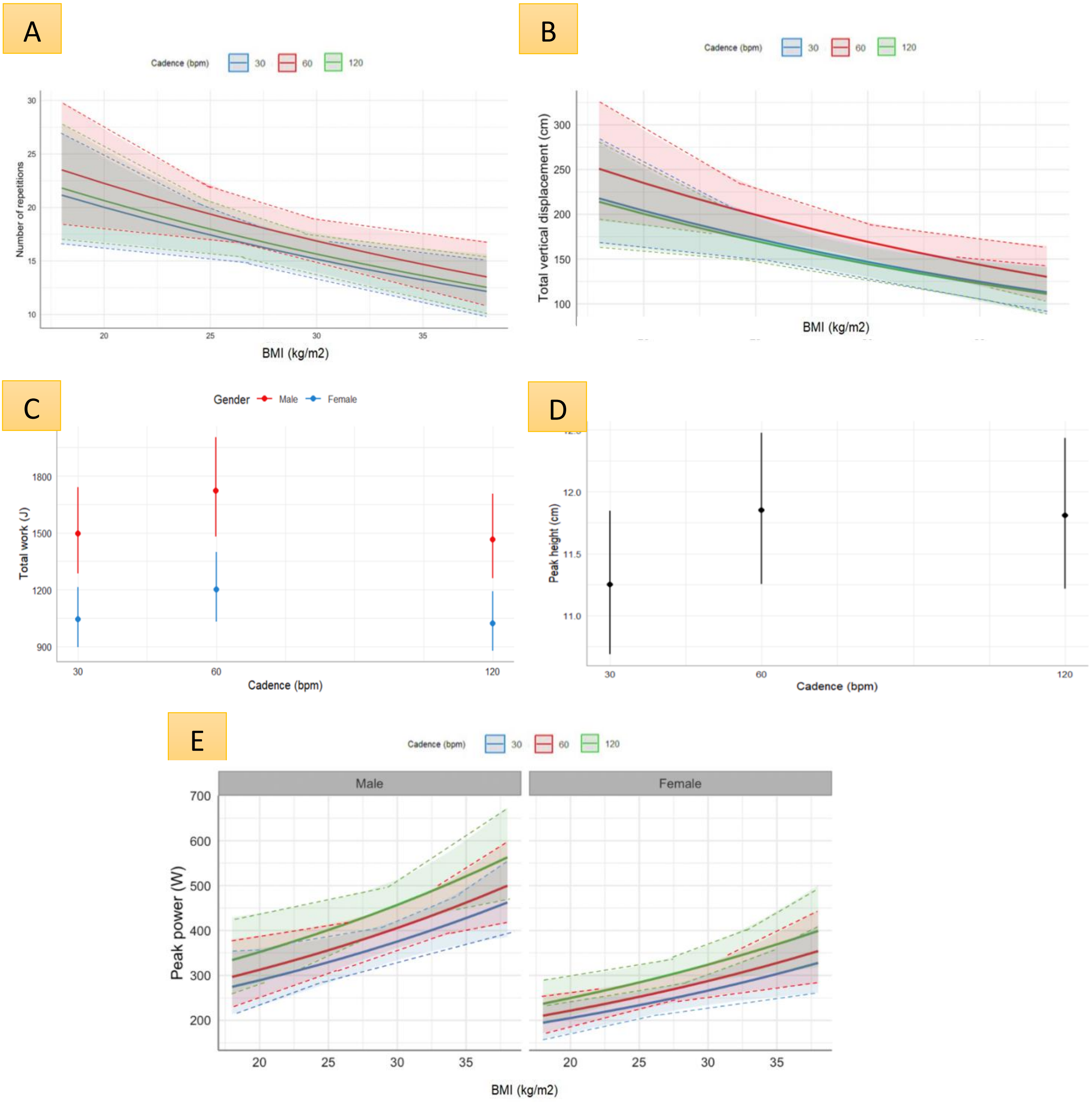

Figure 11. Figures illustrating the effects of the three different calf raise cadences on the calf raise test outcomes and predictors found to significantly affect outcomes.
A. Number of repetitions, B. Total vertical displacement, C. Peak height, D. Total work, E. Peak power. Data are presented as linear graphs or dot plots with mean and standard deviation values. Note that the cadence represents the cadence followed during the test, raising in one beat and lowering in one beat.

5.4 Discussion

We explored the effects of test cadence on CRT outcomes and show that cadence significantly influences total vertical displacement, total work, peak height, and peak power during the CRT, but not repetitions. Thus, our findings are in partial agreement with our stated hypotheses in that cadence influenced most outcomes and is an important parameter to consider. From the predictors examined, gender significantly influenced total work and peak power, whereas BMI significantly influenced the number of repetitions, total vertical displacement, and peak power. These factors should hence be considered when interpreting outcomes. In contrast, age and physical activity levels did not significantly influence any of the CRT outcomes, which may be due to the low heterogeneity of our sample for these characteristics.

Despite the CRT performed at a 60 bpm cadence yielding 10% and 7% more repetitions than at 30 or 120 bpm, respectively, these differences were not statistically significant. These results therefore suggest that it would be possible to pool normative data on the number of repetitions completed from various sources regardless of the cadence used to pace the CRT. Compared to previous studies (Byrne et al., 2017; Fernandez et al., 2022; Hébert-Losier et al., 2017) using a cadence of 60 bpm and 10° incline as we did, the average number of repetitions completed in our cohort (18 repetitions) was lower than others (range: 30 to 34 repetitions). This lower performance may be due to differences in anthropometric characteristics of participants, like BMI which we found to significantly affect the number of repetitions. The BMI and mass of our cohort was approximately 4.6 kg/m^2 and 13 kg greater than previous studies (Byrne et al., 2017; Fernandez et al., 2022; Hébert-Losier et al., 2017), which can contribute to the diverging average repetitions completed.

Cadence did not significantly affect the number of repetitions achieved during the CRT, but cadence did influence the four other CRT outcomes measured: total vertical displacement, total work, peak height, and peak power. Although repetitions are typically used as the primary clinical outcome, research (Byrne et al., 2017; Fernandez et al., 2022; Silbernagel et al., 2010; Svantesson, Osterberg, Thomeé, et al., 1998) suggests measuring other outcomes is important for quantifying CRT performance and can provide a more comprehensive evaluation of plantarflexor function. According to Silbernagel et al. (2010) since total vertical displacement and work consider both calf raise height and the number of repetitions, these are better indicators of plantarflexor endurance than the number of repetitions alone. Indeed, the work metric has been found more sensitive in detecting functional deficits following Achilles tendon rupture (Byrne et al., 2017; Anna Nordenholm et al., 2022). Furthermore, the peak height outcome may indicate tendon elongation and reduced end-range plantarflexor strength, which are common impairments following Achilles tendon rupture (Cramer et al., 2021; Silbernagel et al., 2012; J. A. Zellers et al., 2020). Lastly, peak plantarflexor power (Miyashita et al., 2019; Anna Nordenholm et al., 2022) predicts functional performance, such as walking speed and efficiency. When pace is externally controlled and standardised to a given cadence (e.g., 60 bpm), peak power comparisons between legs and individuals might have little clinical usefulness in the context of the CRT. However, in this study, pace was varied from a slower to a faster cadence, revealing differences in peak power. As such, peak power could be an interesting variable to consider when asking individuals to perform the calf raises as fast as possible (da Silveira et al., 2022) or to consider when prescribing exercises for rehabilitation and training purposes.

We found that performing the CRT at the moderate cadence of 60 bpm produced superior values for most of the other CRT outcomes, except for repetitions and peak power. As one would expect due to changes in velocity, peak power was greatest at the fastest cadence and lowest at the slowest one (i.e., 22% difference). Peak height was also higher in the 60 and 120 bpm cadences than at the slower cadence. Namely, peak height was 5% lower at 30 bpm compared to the other two cadences, which we did not expect. It could be that the slower movement velocity and lower momentum of participants during the task resulted in them reaching a lower peak height, with limited SSC contributions to the concentric action. It may also be that the 5% difference in peak height is not clinically meaningful given that the test-retest change in peak height is reported at 6.6% elsewhere (Byrne et al., 2017).

The 60 bpm cadence resulted in the greatest total vertical displacement and work, with lower outcomes at the slower and faster cadences. It may be that performing the CRT at 60 bpm is the preferred movement velocity for this task, with the triceps surae MTU shown to store and release elastic energy more efficiently at self-selected walking speeds than slower and faster ones (Neptune et al., 2008). Similar to walking, it could be that slower and higher than preferred movement velocities and cadences correspond with greater work and activation costs due to reduced involvement of tendon SCC (Brennan et al., 2017; Neptune et al., 2008). The preferred movement velocity for the CRT resulting in the most efficient movement is currently unknown, but presumably close to 60 bpm.

Based on the force-velocity relationship, muscle forces decrease at faster contractile shortening velocities (Alcazar et al., 2019; Fenwick et al., 2017). In addition, faster contractile shortening velocities performed repeatedly are more fatigable (Spendiff et al., 2002), providing a potential explanation to the lower total vertical displacement and work at the faster cadence of 120 than 60 bpm. At the slowest cadence of 30 bpm, the time under tension is greatest (Wilk et al., 2018) and the triceps surae muscles contract isometrically at end-range plantarflexion for a longer time. Moreover, the performance-enhancing effects of the SCC are velocity dependent (De Monte & Arampatzis, 2008; Herzog & Leonard, 2000). At the slowest cadence, the contribution of the SCC to the concentric output is lowest, hence requiring greater muscular work. The greater time-under tension and lower SSC contribution to the task could explain the lower total vertical displacement and work at 30 than 60 bpm. Since we did not use electromyography or ultrasound or other means of examining MTU mechanics, we are unable to confirm these propositions. Given the greater total vertical displacement and work performed at 60 bpm, this cadence is recommended for the CRT over the other two cadences as it maximises endurance performance.

However, varying the pace of calf raise repetitions from a training and rehabilitation perspective has benefits. For example, performing repeated contractions at low velocities would involve greater contributions from slow twitch fatigue-resistant muscle fibres, whereas at higher velocities would involve fast twitch fatigue-sensitive fibres to a greater extent (Spendiff et al., 2002; Wakeling et al., 2006) and energy storage in the tendon (Schenau et al., 1997; Tomalka et al., 2021). Hence, it is possible that soleus contributes to calf raise performance to a greater extent at slower cadences, and the medial and lateral gastrocnemius muscles at faster ones due to their respective fibre type characteristics (Kim Hébert-Losier et al., 2009). Additionally, slower movement velocities in training have been linked with muscle hypertrophy (Bird et al., 2005; Robert W. Morton et al., 2019; Wilk et al., 2018; Wilk et al., 2021), whereas faster velocities can help develop muscle strength and power (Bird et al., 2005; Headley et al., 2011; Wilk et al., 2021) as well as SCC abilities (Schenau et al., 1997; Tomalka et al., 2021). Hence, varying cadence can be useful in exercise prescription and set based on the sought goals.

We identified a significant difference between genders, with greater work (30%) and peak power (23%) in males, which is likely a direct result of their greater body mass (33%). Indeed, the force used in the work and power computations within the CR_{app} are based on the body mass of individuals (i.e., F_g = mass multiplied by gravitational acceleration). In addition, anatomical (i.e., cross-sectional area and muscle fibre composition) and physiological (i.e., muscle energy metabolism, contractile speed, and hormones) differences exist between genders that may contribute to the CRT differences observed (Haizlip et al., 2015; Landen et al., 2023). We also found that as BMI increased, the number of repetitions and total vertical displacement decreased. This result agrees with previous studies (Hébert-Losier et al., 2022; Hébert-Losier et al., 2017) that showed that increased BMI negatively affected repetitions performed. Moreover, studies have shown a negative relationship between BMI and cardiorespiratory and musculoskeletal function, wherein muscle endurance is negatively affected with increasing BMI (Bonney et al., 2018; Hasan et al., 2016; Huang & Malina, 2010; Qin et al., 2022). Noteworthy is that the significant difference in total vertical displacement seen with BMI was no longer observed for the total work metric once body mass was factored into the equation.

In contrast to our hypothesis and previous literature (Hébert-Losier et al., 2017), physical activity level and age did not significantly affect any of the CRT outcomes. Our study population was relatively homogeneous in terms of age and activity levels; hence, this homogeneity would have reduced data variability and potentially affected our results. We did not specifically design our study to examine the effects of predictors on CRT outcomes. Rather, our study was powered to detect differences in CRT outcomes when varying cadences. Therefore, to specifically explore the effect of age and physical activity levels, a study specifically designed for this purpose is recommended.

Our study has limitations, including the fact that it consists of a sample of young, healthy adults, limiting its generalizability to other populations. Furthermore, we did not examine changes in muscle activation, tendinous contribution, or fatigue patterns at the various cadences, which could have provided further insights into the MTU contributions to the different conditions. Although the 60 bpm cadence appears as the most suitable for use during the CRT as it involved greater total displacement and work, further studies are required to investigate potential benefits of varying cadences during calf raises when prescribed for training and rehabilitation purposes.

5.5 Conclusion

In conclusion, changing CRT cadence significantly influenced total vertical displacement, total work, peak height, and peak power outcomes, but not the number of repetitions. Gender was a significant predictor of total work and peak power, and BMI of the number of repetitions, total vertical displacement, and peak power. When interpreting CRT outcomes and comparing between studies, it is important to consider these factors. On the other hand, age and physical activity levels did not significantly impact CRT outcomes likely due to the homogeneity of participants. Overall, our findings indicate that a 60 bpm cadence is better than a slower 30 bpm or faster 120 bpm cadence for the CRT as maximises total vertical displacement and work. However, using slower and faster cadences in training and rehabilitation might confer benefits and should be selected based on the intended goals, for example, using a faster cadence to elicit greater peak power and slower cadences for hypertrophy or encouraging slow-twitch muscle fibre activation.

Chapter 6

Triceps surae muscle activity and fatigue during standing single leg calf raises: A systematic review

Fernandez, M. R., Athens, J., Kubo, M., & Hébert-Losier, K. (2023). Triceps surae muscle activity and fatigue during standing single leg calf raises: A systematic review. *Under Review*

Prelude: Chapters 4 and 5 examined the effects of changing the ankle starting position and cadence of the CRT on key test outcomes. These previous chapters focused on test outcomes only without measuring muscle activity and fatigue parameters. The following chapter is a systematic review that aims to critically appraise the available literature that examines how variations in calf raise (i.e., test or exercise) clinical parameters influence the triceps surae muscle activity and fatigue-related EMG parameters in healthy individuals. This systematic review will provide insight into how changes in clinical calf raise parameters likely influence the triceps surae muscles with implications for rehabilitation. This review is a starting point for future research into understanding how changes in calf raise parameters influence the triceps surae muscle-tendon unit.

6.1 Introduction

The triceps surae muscle group is the main agonist for ankle plantarflexion and consists of the monoarticular SOL muscle and the bi-articular gastrocnemii muscles, the MG and LG. The latter muscles also contribute to knee flexion (Cresswell et al., 1995; Kawakami et al., 1998; Kinugasa & Akima, 2005). Together, the triceps surae muscle group accounts for 80% of plantarflexion force (Murray et al., 1976), which is transmitted to the ankle via a common Achilles tendon inserting onto the calcaneus. Various functional upright activities and tasks that require plantarflexion motion, like walking, running, and standing up from a chair, depend on adequate triceps surae MTU function (André et al., 2018; Honeine et al., 2013).

Common injuries to the triceps surae MTU include Achilles tendinopathies (Alghamdi et al., 2021; Aufwerber et al., 2020) and triceps surae muscle strains (Green & Pizzari, 2017). These conditions are typically associated with plantarflexion weakness (Arch et al., 2018; Carmont et al., 2020), which may affect physical function (Westin et al., 2018). Consequently, calf raise exercises are often a component of rehabilitation programs for these conditions. The action of performing repeated calf raises, also known as heel rises, involves concentric and eccentric actions of the ankle via lifting and lowering of the heel in weight-bearing. Completing this action to fatigue (i.e., task failure) can also be used as a functional outcome measure (K. Hébert-Losier et al., 2009). The outcomes of this task to failure can assist in diagnosing, grading, and monitoring injuries, as well as quantifying treatment effectiveness (K. Hébert-Losier et al., 2009; Silbernagel et al., 2010).

Various populations can benefit from gastrocnemius and SOL muscle training, including bodybuilders for hypertrophy and aesthetic reasons (Marcori et al., 2017); track and field (Trowell et al., 2022), endurance running (Bohm et al., 2021), and sprint (Pandy et al., 2021) athletes for improving performance; older adults for maintaining functional fitness (André et al., 2018) and physical activity levels (André et al., 2016); and injured populations for regaining lower-extremity function (Baxter et al., 2021). Due to neuromuscular compartmentalization (English et al., 1993; Segal et al., 1991; Wolf et al., 1993) and the force-length relationship (Signorile et al., 2002) of the triceps surae muscles, joint angle variations can influence muscle activation and fatigue patterns (Hébert-Losier et al., 2012a, 2012b; Marcori et al., 2017; Robbins & Goss-Sampson, 2013). Therefore, varying calf raise test or exercise clinical parameters, such as knee and ankle joint position, can be implemented in clinical practice to bias gastrocnemius and/or SOL muscle activation. However, it is not clear to what extent these variations in lower-extremity joint positions during repetitive calf raise performances influence the different triceps surae muscles, which has implications for testing and rehabilitation.

Practitioners and researchers use EMG to measure muscle activity and fatigue-related parameters and to guide exercise prescription (Woodward et al., 2019). Therefore, this paper aimed to systematically review the EMG literature examining how variations in standing calf raise test or exercise clinical parameters influence MG, LG, and SOL muscle activity- and fatigue-related EMG parameters in healthy individuals. The findings of this review may inform clinical practice guidelines for calf raise test and exercise prescription with the goal of improving clinical outcomes and promoting evidence-based practice.

6.2 Methods

This systematic review adheres to the PRISMA guidelines (Page et al., 2021). The protocol of this review was preregistered in the international prospective register of systematic reviews (PROSPERO as CRD420201819).

6.2.1 Search strategy

A comprehensive search was conducted within the following seven electronic databases: Scopus®, Sports Medicine & Education Index, MEDLINE®, SPORTDiscus, PubMed®, Web of Science®, and CINAHL Complete. These databases were initially searched from their inception until 21 January 2022 and continuously monitored up until 3 March 2023 to ensure that all relevant published articles were included and updated. The overall search syntax involved: (“calf raise” OR “heel rise” OR “heel raise”) AND (“EMG” OR “electromyography” OR “muscle activity” OR “muscle fatigue” OR “muscle activation”) AND (“triceps surae” OR “soleus” OR “gastrocnemius” OR “plantarflexors”). English language and journal article publication types were applied as limits. In addition, reference lists of all included studies were screened to identify relevant studies that might have been missed during the database search. The detailed search strategy applied for each database is reported in Appendix D.

6.2.2 Selection of the studies

The Population, Intervention, Comparison, Outcomes, and Study Type (PICOS) framework (Eriksen & Frandsen, 2018; Frandsen et al., 2020) was used to establish inclusion and exclusion criteria. *Participants:* Studies that included healthy adults (over 18 years) were eligible. Research was excluded if the population involved children or adolescent, injured cohorts, or individuals with medical conditions. *Intervention:* Studies were eligible for inclusion when using EMG to identify changes in triceps surae muscle activity- or fatigue-related parameters with change in calf raise (test or exercise) clinical parameters. Studies were excluded when assessing tasks other than the performance of repeated calf raises in standing, using other methods than EMG to examine muscle activity or fatigue, when calf raise clinical parameters were not described in sufficient detail to ensure meeting inclusion, or when not examining one of the triceps surae muscles. *Comparisons:* The influence of calf raise (test or exercise) clinical parameters on triceps surae muscle activity or fatigue were of interest, such as changes in foot or knee positions. Hence, studies that involved comparing MG, LG, or SOL EMG between different variations in calf raise (test or exercise) performance were eligible. *Outcomes:* Outcomes of interest were EMG parameters, which could include root-mean-square (RMS) and median frequency (MF) values for activity and fatigue assessment, respectively. *Studies:* Articles were eligible for inclusion if they were peer-reviewed original research written in English. Acceptable study designs included experimental (randomized and non-randomized trials) and observational (cross-sectional and cohort studies). Articles that were not original research (e.g., reviews, editorials, dissertations, and conferences) or not available in the English language were excluded.

6.2.3 Data collection process and data items

Citations from the database searches were imported into Endnote X9.3.3 (Clarivate Analytics, Philadelphia, PA, USA) and duplicates were identified and removed. Following the PRISMA guidelines, two reviewers (RF and ID) independently screened all remaining titles and abstracts. The remaining potentially relevant articles were retrieved for a full-text assessment. Two reviewers (RF and KHL) then independently screened the remaining full-text articles to determine eligibility. At each stage of the screening process, the two independent reviewers met to discuss any conflicts arising during these processes. A third reviewer was available to arbitrate any unresolved conflicts but was not required.

Data were extracted from the full-text articles meeting inclusion using a data extraction template to facilitate synthesis in a tabulated format, and a second reviewer verified the extracted data. Data extracted from articles included study design; sample size and demographic characteristics of participants; calf raise parameters; main outcome measures;

EMG data items; and key findings. The standards for reporting EMG data as endorsed by the International Society of Electrophysiology and Kinesiology (Medved, 2000) were used to select the EMG data items (i.e., normalization method, EMG processing/analysis, and location of electrodes).

6.2.4 Methodological quality assessment

The methodological quality of the eligible studies was assessed using the modified version of the Newcastle-Ottawa Scale (NOS) for cross-sectional studies (Wells et al., 2014). Prior to assessment, two reviewers met to discuss and familiarize themselves with the scale. A third party removed all identifiable information (i.e., authors, affiliations, countries, and sources of publication) from articles to blind the two reviewers and reduce potential for assessment bias. Following independent assessment, the two reviewers met to discuss any disagreement, with the consensus rating here presented.

Using the NOS star system, a maximum of 10 stars can be allocated wherein more stars indicate superior methodological quality and lower risk of bias. Five stars are allocated to selection (representativeness of the sample, sample size, non-respondents, and ascertainment of the exposure), two stars to comparability, and three stars for outcome (assessment of outcome and statistical test). The overall quality of studies was qualitatively evaluated using previously reported methods (Hanzlíková & Hébert-Losier, 2020; Herzog et al., 2013; Naafs et al., 2020) as 9-10 stars indicating “very good”, 7-8 stars indicating “good”, 5-6 stars indicating “satisfactory”, and 4 stars or less indicating “unsatisfactory” methodology. Based on intraclass correlation coefficient (ICC) values, the intra-rater (ICC 0.98) and inter-rater (ICC 0.94) reliability for the NOS adapted for cross-sectional studies values are excellent (Hanzlíková & Hébert-Losier, 2020).

6.2.5 Risk of bias assessment

Two independent raters (RF and KHL) used the QUality In Prognosis Studies (QUIPS) tool (Hayden et al., 2013) to assess the potential risk of bias in studies. The QUIPS is an evidence-based, peer-reviewed risk of bias assessment tool that assesses six domains (study participation, study attrition, prognostic factor measurement, outcome measurement, study confounding, and statistical analysis and reporting). In using the tool, each of the six domains is rated as presenting a high, moderate, or low risk of bias based on responses (yes, no, or not applicable) to three to seven items. A study was considered at low risk of bias when all domains were rated as low, or one domain was rated as moderate. A study was deemed at high risk of bias when one or more domains scored high, or more than two domains scored moderate. Otherwise, articles were categorized as being at moderate risk of bias (Grooten et al., 2019). Following independent assessment, the two reviewers met to discuss any disagreement, with the consensus rating presented in the results.

6.2.6 Synthesis methods

Data extracted were compiled using Microsoft® Excel for Mac (version 16.57, Microsoft Corp., Redmond, WA, USA). The results were summarized using means and standard deviations (means ± SD) weighted based on sample size when appropriate, minimum-to-maximum ranges, counts, and/or percentages. Meta-analysis of the data was not considered due to the heterogeneity in study design and methods (e.g., variations in data collection methods and outcome measures). Thus, data are presented using a narrative synthesis throughout the results section.

6.3 Results

6.3.1 Study selection

The initial electronic database search identified 365 articles, with seven articles meeting eligibility and assessed for methodological quality and risk of bias. During the monitoring period, no addition articles of relevance were identified. The PRISMA flow diagram illustrating the selection process is shown in Figure 12.

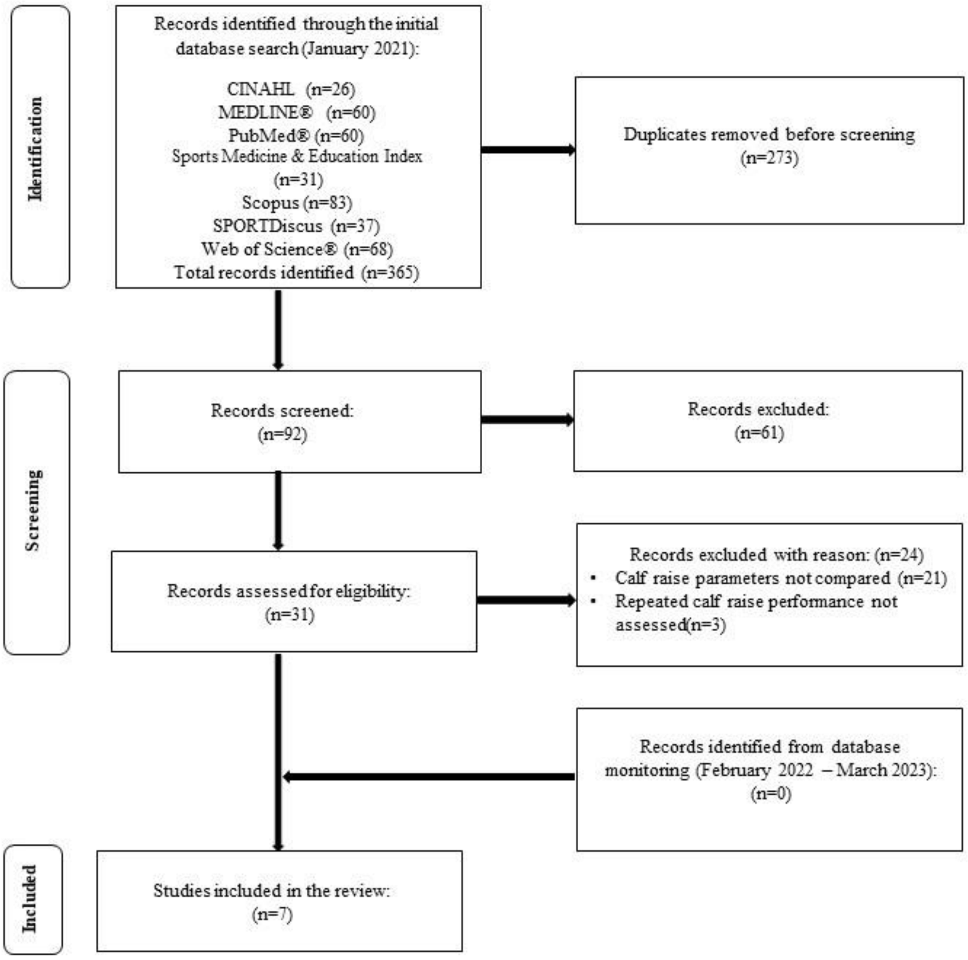

Figure 12. Flow diagram of the article selection process.

6.3.2 Quality assessment

Based on the adapted NOS, the methodological quality of two studies (Hébert-Losier et al., 2012a, 2012b) was good (8 stars), satisfactory (5 to 6 stars) for three studies, and unsatisfactory (4 stars) for two studies (Kinugasa & Akima, 2005; Robbins & Goss-Sampson, 2013). Common causes that lessened study quality were lack of selecting a representative sample, describing non-respondents, or presenting sample size calculations, and incomplete statistical reporting. The NOS rating for each individual NOS item is detailed for each article and is presented in Table 16.

6.3.3 Risk of bias

The risk of bias of the selected studies as assessed using the QUIPS is shown in Table 17. All studies were considered at high risk of bias. The risk of bias was highest for the study attrition, participation, and confounding domains.

6.3.4 Characteristics and key findings of the selected studies

The main characteristics and key findings of the seven included studies are summarized in Table 18. All seven articles were cross-sectional observational studies and used surface EMG, with none using fine-wire or high-density EMG methods. A total of 114 unique participants are represented in this review, as two studies represented the same 48 participants (Hébert-Losier et al., 2012a, 2012b). The weighted mean age of these 114 participants based on a sample size of 28.6 years. Most participants were male (70.18%), with only three studies including females (Hébert-Losier et al., 2012a, 2012b; Riemann et al., 2011). Activity-related EMG parameters of the MG and LG muscles were the most frequently reported (*n* = 6 studies each) and included SOL in four studies. Activity-related EMG parameters were more frequently examined (*n* = 5 studies) than fatigue (*n* = 2 studies).

In terms of calf raise parameter variations, the influence of foot position on lower leg muscle activity during a calf raise exercise was the most researched (Akuzawa et al., 2017; Marcori et al., 2017; Riemann et al., 2011) followed by knee position (Hébert-Losier et al., 2012a, 2012b), additional load (Kinugasa & Akima, 2005), and whole-body vibration (Robbins & Goss-Sampson, 2013). Variations in calf raise (test or exercise) protocols between studies were noted, such as unilateral vs bilateral, lower-extremity position, and cadence (see Table 18). In addition, there was no uniform approach to processing, analysing, and reporting EMG data. For example, muscle activity-related parameters were reported as a percentage of maximal voluntary contraction, a percentage of a set condition, or in raw units.

Table 16. Newcastle-Ottawa Scale (NOS) adapted version for assessing cross-sectional studies.

Study	**Selection (5 stars)**				**Comparability (2 stars)**	**Outcome (3 stars)**		**Overall (10 stars)**
	Representative of the sample	Sample size	Non-respondents	Ascertainment of the exposure	Subjects in different outcome groups are comparable	Assessment of the outcome	Statistical test	Quality
Akuzawa et al. (2017)				*	**	*	*	5
Hébert-Losier et al. (2012b)		*		**	**	**	*	8
Hébert-Losier et al. (2012a)		*		**	**	**	*	8
Kinugasa and Akima (2005)				*	**	*		4
Marcori et al. (2017)				**	**	**		6
Riemann et al. (2011)		*		*	**	*		5
Robbins and Goss-Sampson (2013)				*	**	*		4

Note: The number of stars reflect study quality: 9-10 stars = “very good”, 7-8 stars = “good”, 5-6 stars = “satisfactory”, and 0-4 stars = “unsatisfactory” quality.

Table 17. Assessment of risk of bias using the QUality Assessment in Prognostic Studies (QUIPS) tool.

Study	**Study participation**	**Study attrition**	**Prognostic factor measurement**	**Outcome measurement**	**Study confounding**	**Statistical analysis and reporting**	**Overall bias***
Akuzawa et al. (2017)	High	High	Low	Low	High	Mod	High
Hébert-Losier et al. (2012b)	Mod	High	Low	Low	High	Low	High
Hébert-Losier et al. (2012a)	Mod	High	Low	Low	High	Low	High
Kinugasa and Akima (2005)	High	High	High	Low	Low	High	High
Marcori et al. (2017)	High	High	Low	Low	High	Mod	High
Riemann et al. (2011)	High	High	Low	Low	High	Mod	High
Robbins and Goss-Sampson (2013)	High	High	Low	Low	Low	Low	High

Abbreviation: Mod, moderate.*Low: all domains rated low or one domain rated moderate; high: one or more domains rated high or more than two domains rated moderate; moderate: not overall low or overall high.

Table 18. Summary of the included studies (*n*=7) and associated key findings.

Study	**Participants**	**Calf raise parameters**	**Main outcome measure**	**EMG**			
				Electrodes	**Data treatment**	**Results**	**Interpretation**
Akuzawa et al. (2017) **NOS:** 5 stars **RoB:** High	**Sample:** 14 males **Age:** 24 ± 5.1 y **Height:** 169.2 ± 5.9 cm **Mass:** 63.1 ± 9.5 kg	**Conditions:** foot neutral, foot 30° ABD, foot 30° ADD **Procedure:** Standing unilateral CR (right side). 1 set x 10 reps per condition (random order) with 1 min rest between sets. **Design:** All three conditions examined on the same day. **Device used:** High-speed video camera (240 Hz) **Lower extremity:** Knee extended, foot floor **Cadence:** Tempo monitored using a metronome (but bpm NR)	**Muscles:** MG **Activity:** RMS (% MVIC)	**Placement:** SENIAM guidelines **Shape and interelectrode distance:** 8 mm diameter and 20 mm between electrodes	**Equipment:** NBioLog DL-5000, 1000 Hz **Normalization:** Normalized to the RMS of a 5 s ankle plantarflexion MVIC in sitting, knee extended for MG. **Filtering:** 20 Hz high-pass and 450 Hz low-pass filter. **Processing:** RMS amplitude with 200 ms moving window. **Analysis:** Mean RMS from the middle 5 reps (3rd to 8th rep) of each condition**.**	**MG:** Neutral: 69.3 ± 22.9% MVIC ABD: 74.4 ±24.6%MVIC ADD: 67.8 ±22.2%MVIC ($F_{(1.32,\ 17.02)}$ = 1.32, p = 0.28)	Foot position did not significantly influence MG activity during unilateral.

Hébert-Losier et al. (2012b) **NOS:** 8 stars **RoB:** High	**Sample:** 48 participants **Younger:** 12 males **Age:** 22.4 ± 1.8 y **Height:** 177.4 ± 5.6 cm **Mass**: 71.7 ± 10.2 kg **Younger:** 12 females **Age:** 22.7 ± 2.0 y **Height:** 165.1 ± 4.2 cm **Mass:** 61.1 ± 10.7 kg **Middle aged:** 12 males **Age**: 41.1 ± 3.1 y **Height:** 177.7 ± 5.6 cm **Mass:** 81.7 ± 14.9 kg **Middle aged:** 12 females **Age:** 41.5 ± 3.4 y **Height**: 166.5 ± 8.1 cm **Mass:** 66.6 ± 10.3 kg	**Conditions:** 0° KF; 45° KF **Procedure:** Standing unilateral CR (dominant). 1 set x maximal reps per condition (block randomization) with 40 min rest between sets test conditions. **Design:** Both conditions examined on the same day **Device used:** 3D motion capture and electro goniometer **Lower extremity:** 0°KF and 45°KF, foot floor **Cadence:** 60 calf raises per minute regulated by a metronome	**Muscles:** MG, LG, SOL (dominant) **Fatigue:** MF (Hz), MF-NS (%/s)	**Placement:** SENIAM guidelines. Single ground electrode on tibial tuberosity. **Shape and interelectrode distance:** Ag/AgCl gelled sensors with < 20 mm distance between electrodes	**Equipment:** Noraxon TeleMyo 2400 T G2,3000 Hz **Filtering:** Band-pass filter of 10-500 Hz; no notch filter (50/60 Hz); input impedance > 100 MΩ; > 100 dB mode rejection ratio; baseline AC noise < 1 μV RMS; input range ± 3.5 mV; gain of 1000. **Processing:** MF extracted from power spectrum. MF plotted vs time in 250 ms epochs, linearly regressed, and normalized to intercept for MF-NS. **Analysis:** MF from first 5 (early) and last 5 (late) omitting end-point errors (first and last 2 reps). MF-NS for all reps omitting end-point errors.	**MG:** 0°KF: early 88.6 Hz; late 71.1 Hz; MF-NS -0.6 %/s 45°KF: early 96.1 Hz; late: 78.3 Hz; MF-NS -0.7 %/s **LG:** 0°KF: early 86.4 Hz; late: 69.8 Hz; MF-NS -0.6 %/s 45°KF: early 82.0 Hz; late: 70.6 Hz; MF-NS -0.5 %/s **SOL:** 0°KF early 73.8 Hz; late: 65.3 Hz; MF-NS -0.3 %/s 45°KF early 67.1 Hz; late: 58.9 Hz; MF-NS -0.3 %/s	KF did not influence triceps surae muscle fatigue parameters (p = 0.814). Rate of fatigue (MF-NS) was greater in MG and LG than SOL (p < 0.001). Decrease in MF from early to late was greater in GM than SOL (p = 0.008)

Hébert-Losier et al. (2012a) **NOS:** 8 stars **RoB:** High	See Hébert Losier et al. (2012b)	**Conditions:** 0° KF; 45° KF **Procedure:** Standing unilateral CR (dominant). 1 set x 10 reps per condition (block randomization) with 5 min rest between sets test conditions. **Design:** Both conditions examined on the same day **Device used:** 3D motion capture and electro goniometer **Lower extremity:** 0°KF and 45°KF, foot floor **Cadence:** 60 calf raises per minute regulated by a metronome	**Muscles:** MG, LG, SOL (dominant) **Activity:** RMS (%MVIC)	**Placement:** SENIAM guidelines. Single ground electrode on tibial tuberosity. **Shape and interelectrode distance:** Ag/AgCl gelled sensors with < 20 mm distance between electrodes.	**Equipment:** Noraxon TeleMyo 2400 T G2,3000 Hz **Normalization:** Normalized to the RMS of a 7 s MVIC trial. Peak from any 1 MVIC performed in the following positions: 0° KF (standing), 45°KF (standing), 90 KF° (sitting). **Filtering:** Band-pass filter of 10-500 Hz; no notch filter (50/60 Hz); input impedance > 100 MΩ; > 100 dB mode rejection ratio; baseline AC noise < 1 µV RMS; input range ± 3.5 mV; gain of 1000. **Processing:** RMS amplitude in 250 ms epochs. **Analysis:** RMS from middle 5 reps (3rd to 7th rep).	**MG:** 0°KF 25.0%MVIC, 45°KF 19.6%MVIC **LG:** 0°KF 21.6%MVIC, 45°KF 17.3%MVIC **SOL:** 0°KF 23.2%MVIC, 45°KF 27.0%MVIC Significant main and interaction effect of KF and muscle ($p < 0.001$). GM more active than GL ($p = 0.018$) in 0°KF. SOL more active than GL and GM ($p < 0.001$) in 45°KF.	SOL activity was 4% greater in 45° vs 0°KF. MG and LG activity was 5% lower in 45° vs 0°KF SOL most active triceps surae in 45° KF. GM most active triceps surae in 0°KF. GL least active triceps surae in both KF conditions.

Kinugasa and Akima (2005) **NOS:** 4 stars **RoB:** High	**Sample**: 6 males **Age:** 25.2 ± 0.7 y **Height:** 169.0 ± 2.2 cm **Mass:** 64.8 ± 2.4 kg	**Conditions:** Bilateral exercise; Unilateral exercise; Unilateral exercise with 15% of body-weight load **Procedure:** Standing bilateral CR (Bilateral exercise) or unilateral CR (Unilateral exercise, unilateral exercise with 15% of body-weight load). 5 sets x 10 reps per condition on a columnar bar; with 1 min rest between sets. 30 min rest between bilateral exercise and unilateral exercise. One day between unilateral exercise with 15% of body-weight load and other 2 conditions. Random leg and load order. **Design:** Bilateral exercise and unilateral exercise examined on the same day; unilateral exercise with 15% of body-weight load examined 1 day from 2 conditions. **Device used:** None	**Muscles:** MG, LG SOL (random leg) **Activity:** iEMG (mV)	**Placement:** Mid bellies of MG, LG, SOL, Earth electrode over the bilateral thigh bones **Shape and interelectrode distance:** Preamplifier surface electrodes with 10 mm distance between electrodes.	**Equipment:** DE 2.1, Delsys, 1000 Hz. **Normalization:** None **Filtering:** band pass-filter set to between 15 and 500 Hz **Analysis:** Full-wave rectified and integrated over 40 s to yield iEMG, averaged of 5 sets.	**MG:** Bilateral exercise 26.7 ± 7.5 mV, unilateral exercise 31.2 ± 10.9 mV, U+15% ex 39.4 ± 7.0 mV Unilateral exercise with 15% of body-weight load > Bilateral exercise (p=0.06) **LG:** Bilaterally exercise 10.2 ± 4.3 mV, unilateral exercise 19.5 ± 11.2 mV, unilateral exercise with 15% of body-weight load 25.3 ± 6.4 mV Unilateral exercise with 15% of body-weight load > bilateral exercise (p<0.01) **SOL:** Bilateral exercise: 12.8 ± 2.2 mV, unilateral exercise 17.8 ± 2.0 mV, unilateral exercise with 15% of body-weight load 25.3 ± 4.7 mV	In unilateral exercise with 15% of body-weight load muscle activity in SOL, MG, LG greater than B ex bilateral exercise MG activity greater than LG and SOL generally. SOL activity unilateral exercise with 15% of body-weight load > unilateral exercise > bilateral exercise LG activity: unilateral exercise with 15% of body-weight load > bilateral exercise

	Knee angle: Knee extended, foot edge of column, ankle neutral start position. **Cadence:** 2 s up (max plantarflexion), 2 s down (neutral ankle)		Unilateral exercise with 15% of body-weight load and U ex > bilateral exercise ($p < 0.05$) **Muscles:** MG > LG and SOL in bilateral exercise and unilateral exercise with 15% of body-weight load ($p < 0.05$)

Marcori et al. (2017) **NOS:** 6 stars **RoB:** High	**Sample:** 16 males **Age:** 21 ± 2 y **Height:** 1.75 ± 0.06 m **Mass:** 74.8 ± 7.2 kg	**Conditions:** Feet FO, IN (45° rotation), OU (45° rotation) **Procedure:** Standing bilateral CR. 1 set x 10 reps in each condition, with 4 min rest between sets. **Design:** All 3 conditions examined on 3 different days (at least 48 h later), totalling 3 sets x 10 reps per condition. **Device used:** None **Lower extremity:** Knee extended, foot edge of step **Cadence:** 3 s eccentric; 1.5 s concentric	**Muscles:** MG, LG (side NR) **Activity:** RMS (% FO)	**Placement:** SENIAM guidelines. Reference electrode placed on the tibial tuberosity. **Shape and interelectrode distance:** Ag/AgCl sensors, active and bipolar electrodes, 2 cm between electrode centres.	**Equipment:** Noraxon Myosystem 1400 A, 2000 Hz. **Normalization:** Normalized to the RMS of the FO condition of each day (normalized using dynamic contractions). **Filtering:** Butterworth band-pass, bi-directional filter, with cut-off frequency between 10-50 Hz. **Analysis:** Mean RMS of the 3 sets per condition.	Median (IQR) **MG:** OU ~105.2% (98.5, 108.6) IN ~83.1% FO (80.2, 89.4) OU greater RMS vs FO (FO p ≤ 0.017) and IN (p < 0.001). FO greater RMS vs IN (p < 0.001) **LG:** OU ~95.2%FO (82.9, 101.9) IN ~109.5%FO (104.8, 130.0) IN greater RMS vs OU (p = 0.001) and FO (p = 0.001)	MG activity during bilateral CR with feet outward > forward > inward. LG activity during bilateral CR with feet inward > outward and forward.

Riemann et al. (2011) **NOS:** 5 stars **RoB:** High	**Sample**: 10 males, 10 females **Age:** 23.7 ± 3.1 y **Height**: 1.71 ± 0.07 m **Mass:** 72.75 ± 14.24 kg	**Conditions**: Feet- NE; IR (as far as possible), ER (as far as possible) **Procedure:** Standing bilateral CR.1 set x 12 reps in each condition, on a 3.81 cm wooden block, holding a weightlifting bar (130-135% body mass), with 4 min rest between sets. . **Design:** All 3 conditions examined on the same day (1h session; repeated measures counter balanced) **Lower extremity:** Knee extended, foot edge of step **Device used:** Video camera **Cadence**: up-one thousand, down-one thousand.	**Muscles:** MG, LG (dominant) **Activity:** RMS (% MVIC)	**Placement:** SENIAM guidelines. Reference electrode on superior-medial tibial crest. **Shape and interelectrode distance** Ag rectangular-shaped bipolar with 1 cm distance between electrodes.	**Equipment:** Bagnoli – 8 System, 1000 Hz. **Normalization:** Normalized to the RMS of a 6 s MVIC in standing, ankle midway between neutral and full plantarflexion. **Filtering:** Full-wave rectified, with 10 Hz low-pass Butterworth filter using a zero phase-lag. **Processing:** RMS of each repetition, separated into concentric and eccentric, interpolated to 100 points. **Analysis:** Mean RMS from the 5 selected reps and mean RMS of each concentric and eccentric phase.	**Concentric:** Muscle by foot position interaction in concentric phase ($F_{[2,38]}=16.85$, $p<0.001$, partial ŋ$^2=0.470$) IR LG > MG (*p*=0.003), ER MG > LG (p=0.026), NE MG = LG (*p*=0.460) LG IR > ER (*p*=0.014) **Eccentric:** Muscle by foot position interaction in eccentric phase (F $_{[2,38]}=9.43$, $p<0.001$, partial ŋ$^2=0.332$) ER MG > LG (*p*=0.019), NE MG = LG (p=0.108), IR MG=LG (p=0.564)	In ER, MG significantly greater activity than LG in both concentric and eccentric phases. In IR, LG significantly greater activity than MG in concentric phase. NE position similar MG and LG activity levels. MG similar activity in all three positions, whereas LG less active in ER than IR.

Robbins and Goss-Sampson (2013) **NOS:** 4 stars **RoB:** High	**Sample**: 10 males **Age**: 27 ± 5 y **Height:** 1.78 ± 0.04 m **Mass:** 75.75 ± 11.9 kg	**Conditions:** Vibration; no vibration **Procedure:** Standing bilateral CR performed on a whole-body vibrating platform x 6 alternating sets of 15 s no vibration or vibration. Initial set randomized. **Design:** Both conditions examined on the same day. **Device used:** 3D motion capture **Lower extremity:** Slight knee bend, foot flat on vibrating platform **Cadence:** 1 s up and 1 s down (0.5 Hz) regulated by a 1 Hz metronome	**Muscles:** LG, SOL (right) **Activity:** RMS (% MVIC), timing of peak **Fatigue:** MPF (Hz)	**Placement:** SENIAM guidelines. Single reference electrode on C7 vertebrae. **Shape and interelectrode distance:** Differential bipolar with 10 mm centre to centre distance between electrodes.	**Equipment:** Delsys Bagnoli, 2000Hz **Normalization:** Normalized to the RMS of MVIC performed in sitting with fixed knee resistance. **Filtering:** Signals amplified (1 k gain); band-width 20-450 Hz; RMS full rectification pre-filtering with a 2 Hz cut-off, 2nd order low pass Butterworth filter; 60 Hz cut-off bidirectional 2nd order; high pass Butterworth filter. **Processing:** Peak amplitude normalized to MVIC. **Analysis:** Data sequences of 0.6 s centred on peak (.3 s before and 0.3 s after) exported for MPF analysis.	**LG:** Vibration ~92 ± 3%MVIC, no vibration ~98 ± 2%MVIC ($p > 0.05$) Vibration 105 ± 7 Hz, no vibration 111 ± 7 Hz ($p > 0.05$) **SOL:** Vibration ~90% ± 2%MVIC, no vibration ~77%MVIC ± 4%MVIC ($p < 0.01$) SOL peak earlier than LG both in vibration ($p<0.05$) and no vibration ($p<0.01$). Both LG and SOL peak ~2%MVIC earlier in CR cycle for vibration vs no vibration, but not significant.	Whole vibration has no effect on timing of peak activity, peak activity, or MPF of LG. Whole vibration significantly increased peak activity of SOL, but did not influence timing of peak or MPF.

Abbreviations: ~, data approximated from figures; ABD, abduction; ADD, adduction; CR, calf raises; ER, external rotation; FO, feet pointing forwards; iEMG, integrated electromyography; IN, inwards; IR, internal rotation; KF, knee flexion; LG, lateral gastrocnemius; MF, median frequency; MF-NS, median frequency normalized slope; MG, medial gastrocnemius; MPF, mean power frequency; MVIC, maximum voluntary isometric contraction; NE, neutral; NOS, modified Newcastle-Ottawa Scale adapted for cross-sectional studies; OU, outwards; RMS, root mean square; RoB, risk of bias; SENIAM, Surface Electromyography for the Non-Invasive Assessment of Muscles; SOL, soleus.

6.3.5 Muscle activity and fatigue

6.3.5.1 Medial gastrocnemius

Three studies with satisfactory methodological quality examined the effect of foot position on MG activity-related EMG parameters (Akuzawa et al., 2017; Marcori et al., 2017; Riemann et al., 2011). Although MG activity was significantly greater than LG when feet were externally rotated (i.e., ER) due to a decrease in LG activity (Riemann et al., 2011), foot position did not significantly influence MG activity itself in two of the three studies (Akuzawa et al., 2017; Riemann et al., 2011). Only Marcori et al. (2017) indicated increased MG activity when performing bilateral calf raises with feet pointing outwards (i.e., ER) compared to forwards and inwards, being approximately 5% and 26% more active with feet outwards than forwards and inwards, respectively. Only one study with good methodological quality examined the effect of knee angle on MG activity-related EMG parameters, indicating that MG was more active than LG in an extended knee position, with both gastrocnemii muscles being approximately 5% of maximal voluntary isometric contraction more active with the knee extended than flexed to 45° (Hébert-Losier et al., 2012a). MG was also the most active triceps surae muscle during bilateral and unilateral calf raises with an additional 15% body weight applied as external load, and tended to demonstrate an increased activity with additional load based on a study with unsatisfactory methodological quality (Kinugasa & Akima, 2005). Regarding fatigue, knee flexion angle did not influence the magnitude or rate of MG fatigue-related EMG parameters, with MG exhibiting greater fatigue than SOL and similar fatigue to LG when unilateral calf raises were performed to exhaustion in a study with good methodological quality (Hébert-Losier et al., 2012b).

6.3.5.2 Lateral gastrocnemius

In the two studies with satisfactory methodological quality that examined the effect of foot position on LG activity-related EMG parameters, bilateral calf raises were examined. LG muscle activity was significantly greater with feet pointing inwards or (IR) (Riemann et al., 2011) than outwards or ER (Riemann et al., 2011), although differences were not significant during the eccentric phase when analysed separately from the concentric phase (Marcori et al., 2017; Riemann et al., 2011). LG muscle activity was approximately 10% greater with feet pointing inwards than forwards (Marcori et al., 2017) . LG was more active than MG during the concentric phase with feet IR less active than MG during both concentric and eccentric phases with feet ER and demonstrated similar activity levels than MG with feet in neutral. In the one study with good methodological quality that examined knee position (Hébert-Losier et al., 2012a), LG was 5% of maximal voluntary isometric contraction lower during unilateral calf raises with the knee flexed to 45° compared to extended, and was the least active triceps surae muscle in both knee flexion conditions. LG activity was significantly greater during unilateral calf raises with an additional 15% body weight applied as external load compared to bilateral calf raises with no external load, and tended to demonstrate an increased activity with additional load in one study with unsatisfactory methodological quality (Kinugasa & Akima, 2005). Regarding fatigue-related EMG parameters, knee flexion angle did not influence the magnitude or rate of LG fatigue, with LG exhibiting greater fatigue than SOL and similar fatigue to MG when unilateral calf raises were performed to exhaustion in on study with good methodological quality (Hébert-Losier et al., 2012b). Lastly, integrating whole-body vibration during unilateral calf raises did not influence the time of peak activity, magnitude of peak activity, and fatigue parameters of the LG muscle based on one study with unsatisfactory methodological quality (Robbins & Goss-Sampson, 2013).

6.3.5.3 Soleus

The influence of foot position on EMG-related parameters of SOL was not examined. When varying knee position in studies of good methodological quality (Hébert-Losier et al., 2012a, 2012b), SOL was the most active triceps surae muscle based on percentage of maximal voluntary contraction activation during unilateral calf raises when performed with a 45° knee flexion angle, and was also 4% of maximal voluntary isometric contraction more active in the latter knee flexion position compared to extension (Hébert-Losier et al., 2012a). However, varying knee flexion position during unilateral calf raises to fatigue did not affect the magnitude or rate of SOL muscle fatigue (Hébert-Losier et al., 2012b). Adding whole-body vibration to unilateral calf raises significantly increased SOL peak activity (~13% of maximal voluntary isometric contraction), but did not affect the timing of peak activity or fatigue parameters of SOL based on one study with unsatisfactory methodological quality (Robbins & Goss-Sampson, 2013). Furthermore, SOL activity was significantly greater during unilateral calf raises performed with and without an additional 15% body weight than during bilateral calf raises in one study with unsatisfactory methodological quality (Kinugasa & Akima, 2005).

6.4 Discussion

Altering foot position, knee flexion angle, external load, and incorporating whole-body vibration during standing calf raises have the potential to elicit changes in activity- and fatigue-related EMG parameters of the triceps surae muscles to varying extent based on the seven EMG studies meeting inclusion. Overall, the MG muscle may become more active during standing calf raises with feet ER and knees extended compared to knees flexed. On the other hand, the LG muscle activity during standing calf raises may increase with feet IR and knees extended compared to knees flexed, with limited influence of incorporating whole-body vibration. Lastly, SOL muscle activity may increase when performing standing calf raises with the knee flexed compared to extended and when incorporating whole-body vibration. Additionally, adding load was shown to increase the activity of all three triceps surae muscles. Finally, altering calf raise clinical parameters had limited influence on triceps surae muscle fatigue parameters. These overall findings can assist healthcare professionals in the assessment, rehabilitation, and training of the triceps surae muscles.

6.4.1 Joint position

Changes in triceps surae muscle activity due to variations in a calf raise clinical parameters, particularly ankle or knee joint position, are presumably due to neuromuscular compartmentalisation (English et al., 1993; Segal et al., 1991; Wolf et al., 1993), force-length relationship (Arndt et al., 1998; Ferris et al., 2011; Hessel et al., 2021; Maganaris, 2003; Sale et al., 1982), and shift in the line of force around the ankle joint (Riemann et al., 2011). With changes in ankle (Hali et al., 2021) and knee (Cresswell et al., 1995; Fugl-Meyer et al., 1979; Price et al., 2003) joint position, the gastrocnemii muscles are particularly influenced due to their bi-articular nature compared to SOL, which is mono-articular.

Morphological and anatomical studies (English et al., 1993; Widmer & Morris-Wiman, 2010; Wolf et al., 1993) indicate that the MG and LG muscles are anatomically complex, with multiple functionally distinct neuromuscular compartments. Neuromuscular compartmentalisation refers to a sub-volume of a muscle innervated by a separate muscle nerve branch, containing a motor unit that can be recruited individually or in groups to complete a task (English et al., 1993; Widmer & Morris-Wiman, 2010). Thus, different compartments of the same muscle or muscle group may be recruited together or separately depending on the task or function required (English et al., 1993). The neuromuscular partitioning of the triceps surae muscles supports localised function. The differential activation of motor units in different compartments of the triceps surae may result in variations in the magnitude and direction of force developed and applied via the Achilles tendon. Although the force transmitted to the calcaneus via the Achilles tendon will lead to ankle plantarflexion, the underlying muscle activation pattern may differ based on task requirements (English et al., 1993).

6.4.1.1 Foot position

The effect of foot position on triceps surae muscle EMG parameters during standing calf raises was the most frequently examined (Akuzawa et al., 2017; Marcori et al., 2017; Riemann et al., 2011) especially in regard to MG and LG muscle activity. Overall, the findings of this review indicate a potential increase in MG activity when calf raises are performed with feet ER, and in LG activity when feet are IR. These findings align with results from a training study showing greater muscle hypertrophy in MG and LG when calf raises were performed with the feet in ER and IR, respectively (Nunes et al., 2020). These results also align with isometric weight-bearing and non-weight bearing EMG findings (Cibulka et al., 2017; Hug et al., 2021).

The underlying mechanisms of enhanced MG and LG activation in ER and IR foot positions are unclear, but three mechanisms have been proposed. The first speculation advances that there are alterations in the muscle architectural features of the gastrocnemii muscles (Riemann et al., 2011) and lengthening of these muscles in these given foot positions (Marcori et al., 2017) . Hence, the MG and LG would be at a mechanical advantage in ER and IR foot positions, respectively, based on the force-length curve. Secondly, the gastrocnemii muscles are proposed to contribute to non-sagittal plane motions at the ankle during plantarflexion (Vieira et al., 2013), and rotating the feet outwards (ER) or inwards (IR) would require stabilisation in the non-sagittal plane. The third proposed mechanism relates to differences in MG and LG moment arms and line of action when feet are inverted or everted (Lee & Piazza, 2008). These changes would result in the MG contracting isometrically to maintain the ER position of the tibia on the femur when feet are pointing outwards and LG contracting isometrically to maintain the IR position of the tibia when feet are pointing inwards (Cibulka et al., 2017). Emerging evidence indicates differences in motor unit discharge rate with foot position, wherein motor unit discharge of the LG muscle increases when feet are in IR compared to neutral, but does not change for the MG muscle (Hug et al., 2021).

Performing standing calf raises in an ER or IR foot position affects the amount of rotation at the ankle, knee, and hip joints (Arnsdorff et al., 2011). It has been advanced that when feet are IR, the ankle joint moves laterally and the line of force, therefore, acts medial to the ankle joint (Riemann et al., 2011). In studies focusing primarily on the knee (Besier et al., 2003; Lloyd & Buchanan, 2001), proximal and distal joint positions have been shown to influence muscle activation patterns at the knee during running and cutting tasks. Moreover, biarticular muscles that span two joints can influence the moments across these joints (Besier et al., 2003; Powers, 2010). Hence, changes in joint position more proximally to the ankle could affect triceps surae muscle activation patterns during calf raise, particularly of the biarticular MG and LG. Due to the anatomical attachments of the biarticular gastrocnemii muscles, the MG moment arm is regarded as a tibial external rotator, whereas the LG is considered a tibial internal rotator (Besier et al., 2003). Cibulka et al. (2017) hypothesised that the increased MG activity seen during an isometric plantarflexion contraction in an ER foot (toe-out) position was due to the MG contracting to maintain the tibia in ER. Similarly, to maintain the tibia in IR during an isometric plantarflexion contraction in an IR foot (toe-in) position, the LG muscle activity increases. Although surface EMG signal amplitude is not always an appropriate surrogate for representing muscle force or mechanical stress (Morton et al., 2019; Vigotsky et al., 2018), selective hypertrophy in the gastrocnemii muscles when training in different foot positions has been reported (Nunes et al., 2020), supporting the EMG studies on this topic.

6.4.1.2 Knee position

Given that SOL is monoarticular and the gastrocnemii are biarticular, ankle or knee joint angle modifications can alter the force-length relationships of these muscles and affect their respective force-generating and contractile abilities (Arndt et al., 1998; Ferris et al., 2011; Maganaris, 2003). According to the force-length principle, the amount of force generated by a muscle relates to its length in an inverted-U fashion (Prochazka et al., 2017). Muscles generate less force at extremely shortened or lengthened positions. All three triceps surae muscles operate on the ascending limb of the bell-shaped force-length curve (Maganaris, 2003), indicating that maximum plantarflexion torque is generated in a lengthened muscle position (Sale et al., 1982). Hence, in a knee extended (Cresswell et al., 1995) and ankle dorsiflexed position (Arampatzis et al., 2006), plantarflexion force is maximised. Noteworthy is that the contribution of the gastrocnemii muscles to ankle plantarflexion force generation is affected by both the knee (Cresswell et al., 1995; Kawakami et al., 1998) and ankle (Kawakami et al., 1998; Sale et al., 1982) joint angles, whereas the contribution of SOL is moreover reliant on ankle joint position (Kawakami et al., 1998; Sale et al., 1982).

Differences in triceps surae muscle EMG activation patterns are consistent with the force-length curves for these muscles, wherein MG and LG are generally more active when the knee is extended (MG more so than LG), and SOL activity remains relatively similar across knee flexion angles (Cresswell et al., 1995; Hébert-Losier et al., 2011) or increases at greater knee flexion angles (i.e., 90° versus 0° knee flexion) (Price et al., 2003; Signorile et al., 2002). In extreme knee flexion (110° knee flexion and above), MG and LG are mechanically disadvantaged and contribute minimally to plantarflexion torque (Cresswell et al., 1995; Herzog et al., 1991). The studies on standing calf raises included in this systematic review indicate greater gastrocnemii muscle activity when knees are extended versus flexed to 45° (Hébert-Losier et al., 2012a) with the opposite observed for SOL. However, the 4-5% of maximum voluntary isometric contraction change between knee flexion positions may have limited clinical implications, although a training study would be required to confirm whether or not selective hypertrophy occurs when training in these two knee flexion positions (i.e., 0° versus 45°). It may be that more extreme knee flexion angles are required to cause more selective hypertrophy of SOL than the MG and LG muscles. Noteworthy is that even when training in a knee extended position, hypertrophy of SOL has been documented in elderly participants and can lead to positive changes in functional performance (Fujiwara et al., 2010).

6.4.2 External load

Adding external load while performing standing calf raises was shown to increase the activity of all three triceps surae muscles, with the integrated EMG amplitude of MG remaining greater than that LG and SOL (Kinugasa & Akima, 2005). Adding external load increases force requirements, which leads to an increase in motor unit recruitment and rate of coding (Kinugasa & Akima, 2005), translating to an increase in surface EMG activity. The individual response of each triceps surae muscle is likely to differ from one another due to differences in motor unit discharge behaviours (Hug et al., 2021; Kinugasa & Akima, 2005) and architectural properties, such as fascicle lengths, pennation angles, and muscle fibre type compositions (Edgerton et al., 1975; Friederich & Brand, 1990; Fukunaga et al., 1992). With increasing contractile activity, MG motor unit discharge rates become significantly greater than LG and SOL, which suggests minimal common neural drive between the triceps surae muscles (Hug et al., 2021). In terms of architectural features, MG fascicles are shorter, larger, and more pennate than LG fascicles, which is advantageous for force production (Drazan et al., 2019; Kawakami et al., 1998). On the other hand, LG fascicles are longer and have a greater number of sarcomeres in series than MG fascicles, which is advantageous for velocity generation (Lieber & Ward, 2011). With regards to muscle fibre type, the MG and LG muscles have approximately an equal proportion of Type I (slow-twitch, fatigue-resistant) and Type II (fast-twitch, force and power generating) muscle fibres (Edgerton et al., 1975; Johnson et al., 1973), with MG containing approximately 6% more Type II fibres than LG. In contrast, the SOL has a greater proportion of Type I (>75%) than Type II fibres (Edgerton et al., 1975; Johnson et al., 1973). Theoretically, this fibre type distribution would favour recruitment of MG and LG (to a lesser extent) over SOL with increasing force requirements, although experimental data have shown graded SOL motor unit recruitment and rate of discharge with graded maximal voluntary isometric contraction forces (Oya et al., 2009).

6.4.3 Fatigue

Despite calf raises often being performed to fatigue (i.e., task failure) in a clinical setting to assess the endurance of the triceps surae muscles (Hébert-Losier et al., 2009), only one study addressed how changes in calf raise clinical parameters influence triceps surae muscle EMG fatigue-related parameters (Hébert-Losier et al., 2012b). Given that SOL has a greater proportion of Type I fibres that are more fatigue-resistant and better able to sustain submaximal levels of force for an extended period (Edgerton et al., 1975), it is consistent with muscle physiology that MG and LG demonstrated a greater rate of fatigue than SOL during calf raises performed to volitional cessation (Hébert-Losier et al., 2012b). However, despite a change in muscle activity with knee flexion during calf raises (Hébert-Losier et al., 2012a), muscle fatigue parameters in the three triceps surae muscles were similar across knee positions, inferring that either 0° or 45° knee flexion angles could be used to assess or train the endurance of the MG, LG, and SOL in a clinical context (Hébert-Losier et al., 2012b). Although it could be argued that the amount of knee flexion in the standing calf raise task was insufficient to cause a shift in the triceps surae muscle fatigue parameters in the latter study, changes in EMG amplitude over time (100 maximal isometric plantarflexion contractions) in the three triceps surae muscles was reported as similar between 0° and 90° knee flexion angles elsewhere (Kawakami et al., 2000). On the other hand, time-frequency analysis of a sustained isometric contraction (40% of maximal voluntary isometric contraction) indicates difference in triceps surae muscle activation strategies between 0° and 90° knee flexion angles, wherein SOL plays a greater role when the knee is flexed (Pereira et al., 2011). It is debatable whether results from isometric studies apply to dynamic contractions; and hence, further work in this area would elucidate whether or not the triceps surae muscle fatigue behaviours differ during repeated calf raise exercises when calf raise clinical parameters are altered or different EMG fatigue-related parameters and analyses are undertaken. Furthermore, examining EMG responses during a task to failure will not distinguish between peripherally- and centrally-mediated fatigue, or changes in voluntary activation levels (Gandevia, 2001), which would require a different experimental set-up.

6.4.4 Concentric-eccentric

Although the triceps surae muscles act concentrically and eccentrically to perform repeated calf raises, only three studies examined these two phases separately (Hébert-Losier et al., 2012a, 2012b; Riemann et al., 2011). During the eccentric (lowering) phase of calf raises, the triceps surae muscles were reported as more active than during the concentric (raising) phase (Hébert-Losier et al., 2012a), but the 2% of maximal voluntary isometric contraction difference might have limited clinical implications. Furthermore, despite this greater activity in the eccentric phase, fatigue parameters were similar between concentric and eccentric phases when calf raises were performed to fatigue (i.e., task failure) (Hébert-Losier et al., 2012b). Together, these studies suggest that examining concentric and eccentric phases separately might not be necessary. On the other hand, foot position was shown to influence the triceps surae muscles differently in the concentric than the eccentric phase of bilateral calf raises (Riemann et al., 2011), with greater concentric and eccentric MG than LG activity with feet ER, but lesser concentric MG than LG activity with feet IR.

From a neurophysiological perspective, surface EMG activity and motor unit discharge rate (Duchateau & Enoka, 2016) are typically lower during eccentric than concentric actions due to the enhanced force production ability during lengthening than shortening contractions (Herzog, 2014). These neurophysiological differences warrant examination of the raising (concentric) and lowering (eccentric) phases separately. Indeed, eccentric contractions are considered to be more metabolically and mechanically efficient than concentric ones (Enoka, 1996; Kaneko, 1984), and generally involve greater force and torque outputs at a given intensity. However, the contribution of the stretch-shortening cycle to repetitive calf raises may influence the efficiency of the concentric contraction (Belli & Bosco, 1992; Nicol et al., 2006). Despite repetitive calf raises being typically performed at 30 cycles per minute (K. Hébert-Losier et al., 2009) and therefore likely involving long stretch-shortening cycles (i.e., ground contact times > 250 ms) (Schmidtbleicher, 1992), examining the concentric phase separately from the eccentric phase would not consider the potential for underlying stretch-shortening cycle contribution to this task.

There are a few limitations that should be considered when interpreting the findings of this systematic review. In terms of the included studies, all articles reviewed were considered at high risk of bias based on the QUIPS assessment, with few studies (< 30%) demonstrating at least “good” methodological quality based on the NOS. Most studies did not state their inclusion/exclusion criteria, recruitment and selection methods, or study timeframe (participation bias); did not report dropout rates or missing data (attrition bias); and failed to consider confounders, such as gender, range of motion, and randomisation (confounding bias). Furthermore, sample size was low and unjustified in four of seven studies (Akuzawa et al., 2017; Kinugasa & Akima, 2005; Marcori et al., 2017; Robbins & Goss-Sampson, 2013), and only three studies (Hébert-Losier et al., 2012a, 2012b; Kinugasa & Akima, 2005) examined all three triceps surae muscles.

Given the stringent inclusion criteria, few studies met inclusion leading to only one to three studies examining the different variations in calf raise protocols. In addition, the differences in tasks for many of the included studies are relatively small (i.e., ≤ 5%), with large standard deviations in terms of muscle responses within tasks (i.e., ≥ 20%). The small differences between tasks and large variations in EMG responses limit the potential for generalisation of study findings and ability to make strong clinical recommendations.

Surface EMG is not always an appropriate surrogate for representing muscle force or mechanical stress (Morton et al., 2019; Vigotsky et al., 2018). Of the seven articles reviewed, all used bipolar surface EMG, and none used fine-wire or high-density EMG. Across these studies, muscle activity was reported using different normalisation techniques, which can affect data interpretation (Besomi et al., 2020). Although surface EMG studies can be useful to guide exercise prescription to a certain extent (Vigotsky et al., 2018), there are large inter-individual variations and training studies are advised to determine the extent to which changes in exercise prescription affect muscle architectural and functional properties. Indeed, there is currently a lack of longitudinal studies to confirm that surface EMG predicts hypertrophy outcomes

(Halperin et al., 2018). Surface EMG studies can nonetheless provide insight into muscle force production and be useful in understanding neuromuscular recruitment and function (Vigotsky et al., 2018). Future research can seek to incorporate more recent advancements in EMG signal acquisition and processing in addressing this topic, such as use of high-density EMG (Dick F et al., 2012; Kuruganti et al., 2021).

It has been shown in previous chapters that variations in starting ankle foot position and cadence affect calf raise test outcomes. In this systematic review, it was found that variations in foot rotation and knee flexion angles, integration of additional loads, and addition of whole-body vibration influence the muscle activity of the triceps surae, which may lead to differences in calf raise execution and outcomes. Hence, alterations in calf raise test parameters must be considered when interpreting results. Furthermore, further research is needed to better understand the EMG activity and fatigue of the triceps surae during the calf raise test to better inform test parameters and their selection. This information can provide a better understanding of how the triceps surae muscles function and can be used to develop training programmes tailored to individuals. It can also provide evidence-based guidelines in calf raise test administration and interpretation.

6.5 Conclusion

The findings from the present review can assist clinicians in implementing evidence-based assessment and exercise prescription approaches, notably to achieve different activation levels of the triceps surae muscle. This review provides initial support to the common practice of varying calf raise clinical parameters during calf raise exercises to promote adaptations in the MG, LG, and SOL muscles; however, there are a limited number of studies that have addressed this topic and training studies are needed to confirm these selective adaptations. Future studies may seek to better understand the fatigue process of the three triceps surae muscles when calf raises are performed to fatigue; the relevance or need to examine the concentric and eccentric phases separately; and whether variations in other calf raise clinical parameters, such as cadence, influence triceps surae muscle activity and fatigue.

Chapter 7

Discussion and conclusion

7.1 Thesis synthesis

Conducting a comprehensive assessment in clinical settings is important to provide appropriate rehabilitation management. Functional assessments are used in rehabilitation and sports medicine clinical practice and research to evaluate neuromuscular and musculoskeletal performance. These tests can help identify impairments and assess injury risk in specific functional tasks or sports. The triceps surae MTU plays an important role in human locomotion (Honeine et al., 2013), and is often assessed in clinics using the CRT. Indeed, the CRT is a functional assessment that is widely used in clinical practice and research to assess triceps surae MTU strength and endurance. This test involves "going up on toes and coming back down" as many times as possible, standing on one leg. However, there are various protocols used in the literature, which may contribute to the range of normative values reported (Table 1) and limit cross-study inferences. Furthermore, devices are often used in research to assist in test standardisation and quantification of outcomes other than the number of repetitions that are not easily accessible in clinics. Therefore, the overarching aim of this Thesis was to develop a valid and reliable method to assess the CRT in clinical practice that provides research-grade outcomes, and to examine the influence of changes in CRT protocol on test outcomes and triceps surae function to guide administration and interpretation of the CRT. Two literature reviews and three experimental studies were carried out to achieve the overarching aims of this Thesis, each presented as individual chapters within this Thesis. Table 19 summarises the main findings of these five chapters.

Table 19. Summary of Thesis findings from each literature review or experimental Chapter.

Chapter and Purpose	Methodology	Key findings	Conclusion
Devices to measure calf raise test outcomes: A narrative review. *(Chapter 2)* This review identifies, summarises, and critically appraises the CRT devices used in science to measure test outcomes: number of repetitions, peak height, and total work performed. Also, this review presents the design, reliability, validity, and perceived strengths and limitations of each device for clinical use.	A systematic process aligning with the PRISMA guideline was applied. Four electronic databases were searched in April 2022. Studies that used devices to measure unilateral CRT outcomes (i.e., number of repetitions, peak height and total work) were included.	• Thirty-six studies met inclusion, from which seven CRT devices were identified. • Linear encoder (n=18) was the most used device, followed by laboratory equipment (n=6) (3D motion capture and force plate). These measured the three CRT outcomes. • Other devices used were electrogoniometer, Häggmark and Liedberg light beam device, AMES, Haberometer, and custom-made. • Devices were mostly used in healthy populations or Achilles tendon pathologies. • AMES, Haberometer, and custom-made devices were the most clinician-friendly, but only quantified repetitions completed.	This review details seven devices used to measure CRT outcomes. The linear encoder is the most common in research and quantifies all three CRT outcomes. However, it does not appear to have large uptake in clinical practice potentially due to costs and need for specialised hardware and software.
Concurrent validity and reliability of a mobile iOS application used to assess calf raise test kinematics. *(Chapter 3)* Validate the CR_{app} by examining its concurrent validity and agreement levels against laboratory-based equipment and its intra- and inter-rater reliability.	CRT outcomes (i.e., repetitions, positive work, total height, peak height, fatigue index, and peak power) were assessed in thirteen individuals (6 males, 7 females) on three occasions on both legs using the CR_{app}, 3D motion capture, and force plate simultaneously. Data were extracted from two markers: below lateral malleolus (n=77) and on the heel (n=77). Concurrent validity and agreement were determined from 154 data files using $ICC_{3,k}$, typical errors expressed as CV, and Bland-Altman plots to assess biases and precision. Reliability was assessed using $ICC_{3,1}$ and CV values.	• Validity of CR_{app} outcomes was good to excellent across measures for both markers (mean $ICC_{3,k} \geq 0.878$), with precision plots showing good agreement and precision. • CV ranged from 0% (repetitions) to 33.3% (fatigue index) and were on average better for the lateral malleolus marker. • Inter- ($ICC_{2,1} \geq 0.949$ and CV ≤ 5.6% here) and intra-rater reliability ($ICC_{3,1} \geq 0.970$ and CV ≤ 1.9% here) were excellent.	CR_{app} is valid and reliable within and between users for measuring CRT outcomes in healthy adults. CR_{app} provides a tool to objectivise CRT outcomes in research and practice, aligning with recent advances in mobile technologies and their increased use in healthcare.

Chapter and Purpose	Methodology	Key findings	Conclusion
Effects of ankle starting positions on calf raise test outcomes: Position does matter. *(Chapter 4)* Examine the influence of the three most common ankle starting positions used in conducting the CRT on test outcomes. Also, investigate the potential influence of gender, age, BMI, and level of physical activity on the test outcomes.	In three different test sessions, forty-nine healthy individuals (59% female, 21 ± 4 years) performed single-leg calf raise repetitions to volitional exhaustion in the following randomised conditions: flat (0^{o}), incline (10^{o} dorsiflexion), and step (full dorsiflexion). The CR$_{app}$, which uses a computer-vision algorithm to track the vertical displacement of a marker placed on the foot, recorded the following CRT outcomes: number of repetitions, peak height, total vertical displacement, and total work. Data were analysed using mixed-effects models and stepwise regression.	• Significant main effect ($p<0.001$) of ankle starting position on all CRT outcomes, with all paired comparisons being statistically significant ($p\leq0.023$). • Repetitions, total vertical displacement, and total work were greatest in flat and lowest in step; peak height was greatest in incline and lowest in step. • Gender ($p=0.021$; males>females) and BMI ($p=0.002$) significantly influenced the number of repetitions. Gender ($p<0.001$; males > females) also influenced the total work. • Age and physical activity levels did not significantly influence outcomes.	Variations in ankle starting position significantly affected all CRT outcomes. Among the predictors, gender and BMI influenced the number of repetitions and total work. Interpretation of CRT outcomes and between-study comparisons need to consider these factors.
Effects of cadence on calf raise test outcomes: Cadence does matter. *(Chapter 5)* Examine the influence of cadence (30, 60 and 120 bpm) used in conducting the CRT on test outcomes. Also, investigate the potential influence of gender, age, BMI, and physical activity levels on outcomes.	In three different sessions, thirty-six healthy individuals (50% female, 18 ± 10 years) performed single-leg calf raise repetitions to volitional exhaustion in one of three randomised cadence conditions: 30, 60, and 120 bpm. The CR$_{app}$, which uses a computer-vision algorithm to track the vertical displacement of a marker placed on the foot, recorded the following CRT outcomes: number of repetitions, total vertical displacement, total work, peak height, and peak power. Data were analysed using mixed-effects models and stepwise regression.	• Significant main effect of cadence on all CRT outcomes ($p\leq0.008$), except repetitions ($p=0.200$). • Post-hoc analysis revealed that 60 bpm resulted in significantly greater total vertical displacement and work than 30 and 120 bpm. • Peak height was significantly greater at 60 and 120 than 30 bpm, and peak power was significantly greater at 120 bpm. • Total work and peak power were significantly greater in males ($p\leq0.001$), whereas individuals with greater BMI had lower numbers of repetitions ($p=0.008$), lower total vertical displacement ($p=0.003$), and greater peak power ($p=<0.001$). • Age and physical activity levels did not significantly affect CRT outcomes.	Variations in cadence significantly affected all CRT outcomes except the number of repetitions. Among the predictors, gender influenced total work and peak power, and BMI influenced repetitions, total vertical displacement, and peak power. Overall, a 60 bpm cadence appears better than a slower 30 bpm or faster 120 bpm cadence for the CRT as maximises total vertical displacement and total work.

Chapter and Purpose	**Methodology**	**Key findings**	**Conclusion**
Triceps surae muscle activity and fatigue during standing single leg calf raises: A systematic review. *(Chapter 6)* Examine how changes in standing calf raise test or exercise clinical parameters affect triceps surae surface EMG activity and fatigue measures in healthy individuals	Seven electronic databases were searched: Scopus®, Sports Medicine & Education Index, MEDLINE®, SPORTDiscus, PubMed®, Web of Science®, and CINAHL Complete (PROSPERO registration: CRD420201819).	• Seven articles met inclusion, all of which implemented surface EMG. • All articles were at high risk of bias based on the QUality In Prognosis Studies tool, with five exhibiting good-to-satisfactory and two unsatisfactory methodological quality according to the modified Newcastle-Ottawa Scale • The MG and LG were more frequently assessed than SOL, as were muscle activity-related parameters than fatigue-related ones. • Foot position was the most researched clinical parameter variation (n=3 studies), followed by knee position (n=2), whole-body vibration (n=1), and load (n=1). • Overall, during standing calf raises, MG surface EMG activity increased with feet externally rotated and knees extended; LG activity increased with feet internally rotated, and knees extended, and SOL activity increased with knees flexed and whole-body vibration. • The activity of all three muscles increased with load. • Altering calf raise parameters had limited influence on fatigue-related measures.	The findings provide initial support for the practice of varying calf raise parameters to promote increased activation of MG, LG, and SOL. These findings can assist clinicians in implementing evidence-based practice, but training studies are required to confirm selective muscle adaptations with changes in calf raise parameters, with only one study addressing fatigue.

7.1.1 Devices used to measure calf raise test outcomes

The review in *Chapter 2* critically appraised 35 relevant studies that used measuring devices to evaluate CRT outcomes in healthy individuals as well as those with medical conditions to inform evidence-based use of the CRT. Of the seven thematically grouped devices sourced from the literature, the linear encoder (Silbernagel et al., 2010) was the most frequent device used. It provides reliable outcomes at a moderate financial cost compared to 3D motion and force plate systems. Moreover, the Haberometer (Haber et al., 2004), AMES (Sman et al., 2014), and custom-made device (Sara et al., 2021) were considered the most clinically friendly CRT devices because of their simplicity, portability, affordability, and lack of requirement for specialised hardware or software. Although these devices can assist in standardising CRT parameters, they are not readily available for purchase and only focused on the number of repetitions completed. In clinical settings, the number of repetitions is the primary outcome of CRT performance (Lunsford & Perry, 1995). However, it has been reported that other test outcomes are important for measuring the strength and endurance of the ankle plantarflexors and MTU. Studies have shown that the measures of peak height and total work are more sensitive indicators in the presence of pathology or functional deficits (Byrne et al., 2017; Silbernagel et al., 2010; Svantesson, Osterberg, Thomeé, et al., 1998) than the number of repetitions. Moreover, including these outcomes in addition to the number of repetitions in the CRT could provide a more comprehensive assessment of ankle plantarflexion function.

When considering the strengths and limitations of each device for clinical use, the linear encoder method appeared to offer the best compromise for clinicians seeking research-grade outcomes at a moderate cost. However, the linear encoder does not appear to have large uptake in clinical practice potentially due to these moderate costs and need for specialised hardware and software. Therefore, a mobile application was specifically designed to aid objectivise CRT outcomes in clinical practice.

7.1.2 The validation of a mobile application to quantify calf raise test outcomes

Given that clinicians and practitioners are becoming more accustomed to using mobile applications and digital technologies (Ventola, 2014), a computer vision-based mobile application (Balsalobre-Fernández C et al., 2020; Moreira et al., 2022) could offer a useful and accessible method for quantifying CRT outcomes. An iOS-based application, the CR_{app}, was developed to quantify CRT performance by tracking the vertical displacement of a marker on the foot using computer-vision algorithms (Hébert-Losier & Balsalobre-Fernández, 2020). It was an imperative first step to establish that the mobile application was valid and reliable before promoting its use in clinical practice and scientific research. Therefore, the validity and rater reliability of the CR_{app} was examined for all outcomes measured by the application (number of repetitions, total vertical displacement, peak height, total positive and negative work, peak positive and negative power, and fatigue index).

The agreement between the CR_{app} and laboratory-based measures was excellent for the lateral malleolus ($ICC_{3,k}$ 0.963) and good-to-excellent for the heel ($ICC_{3,k}$ 0.878) markers across outcomes based on ICC values. The absolute measurement error was higher for the heel (mean CV 9.6%) than the lateral malleolus (mean CV 5.8%), which could be aggravated with hindfoot deformity. As a result, using a marker placed directly below the lateral malleolus on the side of the foot is recommended when using the CR_{app}. The concurrent validity of the CR_{app} versus 3D motion capture was superior to that versus force plate for the work and power metrics. This finding is due to the CR_{app} and 3D motion systems using different base units and algorithms to calculate work and power (i.e., force is based on the body mass of individuals) compared to force plate. Therefore, it is not unexpected that the data from the computer-vision motion analysis-based algorithms of the CR_{app} were more comparable to the 3D motion capture system than the force plate-derived ones. Nonetheless, the validity of the CR_{app} measures were good-to-excellent, and comparable to the validity and accuracy of the linear encoder method for quantifying CRT outcomes reported elsewhere (Andreasen et al., 2020). In addition, the intra- and inter-rater reliability of CR_{app} use was excellent. Therefore, the free-to-use CR_{app} could serve as a feasible mobile alternative for quantifying CRT outcomes than those currently used in research, being user-friendly, portable, and adaptable to various clinical settings.

7.1.3 The influence of test parameters on calf raise test outcomes

The literature has reported that varying CRT parameters can affect triceps surae MTU fatigue (Hébert-Losier et al., 2012b) and muscle activity (Hébert-Losier et al., 2012a) parameters. For example, changing the knee flexion angle can alter the muscle activity of the SOL, MG, and LG although this change in knee angle has no meaningful effect on the number of repetitions completed during CRT. Prior to this Thesis, no studies had directly examined the influence of the varying other CRT parameters on test outcomes, specifically the ankle staring position (*Chapter 4*) and cadence (*Chapter 5*). To further enhance the evidence-based supporting the use of the CRT, the effect of changes to these key clinical test parameters was examined using the valid and reliable CR_{app}.

In *Chapter 4*, CRT outcomes were compared between the three most common ankle starting positions [i.e., flat (0°), incline (10° dorsiflexion), and step (full dorsiflexion)]. The results showed that altering ankle position significantly affects the number of repetitions, total vertical displacement, peak height, and total work performed. Performing the CRT on the flat yielded a superior number of repetitions, total vertical displacement, and total work. As the pace of calf raise repetitions was consistent across ankle positions, increasing the dorsiflexion ankle range of motion (i.e., incline and step condition greater range than flat) during the repetitive plantarflexion contractions of the CRT increases the contraction time and presumably the EMG activation of the triceps surae muscles, which may lead to early onset of muscle fatigue and termination of the CRT. Also, the time spent in contact with a supporting surface between repetitions would be greatest in the flat condition, followed by the incline condition. In the step condition, the heel was never in contact with a supporting surface, hence the muscles were presumably always contracted and the time under tension was greatest, leading to earlier fatigue and termination of CRT.

In *Chapter 5*, the effect of three cadences (i.e., 30, 60 and 120 bmp) on CRT outcomes was examined. Results from this study indicate that cadence significantly influenced the total vertical displacement, peak height, total work, and peak power, but not the number of repetitions. Performing the CRT at a moderate cadence of 60 bpm produced superior values for most CRT outcomes, except for repetitions and peak power. This finding may be because the triceps surae MTU stores and releases elastic energy more efficiently at 60 bpm than at slower and faster speeds. At the slowest 30 bpm cadence, time under tension is greatest, and the triceps surae muscles contract isometrically at end-range plantarflexion for a longer time, resulting in lower total vertical displacement and total work than 60 bpm. It was unexpected to observe lower peak heights (i.e., 5% lower) at this slowest cadence. Although this finding may be due to the slower movement velocity and lower momentum of the task at 30 bpm, the difference may not be clinically meaningful. Lastly, as anticipated, peak power was greatest at the fastest cadence as movement velocity was increased.

7.1.4 Predictors of calf raise test outcomes

Literature has shown that the number of repetitions performed during the CRT varies with age (Hébert-Losier et al., 2017; Mishra et al., 2022), between genders (Jan et al., 2005; Sara et al., 2021), with BMI (Hébert-Losier et al., 2022; Sole et al., 2010), and level of physical activity (Hébert-Losier et al., 2017). A secondary aim of this Thesis was to investigate the potential influence of these predictors on test outcomes. In *Chapter 4*, findings reveal that gender (p=0.021; males>females) and BMI (p=0.002; lower BMI > greater BMI) significantly influenced the number of repetitions. In addition, gender (p<0.001; males >females) also influenced total work. In *Chapter 5*, findings were generally similar. BMI significantly influenced repetitions (p=0.008, lower BMI > lower BMI). In addition, individuals with greater BMI had lower total vertical displacement (p=0.003) and greater peak power (p=<0.001). Gender significantly influenced total work and peak power (p<0.001; males > females). The two other predictors, age and physical activity levels, did not influence any of the CRT outcomes. This last finding contrasts with prior studies where age and physical activity levels influenced CRT outcomes. However, the cohorts in *Chapter 4* and *Chapter 5* were relatively homogeneous in nature compared to prior studies, with narrow age ranges and moderate-to-high levels of physical activity. Predictors were included as confounding variables, and studies were not specifically designed to examine their effects on CRT outcomes.

7.1.5 Muscle activation and fatigue with changes in calf raise test parameters

Researchers and practitioners use EMG to assess muscle activity and fatigue-related parameters and guide exercise prescription. The previous chapters of this Thesis addressed how varying calf raise parameters affect test outcomes; however, these chapters did not address how these variations affect triceps surae muscle EMG parameters. The systematic review reported in *Chapter 6* indicated that the triceps surae muscles could be affected by changes in foot position

(Akuzawa et al., 2017; Marcori et al., 2017; Riemann et al., 2011), knee flexion angle (Hébert-Losier et al., 2012a, 2012b), external load (Kinugasa & Akima, 2005), and whole-body vibration (Robbins & Goss-Sampson, 2013) during standing calf raises.

Most of the studies examined the effects of foot position on triceps surae muscle EMG parameters during standing calf raises (Akuzawa et al., 2017; Marcori et al., 2017; Riemann et al., 2011). In these studies, MG activity was found to increase when feet were ER, with LG activity increasing with feet IR. Furthermore, MG and LG were generally more active with the knee extended (MG more so than LG), and SOL activity remained relatively similar across knee flexion angles or increased at increased knee flexion angles (i.e., 90° versus 0°). While performing standing calf raises, adding external load was shown to increase the activity of all three triceps surae muscles, with the integrated EMG amplitude of MG remaining greater than that of LG and SOL. Despite calf raises often being performed to fatigue in a clinical setting to assess the endurance of the triceps surae muscles, only one study addressed how changes in calf raise clinical parameters influenced triceps surae muscle EMG fatigue-related parameters (Hébert-Losier et al., 2012b). The fatigue parameters in the three triceps surae muscles were similar regardless of the knee position. Across studies, changes in triceps surae muscle activation patterns with variations in calf raise parameters were attributed to neuromuscular compartmentalisation (English et al., 1993), force-length relationships (Maganaris, 2003), and changes in the line of forces around the ankle joint.

7.2 Thesis strengths and limitations

The strengths and limitations of each study are described in Table 20. Overall, the strengths of this Thesis include its novel approach to addressing the overarching aim, which includes a systematic methodology, comprehensive analysis taking into account other predictors that could potentially influence test results, and sufficient sample sizes in the experimental studies. However, this Thesis has limitations, such as a lack of diversity in the demographic characteristics of participants, which limits the generalisability of the findings of the experimental studies. Furthermore, triceps surae MTU mechanics were not examined using EMG, ultrasound, or other devices, which could have provided further insight into MTU mechanics and contributions to calf raises.

Table 19. Thesis strengths and limitations.

Chapters	Strengths	Limitations
Devices to measure calf raise test outcomes: A narrative review. *Chapter 2*	• The review process follows a rigorous and systematic approach that adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). • This review focused on the CRT devices and their design, reliability, concurrent validity that can be useful in clinical practice and research. • This review provides the strengths ad limitations of the devices used to assess CRT outcomes that can be valuable in clinical practice and research. • This review highlights the importance of having a measuring device that could help to standardise test administration. • This review presents the CRT devices that can be used to have an objective method of quantifying test outcomes aside from the number of repetitions completed.	• This review only focused on the single-leg CRT performed to fatigue, bilateral or seated calf raises, or test done with predetermined duration were not considered. • This review did not discuss other psychometric properties of the assessment procedures, such as responsiveness of outcomes, sensitivity, or specificity of the CRT measuring devices. • Given with the type of review utilised in this study, no critical appraisal was undertaken due to the varied methods used in the selected studies. • No risk of bias assessment was done as it was not relevant to the review aims.

Chapters	Strengths	Limitations
Concurrent validity and reliability of a mobile iOS application used to assess calf raise test kinematics. *Chapter 3*	• First study to evaluate the psychometric properties of a mobile application to quantify CRT outcomes (i.e., number of repetitions, total vertical displacement, peak height, total positive and total negative work and peak positive and peak negative power and fatigue index). • The validation method was tested against the gold standard laboratory-based equipment (i.e., 3D MOCAP and force plate technology system) • The CR_{app} also demonstrates good-to-excellent inter-rater, intra-rater, and test-retest reliability • The application has demonstrated good-to-excellent validity of CRT outcomes (i.e., repetitions, peak height, total vertical displacement, and total work) against 3D motion capture and force plate. • The CR_{app} can now be used to establish empirically based normative values and used to further standardise test administration. • The CRa_{pp} can now be used to objectivize CRT outcomes (i.e., number of repetitions, total vertical displacement, peak height, total positive and total negative work and peak positive and peak negative power) in research and clinic with confidence.	• This study only includes healthy adult-age individuals that may limit the generalisability of the overall study findings. Given that the CRT is used across a range of populations (i.e., paediatric, older adults and athletes). • The fatigue index outcome was the least valid measure from the CR_{app} and should therefore be used with caution.

Chapters	Strengths	Limitations
Effects of ankle starting position on calf raise test outcomes: Position does matter. *Chapter 4*	• First study to explore the effects of variation in ankle starting positions on CRT outcomes (i.e., total number of repetitions, total vertical displacement, peak height, total work) • This study is powered to detect significant differences in CRT outcomes between ankle starting positions. The sample size is 43 to attain 90% power at a 5% level of significance. • This study used CR_{app}, a valid and reliable method to quantify CRT outcomes. • This study demonstrates that predictors such as gender significantly influence the number of repetitions and total work and BMI predictors significantly influence number of repetition outcome, this provides insights that these predictors should be accounted in CRT administration am test outcomes interpretations. • This study provides an evidence-based assessment that can use to inform ankle functional assessments, progress monitoring, and rehabilitation management. • The CRT can be performed from three ankle starting positions, and each position influences the test outcomes (e.g., expect the least number of repetitions in CRT from a step, and the greatest from flat).	• The step condition was intended to involve a full range of dorsiflexion, but as observed in the video, participants were unable to reach full dorsiflexion. The study did not standardize or quantify the range of motion during testing. • The study did not use other devices that measure muscle activity, fatigue parameters, muscle fibre length, and tendon properties. (e.g., EMG and ultrasound). This could have provided further insight into the effects of variation in ankle starting position. • The homogeneous nature of our population (i.e., relatively narrow age range and moderate-to-high levels of physical activity) limits the generalisability of the results to a broader population.

Chapters	Strengths	Limitations
Effects of cadence on calf raise test outcomes: Cadence does matter. *Chapter 5*	• First study to explore the effects of variation in calf raise cadences on CRT outcomes (i.e., total number of repetitions, total vertical displacement, peak height, total work, and peak power). • This study used CR_{app}, a valid and reliable method to quantify CRT outcomes. • This study is powered to detect significant differences in CRT outcomes between cadences. The sample size was 32 participants to attain 80% power at a 5% level of significance • This study demonstrates that predictors such as gender significantly influence the total work and peak power and BMI significantly influence number of repetitions, total vertical displacement, and peak power outcomes, this provides insights that these predictors should be accounted in CRT administration am test outcomes interpretations. • This study provides an evidence-based assessment that can use to inform ankle functional assessments, progress monitoring, and rehabilitation management.	• The homogeneous nature of our population (i.e., relatively narrow age range and moderate-to-high levels of physical activity) limits the generalisability of the results to a broader population. • The study did not use other devices that measure muscle activity, fatigue parameters, muscle fibre length, and tendon properties. (e.g., EMG and ultrasound). This could have provided further insight into the effects of variation in cadence.

Chapters	Strengths	Limitations
Triceps surae muscle activity and fatigue during standing single leg calf raises: A systematic review. *Chapter 6*	• The review process follows a rigorous and systematic approach that adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). • Included articles were critically appraise using a validated appraisal tool, Newcastle-Ottawa Scale (NOS). • The protocol of this review was preregistered in the international prospective register of systematic reviews (PROSPERO as CRD420201819). • QUality in Prognosis Studies (QUIPS) was used to assess the risk of bias in the included studies. • This review provides initial support to the common practice of varying calf raise clinical parameters during calf raise exercises to promote adaptations in the MG, LG, and SOL muscles.	• All (seven) articles reviewed were considered at high risk of bias based on the QUIPS assessment, with few studies (< 30%) demonstrating at least “good” methodological quality based on the NOS. • Given the stringent inclusion criteria, few studies met inclusion leading to only one to three studies examining the different variations in calf raise protocols. • The differences in tasks for many of the included studies are relatively small (i.e., ≤ 5%), with large standard deviations in terms of muscle responses within tasks (i.e., ≥ 20%). • The small differences between tasks and large variations in EMG responses limit the potential for generalisation of study findings and ability to make strong clinical recommendations.

Abbreviations: 3D MOCAP, three- dimensional motion capture; CR_{app}, Calf Raise application; CRT, calf raise test; EMG, electromyography; iOS, iPhone operating system; LG, lateral gastrocnemius; MG, medial gastrocnemius; NOS, Newcastle-Ottawa Scale; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; QUIIPS, QUality in Prognosis Studies; SOL, soleus.

7.3 Key points and clinical implications

Based on this Thesis, the following key points are worth highlighting:

- The narrative review presented in *Chapter 2* provides insight into the devices used to assess CRT and their strengths and limitations. The linear encoder offers the best compromise for clinicians seeking research-grade outcomes.
- The CR_{app} is valid and reliable for measuring key CRT outcomes in healthy adults and can be employed to establish empirically based normative values across populations. The fatigue index is the least valid measure and should be used with caution. The CR_{app} provides an alternative tool to the linear encoder to clinicians seeking research-grade CRT outcomes.
- The CRT has been performed in research from three different ankle starting positions. The results from *Chapter 4* show that ankle position matters and influences CRT outcomes (e.g., expect the least number of repetitions in CRT from a step and the greatest from flat). The flat ankle starting position demonstrates superior number of repetitions, total vertical displacement, and total work. Gender and higher BMI were significant predictors of CRT outcomes, whereas age and physical activity levels did not significantly impact CRT outcomes.
- The CRT has been performed in research using different cadences. The results from *Chapter 5* show that cadence matters and influences CRT outcomes. Changing the CRT cadence significantly influenced total vertical displacement, total work, peak height, and peak power outcomes, but not total repetitions. Gender and BMI were significant predictors of total work and peak power, whereas age and physical activity levels did not significantly impact CRT outcomes. A 60 bpm cadence leads to superior outcomes in terms of the number of repetitions, total vertical displacement, peak height, and total work, whereas 120 bpm leads to superior peak power.

- The systematic review discussed in *Chapter 6*, provides initial support for the practice of varying calf raise clinical parameters to promote activation of the MG, LG, and SOL muscles during calf raises.

The results from this Thesis have the following clinical implications:

- This Thesis introduces and validates the CR_{app}, an innovative and cost-effective method for quantifying the outcomes of the CRT. Researchers and clinicians can use this tool to obtain reliable and valid CRT outcomes, which relies on validated computer-vision algorithms. The CR_{app} helps to bridge the gap between clinical research and clinical practice, allowing for more objective monitoring of CRT outcomes with potential implications for ankle and foot rehabilitation management.
- Overall, this Thesis provides a better understanding of the effects of changing parameters (i.e., ankle starting position and cadence) on CRT outcomes. Understanding how changes in parameters affect outcomes can assist in clinical decision-making and test interpretation. Furthermore, the results can be used to make informed decisions regarding CRT administration.
- In addition, this Thesis identified that gender and BMI influence CRT outcomes. Hence, it is important to recognise and account for these differences when interpreting outcomes in clinical settings.

7.4 Future research directions

This Thesis addressed the set hypotheses. However, the following are recommendations for future research to address the identified limitations of this Thesis and to draw a more comprehensive conclusion regarding the influence of CRT parameters on outcomes:

1. A computer vision algorithm is used in the Calf Raise mobile application to facilitate automated tracking. The application measures and calculates other test metrics than the number of repetitions by tracking the displacement of calf raises with a marker placed on the foot. It is the first application that measures all the key metrics reported in the literature for CRT. To further improve the application, future research should seek to update the algorithm to strengthen its validity and reliability in quantifying fatigue index and power outcomes. *(Chapter 3)*
2. Future advancements in technology may be incorporated into the CR_{app}, like motion detection and gesture recognition via markerless augmented reality. Incorporating these technological advancements may be costly but can potentially improve the accuracy of outcomes. *(Chapter 3)*
3. Variations in calf raise parameters can affect the range of motion, length of muscles, and amount of muscle force generated, which in turn affect EMG muscle activity and fatigue. Therefore, it is imperative to understand the effects of variations of CRT parameters on muscles themselves, which was not performed in this Thesis. Such data would inform on what calf raise parameters maximise SOL, MG, and LG muscle activation. Furthermore, understanding how variations in CRT parameters affect EMG activity and fatigue should allow a more individualised management of individuals and improve exercise design for specific injuries. *(Chapter 4 and Chapter 5)*
4. The experimental studies of this Thesis involved healthy individuals only. Future research needs to consider the effects of varying CRT ankle starting positions and cadence on pathological and other populations to ensure generalisation of findings. It is pertinent to consider the type of injury and phase of rehabilitation when administering the CRT (e.g., insertional versus mid-portion Achilles tendinopathy

or early-stage versus late-stage post-ATR) and choosing the ankle start position and cadence, as there are different loads and shears applied to the Achilles tendon, which were not examined here. Similarly, individuals from different age groups or athletic abilities may respond differently to changes in CRT parameters and benefit from exercises being prescribed at specific ankle starting positions or cadences *(Chapter 4 and Chapter 5)*

5. The experimental studies in this Thesis involved populations that were relatively homogeneous in terms of age and activity levels. The studies were not specifically designed to examine the effects of predictors on CRT outcomes. Future studies should be purposefully designed to examine the effect of potential predictors on CRT outcomes to better understand if outcomes depend on individual characteristics. *(Chapter 4 and Chapter 5)*

7.5 Conclusion:

Overall, this Thesis enhances the empirical evidence available with regards to CRT administration and interpretation. Notably, this Thesis introduced a valid and reliable innovative method for quantifying all key CRT outcomes (i.e., the number of repetitions, total vertical displacement, peak height, and total work) that is clinically accessible and provided evidence of the effects of change in CRT parameters on key test outcomes. Additionally, the demographic characteristics of participants (i.e., age, gender, BMI, and level of physical activity) were considered when interpreting outcomes, with gender and BMI specifically shown to be significant determinants of test outcomes. This Thesis, therefore, serves as a useful resource for clinicians and researchers to understand the effects of varying test parameters and to improve CRT administration and interpretation. The findings from this Thesis may be used to inform best practice use of the CRT and guide future research. In conclusion, this Thesis contributes to the body of knowledge on CRT administration and interpretation.

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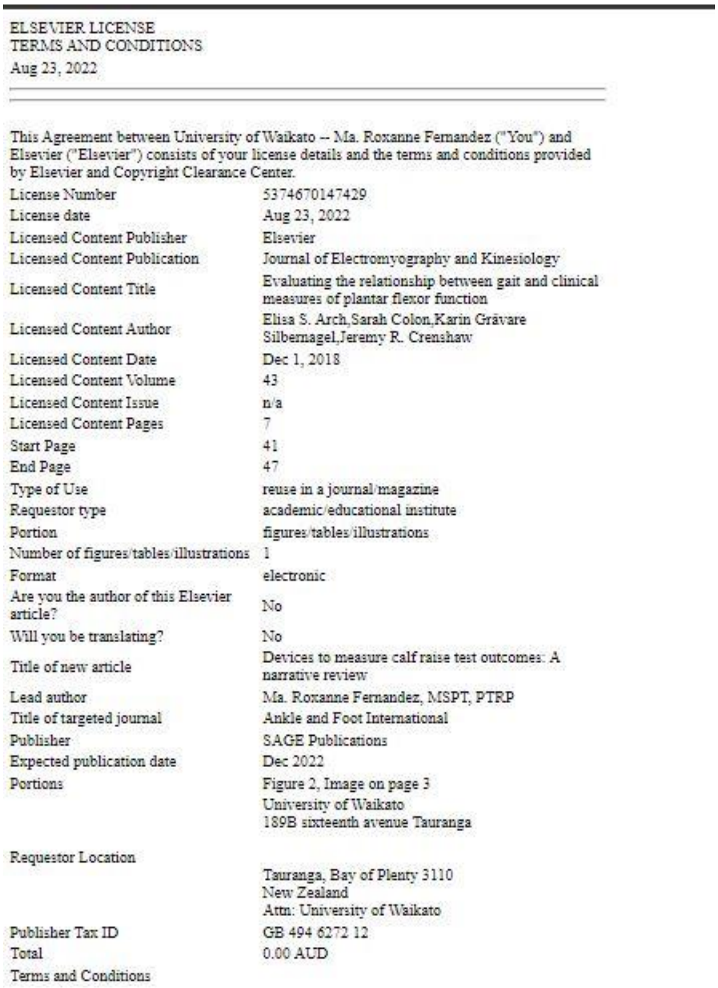

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Expected publication date	Dec 2022
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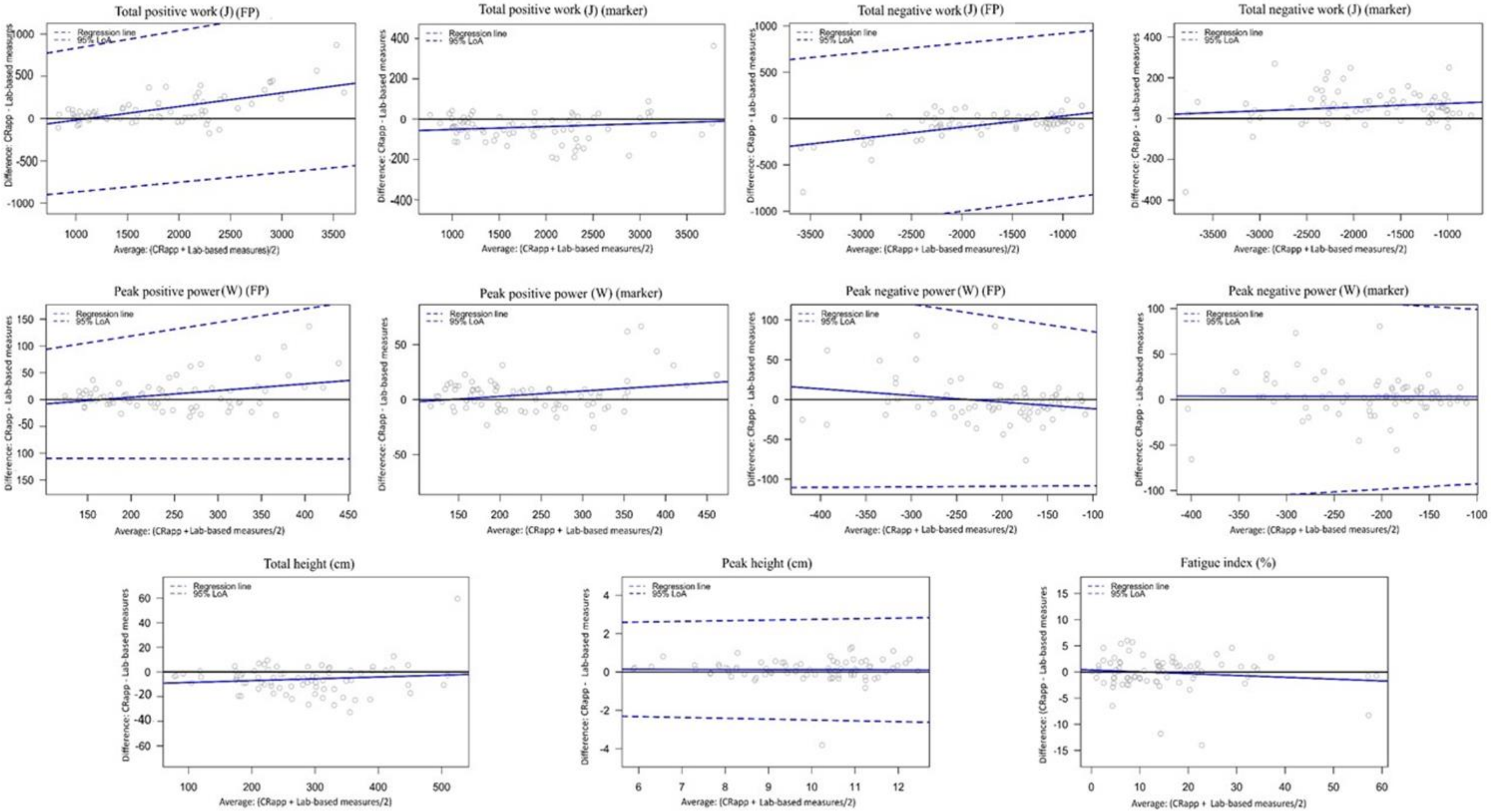
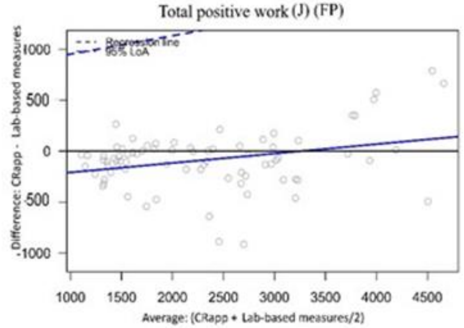
Appendix B. Detailed search strategy for each database

Search strategy	**Key words**
Cochrane (n = 211)	(calf raise OR heel raise OR heel rise):ti,ab,kw AND (test* OR eval*):ti,ab,kw" (Word variations have been searched)
PubMed® (n = 213)	(("calf raise"[All Fields] OR "heel raise"[All Fields] OR "heel rise"[All Fields]) AND ("test"[All Fields] OR "eval"[All Fields])) AND ((humans[Filter]) AND (english[Filter]))
Scopus (n = 252)	(TITLE-ABS-KEY ("heel rise" OR "heel raise" OR "calf raise") AND TITLE-ABS-KEY (eval* OR test*)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English"))
Sports Medicine & Education Index (n = 158)	(noft(calf raise) OR noft(heel raise) OR noft(heel rise)) AND (noft(test?) OR noft(eval?)) Additional limits - Document type: Article; Language: English
SPORTDiscus (n = 213)	("calf raise" OR "heel raise” OR “heel rise”) AND (test* OR eval*) Limiters - Language: English; Publication Type: Academic Journal

Appendix C1. Bland Altman plots for lateral malleoli marker placement



Appendix C2. Bland Altman plots for heel marker placement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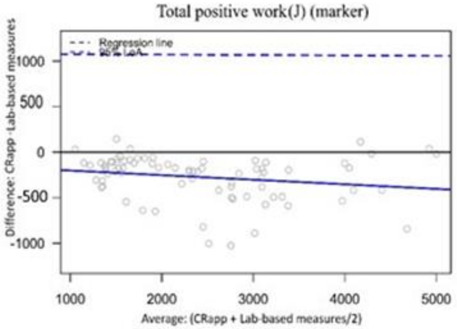
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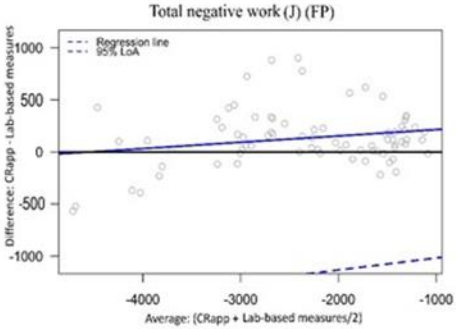
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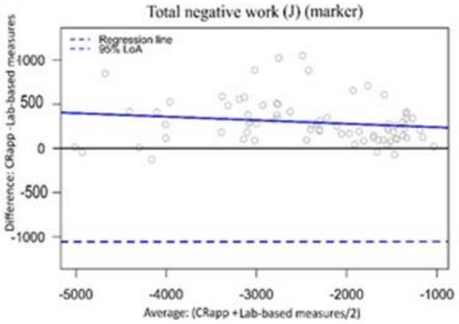
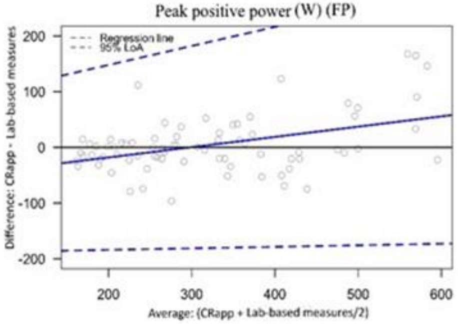
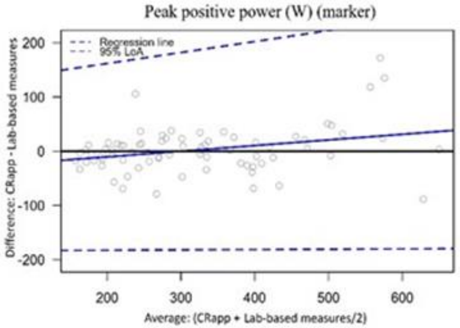

Total negative work (J) (marker)


Peak positive power (W) (FP)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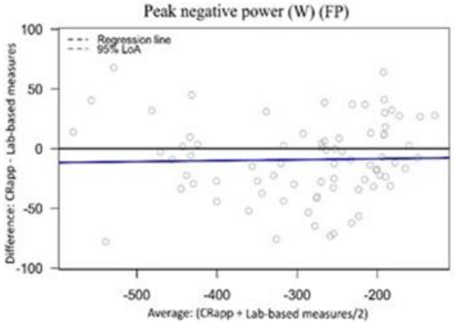
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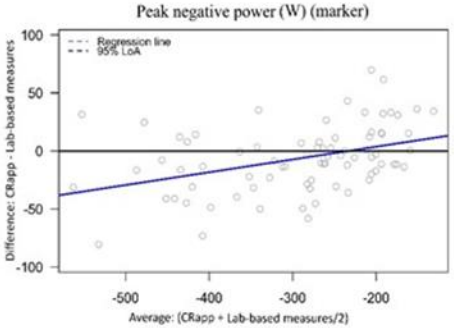
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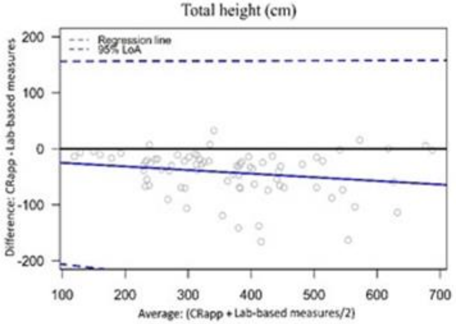
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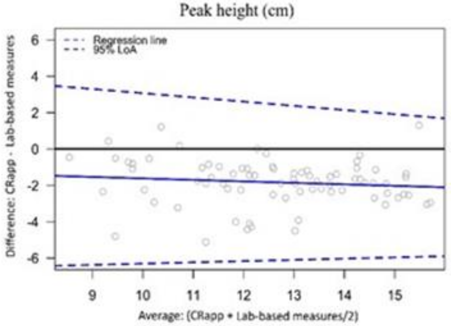
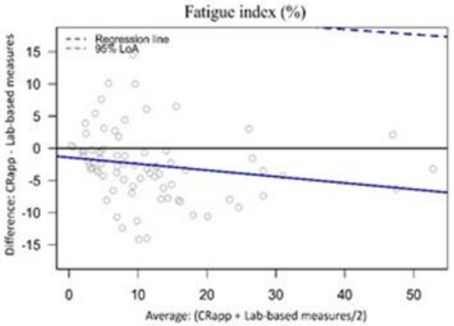

Peak height (cm)


Fatigue index (%)

Appendix C3. Intra-rater reliability of the Calf Raise application for rater 1.

Descriptive data are means (standard deviations) and statistical values are presented with 95% confidence interval [lower, upper].

Outcome measure	**Descriptive**			**Statistics**		
	Day 1	**Day 2**	**Day 3**	**ICC**	**SEM**	**CV (%)**
Repetition (*n*)	23 (9)	23 (9)	23 (9)	0.999 [1.000, 1.000]	0	0
Total height (cm)	175.21 (64.11)	175.82 (64.24)	175.60 (64.29)	0.999[1.000, 1.000]	1.10 [0.97, 1.23]	0.64 [0.56, 0.71]
Peak height (cm)	8.61(1.52)	8.64 (1.53)	8.62 (1.53)	0.998 [0.999, 0.999]	0.05 [0.04, 0.05]	0.57 [0.50, 0.63]
Fatigue index (%)	18.47 (13.19)	18.45 (13.21)	18.43 (13.18)	0.999 [1.000, 1.000]	0.20 [0.16, 0.23]	1.07 [0.88, 1.27]
Total positive work (J)	1435.70 (576.65)	1440.73 (577.62)	1439.06 (579.04)	0.999 [1.00 1.000]	9.24 [8.08, 10.40]	0.65 [0.57, 0.74]
Total negative work (J)	-1436.94 (576.65)	-1442.07 (577.57)	-1440.30 (578.92)	0.999 [1.000, 1.000]	9.30 [8.14, 10.46]	0.66 [0.58, 0.75]
Peak positive power (W)	257.87 (73.33)	258.58 (76.19)	260.31 (77.79)	0.984 [0.980, 0.988]	9.40 [7.84, 10.96]	3.72 [3.10, 4.34]
Peak negative power (W)	-248.70 (66.61)	-248.91 (66.16)	-248.87 (66.58)	0.996 [0.995, 0.997]	4.21 [3.57, 4.85]	1.72 [1.46, 1.98]

Note. Data from *n* = 106 data files of calf raise tests.

Abbreviations: CR_{app}, Calf Raise application; CV, coefficient of variation; ICC, intraclass correlation coefficient; SD, standard deviation; SEM, standard error of the mean measurement.

Appendix C4. Intra-rater reliability of the Calf Raise application for rater 2.

Descriptive data are means (standard deviations) and statistical values are presented with 95% confidence interval [lower, upper].

Outcome measure	**Descriptive**			**Statistics**		
	Day 1	**Day 2**	**Day 3**	**ICC**	**SEM**	**CV (%)**
Repetition (*n*)	23 (9)	23 (9)	23 (9)	1.000	0	0
Total height (cm)	174.87 (63.92)	173.51 (63.04)	173.71 (63.77)	0.999 [0.999, 0.999]	1.66 [1.48, 1.84]	0.96 [0.86, 1.07]
Peak height (cm)	8.58 (1.53)	8.53 (1.51)	8.52 (1.51)	0.997 [0.996, 0.998]	0.08 [0.07, 0.09]	0.96 [0.86, 1.06]
Fatigue index (%)	18.47 (13.43)	18.51 (63.04)	18.45 (13.40)	1.000	0.08 [0.06, 0.09]	0.41 [0.35, 0.47]
Total positive work (J)	1432.91 (576.42)	1423.90 (571.12)	1423,57 (574.77)	0.999 [0.999 1.000]	13.48 [12.07, 14.90]	0.95 [0.85, 1.05]
Total negative work (J)	-1433.96 (576.16)	-1425.09 (571.06)	-1424.87 (574.59)	0.999 [0.998, 0.999]	21.13 [18.52, 23.75]	1.51 [1.32, 1.69]
Peak positive power (W)	257.75 (73.33)	255.19 (71.49)	253.94 (72.77)	0.995 [0.994, 0.997]	4.67 [4.02, 5.32]	1.85 [1.59, 2.10]
Peak negative power (W)	-247.12 (64.26)	-248.46 (66.60)	-247.07 (66.59)	0.996 [0.995, 0.997]	3.86 [3.35, 4.37]	1.58 [1.37, 1.79]

Note. Data from *n* = 106 data files of calf raise tests.

Abbreviations: CR_{app}, Calf Raise application; CV, coefficient of variation; ICC, intraclass correlation coefficient; SD, standard deviation; SEM, standard error of the mean measurement.

Appendix C5. Intra-rater reliability of the Calf Raise application for rater 3.

Descriptive data are means (standard deviations) and statistical values are presented with 95% confidence interval [lower, upper].

Outcome measure	**Descriptive**			**Statistics**		
	Day 1	**Day 2**	**Day 3**	**ICC**	**SEM**	**CV (%)**
Repetition (*n*)	23 (9)	23 (9)	23 (9)	1.000	0	0
Total height (cm)	168.77 (62.08)	167.42 (61.51)	168.16 (61.36)	0.998 [0.998, 0.999]	2.68 [2.33, 3.04]	1.56 [1.35, 1.76]
Peak height (cm)	8.29 (1.48)	8.23 (1.47)	8.26 (1.47)	0.996 [0.994, 0.997]	0.10 [0.09, 0.11]	1.17 [1.05, 1.30]
Fatigue index (%)	18.42 (13.24)	18.43 (13.25)	18.45 (13.26)	0.999 [0.999, 1.000]	0.31 [0.26, 0.37]	1.70 [1.41, 1.98]
Total positive work (J)	1380.31 (555.93)	1369.63 (552.35)	1375.73 (550.36)	0.999 [0.999, 1.000]	18.37 [16.30, 20.43]	1.30 [1.15, 1.45]
Total negative work (J)	-1331.57 (552.20)	-1322.85 (550.29)	-1374.93 (552.07)	0.999 [0.998, 0.999]	18.70 [16.62, 20.79]	1.33 [1.18, 1.48]
Peak positive power (W)	244.48 (68.32)	243.18 (69.68)	242.94 (69.07)	0.970 [0.960, 0.977]	12.64 [10.65, 14.63]	5.00 [4.21, 5.79]
Peak negative power (W)	-239.10 (62.82)	-236.99 (62.82)	-238.43 (62.73)	0.984 [0.979, 0.988]	8.44 [7.03, 9.84]	3.45 [2.87, 4.02]

Note. Data from *n* = 106 data files of calf raise tests.

Abbreviations: CR_{app}, Calf Raise application; CV, coefficient of variation; ICC, intraclass correlation coefficient; SD, standard deviation; SEM, standard error of the mean measurement.

Appendix C6. Inter-rater reliability of the Calf Raise application for day 1.

Descriptive data are means (standard deviations) and statistical values are presented with 95% confidence interval [lower, upper].

Outcome measure	**Descriptive**			**Statistics**		
	Rater 1	**Rater 2**	**Rater 3**	**ICC**	**SEM**	**CV (%)**
Repetition (*n*)	23 (9)	23 (9)	23 (9)	1.000	0.08 [0.06, 0.09]	0.35 [0.29, 0.42]
Total height (cm)	175.21 (64.11)	168.77(62.08)	174.87 (63.92)	0.995 [0.976, 0.998]	2.57 [2.19, 2.95]	1.49 [1.27, 1.71]
Peak height (cm)	8.61 (1.52)	8.29 (1.48)	8.58 (1.53)	0.979 [0.908, 0.991]	0.13 [0.11, 0.15]	1.53 [1.31, 1.74]
Fatigue index (%)	18.47 (13.19)	18.42 (13.24)	18.47 (13.43)	0.997 [0.996, 0.998]	0.69 [0.57, 0.82]	3.76 [3.09, 4.43]
Total positive work (J)	1435.70 (576.65)	1380.31 (555.93)	1432.91 (576.42)	0.995 [0.980 0.998]	24.33 [20.45, 28.21]	1.72 [1.45, 2.00]
Total negative work (J)	-1436.94 (576.65)	-1331.57 (552.20)	-1433.96 (576.16)	0.987 [0.893, 0.995]	27.96 [23.21, 32.72]	1.99 [1.65, 2.33]
Peak positive power (W)	257.87 (73.33)	244.48 (68.32)	257.42 (73.33)	0.951 [0.922, 0.968]	14.03 [11.83, 16.24]	5.55 [4.68, 6.42]
Peak negative power (W)	-248.70 (66.61)	-239.10 (62.82)	-247.12 (64.26)	0.981 [0.963, 0.989]	7.30 [6.18, 8.42]	2.98 [2.53, 3.44]

Note. Data from *n* = 106 data files of calf raise tests.

Abbreviations: CR_{app}, Calf Raise application; CV, coefficient of variation; ICC, intraclass correlation coefficient; SD, standard deviation; SEM, standard error of the mean measurement.

Appendix C7. Inter-rater reliability of the Calf Raise application for day 2.

Descriptive data are means (standard deviations) and statistical values are presented with 95% confidence interval [lower, upper].

Outcome measure	**Descriptive**			**Statistics**		
	Rater 1	**Rater 2**	**Rater 3**	**ICC**	**SEM**	**CV (%)**
Repetition (*n*)	23 (9)	23 (9)	23 (9)	1.000	0.08 [0.06, 0.09]	0.35 [0.29, 0.42]
Total height (cm)	175.82 (64.24)	167.42 (61.51)	173. 51(63.04)	0.993 [0.964, 0.997]	2.92 [2.47, 3.36]	1.69 [1.43, 1.95]
Peak height (cm)	8.64 (1.53)	8.23 (1.47)	8.53 (1.51)	0.974 [0.848, 0.990]	0.12 [0.10, 0.14]	1.43 [1.22, 1.64]
Fatigue index (%)	18.45 (13.21)	18.43 (13.25)	18.51 (13.41)	0.997 [0.996, 0.998]	0.73 [0.60, 0.85]	3.94 [3.24, 4.63]
Total positive work (J)	1440.73 (577.62)	1369.63 (552.35)	1423.90 (571.12)	0.994 [0966 0.998]	23.12 [19.32, 26.92]	1.64 [1.37, 1.90]
Total negative work (J)	-1442.07 (577.57)	-1332.85 (550.29)	-1425.09 (571.06)	0.985 [0.872, 0.994]	28.21 [23.32, 33.10]	2.01 [1.66, 2.36]
Peak positive power (W)	258.58 (76.19)	243.18 (69.68)	255.19 (71.49)	0.950 [0.918, 0.968]	14.18 [12.01, 16.35]	5.61 [4.75, 6.47]
Peak negative power (W)	-248.91 (66.16)	-236.99 (62.82)	-248.46 (66.60)	0.972 [0.940, 0.984]	8.67 [7.22, 10.12]	3.54 [2.95, 4.13]

Note. Data from *n* = 106 data files of calf raise tests.

Abbreviations: CR_{app}, Calf Raise application; CV, coefficient of variation; ICC, intraclass correlation coefficient; SD, standard deviation; SEM, standard error of the mean measurement.

Appendix C8. Table S6. Inter-rater reliability of the Calf Raise application for day 3.

Descriptive data are means (standard deviations) and statistical values are presented with 95% confidence interval [lower, upper].

Outcome measure	**Descriptive**			**Statistics**		
	Rater 1	**Rater 2**	**Rater 3**	**ICC**	**SEM**	**CV (%)**
Repetition (*n*)	23 (9)	23 (9)	23 (9)	1.000	0.08 [0.06, 0.09]	0.35 [0.29, 0.42]
Total height (cm)	175.60 (64.29)	168.16 (61.36)	173.71 (63.77)	0.994 [0.974, 0.997]	2.91 [2.47, 3.35]	1.69 [1.43, 1.94]
Peak height (cm)	8.62 (1.53)	8.26 (1.47)	8.52 (1.51)	0.976 [0.901, 0.990]	0.14 [0.12, 0.16]	1.66 [1.42, 1.90]
Fatigue index (%)	18.43 (13.18)	18.45 (13.26)	18.45 (13.40)	0.997 [0.996, 0.998]	0.72 [0.59, 0.86]	3.92 [3.21, 4.63]
Total positive work (J)	1439.06 (579.04)	1375.73 (550.36)	1423.57 (574.77)	0.994 [0.978 0.998]	26.68 [22.44, 30.92]	1.89 [1.59, 2.19]
Total negative work (J)	-1440.30 (578.92)	-1374.93 (552.07)	-1425.87 (574.59)	0.994 [0.976, 0.997]	27.06 [22.80, 31.32]	1.93 [1.62, 2.23]
Peak positive power (W)	260.31 (77.79)	242.94 (69.07)	253.94 (72.77)	0.949 [0.912, 0.968]	14.25 [11.97, 16.53]	5.64 [4.74, 6.54]
Peak negative power (W)	-248.87 (66.58)	-238.43 (62.73)	-247.07 (66.60)	0.978 [0.957, 0.987]	8.09 [6.75, 9.42]	3.30 [2.76, 3.85]

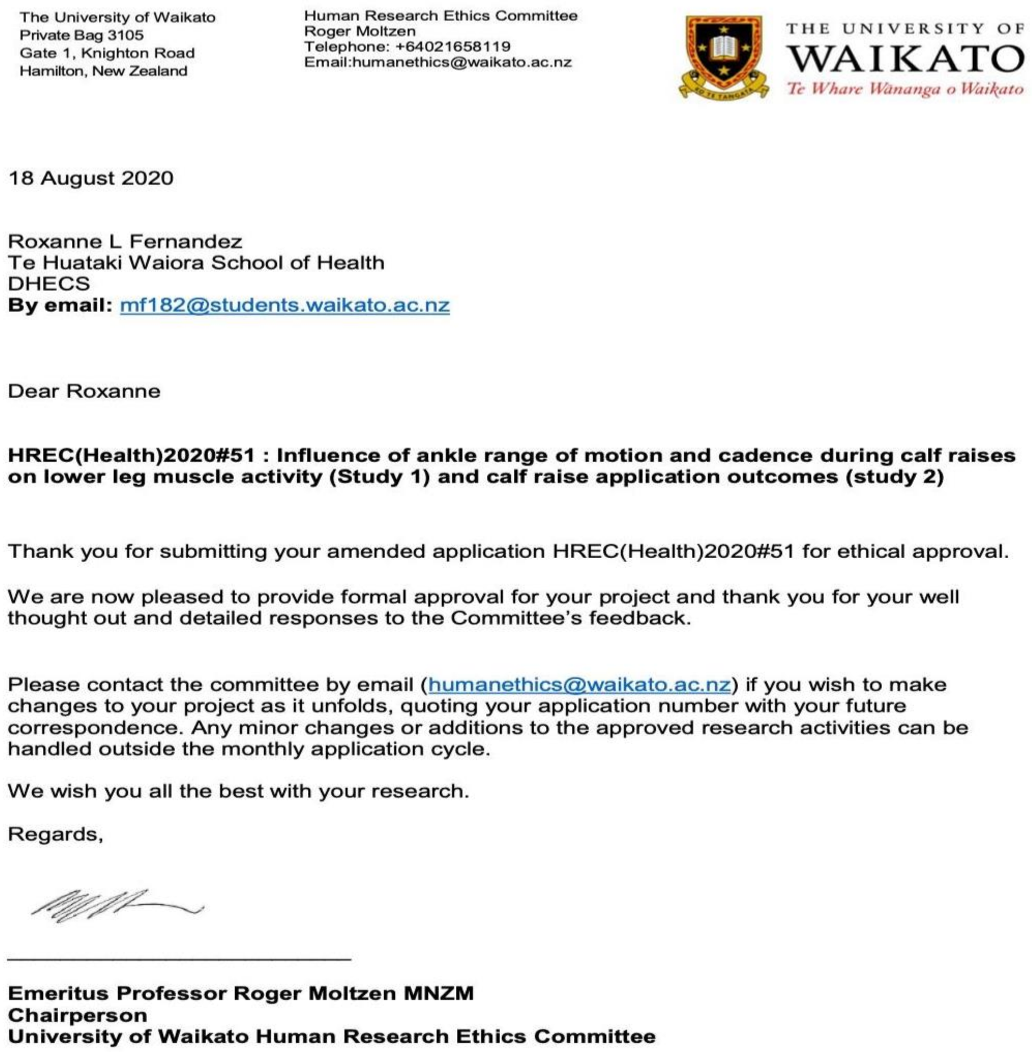
Note. Data from *n* = 106 data files of calf raise tests.

Abbreviations: CR_{app}, Calf Raise application; CV, coefficient of variation; ICC, intraclass correlation coefficient; SD, standard deviation; SEM, standard error of the mean measurement.

Appendix D. Detailed search strategy implemented for each electronic database.

Database	Syntax
CINAHL Complete	(“calf raise” OR “heel rise” OR “heel raise”), AND (“EMG” OR “electromyography” OR “muscle activity” OR “muscle fatigue” OR “muscle activation”), AND (“triceps surae” OR “soleus” OR “gastrocnemius” OR “plantar flexors”) **Limiters -** Full Text **Expanders -** Apply equivalent subjects **Narrow by Language: -** English **Search modes -** Boolean/Phrase • Updated literature search: March 3, 2023 • Number of initial search articles: 28
MEDLINE®	TS=((“calf raise” OR “heel rise” OR “heel raise”), AND (“EMG” OR “electromyography” OR “muscle activity” OR “muscle fatigue” OR “muscle activation”), AND (“triceps surae” OR “soleus” OR “gastrocnemius” OR “plantar flexors”))
PUBMED®	("calf raise"[All Fields] OR "heel rise"[All Fields] OR "heel raise"[All Fields]) AND ("EMG"[All Fields] OR "electromyography"[All Fields] OR "muscle activity"[All Fields] OR "muscle fatigue"[All Fields] OR "muscle activation"[All Fields]) AND ("triceps surae"[All Fields] OR "soleus"[All Fields] OR "gastrocnemius"[All Fields] OR "plantar flexors"[All Fields]) • Updated literature search: March 3, 2023 • Number of initial search articles: 11
Sport Medicine & Education Index	(noft(“calf raise”) OR noft(“heel rise”) OR noft(“heel raise”)) AND (noft(“EMG”) OR noft(“electromyography”) OR noft(“muscle activity”) OR noft(“muscle fatigue”) OR noft(“muscle activation”)) AND (noft(“triceps surae”) OR noft(“soleus”) OR noft(“gastrocnemius”) OR noft(“plantar flexors”)) • Updated literature search: March 3, 2023 • Number of initial search articles: 34
Scopus	(***"calf raise"*** OR ***"heel rise"*** OR ***"heel raise"***) AND (***"EMG"*** OR ***"electromyography"*** OR ***"muscle activity"*** OR ***"muscle fatigue"*** OR ***"muscle activation"***) AND (***"triceps surae"*** OR ***"soleus"*** OR ***"gastrocnemius"*** OR ***"plantar flexors"***) AND (LIMIT-TO (OA , ***"all"***)) AND (LIMIT-TO (DOCTYPE , ***"ar"***)) AND (LIMIT-TO (LANGUAGE , ***"English"***)) • Updated literature search: March 3, 2023 • Number of initial search articles: 198
SPORTDiscus	(“calf raise” OR “heel rise” OR “heel raise”), AND (“EMG” OR “electromyography” OR “muscle activity” OR “muscle fatigue” OR

Appendix E. Ethical approval



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Human Research Ethics Committee
Roger Moltzen
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Email:humanethics@waikato.ac.nz

THE UNIVERSITY OF
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18 August 2020

Roxanne L Fernandez
Te Huataki Waiora School of Health
DHECS
By email: mf182@students.waikato.ac.nz

Dear Roxanne

HREC(Health)2020#51 : Influence of ankle range of motion and cadence during calf raises on lower leg muscle activity (Study 1) and calf raise application outcomes (study 2)

Thank you for submitting your amended application HREC(Health)2020#51 for ethical approval.

We are now pleased to provide formal approval for your project and thank you for your well thought out and detailed responses to the Committee's feedback.

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

We wish you all the best with your research.

Regards,

Emeritus Professor Roger Moltzen MNZM
Chairperson
University of Waikato Human Research Ethics Committee

Appendix F1. Co-authorship form for Chapter 2

KO TE TANGATA
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Co-Authorship Form

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 2: Devices to measure calf raise test outcomes: A narrative review

Nature of contribution by PhD candidate	Writing (original draft; review and editing), Conceptualization, Methodology, Formal analysis
Extent of contribution by PhD candidate (%)	75%

CO-AUTHORS

Name	**Nature of Contribution**
Kim Hébert-Losier (25%)	Writing (review and editing), Conceptualization, Methodology, Formal analysis

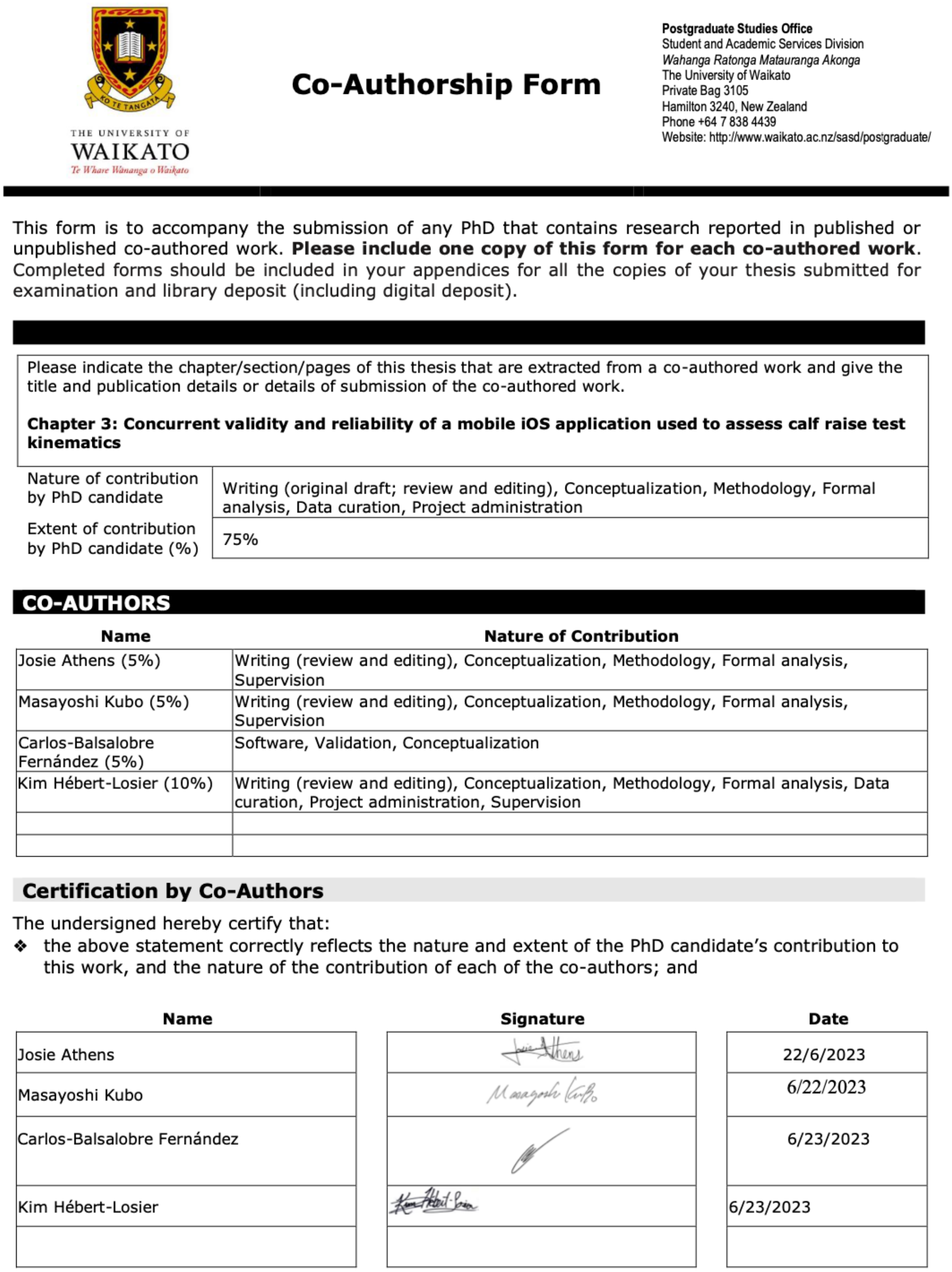
Certification by Co-Authors

The undersigned hereby certify that:

❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	**Signature**	**Date**
Kim Hébert-Losier	Kim Hébert-Losier	23/06/2023

Appendix F2. Co-authorship form for Chapter 3



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Chapter 3: Concurrent validity and reliability of a mobile iOS application used to assess calf raise test kinematics

Nature of contribution by PhD candidate	Writing (original draft; review and editing), Conceptualization, Methodology, Formal analysis, Data curation, Project administration
Extent of contribution by PhD candidate (%)	75%

CO-AUTHORS

Name	Nature of Contribution
Josie Athens (5%)	Writing (review and editing), Conceptualization, Methodology, Formal analysis, Supervision
Masayoshi Kubo (5%)	Writing (review and editing), Conceptualization, Methodology, Formal analysis, Supervision
Carlos-Balsalobre Fernández (5%)	Software, Validation, Conceptualization
Kim Hébert-Losier (10%)	Writing (review and editing), Conceptualization, Methodology, Formal analysis, Data curation, Project administration, Supervision

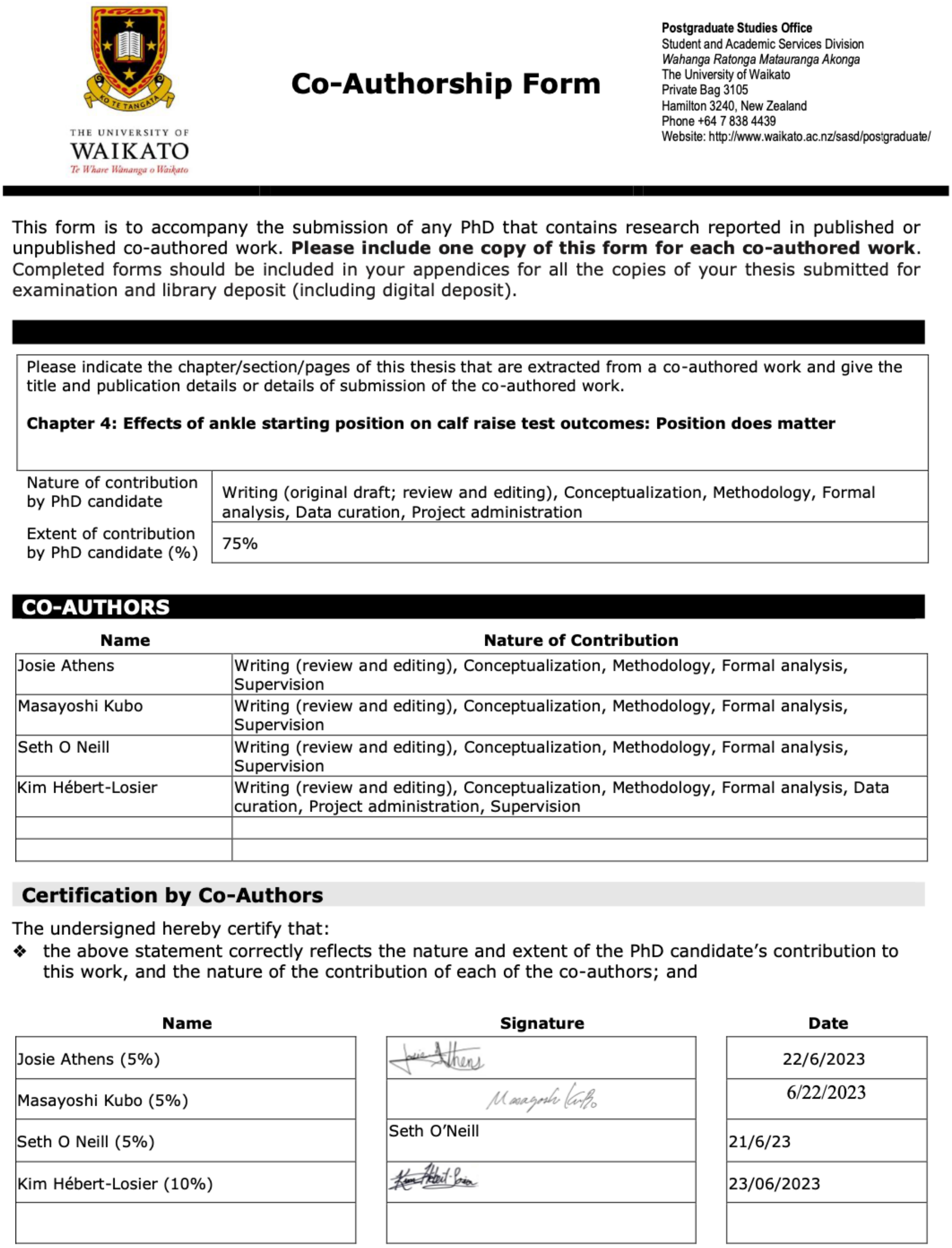
Certification by Co-Authors

The undersigned hereby certify that:

❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Josie Athens	Josie Athens	22/6/2023
Masayoshi Kubo	Masayoshi Kubo	6/22/2023
Carlos-Balsalobre Fernández		6/23/2023
Kim Hébert-Losier	Kim Hébert-Losier	6/23/2023

Appendix F3. Co-authorship form for Chapter 4



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Chapter 4: Effects of ankle starting position on calf raise test outcomes: Position does matter

Nature of contribution by PhD candidate	Writing (original draft; review and editing), Conceptualization, Methodology, Formal analysis, Data curation, Project administration
Extent of contribution by PhD candidate (%)	75%

CO-AUTHORS

Name	Nature of Contribution
Josie Athens	Writing (review and editing), Conceptualization, Methodology, Formal analysis, Supervision
Masayoshi Kubo	Writing (review and editing), Conceptualization, Methodology, Formal analysis, Supervision
Seth O Neill	Writing (review and editing), Conceptualization, Methodology, Formal analysis, Supervision
Kim Hébert-Losier	Writing (review and editing), Conceptualization, Methodology, Formal analysis, Data curation, Project administration, Supervision

Certification by Co-Authors

The undersigned hereby certify that:

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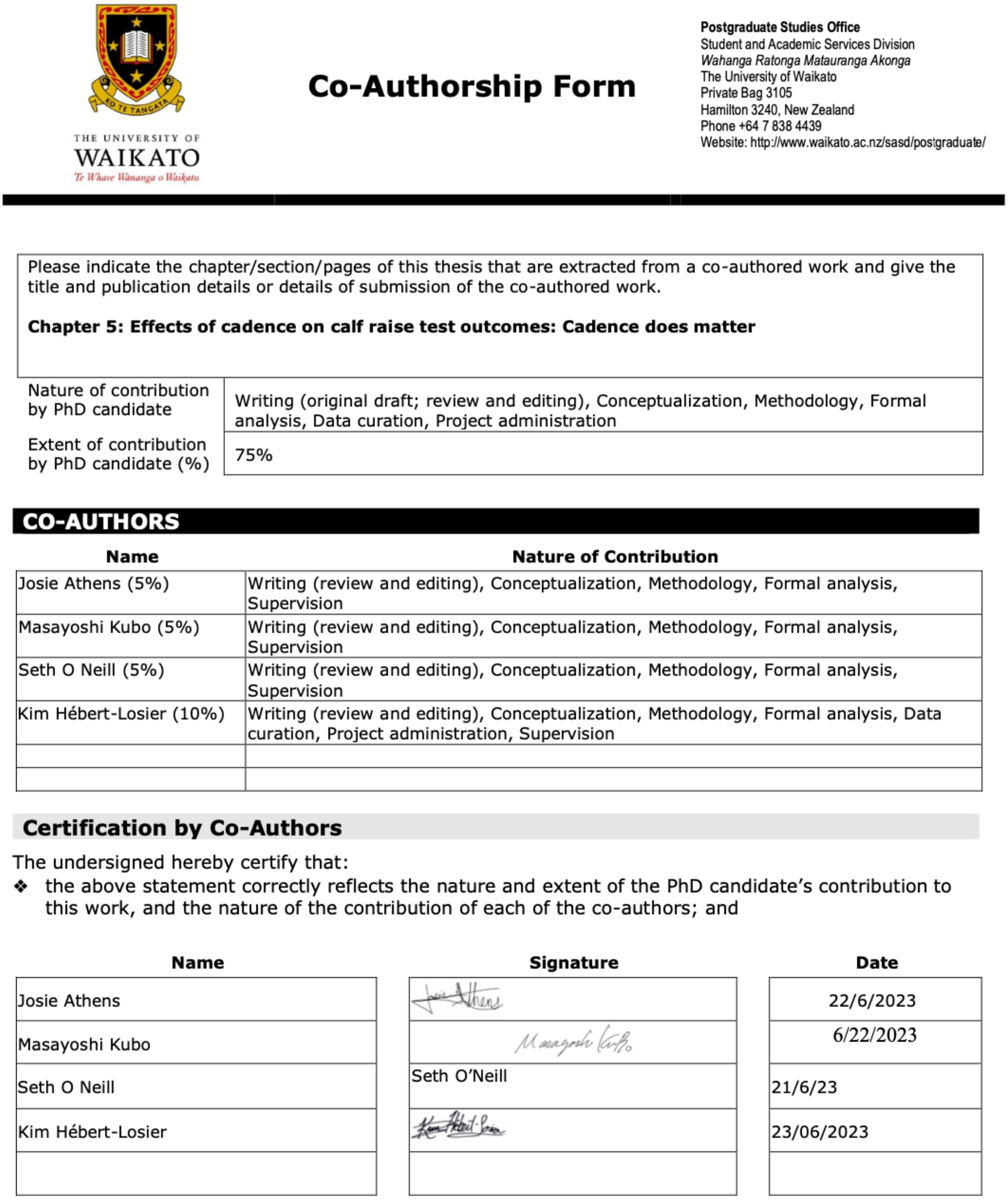
Name	Signature	Date
Josie Athens (5%)	Josie Athens	22/6/2023
Masayoshi Kubo (5%)	Masayoshi Kubo	6/22/2023
Seth O Neill (5%)	Seth O'Neill	21/6/23
Kim Hébert-Losier (10%)	Kim Hébert-Losier	23/06/2023

Appendix F4. Co-authorship form for Chapter 5



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Chapter 5: Effects of cadence on calf raise test outcomes: Cadence does matter

Nature of contribution by PhD candidate	Writing (original draft; review and editing), Conceptualization, Methodology, Formal analysis, Data curation, Project administration
Extent of contribution by PhD candidate (%)	75%

CO-AUTHORS

Name	Nature of Contribution
Josie Athens (5%)	Writing (review and editing), Conceptualization, Methodology, Formal analysis, Supervision
Masayoshi Kubo (5%)	Writing (review and editing), Conceptualization, Methodology, Formal analysis, Supervision
Seth O Neill (5%)	Writing (review and editing), Conceptualization, Methodology, Formal analysis, Supervision
Kim Hébert-Losier (10%)	Writing (review and editing), Conceptualization, Methodology, Formal analysis, Data curation, Project administration, Supervision

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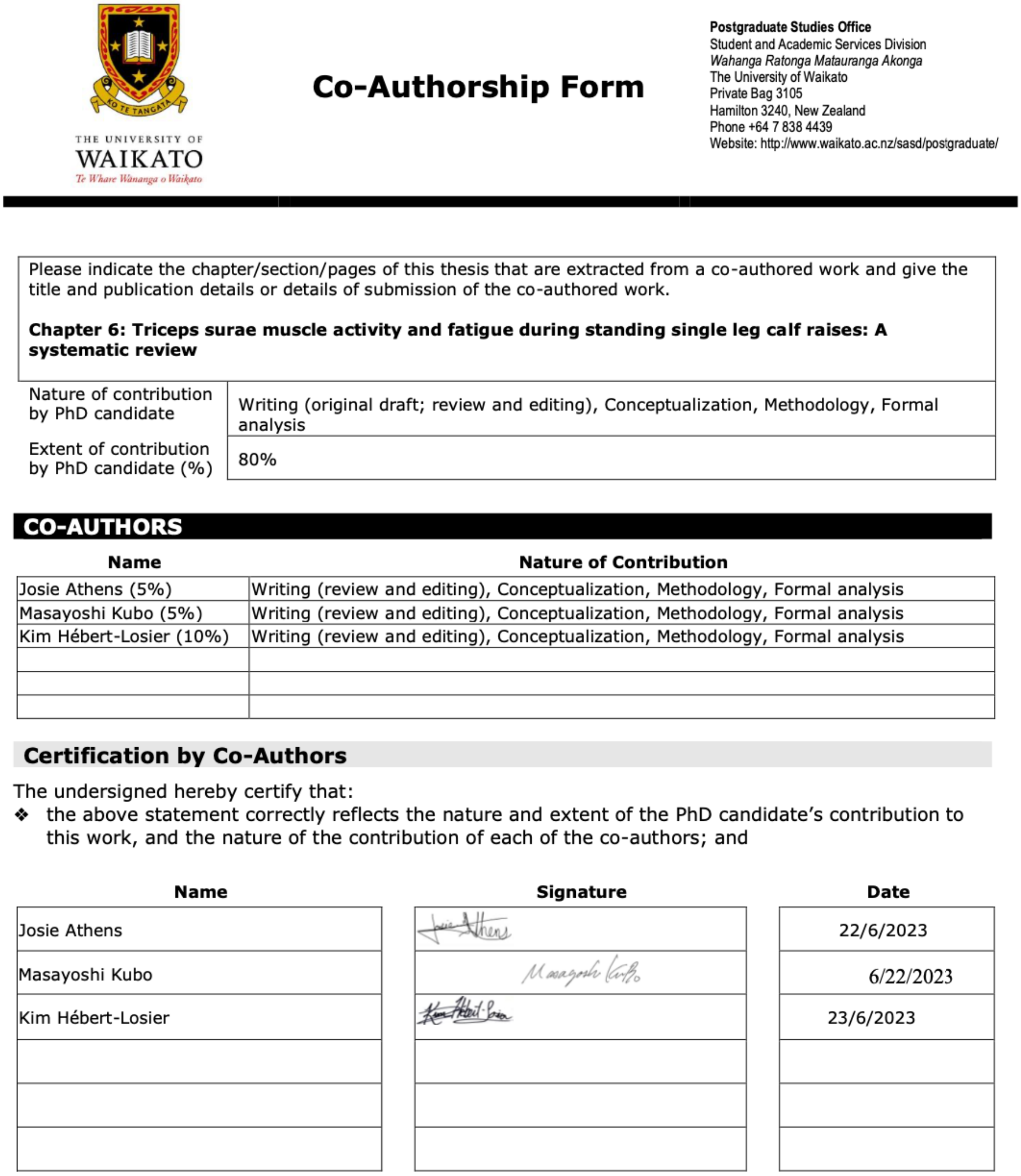
Masayoshi Kubo	Masayoshi Kubo	6/22/2023
Seth O Neill	Seth O'Neill	21/6/23
Kim Hébert-Losier	Kim Hébert-Losier	23/06/2023

Appendix F5. Co-authorship form for Chapter 6



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Chapter 6: Triceps surae muscle activity and fatigue during standing single leg calf raises: A systematic review

Nature of contribution by PhD candidate	Writing (original draft; review and editing), Conceptualization, Methodology, Formal analysis
Extent of contribution by PhD candidate (%)	80%

CO-AUTHORS

Name	Nature of Contribution
Josie Athens (5%)	Writing (review and editing), Conceptualization, Methodology, Formal analysis
Masayoshi Kubo (5%)	Writing (review and editing), Conceptualization, Methodology, Formal analysis
Kim Hébert-Losier (10%)	Writing (review and editing), Conceptualization, Methodology, Formal analysis

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Josie Athens	Josie Athens	22/6/2023
Masayoshi Kubo	Masayoshi Kubo	6/22/2023
Kim Hébert-Losier	Kim Hébert-Losier	23/6/2023