TITLE

Scientific bases and clinical utilisation of the calf-raise test

ABSTRACT

BACKGROUND: Athletes commonly sustain injuries to the triceps surae muscle-tendon unit. The calf-raise test is frequently employed in sports medicine for the detection and monitoring of such injuries. However, despite being widely-used, a recent systematic review found no universal consensus relating to the test's purpose, parameters, and standard protocols.

OBJECTIVES: The purpose of this paper is to provide a clinical perspective on the biophysiological bases and functions underlying the calf-raise test. The paper discusses the clinical utilisation of the test in relation to the structure and function of the triceps surae muscle-tendon unit.

DESIGN: Structured narrative review.

METHODS: Nine electronic databases were searched with MESH headings, entry terms and keywords, as were the reference lists of the retrieved articles and a selection of relevant journals and textbooks.

SUMMARY: There is evidence supporting the clinical use of the calf-raise test to assess soleus and gastrocnemius, their shared aponeurosis, the Achilles tendon, and the combined triceps surae muscle-tendon unit. However, employing the same clinical test to assess all these structures and associated functions remains challenging.

CONCLUSIONS: Further refinement of the calf-raise test for the triceps surae muscle-tendon unit is needed. This is vital to support best practice utilisation, standardisation, and interpretation of the test in sports medicine.

INTRODUCTION

The triceps surae muscles are commonly injured during sport (Adirim & Cheng, 2003; Garrett, 1990; Orchard, 2001) and despite being the strongest and one of the largest human tendons (Jozsa & Kannus, 1992; O'Brien, 1992), acute and overuse injuries are commonly reported in the AT (Higgins, English, & Brukner, 2006; Kolt & Snyder-Mackler, 2007), the latter being a significant challenge for physical therapists (Brotzman & Wilk, 2007; Khan & Maffulli, 1998). Professionals in sports medicine commonly use the calf-raise test (CRT) as a screening tool of lower-limb function and in the assessment of the triceps surae muscle-tendon unit (MTU) (Kolt & Snyder-Mackler, 2007; Kountouris & Cook, 2007; Silbernagel, Thomee, Thomee, & Karlsson, 2001). The test involves concentric-eccentric actions of the plantar-flexors in unipedal stance, with the total number of calf-raises completed documented as the outcome measure (Beasley, 1961; Florence et al., 1992; Lunsford & Perry, 1995).

Although frequently employed by clinicians, a recent systematic review identified no universally accepted description for standardisation of the CRT (Hébert-Losier, Newsham-West, Schneiders, & Sullivan, 2009). While the test has face validity and acceptable reliability, there is no consensus regarding its optimal assessment purpose or administrative protocol: Nor is there strong anatomical-physiological evidence to support its current clinical use. The purpose of this paper is to provide a clinical perspective of the CRT relative to its underlying bio-physiological bases and functions.

METHODS

Nine electronic databases were searched in September 2008 and regularly monitored until March 2009: Ovid MEDLINE (1950–2009), Scopus (1841–2009), ISI Web of Science (1900–2009), SPORTDiscus (1800–2009), EMBASE (1988–2009), AMED (1985–2009), CINAHL (1981–2009), PEDro (1929–2009), and The Cochrane Library (1991–2009) with no limits applied. The search strategy used for this structured narrative review included the MESH headings Achilles tendon, leg and skeletal muscles; the entry terms gastrocnemius and soleus; and the keywords muscle-tendon, triceps surae and calf-raise test as previously described (Hébert-Losier et al., 2009). In addition, the reference lists of the retrieved articles, a selection of sports medicine, physical therapy, biomechanics and orthopaedic journals and textbooks were hand-searched.

Titles, abstracts and full-text of the retrieved documents were sequentially reviewed to determine their relevance to the topic. Articles were selected if they addressed the triceps surae MTU, its structures or its functions, and if their results could be inferred to the CRT.

1. ANATOMICAL STRUCTURES OF THE TRICEPS SURAE MUSCLE-TENDON UNIT

The CRT was originally postulated to assess the triceps surae muscles (Beasley, 1961; Florence et al., 1992). Physical therapists still employ the test for this purpose (Clarkson, 2000; Magee, 2008; Palmer, 1998), but also for the assessment of the AT (Fortis, Dimas, & Lamprakis, 2008) and the triceps surae MTU (Kountouris & Cook, 2007).

1.1 Triceps surae muscle-tendon unit

The triceps surae MTU is unique in that it combines the function of two muscles, soleus and gastrocnemius, through a shared aponeurosis in series with a common tendon (Blitz & Eliot, 2008). This architectural arrangement allows the unit to store energy within the AT and maximise the motor performance and metabolic efficiency of the lower-limb (Benjamin, Kaiser, & Milz, 2008; Fukunaga, Kubo, Kawakami, Fukashiro, Kanehisa, & Maganaris, 2001; Grey, Nielsen, Mazzaro, & Sinkjær, 2007; Maganaris & Paul, 2002).

The subordinate functions of the triceps surae muscles, its aponeurosis and the AT are essential for human bipedal locomotion, anti-gravitational stance and contribute to the physiological efficiency of locomotion (Bramble & Lieberman, 2004; Czerniecki, 1988; Ishikawa, Komi, Grey, Lepola, & Bruggemann, 2005; Lieberman & Bramble, 2007). During walking, the triceps surae MTU acts according to an “inverted pendulum” mechanism of potential and kinetic energy (Vereecke, D'Aout, & Aerts, 2006) that requires eccentric contraction of the triceps surae muscles during stance. At faster speeds, running relies upon a “spring-mass” mechanism of stored elastic energy within the non-contractile elements of the MTU converted into kinetic energy (Bramble &

Lieberman, 2004; Lieberman & Bramble, 2007). This is achieved impart by isometric contractions of the triceps surae muscles.

1.2 Triceps surae muscles

The triceps surae muscles, the soleus and the gastrocnemius, are commonly referred to as the “calf muscle” (DiGiovanni & Greisberg, 2007; Morton, Albertine, & Peterson, 2007; Snell, 2008). The soleus is mono-articular and has a greater physiological cross sectional area and volume than the gastrocnemius muscle, which is more superficial, bi-articular and has a medial and lateral head (Table 1). The combined action of these muscles produces 80% of plantar-flexion force (Murray, Guten, Baldwin, & Gardner, 1976) in association with inversion-supination (Table 1). This combination of moments aids to stabilise the foot in weight-bearing and generate a plantar-flexion moment at toe-off during gait (Czerniecki, 1988; Davis & DeLuca, 1996; Dunblin, 2005).

1.3 Aponeurosis and Achilles tendon

The aponeurosis of the triceps surae muscles anastomoses at various levels along the MTU to ultimately form the AT (Blitz & Eliot, 2008; Pichler, Tesch, Grechenig, Leithgoeb, & Windisch, 2007). Since the functional performance of the triceps surae muscles depends on the integrity of their aponeurosis and AT, pathology or injury to these structures significantly alter the biomechanics of the lower-limb and can require surgery (Blitz & Eliot, 2007; Don et al., 2007; Hansen, 2000).

2. FUNCTIONAL PROPERTIES OF THE TRICEPS SURAE MUSCLE-TENDON UNIT

The CRT is employed in sports physical therapy to explore outcomes from injury prevention strategies and rehabilitation programmes, sequelae of lower-limb injuries, as well as the functional integrity of tendon, muscles and joints (Kaikkonen, Kannus, & Jarvinen, 1994; Kolt & Snyder-Mackler, 2007; Madeley, Munteanu, & Bonanno, 2007). The clinically-oriented literature more often reports the CRT as a test of triceps surae endurance (Hébert-Losier et al., 2009) whereas in the biomechanical literature, the test is a measure of muscle performance (Table 2) relative to other factors, such as load (body weight), fulcrum distance (calf-raise height and foot lengths) and time (Handcock & Knight, 1994; Nagano, Fukashiro, & Komura, 2003).

2.1 Triceps surae muscle-tendon unit

The triceps surae MTU has evolved as an anti-gravitational muscle reflected by the relatively small physiological cross sectional area associated to a substantially long tendon (Chen, 2006; Lieberman & Bramble, 2007). This predominant tendinous configuration is best suited for the “spring-like” action of the aponeurosis and AT where these structures return over 90% of their stored elastic energy (Benjamin et al., 2008; Benjamin & Ralphs, 1997; Stanish et al., 2000), contribute up to 30%-40% of the propulsive energy needed for running (Lieberman & Bramble, 2007; Noakes, 2003) and jumping (Anderson & Pandy, 1993; Kolt & Snyder-Mackler, 2007), increasing both the physiological and biomechanical efficiency of the MTU (Fukashiro, Kurokawa, Hay, & Nagano, 2005; Kawakami, Muraoka, Ito, Kanehisa, & Fukunaga, 2002; Kurokawa, Fukunaga, Nagano, & Fukashiro, 2003)

2.2 Triceps surae muscles

Muscle properties are determined by muscle fibre type and distribution (proportional to functional role), muscle fibre length (proportional to maximum excursion) and muscle physiological cross sectional area and volume (proportional to maximum force) (R. L. Lieber & Friden, 2000). These key features for the triceps surae muscles are summarised in Table 1.

The distribution of fibre type within the triceps surae suggests that gastrocnemius has a greater role in power generation (type IIa/b) and that soleus is designed for endurance (type I) (Table 1). The power role of gastrocnemius is further supported by its fibres being longer, shortening faster, and working over a larger range of movement compared to soleus (Arampatzis, Karamanidis, Stafilidis, Morey-Klapsing, DeMonte, & Brüggemann, 2006; Fukunaga et al., 2001; Ishikawa et al., 2005; Kawakami et al., 2000; Lichtwark & Wilson, 2005; Stafilidis & Arampatzis, 2007).

In neurophysiology, the generally accepted order of recruitment proposes that the type I endurance fibres, smaller motor units, and smaller motor neurons of soleus are recruited more readily at lower intensities of plantar-flexion (Henneman, Somjen, & Carpenter, 1965; Mendell, 2005; Milner-Brown, Stein, & Yemm, 1973; Tucker & Türker, 2004; Winter, 2005). The literature demonstrates that recruitment of gastrocnemius intensifies as plantar-flexion efforts, mechanical demands or load increases (McGowan, Neptune, & Kram, 2008; Price et al., 2003). The overall motor recruitment of the triceps surae muscles is influenced by nerve and fibre morphology, central modulation, and training (Basmajian & DeLuca, 1985; Fleck & Kraemer, 1997; Noakes, 2003).

During gait, both triceps surae muscles support the body irrespective of speed (Neptune, Sasaki, & Kautz, 2008; Sasaki & Neptune, 2006). Soleus is the prime

muscle involved in forward propulsion and acceleration (McGowan, Kram, & Neptune, 2009; McGowan et al., 2008; Neptune, Kautz, & Zajac, 2001; Neptune et al., 2008) whereas gastrocnemius allows power to be transferred through the leg and initiates leg swing (Jacobs, Bobbert, & Van Ingen Schenau, 1993; Neptune et al., 2001; Sasaki & Neptune, 2006; Van Ingen Xchenau, Dorssers, Welter, Beelen, De Groot, & Jacobs, 1995). The power transferring function of gastrocnemius is particularly important in explosive sport movements like sprinting and jumping (Jacobs, Bobbert, & Van Ingen Schenau, 1996; Jacobs & Van Ingen Schenau, 1992; Prilutsky, 1994).

2.3 Tendon properties

At a micro-anatomy level, the collagen fibres within tendons supply high resistance to mechanical stress and their visco-elastic proteoglycans provide compliance. The trade-off between tendon stiffness/resistance and compliance/elasticity is important to promote the efficiency of the spring-like AT function. With increasing stiffness, compliance generally decreases and the triceps surae muscles generate greater work to induce stretch and benefit from the storing and releasing of elastic energy (Anderson & Pandy, 1993; Arampatzis, Karamanidis, Morey-Klapsing, De Monte, & Stafilidis, 2007; Kubo, Kanehisa, & Fukunaga, 2005; Kubo, Kawakami, & Fukunaga, 1999). These properties are stipulated to influence sporting performance (Arampatzis et al., 2007; Kubo, Kanehisa, Kawakami, & Fukunaga, 2000), play a role in tendinopathy aetiology (Kibler, 2003), and be altered by age, training and rehabilitation (Bojsen-Moller, Magnusson, Rasmussen, Kjaer, & Aagaard, 2005; Hansen, Aagaard, Kjaer, Larsson, & Magnusson, 2003).

3. CALF-RAISE TEST PARAMETERS

Standardising test parameters promotes intra- and inter-rater reliability (Roebroek, Harlaar, & Lankhorst, 1993), best clinical practice (Helewa & Walker, 2000; Jewell, 2008) and consistency of test protocols and outcomes (Hopkins, 2000). However, the CRT protocols and key parameters have been found to lack consistency (Hébert-Losier et al., 2009). Varying any of the CRT parameters may alter which of the triceps surae MTU structure or property is primarily involved in, or the clinical outcome of, the test (Table 3).

3.1 Knee position

Since gastrocnemius is bi-articular and soleus is mono-articular, variation of the knee angle on a fixed ankle will selectively alter the length and subsequent function of gastrocnemius (Table 1). A reduction in plantar-flexion force is observed in knee flexion and is mainly attributed to the shortening and decreased mechanical advantage of gastrocnemius (Price et al., 2003).

The CRT is clinically described in two knee positions: full-extension for gastrocnemius and slight-flexion for soleus (Clarkson, 2000; Magee, 2008). In the latter condition, lower clinical outcome measures are expected since mechanically disadvantaging one of the triceps surae muscles (Table 3). However, the clinical outcome measures of the CRT may be similar in both slight-flexion and full-extension since 90° knee flexion is required to induce significant mechanical disadvantage of gastrocnemius (Arampatzis, Karamanidis et al., 2006; Kawakami et al., 1998; Maganaris, 2003; Miaki et al., 1999). As performing a standing CRT in 90° knee flexion increases the recruitment of proximal lower-limb muscles and significantly alters the biomechanical parameters of the standing CRT (Anderson & Pandy, 1993; Nagano, Komura, Fukashiro, & Himeno,

2005), a seated calf-raise may be a suitable alternative to specifically test and condition soleus (Henwood & Taaffe, 2005; McCully, Halber, & Posner, 1994; Shima, Ishida, Katayama, Morotome, Sato, & Miyamura, 2002; Spurrs, Murphy, & Watsford, 2003).

3.2 Ankle position

Ankle position with a fixed knee position will also alter triceps surae output (Bojsen-Møller, Hansen, Aagaard, Svantesson, Kjaer, & Magnusson, 2004; Cresswell, Löscher, & Thorstensson, 1995) with force production increasing almost linearly with dorsi-flexion (Kawakami, Kubo, Kanehisa, & Fukunaga, 2002). The CRT is often performed with the ankle limited to plantar-grade (foot on floor) or allowing dorsi-flexion (forefoot on step). Done in dorsi-flexion, the stretch induced in the AT and aponeurosis, the storing and releasing of elastic energy and the overall efficiency of the MTU during the CRT are greater than in plantar-grade: Consequently, a greater number of calf-raise repetitions is intuitively suggested. However, dorsi-flexion also increases ankle range of motion, fulcrum distance and the work imposed on the muscles ($\text{work} = \text{force} \times \text{distance}$) (Enoka, 2002; Fleck & Kraemer, 1997; Winter, 2005) that may, in contrast, cause earlier triceps surae muscle fatigue and less calf-raise repetition during the CRT.

3.3 Knee and ankle positions summary

In summary, it appears that knee and ankle positions influence and bias specific structures and functions involved in the CRT. Specifically, significant knee flexion biases the test towards soleus, ankle dorsi-flexion with knee extension recruits maximal muscle output and possibly the spring-like action of the aponeurosis and AT, and ankle plantar-grade with knee flexion mechanically disadvantages the gastrocnemius.

3.4 Pace

The most common CRT pace (tempo/cadence) reported in the literature is 60 calf-raises/minute (range 40-120) (Hébert-Losier et al., 2009). Peak ankle angular velocities reach approximately 2.6 rad/s during walking (Palmer, 2002), 6.6 rad/s when transiting from walk-to-run (Hreljac, 1995; Neptune & Sasaki, 2005), 16 rad/s in jumping (Bobbert, Huijing, & van Ingen Schenau, 1986; Kurokawa et al., 2003), but only 1 rad/s during a 92 calf-raises/min CRT (Österberg, Svantesson, Takahashi, & Grimby, 1998). Based on these reported angular velocities, caution is advised to sports physical therapists in the extrapolation of outcomes from the CRT to running, jumping, or even walking activities.

Clinicians need to select a CRT pace according to the functional activity or prime MTU structure provoking symptoms. The literature suggests that significantly increasing the pace of the CRT increases the work contributed by the stored elastic energy which decreases the work required by the muscles (Alexander, 2002; Benjamin et al., 2008; Magnusson, Narici, Maganaris, & Kjaer, 2008). From modelling energy output, MTU architecture and fibre characteristics (Nagano et al., 2003), there is a hypothetical change in recruitment with CRT pace from slow (soleus), to fast (gastrocnemius), to fastest (aponeurosis and AT) (Table 3). As paces above 60 calf-raises/min described in the literature are not always clinically feasible (Li, Devault, & Van Ooteghen, 2007), the CRT is more ideal for assessing the triceps surae muscles rather than specifically the MTU.

3.5 Height of calf-raise

Raising the heel as “high as possible” is a standard clinical instruction given prior to the CRT (Clarkson, 2000; Magee, 2008; Palmer, 1998) and is the most frequent height criterion reported in research (Hébert-Losier et al., 2009). Reaching a height of 5cm from horizontal is also a common height parameter used by scientific CRT monitoring

devices (Fortis et al., 2008; Haber, Golan, Azoulay, Kahn, & Shrier, 2004; Möller, Lind, Styf, & Karlsson, 2005), which can be clinically standardise by other readily available means (rulers or nylon strings).

The height achieved during the CRT influences the relative energy contribution, excursion length variations and elastic energy of the MTU structures (Ishikawa et al., 2005; Kawakami, Muraoka et al., 2002; Stafilidis & Arampatzis, 2007). According to the established force-length relationship, gastrocnemius is preferentially activated at longer triceps surae muscle lengths and soleus at shorter lengths (Finni, 2006; Fukashiro, Hay, & Nagano, 2006; Kawakami, Kubo et al., 2002). Furthermore, gastrocnemius fibres are longer and work over a larger range of movement than soleus fibres (Arampatzis et al., 2006; Fukunaga et al., 2001; Ishikawa et al., 2005; Kawakami et al., 2000; Stafilidis & Arampatzis, 2007). This infers that the CRT at low heights (≤ 5 cm) is biased towards the recruitment of soleus since it involves shorter fascicle lengths and excursion (Table 3). At higher heights (> 5 cm), the CRT is biased towards gastrocnemius since the fascicles work over a larger range of motion.

When considering the concentric-eccentric phases of the CRT, gastrocnemius contributes more at the beginning (longer lengths) and soleus towards the end (shorter lengths) of the concentric phase and vice-versa for the eccentric phase. The eccentric-concentric turnaround speed will dictate the amount of elastic energy stored and released and contribution of the aponeurosis and AT to calf-raise execution (Nagano et al., 2003) .

3.6 Termination criteria

Fatigue is the most cited CRT termination criterion following the criterion of failure to maintain calf-raise height (Hébert-Losier et al., 2009). Expressions of muscle fatigue

include decrease in coordination, loss of balance, or compensatory movements (Dutton, 2008), which have also been cited as CRT termination criteria. These are often expressed as excessive ankle co-contractions, body-sway, or jerkiness in calf-raise motion.

Other muscles involved in CRT performance include the synergists and antagonists of the triceps surae (Table 1). Although the synergists generate much less plantar-flexion force (Morton et al., 2007), they can actively plantar-flex the ankle, counter manual resistance, and contribute up to 40% of plantar-flexion force in the absence of the AT or triceps surae (DiGiovanni & Greisberg, 2007; Murray et al., 1976; Young, Niedfeldt, Morris, & Eerkes, 2005). The antagonists are also important in plantar-flexion function (Benjamin et al., 2006; Maganaris, Narici, Almekinders, & Maffulli, 2004; Tucker et al., 2005; Windhorst, 2007) and become increasingly influential as plantar-flexors fatigue (Patikas et al., 2002). Although the extent to which the synergists and antagonists affect the overall performance of the triceps surae is debated (Magnusson, Aagaard, Rosager, Dyhre-Poulsen, & Kjaer, 2001; Price et al., 2003; Segal & Song, 2005; Wakahara, Kanehisa, Kawakami, & Fukunaga, 2008), the literature demonstrates that an increase in their activation is a sign of triceps surae muscle fatigue (Patikas et al., 2002), is frequently expressed through compensatory movements (Clarkson, 2000; Magee, 2008; Palmer, 1998) and advocates CRT termination. Since fatigue is also governed by many psychosocial factors (Dutton, 2008), it may be difficult to distinguish between “neuro-physiological” and “psychological” (lack of motivation or pain) fatigue. Clinicians should consider these underlying factors and note the reasons for CRT termination.

4. SUMMARY OF CLINICAL CONSIDERATIONS

Numerous CRT protocols have been developed and are commonly employed in clinical practice. Concurrently, there is an increasing amount of literature on the triceps surae MTU function. This review provides evidence supporting the clinical use of the CRT to assess soleus and gastrocnemius, their aponeurosis, the AT, and their combined function as MTU. However, although collectively enhancing functional performance, employing the same test to assess all these structures remains a challenge. To facilitate clinical reasoning underlying the use of the CRT, its purpose and various parameters, the structures involved and the expected outcome measures, a summary is provided in Table 3.

4.1 Purpose

By design and definition (Table 2), the CRT appears ideal for measuring the endurance capacity of soleus. However, gastrocnemius is reported as the main active muscle during unipedal repeated calf-raises (Akima et al., 2003; Kinugasa & Akima, 2005; Segal & Song, 2005) which corroborate well with the respective roles of the triceps surae muscles during locomotion. The CRT requires body support (soleus and gastrocnemius) and power transfer (gastrocnemius), but not forward propulsion (soleus) (McGowan et al., 2009; Neptune et al., 2001; Neptune et al., 2008; Sasaki & Neptune, 2006). This supports the assumptions that both triceps surae muscles are initially involved in the CRT, with gastrocnemius more so initially and soleus modulating its activity as gastrocnemius fatigues (McGowan et al., 2008).

4.2 Selectivity

To further target soleus, the suggested clinical CRT parameters are ankle plantar-grade (gastrocnemius shortening), significant knee flexion (optimally $\geq 90^\circ$ for

gastrocnemius inhibition), maximal calf-raise height (soleus advantage in force-length relationship), slow pace (muscle properties and modelling), and knee extension as a specific termination criterion (gastrocnemius substitution) (Table 3). As for targeting gastrocnemius, in addition to the suggested parameters in Table 3, recruitment principles suggest that adding resistance to the CRT will promote activity within gastrocnemius, which has been corroborated by magnetic resonance imaging during plantar-flexion (Price et al., 2003) and EMG during gait with added body weight (McGowan et al., 2008). Clinicians should consider recording the time taken to perform the calf-raises in order to measure muscle power (Table 2). Finally, a clinical appreciation of the spring-like function, compliance and stiffness of the aponeurosis and AT may be gained through CRT performance since it involves recurring AT stretch and recoil (Nagano et al., 2003), particularly at higher speeds and during the turnaround from eccentric to concentric plantar-flexion.

4.3 Clinical message

There is supporting evidence that varying any of the CRT parameters modifies the relative contribution of each of the triceps surae MTU elements and alters test performance and outcome measures (Nagano et al., 2003). Physical therapists need to select CRT parameters according to their clinical aims, purposes for using the test and the intended structures, functional properties or injuries to be assessed (Kolt & Snyder-Mackler, 2007). A CRT biased towards soleus may be favoured in the assessment of an Achilles tendon injury in the long-distance runner, but biased towards gastrocnemius for the “tennis leg injury” (muscle strain) in the racket-sport athlete. To assist sports physical therapist in the effective use and interpretation of this test, future research should investigate the extent to which the CRT can be clinically biased towards triceps surae MTU structures and properties and investigate the psychometric properties of the different CRT protocols.

CONCLUSION

The widely-used CRT has no universally accepted standardisation despite a multitude of factors influencing its clinical utility and interpretation. This paper reviews the common clinical applications of the CRT and discusses them in relation to their underlying scientific bases. Most CRTs have their clinical utility supported by some research evidence; however, the evidence is open to many clinical interpretations. Based on the current available scientific literature, further refinement of the CRT for the triceps surae MTU is needed. This is vital to establish an evidence-based clinical CRT with universally accepted protocols that ensure a standard, justified, and reliable use of this test in sports medicine and other allied disciplines.

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Table 1

Characteristics of the triceps surae muscles

	Origin ^a	Insertion ^b	Actions ^c	Agonists (plantar-flexors) ^a	Antagonists (dorsi-flexors) ^a	Physiological cross-sectional areas ^d	Volumes ^e	Fibre type, size, and distribution ^f	Myofibre length ^g	Pennation angles ^h	
										Maximal fibre length ⁱ	Variation ^j
Soleus	Posterior aspect of the fibula and tibia (oblique soleal line)	Into the posterior mid-surface of the calcaneus by the AT. The SOL portion is 3-11cm.	Mono-articular plantar-flexion associated with inversion - supination	Plantaris, tibial posterior, flexor hallucis longus, flexor digitorum longus, peroneus longus, peroneus brevis	Tibialis anterior, extensor hallucis longus, extensor digitorum longus, peroneus tertius	• Triceps surae muscles 200-440cm ² • 6:2:1 ratio for SOL:GM:GL • SOL≈3X GM • SOL≈8X GL	• Triceps surae muscles 640-870cm ³ • SOL≈2XGM • SOL≈3X GL	• ≈30% larger than GM+GL • ≈70-90% type I and 10-30% type II (IIa only)	20-39mm	• Passive: 15°-20° • MVC: 26°-40°	• Passive: 19° • MVC: 49°
Gastrocnemius (GM and GL)	Posterior aspect of the femur with GM superior to the medial condyle and GL on the lateral condyle and popliteal surface	As above. The GM/GL tendon portion is 11-26cm in length and fuses with the SOL portion 2-5cm proximal to the AT insertion	Bi-articular plantar-flexion associated with inversion - supination and knee-flexion	As above	As above	As above GM≈2.5X GL	As above GM≈2X GL	• ≈30% smaller than SOL • ≈50% type I and type IIa/b • % type II in GL>GM	• GM: 35-57mm • GL: 44-77mm	• Passive: GM 16°-19° GL 9°-14° • MVC: GM 27°-35° GL 16°-24°	• Passive: GM 22° GL 12° • MVC: GM 67° GL 35°

SOL: soleus; GM: gastrocnemius medial head; GL: gastrocnemius lateral head; AT: Achilles tendon; MVC: maximal voluntary contraction; ≈: approximately

^a Compiled from (Greene & Netter, 2006; Miller & Sekiya, 2006; Morton et al., 2007; Snell, 2008)^b Compiled from (Benjamin et al., 2006; Gray, 1995; Greene & Netter, 2006; Miller & Sekiya, 2006; Netter, Hansen, & Lambert, 2005; Reynolds & Worrell, 1991; Stanish et al., 2000)^c Compiled from (Czerniecki, 1988; Gray, 1995; Greene & Netter, 2006; Ishikawa et al., 2005; Komi, 2000; Miller & Sekiya, 2006; Netter et al., 2005)^d Compiled from (Arampatzis, De Monte et al., 2006; Bamman, Newcomer, Larson-Meyer, Weinsier, & Hunter, 2000; Fukunaga et al., 1992; Kawakami et al., 1998; Stafilidis & Arampatzis, 2007)^e Compiled from (Elliott et al., 1997; Fukunaga et al., 1992; Trappe et al., 2001; Tucker et al., 2005)^f Compiled from (Houmard et al., 1998; M. A. Johnson, Polgar, Weightman, & Appleton, 1973; Kawakami et al., 2000; Miaki et al., 1999; Trappe et al., 2001; Tucker et al., 2005)^g Compiled from (Albracht, Arampatzis, & Baltzopoulos, 2008; Chow et al., 2000; Friederich & Brand, 1990; Richard L. Lieber, 1992; Wickiewicz et al., 1983)

Table 2

Definitions of muscle performance measures according to human kinetics

	Definition
Performance	The ability of a muscle to function at high intensity levels
	May be defined in terms of endurance, strength, and power
Strength	The greatest force a muscle can generate in one effort against a maximal load.
Endurance	The ability of a muscle to sustain the same force during a series of sub-maximal efforts.
Power	The amount of work a muscle generates within a given time.

Compiled and adapted from (Dutton, 2008; Enoka, 2002; Martini, 2003; Nyland, 2006)

Table 3

Clinical considerations for the CRT according to the triceps surae MTU structures and functions

	Triceps surae muscles	Soleus	Gastrocnemius	Muscle-tendon unit	Achilles tendon
Purpose	Performance	Endurance	Power	Function	Store-release energy (spring-mass)
Ankle position	Dorsi-flexion	Dorsi-flexion	Plantar-grade	Dorsi-flexion	Plantar-grade with prior dorsi-flexion
Knee position	Extension, but allowing flexion	Flexion (optimal $\geq 90^\circ$)	Extension	Extension, but allowing flexion	Extension
Height	Highest (full ROM)	Higher	Lower	Highest (full ROM)	Highest (full ROM)
Pace	Moderate	Slow (< 100 calf-raises/min)	Fast (< 100 calf-raises/min)	100 calf-raises/min ^a	Fastest (≥ 100 calf-raises/min)
Termination	Sign of fatigue ^b	Sign of fatigue ^b	Sign of fatigue ^b	Sign of fatigue ^b	Sign of fatigue ^b
	Complete fatigue option ^c	Knee extension	Knee flexion	Complete fatigue option ^c	Knee flexion
Expected outcome	More calf-raises	Less calf-raises	Least calf-raises	Most calf-raises	Dependent on muscle function

ROM: range of motion; WB: weight-bearing

^a Adapted from (A. Nagano et al., 2003)

^b Unable to maintain height, pace, or ankle-knee parameters; Compensatory movements; Excessive co-contractions; Decreased coordination; Loss of balance

^c Continue until unable to lift heel to fatigue all the structures involved in CRT performance