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Biomechanical Profiling and Physiological Responses to Eccentric Quasi-Isometric Loading

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Abstract

Muscle structure and function are important to quality of life and physical performance. With eccentric and isometric resistance training established for improving muscle size and strength, eccentric quasi-isometric (EQI) contractions, defined as “holding a position until isometric failure and maximally resisting the subsequent eccentric phase”, are the focus of this thesis. The primary aims were to answer the overarching research question: “What are the acute, and long-term effects of EQI loading on muscle form and function?”. Systematic and narrative reviews were conducted, followed by the evaluation and optimization of testing methods, culminating in acute and short-term experimental studies.

Reviews of the literature established that isometric training at longer muscle lengths produced greater hypertrophy than volume-equated shorter muscle length training (0.1-1.0%·week^{-1}, effect size (ES) = 0.05-0.2·week^{-1}), and transferred better to full range of motion (ROM) performance. Ballistic intent resulted in greater increases in rate of torque development (RTD) and neuromuscular activation (-1.5-3.6%·week^{-1}, ES = 0.03-0.28·week^{-1}). Hypertrophy and strength improvements were not related to isometric training intensity, however, contractions ≥ 70% were likely required to improve tendon qualities. While there is a lack of studies directly examining EQIs, they may provide a practical means of increasing metabolic and hormonal factors, while safely applying large quantities of mechanical tension. EQI training appears to be effective for improving musculotendinous morphological and performance variables with low injury risk.

To be confident in the primary findings of the PhD, it was important to test and determine an optimized assessment battery for the acute and long-term effects and adaptations to EQI loading. Repeated between-day testing determined that ultrasound derived muscle thickness (MT) and subcutaneous fat corrected echo intensity (EI) had low variability in all quadriceps muscles and regions. Pennation angle (PA) and extended field-of-view fascicle length (FL) could only be reliably assessed in the vastus lateralis. Concentric torque and impulse were reliable between 90-20° of knee-flexion. Maximal voluntary isometric torque (MVIT), and RTD and impulse from 0-200 ms can be confidently assessed regardless of joint angle. Correlational analysis revealed that the isometric length-tension relationship was minimally associated with regional architecture and that the middle and distal architecture were the strongest predictors of MVIT.

When comparing impulse-equated bouts of EQI and isokinetic eccentric loading (ECC), physiological responses were similar in 21/56 variables. EQIs resulted in greater vastus intermedius swelling (7.1-8.8%, ES = 0.20-0.29), whereas ECC resulted in greater soreness at the distal and middle vastus lateralis and distal rectus femoris (16.5-30.4%, ES = 0.32-0.54) and larger echogenicity increases at the distal rectus femoris and lateral vastus intermedius (11.9-15.1%, ES = 0.26-0.54). Furthermore, ECC led to larger reductions in concentric (8.3-19.7%, ES = 0.45-0.62) and isometric (6.3-32.3%, ES = 0.18-0.70) torque and RTD at medium-long muscle lengths. There were substantial differences in the number of contractions required to impulse-match the conditions (ECC: 100.8 ± 54 vs EQI: 3.85 ± 1.1). Mean contraction velocity over four contractions was $1.34^{o} \cdot s^{-1}$ with most (62.5 ± 4.9%) impulse produced between 40-70º. Most between-contraction changes in total angular impulse, contraction velocity, and time-under-tension occurred between 30-50º (ES = 0.53 ± 0.31, 60 ± 52%), while kinetics and kinematics relatively constant between 50-100º (ES = 0.10 ± 0.26, 14.3 ± 24.6%). Findings suggest that EQI loading could be an alternative to traditional resistance-training, possibly for individuals suffering from, or susceptible to musculoskeletal injury. Practitioners could shift the loading distribution to longer muscle lengths by prescribing a greater number of contractions, reducing rest periods, or implementing EQI contractions towards the end of a traditional training session where fatigue may be present.

Although extensive future research is required to understand underlying mechanisms and long-term adaptations, the thesis provided novel and original information on the biomechanics and physiological effects of EQI loading. With the benefits of time-efficiency and minimal negative effects, EQI training is likely best applied in rehabilitation, general preparatory, unloading, or transition periods of the periodized plan.

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Attestation of authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Chapters 2 to 10 represent separate papers that have either been published or have been submitted to peer-reviewed journals for consideration for publication. My contribution and the contributed by the various co-authors to each of these papers are outlined at the beginning of each chapter. All co-authors have approved the inclusion of the joint work in this doctoral thesis.

Dustin Jay Oranchuk

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Co-authored works

Chapter 2. Oranchuk DJ, Storey AG, Nelson AR, and Cronin JB. Isometric training and long-term adaptations: Effects of muscle length, intensity, and intent: A systematic review. *Scand J Med Sci Sports* 29: 484-503, 2019.	DJO: 80%, AGS: 5%, ARN: 5%, JBC: 10%
Chapter 3. Oranchuk DJ, Nelson AR, Storey AG, and Cronin JB. Scientific basis of eccentric quasi-isometric resistance training: A narrative review. *J Strength Cond Res* 33: 2846-2859, 2019.	DJO: 80%, ARN: 10%, AGS: 5%, JBC: 5%
Chapter 4. Oranchuk DJ, Nelson AR, Storey AG, and Cronin JB. Variability of regional quadriceps architecture in trained men assessed by B-mode and extended-field-of-view ultrasonography. *Int J Sports Physiol Perform* 15: 430-436, 2020.	DJO: 80%, ARN: 5%, AGS: 5%, JBC: 10%
Chapter 5. Oranchuk DJ, Stock MS, Nelson AR, Storey AG, and Cronin JB. Variability of regional quadriceps echo intensity in active young men with and without subcutaneous fat correction. *Appl Physiol Nutr Metab* 45: 745-752, 2020.	DJO: 80%, MSS: 8%, ARN: 4%, AGS: 4%, JBC: 4%
Chapter 6. Oranchuk DJ, Neville JG, Nelson AR, Storey AG, and Cronin JB. Variability of concentric angle-specific isokinetic torque and impulse assessments of the knee extensors. *Physiol Meas* 41: 01NT02, 2020.	DJO: 80%, JGN: 8% ARN: 4%, AGS: 4%, JBC: 4%
Chapter 7. Oranchuk DJ, Storey AG, Nelson AR, Neville JG, and Cronin JB. Variability of multiangle isometric force-time characteristics in trained men. *J Strength Cond Res* Ahead of print, 2019.	DJO: 80%, AGS: 8% ARN: 4%, JGN: 4%, JBC: 4%
Chapter 8. Oranchuk DJ, Hopkins WG, Nelson AR, Storey AG, and Cronin JB. The effect of regional quadriceps anatomical parameters on angle-specific isometric torque expression. *Appl Physiol Nutr Metab* 46: 368-378, 2021.	DJO: 80%, WGH: 10%, ARN: 4%, AGS: 3%, JBC: 3%
Chapter 9. Oranchuk DJ, Nelson AR, Storey AG, Diewald SN, and Cronin JB. Short-term neuromuscular, morphological, and architectural responses to eccentric quasi-isometric muscle actions. *Eur J Appl Physiol* 121: 141-158, 2021.	DJO: 80%, ARN: 6%, AGS: 4%, SND: 5%, JBC: 5%
Chapter 10. Oranchuk DJ, Diewald SN, McGrath JW, Nelson AR, Storey AG, and Cronin JB. Kinetic and kinematic profile of eccentric quasi-isometric loading. *Sports Biomech* Ahead of print, 2021.	DJO: 80%, SND: 8%, JWM: 4%, ARN: 2%, AGS: 2%, JBC: 4%

We, the undersigned, agree to the percentages of participation to the aforementioned chapters.

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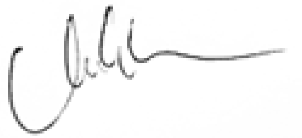

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Ethical approvals

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- Ethics application 18/232: The effect of eccentric quasi-isometric training on the muscle morphology and performance of healthy males

Ethical approval was granted by the Victoria University (Melbourne) Human Research Ethics Committee (VUHREC) until the 1st of October 2022.

- Ethics application HRE19-110: Acute and chronic physiological, neuromuscular, and morphological responses to eccentric quasi-isometric training.

Chapter 1 - Introduction

Rationale and significance of the thesis

Muscle form and function are of utmost importance to ensure a high quality of life and optimal performance. Therefore, sport and rehabilitation professionals constantly search for new methods and applications that will improve these physiological qualities. Scientists and practitioners are also educated and interested in the mechanistic outcomes of training modalities, which serve to improve the evidence base of exercise physiology, biomechanics, and motor control. While educated practitioners stay up to date with the latest research, several training methods are commonly utilized and have significant anecdotal backing, but little to no peer-reviewed data to support their use. Variations of eccentric and isometric resistance training, including eccentric quasi-isometric (EQI) contractions (coined by Yuri Verkhoshansky (377)), are such methods, with the latter providing the focus of this thesis. For this thesis, EQIs is defined as "holding a position until isometric failure and maximally resisting the subsequent eccentric phase". As very little literature exists on EQIs, a background into the morphological and neuromuscular adaptations and the importance of their biomechanical characteristics are briefly discussed below.

Muscle morphology

Mechanical tension is produced by force generation and stretch, both of which are effective in promoting muscular hypertrophy (308). While eccentric contractions have the highest potential for muscular force production, isometric muscle actions can be easily prescribed to specific points in the range of motion and are less likely to result in muscle damage due to the less calcium ion influx into muscle cells and subsequent activation of calpain when compared to lengthening contractions (399). Strength gains are joint-angle specific (205), however, increases in muscular hypertrophy, at longer muscle lengths (228), tend to transfer to all joint angles (9, 188, 250, 251). Although static contractions result in less muscle damage and less dramatic muscular-tendinous adaptations compared to maximal eccentrics, isometrics at long muscle lengths produce greater acute muscle damage and soreness compared to short muscle length (11).

Cumulative tension and total workload are key determinants of hypertrophic adaptation regardless of contraction type (236). This was demonstrated by Moore et al. (236) who compared the effects of load matched concentric and eccentric resistance training. Despite the 40% greater time efficiency of the eccentric training, there were no significant differences in torque or muscle thickness adaptations between groups (236). Acute hypoxia and metabolic stress are two additional mechanisms thought responsible for hypertrophy (207). While low intensity single-joint isometric contractions have been found to result in blood flow restriction, the effects of multi-joint isometric and quasi-isometric contractions have yet to be examined. Exercise-induced muscle damage is another important factor to consider. Eccentric muscle actions typically result in a greater degree of acute myofibril micro-trauma and delayed onset muscle soreness as determined by elevated serum creatine kinase, myoglobin, and skeletal troponin-1 levels (72). At least in the short term, these markers coincide with a temporary reduction in muscle force, rate of force development, and power (72). While the aforementioned effects of eccentric and isometric loading in isolation are known, the effects of EQI loading on muscle morphology are not.

Contractile performance

As previously mentioned, the larger morphological and architectural adaptations following long muscle length isometric and eccentric loading are presumably due, at least in part to the greater degree of fascicle stretch, which results in greater muscle damage and altered length-tension relationships (11, 59). This increase in sarcomere compliance, is demonstrated by acute and long-term shifts in the length-tension relationship (135). These shifts are proposed to reduce injury potential, and joint-angle-specific performance (55, 211).

Contraction duration and intent are other factors to consider when evaluating the effect of resistance training (74). Although a variety of isometric training and exercise methods have been described (122, 157, 305), the majority of isometric literature utilized maximally contracting against an immovable object. Researchers have demonstrated that "yielding" isometrics, with the intent of preventing eccentric contraction, create different fatigue and neuromuscular characteristics compared to "pushing" isometrics with a consensus of yielding contraction leading to faster task failure and greater antagonist and synergist activation (122, 157, 300, 305). Whether "yielding isometrics" or EQI loading/training, affects the length-tension/torque-angle relationship are unknown and warrants investigation. As with muscle structure and form, the potential acute and long-term changes in contractile performance, including maximal, and joint-angle-specific outputs requires examination.

Biomechanical profiling

As discussed above, contraction kinetics and kinematics play a major role in determining acute morphological and performance shifts, and long-term adaptations. Several studies have determined that fast eccentric contractions cause greater muscle damage, soreness, and acute performance reductions, relative to slow velocities (54, 65, 66). Additionally, researchers have examined the effects of range of motion, and contraction duration with a consensus supporting longer time-under-tensions (164, 344), and larger ranges of motion when aiming to improve muscle size and performance (310). Therefore, it is important to characterize the above biomechanical variables when examining new contractions, or altered loading parameters, including EQIs.

Potential applications

While the above factors are important to understand, implementable, practical applications must be established. Several training models account for hypertrophy focused periods or plans for individual exercises or sets within a training program. While heavy loading, including supra-maximal eccentric training, offers a strong stimulus to promote muscular growth, training volume is the most important factor (236, 308).

There is no one-size-fits-all approach to injury rehabilitation protocols. However, injuries to any of the structures involved in force transmission require mechanical overload at some point in the rehabilitation process. Isometric and quasi-isometric exercises are already commonplace in the initial phases of muscular and tendon rehabilitation protocols as they allow for tight control over the range of motion and intensity (178, 293-295, 357); likely as peak joint forces would typically be lower than other loading strategies including eccentric contractions or stretch-shortening cycle activity (288). Furthermore, while progressive mechanical tension is crucial (172, 174), slow movement velocities should be prescribed to stimulate damaged fibers (22). Therefore, the combined static and lengthening phases of EQI contractions may serve the dual purpose of providing an analgesic effect while also stimulating connective tissue reformation in a time-efficient manner.

Originality of the thesis

Researchers pride themselves on being on the cutting edge of knowledge. However, athletes and practitioners often utilize training methods that have not been scientifically validated but are practically beneficial. Therefore, it is common for “novel” scientific findings to confirm, contradict, or reshape what coaches had been practicing. Therefore, the topic of EQI loading is extremely original as no current peer reviewed research, acute, long-term, or otherwise, exists examining this hybrid contraction type. The thesis is also original as several of the morphological, architectural, and neuromuscular evaluations are expanded and optimized versions of pre-existing methodological approaches. This thesis is also one of the first to use total angular impulse to match conditions, a method that may assist in similar future research. Finally, the use of resistance-trained participants is original as the vast majority of the relevant literature is exclusive to untrained, or ‘physically active’ populations.

Research aims

Given the above factors, the overarching research question of the thesis is: “What are the acute, and long-term effects of EQI loading on muscle form and function?”. To address these questions, the following aims were identified.

1) Critically review the relevant literature to determine the possible outcomes of EQI loading and identify best practices and current methodological limitations for performing such research.
2) Test and determine an optimized assessment battery to determine the acute and long-term effects and adaptations to EQI loading.
3) Define the biomechanical profile of EQI contractions, while determining between-contraction kinetic and kinematic shifts.
4) Determine the short-term effects of EQI contractions on delayed onset muscle soreness, muscle structure, and neuromuscular performance relative to a typical bout of eccentric contractions.
5) Compare the acute hormonal, physiological and morphological effects, and long-term structural and neuromuscular adaptations to EQI resistance-training.

Structure of the thesis

The structure of the thesis is summarized in Figure 1.

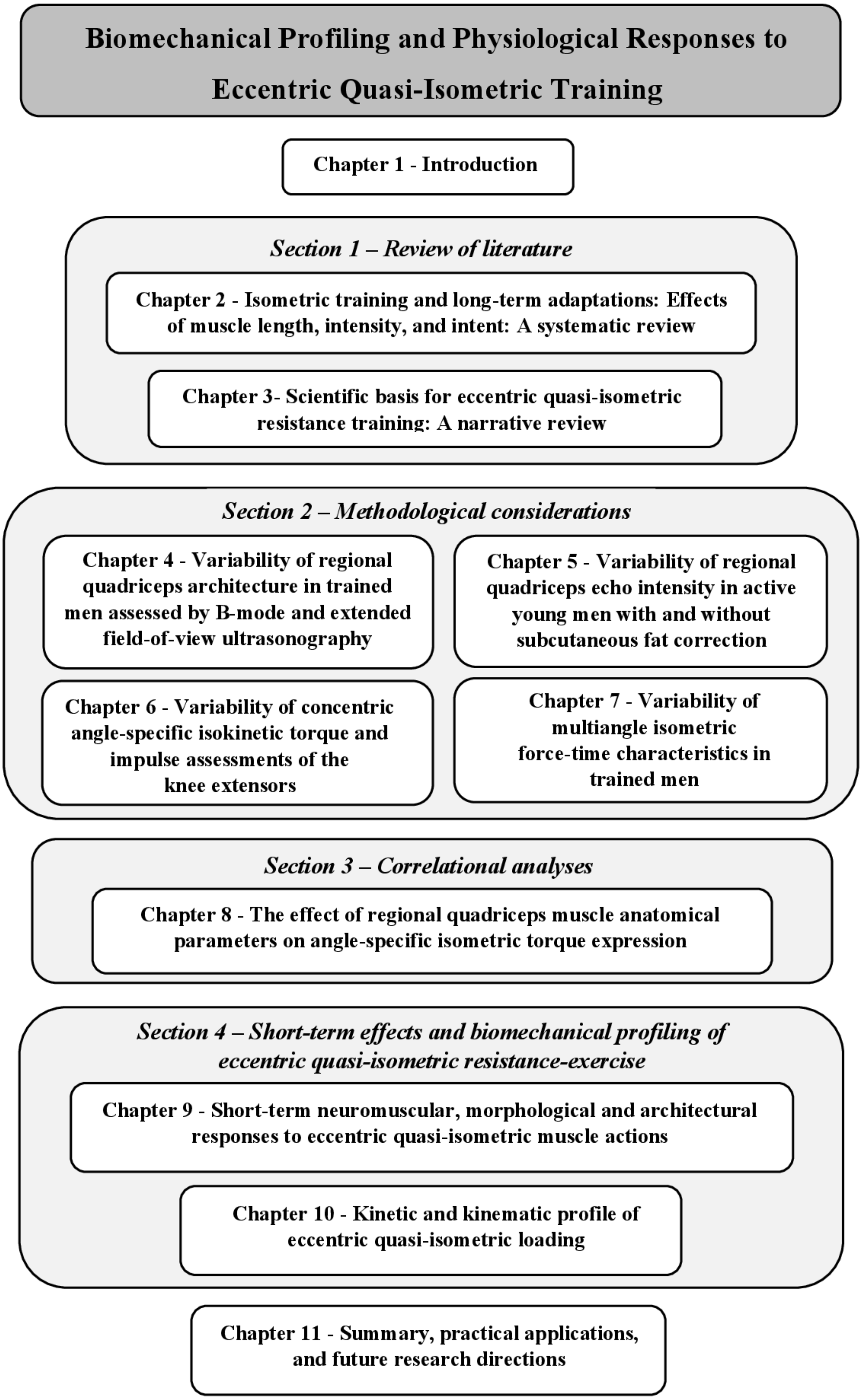

Figure 1. Thesis structure schematic.

Literature reviews

Chapters 2 and 3 present literature reviews on EQIs and adjacent training methodologies. As there are currently no studies examining EQI loading or training, a systematic review of isometric training, arguably the most similar established contraction type, was performed (Chapter 2). The systematic search, critical evaluation, and synthesis of findings aided in determining the likely effects of specific EQI relevant training variables, including muscle length, and contraction duration, intensity, and intent. Additionally, the systematic review provided a detailed overview of current study designs, methods, and measurements used to determine contraction characteristics and track adaptations to the musculotendinous system and alterations in contractile and neuromuscular performance.

With the long-term adaptations to different isometric training established, a narrative review speculating on the biomechanical profile, and acute, short-term, and long-term effects of eccentric quasi-isometric loading was performed (Chapter 3). A search of relevant biomechanical, physiological, and biological scientific research was performed, synthesized, and critically evaluated. The purpose was multi-faceted, including developing a context relevant rationale for the value of EQI training, determining potential practical applications, and highlighting areas for research and appropriate methods and research designs.

Methodological considerations

The literature reviews highlighted several common evaluations of muscle structure and function, with the potential for these methods to be improved, assisting the identification of acute changes and long-term training adaptations. Therefore, chapters 4-7 focused on the determination of measurement variability and optimization. Thus, several regional muscle-specific, and joint-angle-specific evaluations of muscle structure and function were examined. Finally, while each evaluation could be useful, it was important to determine which evaluations were most practically useful in the context of this thesis. Therefore, a correlational analysis between several of the examined evaluations was performed (Chapter 8).

Acute and short-term effects

While gathering information, introducing EQIs to the scientific literature, and establishing a robust battery of tests were important features of the thesis, the main purpose was to be the first to directly study EQI loading. Therefore, a short-term investigation was implemented to compare the effects and recovery of isotonically loaded EQIs with an impulse-equated bout of isokinetic eccentric contractions (Chapter 9). The short-term study intended to determine the effect of EQIs on contractile performance, morphological and architectural shifts, and muscle soreness, offering a snapshot of the effects of EQIs in comparison to the well-studied eccentric contraction. Thus, practitioners could be informed as to when, where, and how to implement EQI training.

Chapter 10 was an acute investigation that was performed to further categorize EQI contractions, and to better inform future training studies where possible. The purpose of the acute session was to determine the biomechanical profile of EQI loading and to analyze changes in the kinetic and kinematic characteristics over a series of contractions. The kinetic and kinematic analysis would guide the implementation of EQI loading through a single session to inform researchers as to the between-set drop in performance, informing long-term training studies. Furthermore, the study aimed to propose total angular impulse, throughout the ROM, as a means of tracking training load and comparing EQI loading with other training modes; something that could be utilized when comparing contractions of all varieties.

Long-term effects

Once informed on the background scientific literature, and the short-term effects, the final proposed study was primarily designed to determine the medium to long-term effects of EQI training. While short-term studies are important to understanding exercise, it is difficult to predict the long-term effects of training without performing a training intervention. Therefore, the purpose of the proposed training intervention was to determine the effect of EQI training on the isometric and isokinetic force-time characteristics throughout the length-tension relationship and to examine the effects of training on region-specific muscle morphology and architecture. Like the short-term study, isokinetic eccentric training was proposed as the second experimental condition due to its frequent use in research and strength and conditioning circles. As a secondary purpose, blood and biopsy measures were to be taken following the initial and final sessions of EQIs and eccentric contractions to examine the correlation between acute physiological shifts and long-term morphological adaptations.

Unfortunately, the Covid-19 situation forced an abrupt stop to the longitudinal study, and the continued closure of Australian laboratories rendered the analysis of any acute blood and biopsy measures impossible.

Section 1 – Review of literature

Chapter 2 - Isometric training and long-term adaptations: Effects of muscle length, intensity, and intent: A systematic review

Reference

Oranchuk DJ, Storey AG, Nelson AR, and Cronin JB. Isometric training and long-term adaptations: Effects of muscle length, intensity, and intent: A systematic review. *Scand J Med Sci Sports* 29: 484-503, 2019.

Author contribution

Oranchuk DJ, 80%; Storey AG, 5%; Nelson AR, 5%; Cronin JB, 10%.

Prelude

The distinct lack of literature examining eccentric quasi-isometric resistance-training, made performing a systematic review on the topic impossible. However, the ability to collect, evaluate and understand existing and eccentric quasi-isometric relevant data was an important step in the process of examining the unique muscle action. Understanding these training variables and their effects on muscular hypertrophy, neural characteristics and performance alterations forms the base of the thesis and allows for the discovery of important questions to be addressed in the proceeding chapters. Additionally, the systematic review was performed to identify relevant research designs and methodologies to robustly examine training induced physiological, musculoskeletal, and neuromuscular characteristics and adaptations. Therefore, chapter two utilized a systematic search and review of literature to improve the understanding of isometric training variables including muscle length, intensity, duration, and contraction intent.

Introduction

Resistance training is widely utilized as a component of physical preparation for populations ranging from elite strength and power athletes to injured members of the general public (180). Commonly documented resistance training adaptations include increased muscle mass (79), tendon quality (76, 175, 218), strength, power, and range of motion (239), delaying muscular fatigue (1, 350), and improving voluntary activation (3). Dynamic movements incorporating the stretch-shortening cycle comprise the overwhelming majority of resistance training programs (179). However, isolated concentric, eccentric and isometric contractions have specific advantages when improving musculoskeletal properties and neuromuscular function (58, 185, 219), and are increasing in popularity (86). Isometric contractions (where the muscle-tendon unit remains at a constant length) and their role as a training option provide the focus of this chapter.

Training with isometric contractions has been purported to have several advantages. First, isometric training allows for a tightly controlled application of force within pain-free joint angles in rehabilitative settings (140, 182). Second, isometric training provides a means to induce force overload as maximal isometric force is greater than that of concentric contractions (4). Third, a practitioner who understands the physical demands of a sport may be able to utilize isometric training to focus on specific weak points in a range of motion that can positively transfer to performance (361) and injury prevention (367). Isometric contractions can also be used to provide an acute analgesic effect and allow for pain-free dynamic loading (293, 295) by altering excitatory and inhibitory functions in the corticomotor pathways (131). Additionally, isometric contractions are a highly reliable means of assessing and tracking changes in force production (242, 243, 390). However, the ability of isometric assessments to predict dynamic performance is questionable (242, 243, 390), despite multi-joint appraisals showing promise (92, 168, 226, 266).

Isometric training can elicit changes in physiological qualities including muscle architecture (9), tendon stiffness and health (188, 295), joint angle-specific torque (188, 250, 251), and metabolic functions (314). As with any mode of resistance training, several variables can be manipulated to alter the stimulus. The most common isometric training variations include altering joint angles (9, 35, 188, 205, 231, 250, 251, 289, 335, 353) and contraction intensity or duration (19, 21, 32, 164, 169, 231, 314, 344, 354). Less frequently researched variations include contraction intent (eg. ramp vs ballistic) (32, 216, 354) and incorporating special methods such as blood flow restriction (83, 327), vibration (104, 325), and electrical stimulation (8). Additionally, emerging research has demonstrated unique neuromuscular characteristics between “pushing” (i.e., exerting force against an immovable object) and “holding” (i.e., maintaining a joint position while resisting an external force) isometric contractions (122, 157, 299-301, 305, 320). Understanding the loading parameters that achieve a desired adaptive response in muscle and tendon would be of benefit to practitioners. Therefore, the purpose of this review was to systematically evaluate research directly comparing the outcomes of isometric training variations and to provide training guidelines for a variety of desired outcomes.

Methods

The systematic review conformed to the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses” (PRISMA) guidelines (203). Therefore, no Institutional Review Board approval was necessary.

Literature search methodology

An electronic search was conducted utilizing MEDLINE, SPORTDiscus, PubMed, and CINAHL databases from inception to March 2018. Key terms were searched for within the article title, abstract, and keywords using conjunctions ‘OR’ and ‘AND’ with truncation ‘*.’ Combinations of the following Boolean phrases comprised the search terms: (Isometric train*) AND (strength* OR stiff*); (Isometric train*) AND (muscle* OR tendon*); (Isometric train*) AND (session* OR week*).

Inclusion and exclusion criteria

Studies were included in the review based on the following criteria: 1) full text available in English; 2) peer-reviewed journal publications or doctoral dissertations; and 3) the study compared two or more variations of isometric training. Studies were excluded if they; 1) were conference papers/posters/presentations; 2) focused on small joints or muscles such as fingers or toes; 3) primary dependent variables were related to cardiovascular health; 4) non-human subjects; 5) in-vitro; 6) the intervention period was less than three weeks in duration, 7) included variables such as blood restriction, vibration or electrical stimulation. Search strategy and inclusion/exclusion results are summarized in Figure 2.

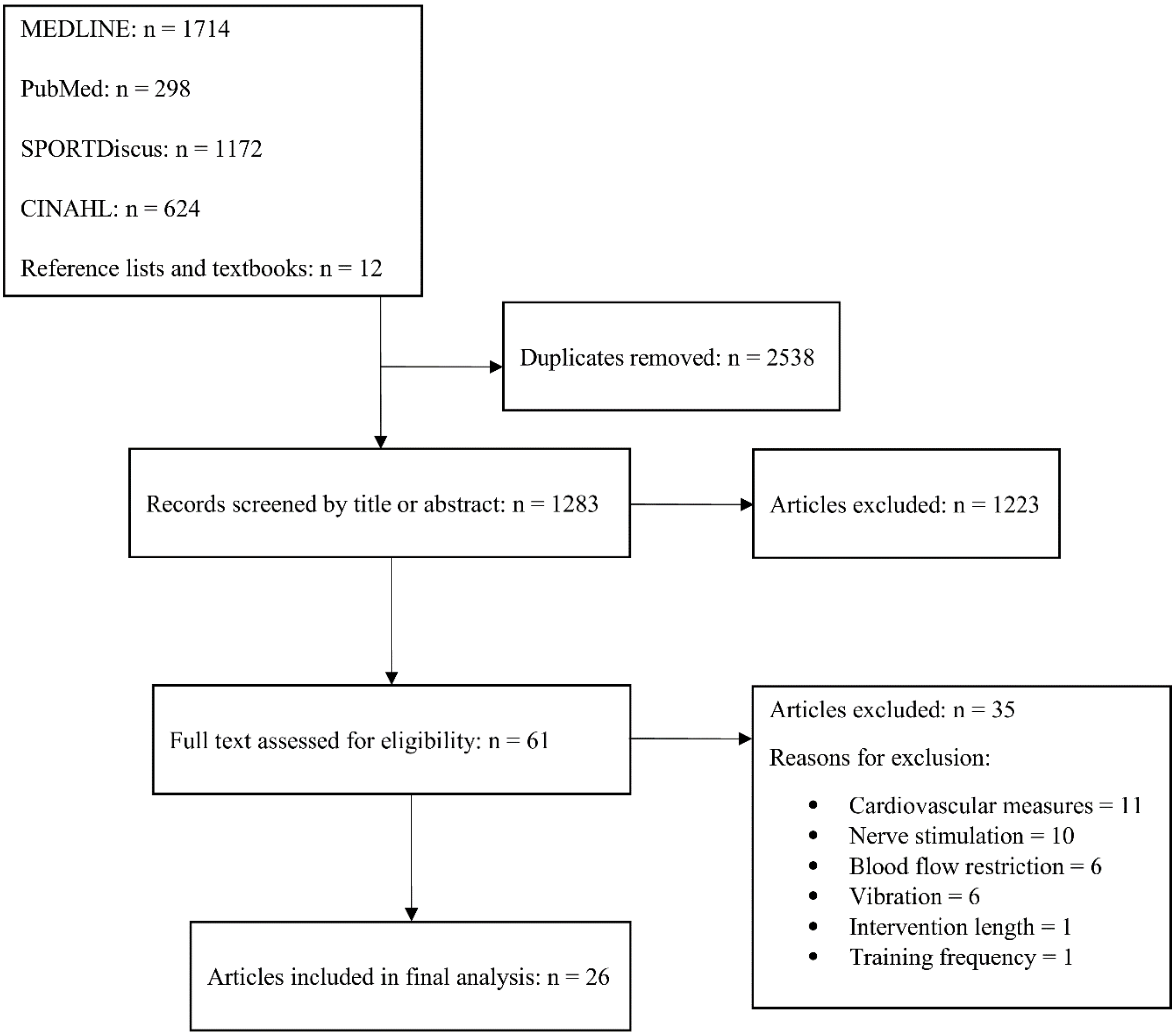

Figure 2. Search strategy.

Quality assessment

Studies that met the inclusion criteria were assessed to determine their quality based on established scales utilized in the fields of sport and exercise science, kinesiology, health care, and rehabilitation. Adapted from a systematic review by Brughelli et al. (56), the scale developed for the current review is illustrated in **Appendix 1**. Ten items were scored as zero (clearly no), one (maybe), or two (clearly yes) based on this scoring rubric (56). Therefore, each study received a quality score ranging from zero to 20. Two researchers completed the quality assessments of each paper with a third researcher settling any discrepancies in scoring.

Statistical analysis

Percent change and Cohen's *d* effect sizes (ES) were calculated wherever possible to indicate the magnitude of the practical effect. Effect sizes were averaged across the length of an intervention where applicable. As recommended by Rhea (292), ESs were interpreted as: trivial < 0.35, small = 0.35-0.80, medium = 0.80-1.50 and large > 1.5 for recreationally active participants (292). Where possible, data were pooled and average ES change and percentage change (pre-post) per week were calculated. All reported ESs and percentage changes are pre-post within–group, unless otherwise stated.

Results

A total of 26 studies with a mean quality score of 14.3/20 (range = 10-18) met the inclusion criteria for the review (**Appendix 2**). A total of 713 participants (463 male, 250 female) were recruited with an average sample size of 27.4 ± 28.1 (4-120). Of the accepted investigations, the mean age of the reported participants was 24.3 ± 3.3 years (19.3-31.8); seven studies failed to report participant mean age. Most studies (16/26) recruited untrained participants, while the remainder (11/26) utilized "active" or "recreationally trained" participants. None of the accepted studies examined competitive athletes or well-trained participants. All 26 accepted investigations clearly stated independent and dependent variables, and 10 included a non-exercise control group. The mean length of intervention was 8.4 ± 3.6 (range = 3-14) weeks, with an average of 3.5 ± 0.96 (range = 2-7) sessions per week for an average of 28.6 ± 13.2 (range = 15-56) total training sessions. Interventions were volume equated in 17/26 studies, while 10/26 studies included a non-exercise control group. Closed chain movements were only utilized in three studies, whereas 23/26 utilized single joint contractions.

Nine published journal articles and one unpublished doctoral dissertation examining the chronic (5-12 weeks) effects of isometric training at varying joint angles fulfilled the inclusion criteria (Table 1) (9, 35, 49, 188, 205, 250, 251, 289, 335, 353). Of the ten included studies, eight centred on the knee extensors (9, 35, 49, 188, 205, 250, 251, 335), with two utilizing the elbow flexors (289, 353). Six published articles examining the effect of contraction intensity (Table 2) fulfilled the inclusion criteria (19, 21, 164, 169, 344, 396). Of these studies, three examined plantar flexors (19, 21, 396), one examined knee extensors (344), while single studies examined the elbow flexors (169) and extensors, respectively (164). Training variations outside of joint position or contraction intensity were also included. These variations include; 1) intent of contraction which included "progressive" vs "rapid" (216, 389) and "explosive" vs “sustained” (32, 225, 354) contractions (Table 3); 2) total volume (231); 3) contraction duration (185, 314); 4) rest period duration (385); and 5) periodization schemes (362) (Table 4).

Table 1. Joint angle

Study, year (quality)	Subjects	Intervention	Mechanical and neural adaptations ($p < 0.05$, ES ≥ 0.50)	Performance effect ($p < 0.05$, ES ≥ 0.50)
Alegre, Ferri-Morales, Rodriguez-Casares, & Aguado, 2014 (9) (18/20)	Healthy, untrained university students M = 22 F = 7 19.3 years	Isometric knee extension SML = 50° LML = 90° ~74% of MVIC 8 wks, 2-3/wk	SML: ↑VL thickness at 25% and 50% muscle length (5.2-6.1%, ES = 0.23-0.24) ↑isokinetic EMG at 60-70° (ES = 1.0) and 50-60° (p = 0.21, ES = 0.77) LML: ↑VL thickness at 25%, 50%, and 75% muscle length (9-13.5%, ES = 0.31-0.65) ↑VL pennation angle (11.7%, ES = 0.45)	SML: ↓Optimum angle (7.3%, ES = 0.91) LML: ↑Concentric torque at $60°\cdot s^{-1}$ (22.6%, ES = 1.1) ↑Optimum angle (14.6%, ES = 1.38)
Bandy & Hanten, 1993 (35) (18/20)	Healthy, untrained, university students F = 107 23.9 years	Isometric knee extension SML = 30° MML = 60° LML = 90° 100% of MVIC 8 wks, 4/wk	SML: ↑EMG at 15°, 30°, 45° and 60° vs ↑EMG in control (ES = 0.87-1.65) MML: ↑EMG at 15°, 30°, 45°, 60° and 70° vs ↑EMG control (ES = 0.36-2.26) LML: ↑EMG at 30°, 45°, 60°, 75°, 90°, and 105° vs ↑EMG in control (ES = 0.74-2.28)	SML: ↑MVIC at 15°, 30°, 45° and 60° (ES = 0.88-1.94) MML: ↑MVIC at 15°, 30°, 45°, 60° and 75° (ES = 1.01-2.25) LML: ↑MVIC at 15°, 30°, 45°, 60°, 75°, 90°, and 105° (ES = 0.94-3.26)
Bogdanis et al., 2018 (49) (15/20)	Healthy, active university students M = 15 21.5 ± 2.1 years	Isometric leg press (+ countermovement jumps) SML = 35° of knee flexion LML = 95° of knee flexion 100% of MVIC 6 wks, 3/wk		SML: ↓Optimum angle (9.7%, ES = 1.77) ↑MVIC at 18° (22%, ES = 0.88) and 34° (57.4%, ES = 2.41) ↓RFD 0-200 ms and 0-300 ms at 80° (11.8-13.8%, ES = 0.51-0.60) ↑RFD 0-200 ms and 0-300 ms at 18° (40.7-45.4%, ES = 1.2-1.52) and 34° (17.9-20.9%, ES = 0.62-0.77) ↑1-RM squat (9.6%, ES = 0.61) ↑CMJ height (7.2%, ES = 0.66)

				LML: ↑MVIC (main time effect: p = 0.028) at all joint angles (18-98°) (~12.3%) *↑RFD 0-300 ms at 34° (14.4%, ES =0.52) ↑1-RM squat (11.9%, ES = 0.64) ↑CMJ height (8.4%, ES = 0.51)
Kubo et al., 2006 (188) (11/20)	Healthy university students M = 9 24 ± 1 years	Isometric knee extension SML = 50° LML = 100° 70% of MVIC 12 wks, 4/wk	SML: ↑Quadriceps muscle volume (10%, ES = 0.82) ↑EMG at all joint angles (3.1-7.5%, ES = 0.25-0.44) LML: ↑Quadriceps muscle volume (11%, ES = 1.06) ↑Tendon stiffness (50.86%, ES = 1.22) ↓Tendon elongation (-14.01%, ES = 0.62) ↑EMG at all joint angles (7-8.84%, ES = 0.45-0.72)	SML: ↑MVIC at 40°, 50°, 60°, 70° and 80° LML: ↑MVIC at 40°, 50°, 60°, 70°, 80°, 90°, 100° and 110°
Lindh, 1979 (205) (13/20)	Healthy F = 10 26.5 years	Isometric knee extension SML = 15° LML = 60° 100% of MVIC 5 wks, 3/wk		SML: ↑MVIC in SML at 15° (32%) ↑MVIC at 60° (14%) ↑Con torque at $30°\cdot s^{-1}$ LML: ↑MVIC at 15° (11%) ↑MVIC at 60° (31%) ↑Con torque at $30°\cdot s^{-1}$
Noorkoiv, Nosaka, & Blazevich, 2014 (250) (17/20)	Healthy, untrained M = 16 23.7 ± 4.0 years	Isometric knee extension SML = 38.1 ± 3.7° LML = 87.5 ± 6.0° 100% of MVIC 6 wks, 3/wk	SML: ↑Mid VL fascicle length (5.6%, ES = 0.63) LML: ↑Voluntary activation at 50° (ES = 0.53) and 60° (ES = 1.02) ↑Total quadriceps muscle volume (5.2%, ES = 0.19)	SML: ↑MVIC at 40° and 50° (8.0-14.2%, ES = 0.34-0.54)

			↑Distal VL fascicle length (5.8%, ES = 0.33)	
Noorkoiv, Nosaka, & Blazevich, 2015 (251) (17/20)	Healthy, untrained M = 16 23.7 ± 4.0 years	Isometric knee extension SML = 38.1 ± 3.7° LML = 87.5 ± 6.0° 100% of MVIC 6 wks, 3/wk		LML: ↑Concentric torque at 30, *60, *90, and $120^{\circ}\cdot s^{-1}$ (10.1-13%, ES = 0.55-0.70)
Rasch & Pierson, 1964 (289) (13/20)	Healthy, untrained university students M = 29	Isometric elbow flexion Single angle = 3 sets at 90° Multi-angle = 1 set at 60°, 90° and 120° 100% of MVIC 5 wks, 5/wk		
Sterling, 1969 (335) (18/20)	University physical education students M = 120	Isometric "hip press" SML = 25° MML = 55° LML = 85° 100% MVIC 7 wks, 3/wk		SML: ↑MVIC at 25° and 55° (21-37.2%) MML: ↑MVIC at 25° and 55° (15.4-51.4%) LML: ↑MVIC at 85° (3.1%)
Thepaut-Mathieu, Van Hoecke, & Maton, 1988 (353) (11/20)	Untrained M = 24 31.8 years	Isometric elbow flexion SML = 60° MML = 100° LML = 155° 80% MVIC 5 wks, 3/wk	SML, MML & LML: ↑EMG at all angles	SML: ↑MVIC at 60° and 80° (10-25%) MML: ↑MVIC at 60-155° (22-30%) LML: ↑MVIC at 80-155° (24-54%)

SML = short muscle length. MML = medium muscle length. LML = long muscle length. MVIC = Maximal voluntary isometric contraction. EMG = electromyography. Con = concentric. VL = vastus lateralis, VM = vastus medialis, RF = rectus femoris. 1-RM = one-repetition maximum. CMJ = Countermovement jump. ES = effect size (Cohen's *d*). *Denotes $p > 0.05$.

Table 2. Contraction intensity

Study, year (quality)	Subjects	Intervention	Mechanical and neural adaptations ($p < 0.05$, ES ≥ 0.50)	Performance effect ($p < 0.05$, ES ≥ 0.50)
Arampatzis, Karamanidis, & Albracht, 2007 (19) (14/20)	Healthy, untrained university students M = 7 F = 14 28 years	Isometric plantar flexion LI = 55% MVIC (24 contractions) HI = 90% MVIC (16 contractions) 14 wks, 4/wk	LI: ↑Tendon elongation (16.2%, ES = 0.56) ↑Tendon strain (17.4%, ES = 0.57) ↑Calculated maximum tendon force (28.4%, ES = 1.76) HI: ↑Tendon stiffness (36%, ES = 1.57) ↑Tendon cross-sectional area at 60% and 70% of tendon length ↑Calculated maximum tendon force (43.6%, ES = 2.04)	
Arampatzis, Peper, Bierbaum, & Albracht, 2010 (21) (14/20)	Healthy, untrained university students M = 11 23.9 years	Isometric plantar flexion LI = 55% MVIC (20 contractions) HI = 90% MVIC (12 contractions) 14 wks, 4/wk	LI: ↑Tendon elongation (14%, ES = 0.84) ↑Tendon strain (13.7%, ES = 0.67) ↑Calculated maximum tendon force (11.7%, ES = 0.89) HI: ↑Tendon stiffness (17.1%, ES = 0.82) ↑Calculated maximum tendon force (11.9%, ES = 0.81)	
Kanehisa et al., 2002 (164) (16/20)	Healthy, untrained M = 12 27.5 years	Isometric elbow extension LI = 60% MVIC (4 x 30s) HI = 100% MVIC (12 x 6s) 10 wks, 3/wk	LI: ↑Muscle volume (5.3%, ES = 0.26) HI: ↑Muscle volume (12.4%, ES = 0.28)	LI: ↑MVIC (61%, ES = 1.91) HI: ↑MVIC (60.3%, ES = 2.71)
Khouw & Herbert, 1998 (169) (11/20)	51 untrained university students M = 18 F = 33	Isometric elbow flexion Each subject assigned to an individual intensity between 0% and 100% in 2% increments 6 wks, 3/wk		Greater ↑MVIC (slope = 0.19, 5.3%, $p = 0.006$) when training closer to 100%

Szeto, Strauss, De Domenico, & Sun Lai, 1989 (344) (11/20)	University students M = 6 F = 12	Isometric knee extension LI = 25% MVIC MI = 50% MVIC HI = 100% MVIC 3 wks, 5/wk	LI: *↑MVIC (22.3%, ES = 0.61) MI: ↑MVIC (31.3%, ES = 1.14) HI: ↑MVIC (45.7%, ES = 1.44)
Young, McDonagh, & Davies, 1985 (396) (12/20)	Healthy M = 4 20.5 years	Isometric plantar flexion LI = 30% MVIC (7-15 x 60s) HI = 100% MVIC (3s contractions HI, 5 wks; and LI, 8 wks, 7/wk	LI: ↑MVIC (3.3%/wk) ↑MVIC (30.2%, ES = 2.22) ↑Fatigue index (19.4%, ES = 1.72) HI: ↑MVIC (5.5%/wk ↑MVIC (21.2%, ES = 1.67)

LI = low intensity. MI = medium intensity. HI = high intensity. MVIC = maximal voluntary isometric contraction. ES = effect size (Cohen's *d)*. *Denotes $p > 0.05$.

Table 3. Contraction intent

Study, year (quality)	Subjects	Intervention	Mechanical and neural adaptations ($p < 0.05$, ES ≥ 0.50)	Performance effect ($p < 0.05$, ES ≥ 0.50)
Balshaw, Massey, Maden-Wilkinson, Tillin, & Folland, 2016 (32) (15/20)	Healthy, untrained M = 43	Isometric knee extension MST = 1s build to 75% of MVIC, hold for 3s (40 contractions) EST = rapidly built to ≥ 80% of MVIC and hold for 1s (40 contractions) 12 wks, 3/wk	MST: ↑Muscle volume (8.1%, ES = 0.50) ↑EMG at MVIC (27.8%, ES = 0.67) ↑EMG 0-150 ms (14.3%, ES = 0.36) EST: ↑EMG 0-100 and 0-150 ms (12.5-31.3%, ES = 0.26-0.67)	MST: ↑MVIC (23.4%, ES = 1.19) ↑Force at 150 ms (12.1%, ES = 0.74) EST: ↑MVIC (17.2%, ES = 1.24) ↑Force at 50, 100, 150 ms (14.4-32.6%, ES = 0.65-1.06)
Maffiuletti & Martin, 2001 (216) (17/20)	Healthy untrained M = 21	Isometric knee extension RC = 4 seconds to reach MVIC BC = 1 second to reach MVIC 7 wks, 3/wk	RC: ↓VL EMG BC: ↑Peak twitch (29.8%) ↓Contraction time ↓Maximal twitch relaxation	RC: ↑MVIC at 55°, 65° (15.7%) and 75° ↑Eccentric torque at $60°·s^{-1}$ (15.6%) ↑Concentric torque at $60°·s^{-1}$ and $240°·s^{-1}$ BC: ↑MVIC at 55°, 65° (27.4%) and 75° ↑Eccentric torque at $60°·s^{-1}$ (18.3%) ↑Concentric torque at $60°·s^{-1}$ and $240°·s^{-1}$
Massey, Balshaw, Maden-Wilkinson, Tillin, & Folland, 2018 (225) (18/20)	Healthy untrained M = 42 MST = 25 ± 2 years EST = 25 ± 2 years CON = 25 ± 3 years	Isometric knee extension MST = 1s build to 75% of MVIC, hold for 3s (~ 10 contractions) EST = rapidly built to ~80% of MVIC (~ 10 contractions) 12 wks, 3/wk	MST: ↑Muscle volume (8.1%, ES = 0.47) ↑VL aponeurosis area (5.9%, ES = 0.34) ↑Tendon stiffness (14.3%, ES = 0.79) ↑Young's modulus (14.4%, ES = 0.60) ↑Tendon-aponeurosis stiffness (22.7%, ES = 0.54) EST: ↑VL aponeurosis area (4.4%, ES = 0.38) ↓Tendon CSA (2.8%, ES = 0.31) ↓Tendon elongation (11%, ES = 0.75) ↑Tendon stiffness (19.9%, ES = 0.95)	MST: ↑MVIC (23.6%, ES = 1.17) EST: ↑MVIC (16.7%, ES = 1.23)

			↓Tendon strain (11.8%, ES = 0.56) ↑Young's modulus (21.1%, ES = 1.13) ↑Tendon-aponeurosis elongation (16%, ES = 1.0)	
Tillin & Folland, 2014 (354) (12/20)	Healthy, recreationally active male university students N = 19 MST = 20.9 ± 1.1 years EST = 20.2 ± 2.4 years	Isometric knee extension MST = 1s build to 75% of MVIC, hold for 3s (10 contractions) EST = rapidly built to ≥ 90% of MVIC and hold for 1s (10 contractions) 4 wks, 4/wk	MST: ↑M-wave at MVIC (28.1%, ES = 1.28) ↓%EMG at 50 and 150 ms (11.7-22.1%, ES = 0.59-0.79) EST: ↑M-wave at 50 and 100 ms (25-42%, ES = 0.95-1.05)	MST: ↑MVIC (20.5%, ES = 1.46) ↑MVIC at 50, 100 and 150 ms (3.09-7.39%, ES = 0.084-0.52) EST: ↑MVIC (10.6%, ES = 0.56) ↑MVIC at 50, 100 and 150 ms (13.1-53.7%, ES = 0.96-1.2)
Williams, 2011 (389) (15/20)	Healthy, untrained university students M = 11 F = 12 Ramp = 9 Ballistic = 8 22.8 years	Isometric knee extension RC = 4 seconds to reach MVIC BC = 1 second to reach MVIC 6 wks, 3/wk	RC: ↑Ramp VA (7.7%, ES = 1.99) ↑Ballistic VA (8.3%, ES = 1.75) *↑150 ms VA (9.82%, ES =0.74) BC: ↑Ramp VA (4.1%, ES = 1.07) ↑Ballistic VA (7.9%, ES = 1.50) ↑150 ms VA (31.6%, ES = 1.84)	RC: ↑Ramp MVIC (20%, ES = 1.95) ↑Ballistic MVIC (17.8%, ES = 1.56) *↑150 ms force (14.3%, ES = 1.10) BC: ↑Ramp MVIC (15.7%, ES = 0.75) ↑Ballistic MVIC (18.9%, ES = 0.88) ↑150 ms force (48.8%, ES = 3.66)

MST = maximal strength training. EST = explosive strength training. RC = ramp contraction. BC = ballistic contraction. MVIC = maximal voluntary isometric contraction. VA = voluntary activation. EMG = electromyography. ES = effect size (Cohen's *d*). *Denotes $p > 0.05$.

Table 4. Other independent variables

Study, year (quality)	Subjects	Intervention	Mechanical and neural adaptations ($p < 0.05$, ES ≥ 0.50)	Performance effect ($p < 0.05$, ES ≥ 0.50)
Kubo, Kanehisa, & Fukunaga, 2001 (185) (14/20)	Healthy, untrained M = 8 22.6 years	Isometric knee extension SC = 3 x 50 rapid contractions LC = 4 x 20s 70% MVIC 12 wks, 4/wk	SC: ↑Muscle volume (7.4%, ES = 0.36) *↑Tendon stiffness (17.5%, ES = 0.57) ↑Elastic energy (25.6%, ES = 1.85) LC: ↑Muscle volume (7.6%, ES = 0.38) ↑Tendon stiffness (57.3%, ES = 1.38) ↑Elastic energy (12%, ES = 0.58)	SC: ↑MVIC (49%, ES = 2.47) LC: ↑MVIC (41.6%, ES = 2.21)
Meyers, 1967 (231) (13/20)	Healthy university students M = 29	Isometric elbow flexion LV = 3 x 6s HV = 20 x 6s 100% MVIC 6 wks, 3/wk	LV: ↑Muscle girth at 170° in trained arm HV: ↑Muscle girth at 170° in trained and untrained arm ↑Muscle girth at 90° in trained arm	LV: ↑MVIC at 170° (15.4%, ES = 0.93) *↑Muscle endurance (49.7%, ES = 0.71) HV: ↑MVIC at 170° (15.5 %, ES = 0.46) *↑MVIC at 90° (9%, ES = 0.50) ↑Muscle endurance (42.7%, ES = 0.67)
Schott, McCully, & Rutherford, 1995 (314) (10/20)	Healthy, untrained M = 1 F = 6 22.7 years	Isometric knee extension SC = 4 x 10 x 3s LC = 4 x 30s 70% of MVIC 14 wks, 3/wk	LC: ↑Muscle anatomical cross-sectional area at lower (11.1%) and upper (10.1%) femur	SC: ↑MVIC (31.5%) ↑Concentric torque at $120°·s^{-1}$ and $180°·s^{-1}$ (11.3-11.6% LC: ↑MVIC at 90° (54.7%)
Ullrich, Holzinger, Soleimani, Pelzer, Stening, & Pfeiffer, 2015 (362) (16/20)	Healthy, active university students F = 10 24.4 ± 3.2 years	Isometric knee extension TP limb = 3 wks 60%, 4 wks 80%, 3 wks 60%, 2 wks 80% of MVIC	TP: ↑Thigh circumference (6.2%, ES = 0.45) ↑VL thickness at 25%, 50%, and 75% muscle length (15.5-18.5%, ES = 0.98-1.23) ↑VL fascicle length (13.7%, ES = 1.17)	TP: ↑IMVC (24%) ↑Concentric torque at $60°·s^{-1}$ (19%) DUP: ↑IMVC (23%)

		DUP limb = Alternating sessions at 60% and 80% of MVIC in one limb 16 wks, 2/wk	↑IMVC EMG (45%) DUP: ↑Thigh circumference (5.0%, ES = 0.37) ↑Vastus lateralis thickness at 25%, 50%, and 75% muscle length (12.4-19.7%, ES = 0.72-1.01) ↑Vastus lateralis fascicle length (14.2%, ES = 0.90) ↑IMVC EMG (46%)	↑Concentric torque at $60°{\cdot}s^{-1}$ (15%)
Waugh, Alktebi, De Sa, & Scott, 2018 (385) (14/20)	Healthy, physically active M = 8 F = 10 30.1 ± 7.9 years	Isometric plantarflexion SR = 3s between reps LR = 10s between reps 90% MVIC 12 wks, 3/wk	SR: ↑Echo-type II (collagen re-organization) SR & LR: ↑Stiffness ↑Tendon stress ↑Young's modulus ↓Strain % ↓Tendon elongation	SR & LR: ↑MVIC

SC = short contraction. LC = long contraction. LV = low volume. HV = high volume. SR = short rest. LR = long rest. EMG = electromyography. TP = traditional periodization. DUP = daily undulating periodization. MVIC = maximal voluntary isometric contraction. ES = effect size (Cohen's *d*). *Denotes $p > 0.05$.

When synthesising statistically significant findings, measures of muscular size increased in nine studies (5-19.7%, ES = 0.19-1.23) by 0.84%·week^{-1} and 0.043 ES·week^{-1} (9, 32, 164, 185, 188, 225, 250, 314, 362). Maximal isometric force significantly increased in 14 studies (8-60.3%, ES = 0.34-3.26) by 4.34%·week^{-1} and 0.20 ES·week^{-1} (32, 35, 49, 164, 205, 216, 225, 250, 335, 344, 353, 354, 389, 396). The comparison between joint angle and hypertrophic adaptation (n = 3 studies) revealed that training with joint angles ≤ 70º (46 ± 6.9º) improved muscle size by an average of 0.47 ± 0.48%·week^{-1} and 0.032 ± 0.037 ES·week^{-1}, compared to 1.16 ± 0.46%·week^{-1} and 0.067 ± 0.032·week^{-1} when training at > 70º of flexion (Figure 3) (9, 188, 250). When comparing the nine studies that reported training joint angle and hypertrophic adaptations, training with joint angles ≤ 70º (59.8 ± 11.1º) improved muscle size by an average of 0.61 ± 0.42%·week^{-1} and 0.045 ± 0.034 ES·week^{-1}, compared to 0.88 ± 0.8%·week^{-1} and 0.046 ± 0.027 ES·week^{-1} when training at > 70º (88.6 ± 6º) of flexion (**Appendix 3**) (9, 32, 164, 185, 188, 225, 250, 314, 362). The comparative effects of training intensity on muscular hypertrophy were that intensities ≤ 70% (68.9 ± 3.3%) of MVIC improved muscle size by 0.77 ± 0.26%·week^{-1} and 0.13 ± 0.12 ES·week^{-1}, compared to 0.70 ± 0.55%·week^{-1} and 0.13 ± 0.21 ES·week^{-1} when training at > 70% (85.3 ± 12%) of MVIC (Figure 4) (9, 32, 164, 185, 188, 225, 250, 314, 362). The comparisons of training intensity and improvements in isometric force (n = 3 studies) found that training at ≤ 70% (41.3 ± 16.5%) of MVIC improved muscle size by 6.8 ± 3%·week^{-1} and 0.32 ± 0.13 ES·week^{-1}, compared to 8.9 ± 5.5%·week^{-1} and 0.36 ± 0.11 ES·week^{-1} when training at > 70% (100 ± 0%) of MVIC (Figure 5) (164, 344, 396). The joint angle-isometric force comparison (n = 7) showed that training at ≤ 70º (42.8 ± 16.4º) resulted in MVIC improvements of 4 ± 2.1%·week^{-1} and 0.15 ± 0.1 ES·week^{-1}, compared to 3.4 ± 4.2%·week^{-1} and 0.15 ± 0.17 ES·week^{-1} when training at > 70º (101.8 ± 24.2º) of flexion (**Appendix 4**) (35, 49, 188, 205, 250, 335, 353).

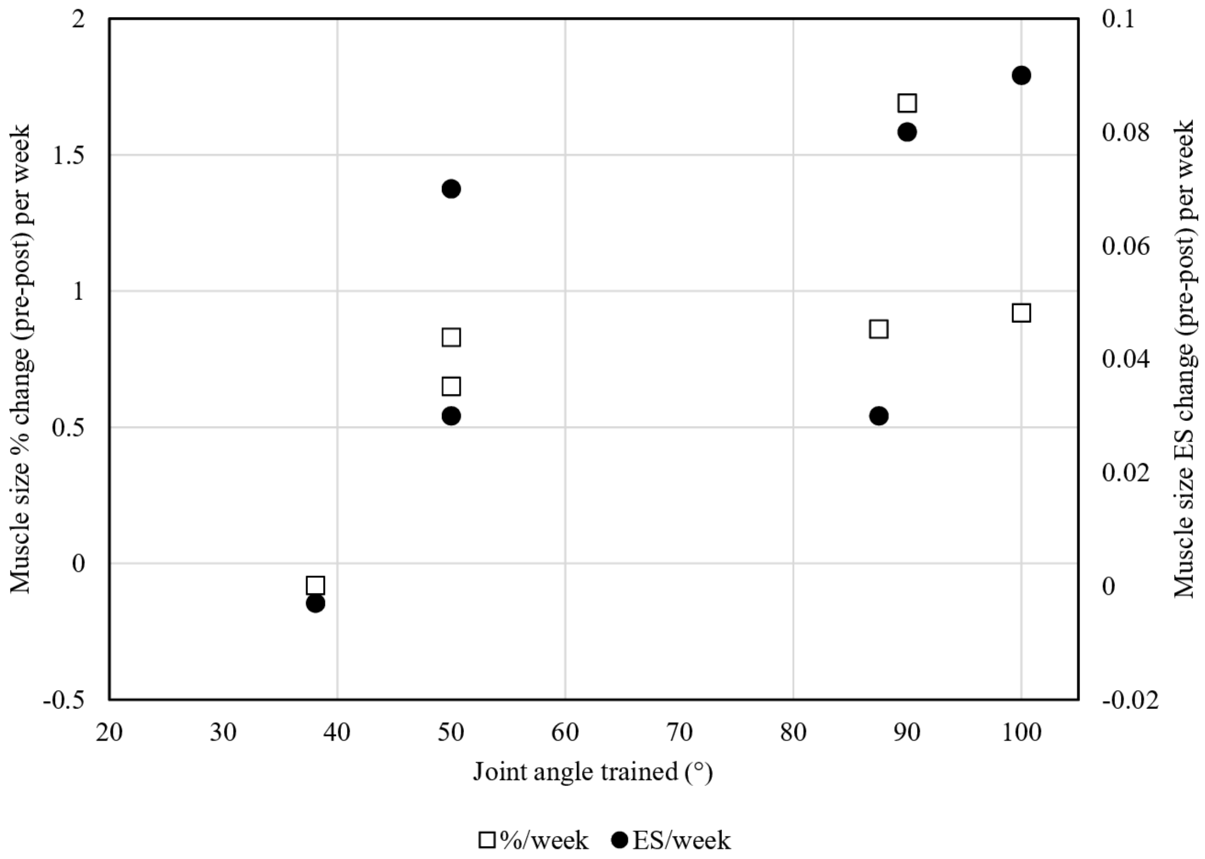

Figure 3. Isometrically trained joint angle and hypertrophic adaptations (n = 3).

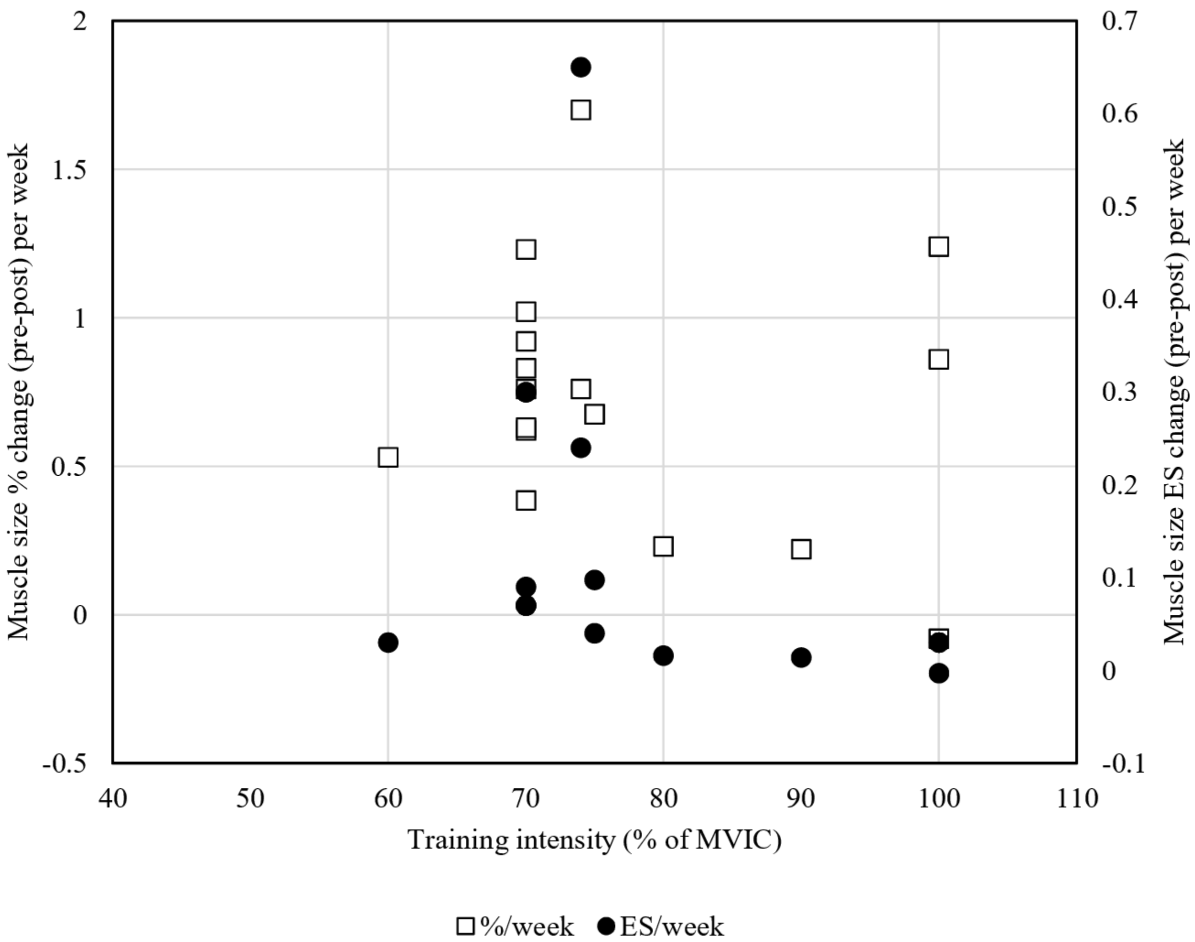

Figure 4. Isometric training intensity and hypertrophic adaptations (multiple comparison. n = 9).

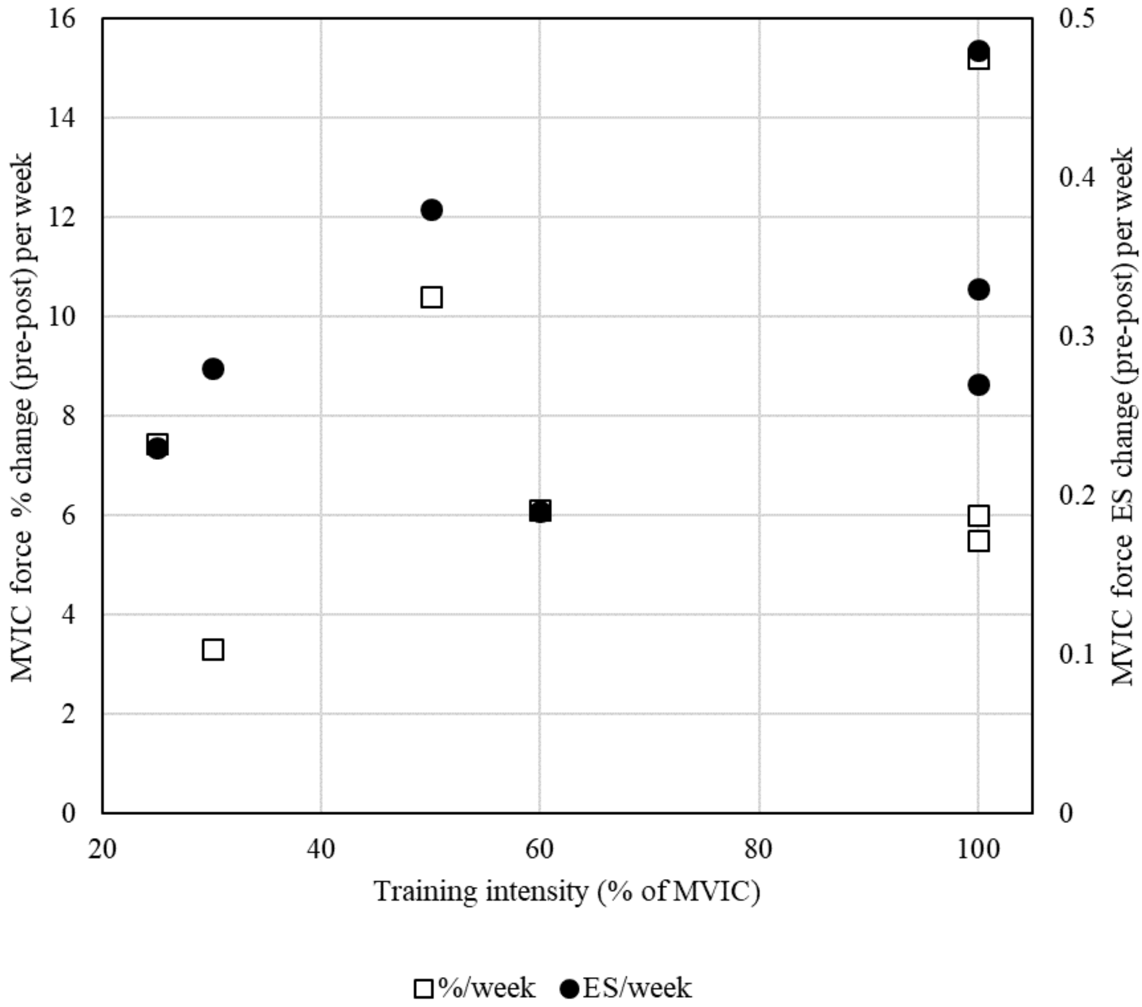

Figure 5. Isometric training intensity and force production (n = 3).

Discussion

Morphological adaptations

Adaptations to the physical structure of tissues can be caused by several factors, including mechanical, metabolic, and hormonal factors, and often results in altered function. The morphology of the musculoskeletal system is of relevance to this review and provides the focus for subsequent discussion.

Muscle volume

While most methods of progressive resistance training can result in increased muscular size, it is important to understand how to optimally alter variables including intensity, frequency, and duration of each training method for maximal efficiency. Isometric resistance training has been demonstrated to induce significant hypertrophy (9, 32, 164, 185, 188, 231, 250, 314).

When comparing adaptations in muscle volume between isometric training variations several patterns emerged, conforming to accepted dynamic training principles. Of the studies comparing isometric training at differing joint angles (Table 1), only three evaluated muscle volume or thickness (9, 188, 250). All three studies found that isometric training at long muscle lengths (LML) was superior to equal volumes of training at short muscle lengths (SML) for increasing muscle size (9, 188, 250). These findings are not surprising as a large portion of the existing literature has demonstrated that dynamic training through a large range of motion is beneficial when hypertrophy is desired (36, 136, 224). Additionally, contractions at LML tend to produce higher quantities of muscle damage, likely by altering the joint moment arm and increasing mechanical tension when compared to a SML (11). Contractions at LML also result in greater blood flow occlusion, rates of oxygen consumption, and metabolite build-up when compared to SML contractions (83). These metabolic factors are well established to contribute to muscular hypertrophy (82, 207).

While volume equated isometric training leads to greater improvements in hypertrophy when performed at LML (9, 250, 251), the magnitude of hypertrophy was not significantly different in any of the seven included studies investigating/reporting training intensity (9, 32, 164, 185, 188, 250, 314). Interestingly, the pooled data of included study outcomes suggest that training intensity has a small effect on hypertrophy, and explains little of the variation in hypertrophic adaptation (Figure 4). For example, Kubo et al. (185) compared the effects of load equated isometric contractions held for short (~1 s) or long (20 s) periods. While both long and short duration contractions led to small, but significant increases muscle thickness, there was little difference ($p > 0.05$) between groups (7.6%, ES = 0.38, $p = 0.023$ vs 7.4%, ES = 0.36, $p = 0.018$) (185). Similarly, Kanehisa et al. (164) employed ten weeks of volume equated isometric training at either low (60%) or high (100%) intensity. While both low and high-intensity training programs significantly increased triceps brachii hypertrophy, there was no statistical between-group difference ($p = 0.061$) in anatomical cross-sectional area (low: 12.1%, ES = 1.72 vs high: 17.1%, ES = 1.65) (164). However, high intensity training had a greater effect on muscle volume than the lower intensity (12.4%, ES = 0.28 versus 5.3%, ES = 0.26; $p = 0.039$) despite nearly identical ESs (164). These findings are in close agreement with recent studies and meta-analyses that concluded that hypertrophic adaptations are similar if the total load is equated and training intensity is greater than 20% of maximal voluntary contraction (196, 312).

When the training volume is not equated between groups, it seems higher volumes are better for inducing muscular hypertrophy, regardless of contraction intensity. Meyers (231) compared low (3 x 6-s MVIC) and high (20 x 6-s MVIC) volume isometric training of the elbow flexors. Following the six-week intervention, the high-volume training program resulted in significantly greater improvements in muscle girth compared to the low volume group ($p < 0.05$). Similarly, Balshaw et al. (32) and Massey et al. (225) compared “maximal strength” (40 x 3-s contractions, 75% of MVIC) and “explosive” (40 x 1-s contractions, 80% of MVIC) isometric training. Following the 12-week interventions, the “maximal strength” training groups experienced significant improvements in quadriceps muscle volume (8.1%, ES = 0.50, $p = 0.001$) whereas the “explosive” training groups (2.6%, ES = 0.17-0.26, $p = 0.195$-0.247) did not (32). Furthermore, the difference between groups was statistically significant ($p < 0.05$) (32, 225). Interestingly, Schott, McCully, and Rutherford (314) found that long duration (4 x 30-second MVIC) contractions resulted in greater hypertrophic adaptations when compared to short (4 sets x 10 x 3-second MVIC) duration contractions despite total time-under-tension being equated between groups. Following 14 weeks, the long duration contraction group significantly ($p = 0.022$) improved vastus lateralis anatomical cross-sectional area at the proximal (10.1%) and distal (11.1%) portion of the femur, whereas no significant hypertrophic adaptations were observed in the short duration group ($p > 0.05$) (314). Schott, McCully, and Rutherford’s (314) findings are somewhat surprising as both groups underwent the same time-under-tension. However, sustained contractions are known to restrict blood flow, reduce muscle oxygen saturation and increase metabolite concentrations in the muscle (7, 333) stimulating hypertrophy via multiple local and systemic mechanisms (82, 207). Additionally, muscle contractions at LML consume more oxygen (83), which may in-part explain the advantage of LML training when muscular hypertrophy is the primary goal.

Muscle architecture

Unlike changes in muscle volume, which is highly dependent on total training volume, there are demonstrable differences between contraction type and alteration in fascicle length and pennation angle (111). To date, very few studies have compared the effect of isometric resistance training variations on changes in muscle architecture; of those that have, results are equivocal. Noorkoiv, Nosaka, and Blazevich (250) compared isometric training at SML (38.1

± 3.7° knee flexion) and LML (87.5 ± 6° knee flexion). Interestingly, the vastus lateralis fascicle length at the mid-portion of the femur significantly increased following SML (5.6%, ES = 0.63, $p = 0.01$), but not LML (3.8%, ES = 0.34, $p = 0.20$) training (250). Conversely, LML (5.8%, ES = 0.33, $p = 0.02$) significantly ($p = 0.01$) outperformed SML training (-1.1%, ES = 0.04, $p > 0.05$) for increasing distal fascicle length of the same muscle (250). Furthermore, LML training resulted in greater ($p < 0.01$) physiological cross-sectional areas in three of the four quadriceps muscles, whereas the SML training did not ($p > 0.05$) (250). Only one other isometric training comparison study reported meaningful changes in muscle architecture, and found that vastus lateralis pennation angle increased following LML (10.6%, ES = 0.45, $p = 0.038$), but not SML training (6.5%, ES = 0.46, $p = 0.076$) (9). However, Alegre et al. (9) only measured the vastus lateralis pennation angle at the midpoint of the femur and potentially missed out on possible adaptations at the distal portion of the muscle.

Tendon morphology

The primary function of the tendon is to transfer forces between bone and muscle, facilitating joint motion (218). Although originally assumed to be inert, tendinous structures can experience adaptations and are capable of significant architectural adaptations from habitual loading and injury (76, 175, 187, 217, 218, 291). Injured tendons tend to be less stiff, despite increased thickness (24) due to a shift in viscoelastic properties (218). Additionally, tendinopathy negatively affects tendon structure, leading to increased vascularization and overall thickness (24, 218). Although long-term alteration in tendon morphology is minimal in healthy, mature human tissue (218), tendons can increase in stiffness to optimize the time and magnitude of force transmission between muscle and bone (76, 175, 291). Conversely, healthy increases in tendon thickness and stiffness in response to exercise, are region specific and may have rehabilitative, pre-habilitative, and performance benefits (76, 175, 217, 291, 293). For instance, heavy (resistance) training can lead to an increase in maximal muscular force and rate of force development by increasing tendon stiffness, thus reducing the electromechanical delay (184, 187, 218). Additionally, increased tendon stiffness through chronic loading can be due to increased tendon cross-sectional area without alterations in viscoelastic properties, potentially improving safety when performing ballistic movements (218). While widely used in rehabilitation settings, there is a general lack of information regarding what isometric training variables are important for triggering specific tendonous adaptations.

Of the studies included in this review, only six directly assessed tendon structure or function. Two studies compared contraction intensity (19, 21), with others examining the effects of contraction length (185), intent (225), rest periods (385), and joint angle (188). Arampatizis et al. (19, 21) compared 14-week training programs consisting of volume equated isometric plantar flexion at low (~55%) or high (~90%) intensities. Both investigations found increased Achilles tendon cross-sectional area and stiffness following high (17.1-36%, ES = 0.82-1.57, $p < 0.05$), but not low (-5.2-7.9%, ES = 0.26-0.37, $p > 0.05$) intensity training (19, 21). Furthermore, tendon elongation under stress (an indication of elasticity) increased following low (14.0-16.1%, ES = 0.56-0.84, $p > 0.05$), but not high (-1.4-3.9%, ES = 0.06-0.20, $p > 0.05$) intensity training (19, 21). Additionally, the included studies only compared isometric training at ~55% and 90% of MVIC which leaves a large range of potential intensities. However, previous interventions have reported large increases (17.5-61.6%, ES = 0.57-4.9, $p < 0.05$) in tendon stiffness following training between 70-100% of MVIC (58, 184, 185). Therefore, it might be that a minimum intensity of ~70% MVIC is required to induce meaningful changes in tendon thickness and stiffness.

While only a single study has examined the effect of isometric training at different muscle lengths on tendon adaptation (188), the results tend to support a paradigm of LML training being superior to SML training. Kubo et al. (188) trained the knee extensors at either 50° or 90° of flexion and observed a significantly greater increases in tendon stiffness (p = 0.021) following LML (50.9%, ES = 1.22, p = 0.014), when compared to SML training (6.7%, ES = 0.26, p = 0.181). Similarly, distal tendon and deep aponeurosis elongation decreased following LML training (-14%, ES = 0.62, p = 0.034), whereas the SML group experiences a trivial increase (3.9%, ES = 0.15, $p > 0.05$). When comparing isometric contraction duration and tendon adaptations, only a single study exists (185). While both long (57.3%, ES = 1.38, p = 0.003) and short (17.5%, ES = 0.57, p = 0.217) contraction durations increased tendon stiffness, a significant between-group difference was reported (p = 0.045) (185). Additionally, no significant differences in tendon elongation were present in either long (-2.2%, ES = 0.19, $p > 0.05$) or short (4.1%, ES = 0.29, $p > 0.05$) contraction duration groups. Similarly, calculated elastic energy absorption increased in both long (12%, ES = 0.58, p = 0.007) and short (25.7%, ES = 1.85, p = 0.002) duration groups with no significant difference between groups (p = 0.056) despite large differences in percent change and ESs along with a relatively low p-value. While the total time-under-tension was equalized between groups, the one-second duration of the short contraction group meant that a larger relative proportion of each effort would be spent building isometric force. Therefore, the maximal-force time-under-tension was not equalized (185). Similar to muscle tissue, tendon adaptations are responsive to chronic changes in total mechanical load (76, 141, 142); therefore, the potentially greater load in the long contraction group could explain the discrepancy in tendonous adaptations.

Massey et al. (225) were the only researchers to compare contraction intent on morphological tendon adaptations. Both "maximal strength training" and "explosive strength training" produced significant improvements in vastus lateralis aponeurosis area (5.9%, ES = 0.34 vs 4.4%, ES = 0.38), Young's modulus (14.4%, ES = 0.60 vs 21.1%, ES = 1.13) and tendon stiffness (14.3%, ES = 0.79 vs 19.9%, ES = 0.95) (225). However, only the "explosive strength training" group experienced significant increases in tendon-aponeurosis complex elongation (16%, ES = 1.0 vs -2.96, ES = 0.10) and decreased tendon cross-sectional area (-2.8%, ES = 0.31 vs 0.41%, ES = 0.03), tendon elongation (-11%, ES = 0.75 vs -4.95%, ES = 0.27) and tendon strain (-11.8%, ES = 0.56 vs -4.17, ES = 0.19) (225). Therefore, intent and rate of contraction appear to be an important training consideration. Lastly, Waugh et al. (385) compared load equated isometric plantar flexions with intra-contraction rest periods of three, or 10 seconds. While there were differences ($p > 0.05$) in type-I and type-II collagen (factors in fibre re-organization) (87, 373), there were no between-group discrepancies ($p > 0.05$) in any other dependent variables following the 14-week intervention (385). These data support a paradigm of a threshold intensity for mechanical loading to achieve tendon adaptations (141, 142).

Neurological adaptations

Of the 26 studies included in this review, 12 directly measured neural function (9, 32, 35, 185, 188, 216, 250, 353, 354, 385, 389, 396). Of these 12 studies, it is notable that one did not report any neurological data in their results (385), while two reported no significant changes following training, regardless of the condition (185, 396). When examining electromyographic amplitude assessed through electromyography (EMG), a clear trend existed between the studies comparing isometric training at different muscle lengths. Electromyographic amplitude tends to increase by larger magnitudes and over a larger range of joint angles following LML training, compared to training at SML. For example, Bandy and Hanten (35) examined isometric knee extension training at SML (30°), medium muscle length (MML; 60°), and LML (90°), assessing EMG amplitude at seven joint angles from 15-105° of flexion. Medium to large (ES = 0.74-2.28) improvements at six joint angles were observed following LML training, whereas

MML and SML training only improved EMG activity at five (ES = 0.36-2.26), and four (ES = 0.87-1.65) of the assessed joint angles, respectively (35). Similarly, Kubo et al. (188) observed larger increases in EMG activity at all measured angles following LML (7-8.8%, ES = 0.45-0.72) compared to SML (3.1-7.5%, ES = 0.25-0.44) training. Conversely, Alegre et al. (9) reported an increase in EMG amplitude in favor of the SML training group, the only investigation to do so. Although the magnitude of increases in EMG amplitude were medium-large, the changes were limited to 50-60° (ES = 0.77, p = 0.205) and 60-70° (ES = 1.00, p = 0.36) of knee flexion during isokinetic knee extensions (9). These findings are consistent with the findings of other investigations in that alterations in EMG amplitude are most specific at shorter muscle lengths (36, 224, 353).

All four studies comparing the effects of isometric training with different contraction intents (ballistic vs ramp) assessed neurological and neuromuscular adaptations via EMG and peripheral nerve stimulation (32, 216, 354, 389). As expected, adaptations were specific to the intent utilized in training. For example, Balshaw et al. (32) examined the effects of 12 weeks of “maximal strength training” (1-s build to ~75% of MVIC and maintain for 3-s), with “explosive strength training” (rapid build to ≥ 90% of MVIC and maintain for 1-s). The improvements in EMG amplitude at MVIC were larger (ES = 0.36, p = 0.370) following “maximal strength training” (27.8%, ES = 0.67, p < 0.001) compared to “explosive strength training” (19.1%, ES = 0.44, p = 0.099). Conversely, “explosive strength training” (31.3%, ES = 0.67, p = 0.003) increased EMG activity to a greater (p < 0.001) degree during the 0-100 ms and 0-150 ms period of muscle contraction compared to “maximal strength training” (14.3%, ES = 0.36, p = 0.009) (32). Additionally, only the rapid contraction group significantly increased EMG amplitude in the first 100 ms of muscle contraction (12.5%, ES = 0.26, p = 0.048) (32). Similarly, previous investigations examining contraction intent found greater improvements in EMG amplitude during MVIC with maximal strength training (1.28-7%·week^{-1}, ES = 0.06-0.33·week^{-1}) when compared to explosive strength training (0.68-1.31%·week^{-1}, ES = 0.18-0.25·week^{-1}) (216, 354, 389). Furthermore, participants training with a ballistic intent (1.04-10.5%·week^{-1}, ES = 0.26-0.31·week^{-1}) achieved greater improvement in EMG amplitude during the initial 150 ms of maximal contraction when compared to ramped contractions (2.93-5.53%·week^{-1}, ES = 0.03-0.07·week^{-1}) (32, 216, 354, 389). These findings support the principle of training specificity as only the groups who intended to produce force quickly, improved in that regard.

Performance enhancement

Isometric training is commonly prescribed in rehabilitation settings, or early in physical preparation plans to increase neuromuscular, musculoskeletal, and proprioceptive function. It is thought that the aforementioned improvements will later transfer to dynamic performance once specific movement patterns are integrated into the physical preparation plan. Despite existing literature reporting the benefits of isometric training on multi-joint dynamic performance (58, 184, 189), none of the studies included in the current review included dynamic multi-joint assessments.

Isometric peak force

Only four studies included in the present review directly compared MVIC production between groups training at different intensities (164, 169, 344, 396). Isometric peak force is considered a highly reliable measure, with a growing body of research reporting the validity of isometric measurements for assessing health and athletic performance (92, 388). While training specificity is a major factor in performance improvements, if MVIC force is the desired outcome there does not appear to be a clear advantage to training at high or low intensities (Figure 5). Szeto et al. (344) was the only study that reported statistically significant improvements in MVIC force in some, but not all training groups. Szeto et al. (344) had subjects train their knee extensors at 25%, 50%, or 100% of MVIC. Following 15 sessions over three weeks, the group training at 25% did not experience statistically significant strength improvements despite medium effect sizes (22.3%, ES = 0.61, $p = 0.085$) (344). Conversely, large and statistically significant improvements were observed when training at 50% (31.3%, ES = 1.14, $p = 0.002$) and 100% (45.7%, ES = 1.44, $p = 0.013$) of MVIC (344). However, time-under-tension, not total load, was equalized between groups, meaning that the 50% training group produced twice as much total force as the 25% group. While no data about fatigue is presented, it could be hypothesized that the group training with maximal effort underwent significantly greater loading than the other groups (344). Additionally, the inclusion of perceived effort or a fatigue scale may have been valuable.

A clear pattern can be observed when comparing maximal force production following training at different muscle lengths. Despite LML resulting in greater hypertrophic adaptations, there is no difference in maximal force production at the trained joint angle between SML and LML interventions when analyzing the seven studies that directly compared joint angles (**Appendix 4**) (35, 49, 188, 205, 250, 335, 353). However, transfer to non-trained joint angles is much lower following SML training. For example, Bandy and Hanten (35), Bogdanis et al. (49), Kubo et al. (188), and Thepaut-Mathieu, van Hoecke and Maton (353) all trained participants at different muscle lengths and measured MVIC at numerous joint angles pre- and post-training. Bandy and Hanten (35) observed significant ($p < 0.05$) improvements at four, five, and seven of the tested joint angles following SML, MML, and LML respectively. Bogdanis et al. (49) reported increased MVIC at two of the assessed joint angles following SML training (22-57.4%, ES = 0.88-2.41), while the LML group improved in all six angles (~12.3%). Similarly, the SML group in Kubo et al.'s (188) investigation significantly ($p < 0.05$) improved MVIC at five angles while the LML group experienced significantly improved force production at eight of the tested angles. Interestingly, Thepaut-Mathieu, Van Hoecke and Maton (353) found that their LML group significantly ($p < 0.05$) improved at four angles, compared to two and five angles in the SML and MML group respectively. These data suggest that LML and MML isometric resistance training is superior to SMLs when the aim is to improve force throughout a range of motion.

Length-tension

The length-tension relationship, typically assessed by isometric or isokinetic contractions, is defined as the muscle length or joint angle at which peak force/torque is produced (355). Many studies have demonstrated acute optimal angle/length shifts towards longer muscle lengths following concentric, isometric, and eccentric exercise (11, 52, 53, 135, 278, 280, 393). Additionally, eccentric resistance training and training over a larger range of motion are well established for increasing the optimal angle long-term (135, 136). It is plausible that the same relationship exists between muscle length and a shift in the optimal angle following isometric contractions. However, only a single study included in this review reported the angle of peak isokinetic torque (9), while another examined the optimal angle through an isometric leg-press (49). Alegre et al. (9) observed a shift of 11° (14.6%, ES = 1.1, $p = 0.002$) towards longer muscle lengths following eight weeks of training at LML, whereas the SML group experienced a shift of 5.3° (7.3%, ES = 0.91, $p = 0.039$) in the opposite direction. Likewise, Bogdanis et al. (49) reported a decrease in optimal angle following SML training (-9.7%, ES = 1.77) while the optimal angle was maintained in the LML group. While the length-tension curve shifted toward the angle of training in several other studies, none were significant or altered the angle at which maximal isometric force was produced (9). While a very limited sample, the report of Alegre et al. (9) is unsurprising given that isometric exercise at LMLs is preferable to SMLs for acutely altering the length-tension relationship (279). Finally, it should be noted that no included study reported any significant differences in isometric or isokinetic length-tension curves between groups training with different intensities, contraction intents or any other independent variable.

The rate of force development

The rate of force development (RFD) is an important measurement in sports performance, as force application in many activities occurs over short periods (43, 86, 138, 198). Therefore, while peak force is a valid and highly reliable means of broadly monitoring neuromuscular function, rapid force production characteristics are equally valuable and more specific to the execution of explosive tasks (43, 79, 138, 198, 209). Unfortunately, only three training studies examining different contraction intents reported RFD variables (32, 216, 354). Regardless, all three studies reported that isometric training with an "explosive" or "ballistic" intent was superior to ramping contractions for improving rapid force production (32, 354, 389). These findings align with the previously discussed alterations in EMG amplitude between contraction intents. For example, Williams (389) compared the adaptations following ballistic or ramp isometric training. While the ramp group experienced larger, improvements in MVIC (ramp, 17.8-20%, ES = 1.56-1.95, $p = 0.0008$ vs ballistic, 15.7-18.9%, ES = 0.75-0.88, $p = 0.0036$), only the ballistic training group significantly improved voluntary activation (31.6%, ES = 1.84, $p = 0.0096$) and force at 150 ms (48.8%, ES = 1.29, $p = 0.0074$) (389). Similar findings are reported by Balshaw et al. (32) and Tillin and Folland (354) where only the ballistic training groups significantly ($p < 0.05$) improved force at 50 ms and 100 ms (Table 3). These findings are not surprising, as several researchers have reported increased rapid force and power production, driven heavily by neurological alterations (31, 161, 391). Additionally, there is evidence to suggest that the intent of movement may be of similar value to actual external contraction velocity when improving RFD characteristics (41).

Dynamic performance

The transferability of isometric resistance training to dynamic performance is questionable, despite specific isometric assessments closely relating to sports performance (388). Likewise, the degree of transference of isokinetic contraction to real-world movements has yet to be elucidated fully (168, 226, 243). Regardless, isokinetic testing provides a valuable means of assessing dynamic performance. Five studies utilized isokinetic assessments with three comparing various trained joint angles (9, 205, 216), and two studies comparing contraction intent (216) or length of contraction respectively (314). Maffiuletti and Martin (216) reported similar improvements in eccentric torque at $60°\cdot s^{-1}$ and concentric torque at slow ($60°\cdot s^{-1}$) and faster ($120°\cdot s^{-1}$) angular velocities regardless of contraction intent. When comparing isometric training at different muscle lengths, Alegre et al. (9) and Noorkoiv et al. (251) observed significant ($p < 0.05$) improvements after training at LML, but not SML in concentric torque at $60°\cdot s^{-1}$ and $30°\cdot s^{-1}$, and $60°\cdot s^{-1}$, $90°\cdot s^{-1}$ and $120°\cdot s^{-1}$ respectively, despite no significant differences in MVIC improvements between groups. Conversely, Lindh (205) reported that neither SML nor LML training groups improved isokinetic torque at $180°\cdot s^{-1}$ while both groups significantly ($p < 0.01$) improved peak torque at $30°\cdot s^{-1}$. Finally, Bogdanis et al. (49) observed similar improvements in one-repetition maximum squat (9.6%, ES = 0.61 vs 11.9%, ES = 0.64) and countermovement jump height (7.2%, ES = 0.66 vs 8.4%, ES = 0.51) following SML and LML leg press training, respectively. One possible explanation for these findings is that the LML training groups in Alegree et al. (9) and Noorkoiv et al.'s (251) experienced larger hypertrophic adaptations than the corresponding SML participants. Unfortunately, neither Lindh (205) or Bogdanis et al. (49) assessed morphological adaptations, making further analysis difficult.

Applications

While the direct transfer of isometric resistance training to dynamic movements is questionable, physiological adaptations such as increased muscle mass and improved tendon qualities are beneficial in a variety of contexts. There is a well-established relationship between muscle mass, strength, and functional performance in a variety of activities and populations (102, 183, 277). While it may require specific training in a movement to optimize neuromuscular performance (36, 160), it is clear that producing and maintaining muscle mass and strength should be a priority for athletes and special populations alike. For this reason, isometric contractions are regularly used in rehabilitation programs and during specific training phases where dynamic contractions may be contraindicated.

The long-held belief that isometric resistance training should occur at the most important angle present in a dynamic activity holds true (127, 255-257) as the largest improvements in neuromuscular function occur at the trained angle (35, 188, 205, 250, 353). However, large neurological discrepancies exist between isometric and dynamic movements (390) suggesting that static training may not be an effective strategy for directly improving sports performance and should be primarily employed to alter morphology. Therefore, isometric training should occur predominantly at relatively LMLs as there is a clear advantage for improving muscle volumes (Figure 3), and strength throughout a range of motion (9, 35, 188, 250, 251, 353). Additionally, large increases in tendon stiffness following LML have been reported, which would likely reduce electromechanical delay and therefore improve RFD (188, 218, 241). Furthermore, LML isometric training may have beneficial effects on the length-tension relationship (9), although greater evidence is needed to solidify optimal angle as a key variable in performance and injury prevention (355). Similarly, architectural qualities of muscle may underpin the length-tension relationships. However, Alegre et al. (9) observed no significant ($p > 0.05$) shift in fascicle length regardless of training angle, while Noorkoiv et al. (250) reported conflicting findings depending on which quadriceps head was evaluated. However, it must be noted that Alegre et al. (9) utilized a relatively small (5 cm) probe and reported highly variable changes (CV = 4.7-12.7%) in fascicle length. Therefore, a greater number of studies with robust methods are required before strong conclusions are made.

Training intensity is a key variable prescribed in intelligently designed resistance training programs. Evidence suggests that high-intensity resistance training is superior for improving force production (169, 312, 313). However, the studies cited in this review show a questionable relationship between intensity and force production adaptations (Figure 5) (9, 32, 164, 185, 188, 250, 314, 344, 396). Consistent with recent original research and meta-analyses, isometric training intensity does not appear to affect hypertrophic adaptations (196, 312). While the lack of relationship between contraction intensity and force production is somewhat surprising, previous literature has reported that submaximal intensities can produce similar strength improvements when taken to failure, or when the volume is equated between groups (196, 236). These findings suggest that isometric training intensity is not important when aiming to improve force production or alter muscle morphology. Therefore, increasing contraction durations (314), increasing total volume, or shifting to longer muscle lengths (9, 35, 188, 205, 250) are likely more efficient means of progressing isometric resistance training if strength and muscle size are a priority. Conversely, high-intensity (≥ 70% of MVIC) isometric contraction exclusively produced increased tendon thickness and stiffness (19, 21). As overly compliant tendons are often an issue in untrained and injured populations, progressively increasing intensity during isometric contractions may be a safe and efficient means of preparing tendinous tissue for future dynamic loading (219, 291). Additionally, sports requiring a high degree of reactive strength require relatively stiff tendinous structures to optimize performance (118, 186, 189).

Isometric training, like other modes of resistance exercise, should be executed in a way that most closely relates to the primary outcome goal. When muscular hypertrophy or maximal force production is the priority, the evidence demonstrates that there is little difference between contractions completed with a ballistic, or a gradual ramp to the prescribed intensity (32, 216, 354, 389). However, if rapid force production takes precedence, as it would in several sports, then isometric contractions should be performed as such (32, 354, 389). Conversely, ballistic contractions may be contra-indicated or cause excessive pain in rehabilitative or special populations (293), despite the potential to provide unique morphological tendon adaptations (225). Therefore, while ballistic contractions offer unique neuromuscular benefits, sustained contractions generally offer similar or greater morphological adaptations that are likely of interest to a wider variety of trainees (32, 216, 389).

Limitations and directions for future research

While trends, or lack thereof, are evident in many of the key independent variables discussed in the current review, several limitations exist. While the widely homogeneous populations inter, and intra-study allowed for simple analysis, none of the included studies utilized special populations such as patients with tendon disorders, high-performance athletes, or experienced resistance trainees. Likewise, while several studies have demonstrated positive effects of isometric training with neuromuscular electrical stimulation (42), the present review included only voluntary contractions. Researchers and practitioners alike need to be cognizant of these limitation if wishing to generalize findings. Similarly, very few of the included studies examined the effect of isometric training on dynamic performance, and only one utilized closed-chain or functional performance tasks in their testing batteries. Finally, while 26 studies were included, the large variety of independent and dependent variables made extensive inter-study analysis difficult and hence definitive conclusions problematic.

While the limitations present are broad, several directions for interesting future research exist. Isometric resistance training is often utilized by strength and conditioning coaches early in a training plan with the intent of preparing muscle and tendon morphologies for future dynamic loading. However, to the authors' knowledge, no published studies have examined the effect of a proceeding isometric training phase on dynamic or ballistic training periods despite a rise in popularity with this approach (86). On a related note, a limited number of studies have examined isometric training with free-weights. Isometric contraction intensity does not play a large role in driving morphological or neuromuscular adaptations, and total volume is likely a more important variable. However, resistance training modes have specific load cut-off points for altering tissue or neural properties (179, 180). As such, future studies should aim to establish approximate weekly loading guidelines for a variety of populations, muscle groups, and dependent variables. Another interesting direction is determining whether isometric training can improve dynamic muscular endurance. Unfortunately, only a single included study evaluated fatigue (396), and no studies examined fatigue during dynamic or stretch-shortening cycle activities such as cycling or running.

Another avenue for research geared towards rehabilitative populations is a multivariate examination of contraction intensity and joint angles. Physical therapists often prescribe isometric training to stimulate morphological adaptations and improve neuromuscular function while tightly maintaining a pain-free range of motion. Anecdotally, therapists often limit isometric contractions to moderate joint angles as the increased ligament strain and pressure synonymous with maximal contraction intensities at large degrees of joint flexion may cause unwanted pain and inhibition (140, 182). However, training at LML is superior to SML training for producing morphological and neuromuscular adaptations. Therefore, it would be fascinating to compare the effects of submaximal isometric training at LMLs with maximal isometric training at SMLs. As previously mentioned, the body of literature examining the characteristics of “pushing”, “holding” and “quasi” isometric actions is growing (122, 157, 299-301, 305, 320, 333). However, there is a paucity of long-term experimental studies examining these isometric contraction subsets.

Perspectives

Despite a relatively limited quantity of studies to base conclusions upon, the specificity of training applies to isometric resistance training as it does to traditional dynamic resistance training. Therefore, isometric training should be prescribed in line with the primary outcome goals. Training at LML and with sustained contractions have been found to beneficial for improving muscle morphology, while high-intensity contractions (> 70% MVC) are likely required to substantially improve tendon structure and function (e.g., tendon stiffness). Similarly, ballistic intent has been found to improve rapid force production even though movement velocity is zero. Finally, a greater number of studies, with a broader application of isometric training variations are needed to determine optimal applications for altering the morphology and improving dynamic performance in athletic, rehabilitative, and special populations alike.

Chapter 3 - Scientific basis for eccentric quasi-isometric resistance training: A narrative review

Reference

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Author contribution

Oranchuk DJ, 80%; Nelson AR, 10%; Storey AG, 5%; Cronin JB, 5%.

Prelude

The previous chapter gathered and synthesized research designs, methodologies, and characteristics and adaptations of isometric training while exposing gaps in the existing literature. As it was impossible to perform a systematic review on a topic as novel as eccentric quasi-isometric resistance-training, it was imperative to gather information and knowledge adjacent to the thesis topic. Unlike the previous chapter, the importance of understanding the acute, short-term, and long-term effects and adaptations of eccentric quasi-isometric adjacent exercise and training was a high priority. Therefore, the primary objective of chapter three was to synthesize and critically analyze relevant biological, physiological, and biomechanical research, and develop a rationale for the value of eccentric quasi-isometric training. Additionally, this review aimed to provide potential practical applications, highlight future areas of research, and determine appropriate research design.

Introduction

Apparently coined by Yuri Verkhoshansky (378), eccentric quasi-isometric (EQI) contractions, also known as yielding, holding, or eccentric isometrics (122, 157, 305), have many variations and proposed applications. However, for this review, EQIs will be defined as "holding a position until isometric failure and maximally resisting the subsequent eccentric phase". Theoretically, the prolonged quasi-isometric and eccentric components enable a large accumulation of mechanical tension and metabolic stress that would contribute to improvements in work capacity, muscle size, and connective tissue health. While traditional high-intensity isometric contractions and eccentric muscle actions are commonly used by practitioners, with well-established value in the modern scientific literature (89, 101, 103, 172, 193, 268), EQIs remain relatively unexplored. Therefore, this review aims to synthesize and critically analyze relevant research and subsequently develop a rationale for the value of EQI training, and highlight potential areas of future research.

Defining eccentric quasi-isometric training

Prior to the EQI contraction, a submaximal (being hereafter relative to one-repetition maximum (1-RM)) eccentric contraction is performed, where the muscle-tendon unit undergoes an active lengthening. Once the prescribed joint position is met, the trainee shifts to yielding isometric muscle action and attempts to hold the position for as long as possible. The final phase occurs as fatigue accumulates, and an eccentric contraction commences while the trainee attempts to resist muscle lengthening maximally. Some practitioners contend that this second lengthening phase places additional strain on the musculotendinous system similar to supramaximal eccentric training (238, 316). Practitioners have recommended a wide range of loads, with the goal of holding the quasi-isometric contraction for 5-90 seconds (238, 316). Consistent with traditional resistance training, greater intensities and shorter contraction durations are recommended for strength and power athletes while lower loads and longer contractions may be advantageous for oxidative or rehabilitative purposes (238, 316). Anecdotally, increased muscle thickness, improved range of motion (ROM), altered force-angle relationships, and improved tendon health, have been reported following EQI training (238, 316). Although quasi-isometric muscle actions have been used to describe sport-specific and stabilizing positions in sailing, speed-skating, cycling, and sprinting gait (51, 210, 333, 340, 369, 371, 372, 378), there is no published empirical data on EQIs, and much of the related literature utilizes animal models.

Methods

Literature search methodology

An electronic search for relevant literature was conducted utilizing MEDLINE, SPORTDiscus, PubMed, and CINAHL databases from inception to May 2019. Key terms were searched for within the article title, abstract, and keywords using conjunctions 'OR' and 'AND' with truncation '*.' Combinations of the following Boolean phrases comprised the search terms: isometric, static, eccentric, contraction, occlusion, blood flow restriction, hypertrophy, strength, power, endurance, muscle, fiber, cross-sectional area, tendon, fascicle, pennation and neuromuscular. Reference lists and books were also utilized.

Inclusion and exclusion criteria

Studies were included in the review based on the following criteria: 1) full text available in English; and, 2) peer-reviewed journal publications or doctoral dissertations. Studies were excluded if they; 1) were conference papers/posters/presentations.

Statistical analysis

Percent change and Cohen's *d* effect sizes (ES) were calculated wherever possible to indicate the magnitude of the practical effect. Effect sizes were interpreted using the following criteria: trivial < 0.2, small 0.2-0.49, moderate 0.5-0.79, large > 0.8 (115). All reported ES and percentage changes are pre-post within–group, unless otherwise stated.

Eccentric quasi-isometrics and morphological adaptations

Based on the relevant literature, EQI training could be a potentially valuable tool for targeting specific musculotendinous morphological adaptations such as increased muscle thickness and fascicle length, and tendon stiffness and elasticity. Functional morphology refers to the structure and function of organisms and their specific structural features. Although morphology affects function in all tissues, this review will focus on the musculoskeletal system, which is often broken down into the three-component model of force transmission (Figure 6) (147). The three-component model provides insight into the determinants of force production and transmission - the contractile element (CE), series elastic component (SEC), and parallel elastic component (PEC) (155, 156, 223, 286). Before continuing, readers should be aware that several of the structures mentioned in the following sentences are present in more than one 'element' or 'component'. As such, the following descriptions are utilized for simplicity. The

PEC, synonymous with the extracellular matrix, includes the elastic tissues surrounding the myofibrils (the endo, peri, and epimysium) as well as the sarcolemma and fascia. These tissues are thought to contribute to sensations of pressure, and although yet to be fully quantified, may play a meaningful role in force transmission between joints and body segments (155, 156, 223). The SEC encompasses the spring-like tissues in series with actin and myosin, the tendon and aponeurosis being most obvious. Controversy exists regarding the exact function of the titin myofilament, which appears to play a role in both active and passive force transmission (94, 144, 153). For example, titin was originally thought to be somewhat innate and only contributes to passive tension in a fully stretched sarcomere (153). However, contemporary research has demonstrated that titin is activated by calcium ions and adenosine triphosphate, contributing to not only active force transmission, but also production (94, 144, 202). Finally, the CE consists of the myofibril, and more specifically, the myofilaments of actin and myosin.

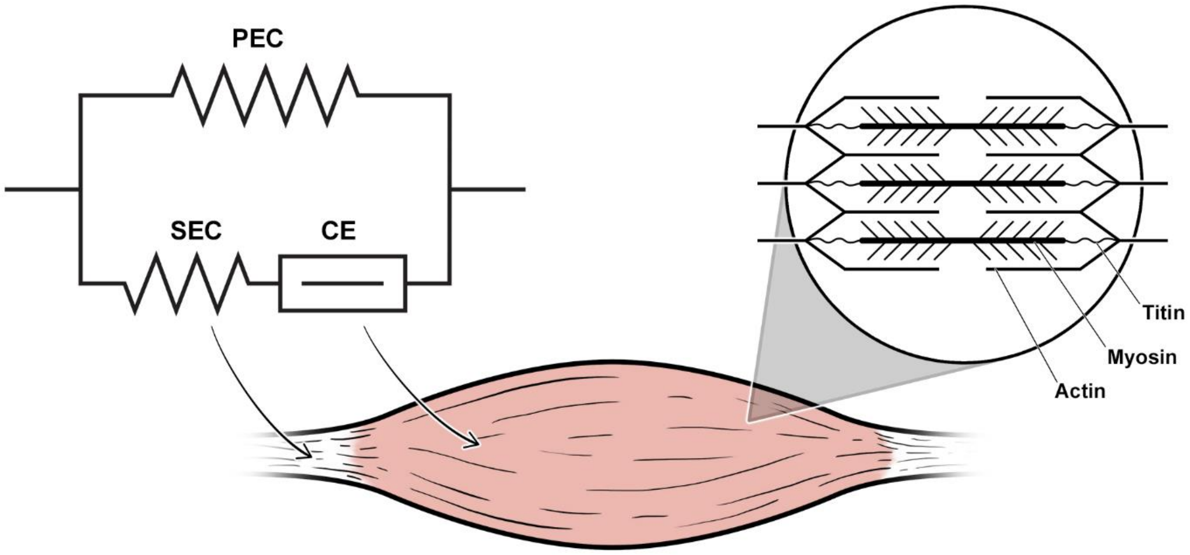

Figure 6. The three-component model of force transmission. CE = contractile element; SEC = series elastic element; PEC = parallel elastic element.

Contractile element

Muscle length and joint angle

Typically initiated at long muscle length (LML) or held through full ROM, EQIs fulfill the scientifically based criteria of mechanical stretch and tension for improving muscular hypertrophy and function. Produced by force generation and stretch, mechanical tension is effective in promoting muscular hypertrophy regardless of contraction type (26, 129, 308). In animal models, prolonged mechanical tension has been shown to produce dramatic increases in muscle size. For instance, extreme increases in muscle mass (318%), muscle length (51%), mean fiber thickness (39%), and fiber number (82%) were reported following loaded stretching of avian wings over 28 days (17). Similarly, Tabary et al. (345) reported that cat soleus muscles immobilized in a lengthened position had 20% more serial sarcomeres whereas a shortened soleus group had 40% fewer sarcomeres in series than normal muscle, respectively (345). An increase in muscle hypertrophy of up to 30%, with an increase of up to 250% RNA content in four days was observed following electrically induced overload in stretched rabbit tibialis anterior muscles (129). The effect of mechanical tension on skeletal hypertrophy was examined by Ashida et al. (26) utilizing electrically induced contractions in mice. Peak torque and torque-time integrals were highly correlated with increased muscle mass and mTOR regulating p7S6k phosphorylation in isometric contractions and eccentric muscle actions (26). Thus, animal models suggest that loaded stretching may provide a unique stimulus for inducing gene transcription and muscular hypertrophy (129).

Recently, loaded stretch training with human subjects has grown in popularity (18, 143, 326). For example, following six weeks of loaded (20-45% of maximal voluntary contraction (MVC)) stretching for five, 3-minute sessions per week, fascicle length (25%), ROM (14.9%), and muscle thickness (5.6%) significantly increased, while the pennation angle of the lateral gastrocnemius significantly decreased (7.1%) (326). However, no change ($p = 0.94$, ES = 0.08) in MVIC or voluntary activation ($p > 0.05$, ES = 0.13) was present (326), despite several cross-sectional investigations supporting the relationship between muscle architecture and performance (6, 13, 48, 190, 263, 360). Yet, the causal relationship between alterations in muscle architecture and muscular strength has become a hot topic in contemporary literature (81, 254). Additionally, the concept of constant-torque versus constant angle-stretching has been recently examined (18, 143). For example, Herda et al. (143) examined the short-term effects of acute knee flexor stretching at a constant-angle, or under constant-torque where the muscle was initially held at a point of mild discomfort followed by additional muscle-tendon unit lengthening via “muscle creep,” and stretch-induced analgesia occurred. While both groups experienced similar improvements in passive ROM and passive torque, only the constant-torque treatment resulted in decreased muscle-tendon-unit stiffness ($p < 0.001$) (143). Unfortunately, Herda et al. (143) did not report any performance measures, a trend that is common in stretching research (18). From these results, it appears that, in young males, loaded stretching can provide sufficient stimulus to affect musculotendonous architecture, viscoelastic properties and likely, acute pain thresholds (18, 143, 326). As variants of loaded stretching utilize extended periods at or near end ROM, the results of the aforementioned research lend credence to the hypothesis that EQI training may be a valuable training methodology for improving acute and chronic flexibility and musculotendonous function. However, there is a dearth of stretch research elucidating the ideal stretching intensity and the efficacy of loaded stretching to improve muscular or athletic performance (18).

Although eccentric muscle actions have the highest potential for muscular force production, isometric muscle actions are the only contraction type that has no ROM dependent endpoint. Isometric training is also easily implemented as simply flexing (co-contracting the agonists and antagonists of a limb) can increase muscle size and strength in active men (214, 398); though the value of co-contraction training in a well-trained population has yet to be elucidated. Additionally, isometric contractions enable training at specific joint angles and, therefore, muscle-tendon lengths. While strength improvements are joint-angle specific (205), increases in muscular hypertrophy, which is larger following full ROM and LML training, (228), transfer to all joint angles (9, 188, 250, 251). McMahon et al. (228) compared the effects of dynamic resistance training executed with full or partial ROM. The full ROM group experienced significantly greater improvements in the distal anatomical cross-sectional area (59% vs 16%), fascicle length (23% vs 10%), and isometric force at all seven (30-90° of flexion) measured knee joint angles (11-30% vs -1-6%) (228) when compared to the partial ROM group. Although isometric contractions resulted in less muscle damage and less dramatic muscular-tendinous adaptations compared to maximal eccentrics, maximal voluntary isometric contractions (MVICs) at LML increased markers of acute muscle damage and soreness relative to MVICs at short muscle length (SML) despite lower torque outputs (11). Isometric training at LML produces greater hypertrophy, force production at different joint angles, and dynamic performance benefits compared to training at SML following long-term trials (9, 35, 188, 250, 251, 353). The systematic review in Chapter 2 delved into effects of isometric training variations (268), and determined that isometric training at LML produced greater increases in muscular hypertrophy than volume-equated SML training, (0.86-1.69%$\cdot$week^{-1}, ES$\cdot$week^{-1} = 0.03-0.09; and 0.08-0.83%$\cdot$week^{-1}, ES$\cdot$week^{-1} = -0.003-0.07, respectively) (268) likely due to increased mechanical tension throughout all tissues involved in force transmission (Figure 7).

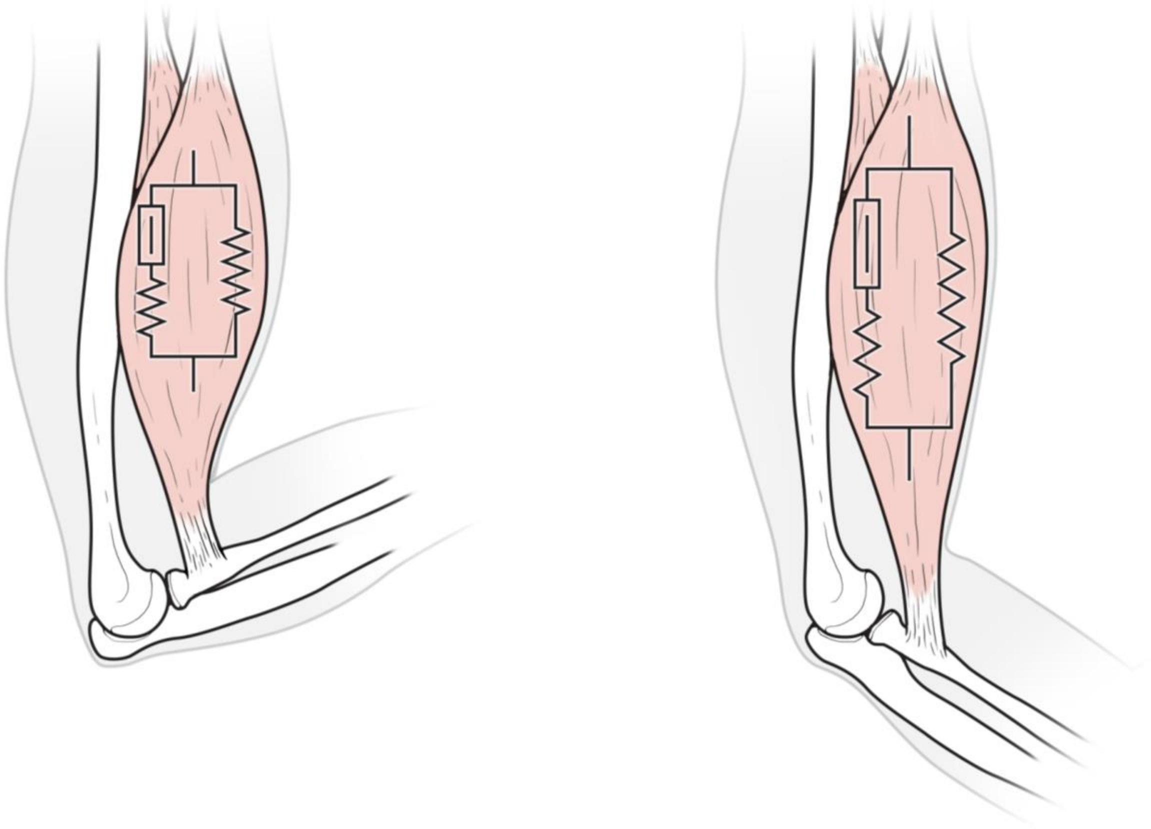

Figure 7. The three-component model of force transmission in a muscle contracting at short and long muscle lengths.

The larger architectural and functional adaptations following LML training might be due, at least in part, to the greater initial fascicle length, which results in increased muscle damage, and sarcomere compliance, demonstrated by acute optimal angle shifts towards longer muscle lengths (11, 59). Although more dramatic following eccentric muscle actions, these angle shifts have also been observed following concentric contractions at long fascicle lengths (135). For example, Guex et al. (136) examined the effect of three weeks of maximal eccentric knee flexions at either LML or SML on fascicle length and optimal angle. While fascicle length increased in both groups (SML, 4.9%, ES = 0.57: and LML; 9.3%, ES = 0.89), the SML group only experienced a shift in the optimal concentric angle (8.8°), whereas the LML group experienced optimal angle shifts in both concentric contractions and eccentric muscle actions (17.3° and 10.7°, respectively) (136). There is evidence to support the principle that mechanical tension can increase muscle volume, and that isometric training at LML leads to greater hypertrophy and a shift in the optimal angle.

Contraction intensity and duration

Cumulative tension and total workload are key determinants of hypertrophic adaptation, regardless of contraction type (236). Moore et al. (236) found that changes in torque and muscle thickness were not significantly different between load-matched concentric and eccentric resistance training groups, despite the eccentric group requiring 40% fewer contractions to match training load. Morphological adaptations to isometric resistance training are similar between work matched high and low-intensity training (268). While much of the literature recommends high-load over low-load resistance training for strength development (220), many periodization models emphasize muscular hypertrophy and general muscular endurance early in macro and mesocycles (75, 378). Accordingly, EQI training emphasizing time under tension with the application of practitioner-recommended intensities of 30-80% of 1-RM may be a useful training method to alter muscle size.

Metabolic factors

Total time under tension, acute hypoxia, and metabolic stress are mechanisms that contribute to morphological adaptations (57, 117, 123, 268, 281, 314, 348, 349). Several studies have reported significant reductions in oxygen availability from submaximal isometric contractions at 30-50% of MVC (7, 333). Additionally, blood flow does not appear to decrease linearly with intensity (229). Isometric contractions at 60% of MVIC result in greater short-term blood flow restriction relative to 30% and 100% MVICs, as the moderate-intensity contraction could be sustained for a significantly greater duration than 100% while the tension created by the 30% contraction was insufficient to reduce blood flow and metabolite clearance (229). This occlusion has several potential effects, including increased metabolite build-up and post-contraction blood flow, both of which stimulate muscular hypertrophy (208). Several studies have examined the impact of blood flow restriction on hormones and hypertrophic markers in humans (117, 281, 348, 349). Fujita et al. (117) examined the metabolic and hormonal effects of blood flow restriction during low-intensity resistance training and found 46% greater mTOR regulated muscle protein synthesis, via significantly greater S6K1 phosphorylation markers compared to the exercise-only group. Gentil et al. (123) also found that both isometric contractions and vascular occlusion resulted in greater blood lactate responses which can increase muscle cell myogenesis, satellite cell activation, and phosphorylation of mTOR and P70SK (244). Additionally, acute ischemia combined with low-intensity muscular contraction can significantly increase growth hormone, insulin-like growth factors, and mechano-growth factor production (95), which are physiological responses to decreased muscle and blood pH (281, 348, 349). Occlusion may also reduce the amount of oxygen available for the oxidative type-1 motor units, potentially resulting in earlier recruitment of fast-twitch fibers at relatively low intensities (237). Long-term morphological adaptations to blood flow restriction training include increased muscle thickness and function in a variety of training circumstances (208, 351, 383).

Though sparse, a few studies have examined the effect of blood flow and metabolites during isometric training (83, 314). de Ruiter et al. (83) examined the oxygen consumption characteristics of isometric contractions at several knee angles. Isometric contractions at LML (60° and 90°) consumed more oxygen than SML contractions (30°) at 10%, 30%, and 50% of MVC (83). These findings may, in part, explain why long-term isometric training at LML has a greater effect on muscle thickness and strength, compared to SML training at least in "healthy", or "recreationally active" subjects (9, 35, 188, 205, 250, 251, 268). Schott, McCully, and Rutherford (314) compared the metabolic response and adaptations to short (four sets of 10 x three-second contractions) or long (four contractions of 30 seconds) duration isometric contractions at 70% MVC. Although blood flow was not measured, the long-contraction limbs experienced greater changes in metabolites and larger decreases in pH (314). Muscle thickness also significantly increased in the upper (10.1%) and lower (11.1%) portions of the quadriceps in the long-contraction, but not short-contraction limb (314). Although blood flow restriction has many benefits in older and injured populations, it does not appear to offer any additional adaptations in healthy well-trained athletes (315). Furthermore, while low intensity single-joint isometric contractions have been found to result in blood flow restriction, the effects of multi-joint isometric and quasi-isometric contractions have yet to be examined.

Exercise-induced muscle damage

Although exercise-induced muscle damage is not needed to promote muscular hypertrophy (308), emerging research suggests that exercise-induced muscle damage may play some role in morphological adaptations (309). When exposed to a novel stimulus, acute myofibril micro-trauma occurs as an abundance of Ca^{2+} enters and remains in the myofibril (78). Eccentric muscle actions typically result in a greater degree of acute trauma as evidenced by elevated serum creatine kinase, myoglobin, and skeletal troponin-1 levels, and delayed onset muscle soreness (72). These markers typically coincide with a temporary reduction in muscle force and power (72). While detrimental to short-term performance, exercise-induced muscle damage is associated with changes in a variety of chemokines that attract inflammatory cells, which influence muscle hypertrophy remodeling associated with phagocytosis, free radical production, and circulating cytokines and growth factors (173). Additionally, a novel delayed onset muscle soreness inducing stimulus may lead to increased sarcoplasmic reticulum re-uptake of Ca^{2+} by altering t-tubule structure (78) and increasing the concentrations of proteins such as calsequestrin (40) and dysferlin (167). These proteins function to promote debris clearance and increased concentrations of IGF-1, fibroblast growth factor, nerve growth factor, and interleukin-6, which increase satellite cell proliferation (34, 37) and rates of protein and collagen synthesis (166). Although acute increases in myofibril protein synthesis do not necessarily correlate with long-term hypertrophy (233), these increased synthesis rates, theoretically result in thicker, stronger tissues that are less susceptible to future damage (103).

The repeated bout effect refers to the substantial reduction in muscle damage from subsequent training (227). While most commonly observed following eccentric exercise (103, 227), the protective effects have also been found to occur following isometric exercise (5), especially at LML (11, 69). Isometric training at LML results in greater delayed onset muscle soreness and acute performance decrements (11) as well as chronic adaptations, compared to isometrics at SML (9, 188, 250, 251, 268, 353). Likewise, greater exercise-induced muscle damage and delayed onset muscle soreness are reported following maximal effort high-velocity (210°·s^{-1}) isokinetic eccentric muscle actions when compared to an equal volume bout at low-velocity (30°·s^{-1}) (65). As a greater number of high vs low-velocity eccentric muscle actions are needed to equalize volume, the difference in muscle damage and soreness is likely due to increasing the total number of sarcomere bonds and therefore calcium ion influx and subsequent activation of calpain (399). Additionally, higher velocity eccentrics may preferentially recruit high-threshold, type-II motor-unitis, which are more suseptable to muscle damage in comparison to the type-I fibers (245). Similarly, eight weeks of maximal high-velocity (180°·s^{-1}) eccentric training resulted in greater hypertrophic adaptations when compared to maximal low-velocity (30°·s^{-1}) training (101). Conversely, submaximal (70% 1-RM) slow velocity (~3 s) eccentric muscle actions during the barbell bench press have been found to stimulate higher blood lactate and endogenous human growth hormone, by promoting a hypoxic environment (61). While EQIs may lead to substantial levels of local fatigue due to a potential lack of blood flow and high metabolite levels, it is unlikely that the low-velocity eccentric component would produce exercise-induced muscle damage (65).

Series elastic component

Tendon, the primary tissue of the SEC, can undergo morphological and functional adaptations through inactivity, injury, sporting activities, and resistance training (24, 187, 218, 291). Tendon and other connective tissues comprised of specifically aligned collagen fibers have significant resistance to mechanical strain (218). Optimal performance requires the efficient transfer of force from muscle to bone (218, 249) necessitating transmission via a tendon that is sufficiently stiff to minimize electromechanical delay while avoiding rupture (218). Properly executed dynamic, eccentric and isometric training can improve tendon structure and function (19, 21, 174, 175, 185, 187, 193, 218, 291).

Joint angle

A single study has directly investigated the effect of joint angle on tendon morphology by comparing volume-equated isometric knee flexion training at LML (100°) or SML (50°) (188). While both SML (10%, ES = 0.82) and LML (11%, ES = 1.06) groups improved quadriceps volume, only LML training resulted in significant tendon stiffness improvements (50.9%, ES = 1.22) (188). While the sparse results of the preceding studies expose a gap in existing literature, they tend to support holding prolonged isometric contractions at LML with near maximal loads if tendon structural adaptations are paramount.

The titin myofilament, although thought to be a secondary structure to a tendon in the SEC has several important functions and is likely partly responsible for the residual force enhancement following an active stretch (107, 145, 283, 318, 319, 321, 323). Titin adds stability, stiffness, and passive and active force transmission at LMLs (144, 284) and is a likely factor in injury prevention. Several studies have found titin to regulate muscle force and length in mechanically lengthened fibers (202, 284). Baumert et al. (39) examined the relationship between force production, delayed onset muscle soreness, and genotyping related to titin stiffness (39). Subjects with the allele linked to greater titin stiffness (TRIM63 A-allele) had greater MVICs (35%, ES = 1.42, $p = 0.006$) and recovered more quickly (ES = 1.14 , $p = 0.022$) compared to the other subjects (TRIM63 G-allele) (39). Titin protein fragments have been found in the urine of healthy young males following bouts of a dynamic calf-raise exercise and were strongly correlated with traditional markers of exercise-induced muscle damage (163). While the eccentric muscle action following a fatiguing isometric contraction with EQIs is unlikely to produce significant muscle damage due to low velocities (65), it is plausible that titin may be activated. Although occurring at a range of joint angles (318), residual force enhancement magnitude is greater at LMLs (323), suggesting that LML training may preferentially utilize titin (145). Thus, it may be prudent to examine the effects of quasi-isometric holds in the lengthened position on markers of breakdown and expression of titin.

Movement velocity and muscle action

The SEC appears to be affected differently by movement velocity. The impact of movement velocity on titin is difficult to determine as many questions remain regarding the myofilaments' contributions to phenomena such as residual force enhancement (162, 321). While studies have observed the breakdown of titin following resistance training movements, which tend to be relatively slow when compared to activities such as sprinting or jumping (163), there are conflicting data regarding the velocity of stretch and residual force enhancement. Although the majority of residual force enhancement examinations utilize eccentric angular velocities between $30°\cdot s^{-1}$ and $60°\cdot s^{-1}$ (107, 283, 319, 323), Lee and Herzog (200) compared stretch angular velocities of $10°\cdot s^{-1}$, $20°\cdot s^{-1}$, and $60°\cdot s^{-1}$. While eccentric force during the stretch increased with velocity, there was no significant difference in proceeding isometric force between the three protocols (200). Though the above research is intriguing as the effect of velocity on titin is unknown due to several confounding variables, including different neuromuscular strategies and contributions from the CE and PEC (98, 273).

The relationship between velocity, residual force enhancement, and titin is not yet determined; however, the effect of movement velocity on the tendon holds greater clarity. Acutely, it appears that isometric contractions provide superior analgesic effects compared to dynamic resistance exercise (293, 295, 357). Rio et al. (293), examined patellar tendon pain during a decline squat exercise in six male volleyball players with tendonitis. The pain was evaluated before and after performing either slow isotonic leg extensions for four sets at an 8RM load or five sets of 45s isometric knee extensions at 70% of MVIC (293). While both the isometric (-97%, ES = 3.6) and dynamic (-40%, ES = 0.67) groups significantly reduced pain acutely, pain reduction only remained significant at the 45 minutes mark following isometric exercise (293). Loaded between 30% and 80% of 1-RM (305, 378), and maintained for similar periods as Rio et al.'s (293-295), the zero to low-velocity EQI contractions may have the potential to reduce tendon pain, despite recent controversy (132).

Long-term changes in tendon morphology seem minimal in healthy, mature human tissue (172, 218). However, injured tendinous tissue can undergo dramatic adaptations (172, 305). Tendon adaptation is independent of contraction type, so long as a minimum mechanical load threshold is reached (141, 142, 156), which likely explains why traditional exercises with an eccentric emphasis have been found to be superior to dynamic contractions in tendon rehabilitation (174, 193, 218). However, movement velocity is critical as healthy tendon fibers will "spare" the damaged tissue by transmitting a greater portion of the load when high velocities are utilized (22, 218). Conversely, damaged tendon tissue can undergo sufficient loading during slow contractions (22, 218). For example, Kongsgaard et al. (174) compared 12 weeks of single-leg decline squats with an eccentric emphasis, bilateral heavy and slow (three-second eccentric and concentric phases) resistance training, and corticosteroid injections. While both resistance training groups experienced significant improvements in several measures of performance and architectural and physiological markers, the heavy and slow resistance training group reported greater satisfaction of clinical outcomes (70%) compared to the eccentric (42%) group (174). The researchers theorized that the decreased tendon pain, tendon collagen content, and voluntary force production were due to the greater intensity-induced mechanical overload throughout the training period (174). These data demonstrate that tendon adaptation can be achieved via relatively slow movement velocities and that maximal or supramaximal eccentric exercise is not necessarily required. As EQI contractions are slow and submaximal, they may be a viable tool for treating diseased tendonous tissues.

Contraction intensity and duration

Contraction intensity, duration, and type have different effects on tendon properties. Kubo et al. (184) compared the effects of 12 weeks of isometric and plyometric training on muscle and tendon stiffness. Active muscle stiffness at 30%, 50% and 70% of MVIC only increased significantly following plyometric training (38.1-69.6%, ES = 1.35-2.57 vs 12.4-23.6%, ES = 0.46-0.75) whereas ballistic and ramp tendon stiffness increased exclusively following isometric training (23.7-42.1%, ES = 0.92-1.21) (184). Likewise, Burgess and colleagues (58) compared the effects of isometric and plyometric training on the plantar flexors. While no statistically significant difference between groups were present ($p < 0.05$), the isometric group experienced very large increases (61.6%, ES = 4.91) in tendon stiffness when compared to the plyometric group (29.4%, ES = 1.44) (58). Interestingly, no significant differences between the isometric and plyometric groups were apparent for concentric-only jump height (64.3%, ES = 2.87 vs 58.6%, ES = 2.85), or rate of force development (28.1%, ES = 1.89 vs 14.6%, ES = 1.38); however, no measures of stretch-shortening cycle function were included (58). These findings demonstrate that while isometric contractions are effective in improving tendon stiffness (thereby reducing electromechanical delay) and improving tendon health (24, 293), improvements in stretch-shortening cycle performance likely require specific training to increase ultrasonically assessed elasticity (187-189), suggesting that isometric contractions are an effective addition to traditional resistance training.

In regards to contraction intensity, Kongsgaard et al. (175) examined the effect of a 12-week, work-equated dynamic isotonic leg extension training program using either "heavy" (70% 1-RM) or light loads. The "heavy" group experienced thickening of the distal (4%, $p < 0.05$) and proximal (6%, $p < 0.05$) patella tendon, whereas the light group only saw significant proximal hypertrophy (7%, $p < 0.05$) (175). Additionally, tendon stiffness significantly improved following "heavy" resistance training (14.6%, ES = 1.37), whereas the light load group experienced a non-significant decrease (-9.18%, ES = 0.83) (175). Similarly, Arampatizis et al. (19, 21) compared 14 week training programs consisting of volume equated isometric plantar flexion at low (~55% MVIC) or high (~90% MVIC) intensities. Only the high intensity training groups improved Achilles tendon cross-sectional area and stiffness (17.1-36%, ES = 0.82-1.57, $p < 0.05$. vs -5.2-7.9%, ES = 0.26-0.37, $p > 0.05$) (19, 21). Furthermore, tendon elasticity only increased following low intensity training (14-16.1%, ES = 0.56-0.84, $p > 0.05$. vs -1.4-3.9%, ES = 0.06-0.20, $p > 0.05$) intensity training (19, 21). Though the aforementioned studies investigated different tendons and utilized different training intensities, both point to the superiority of high over low-intensity contractions when an improvement in tendon stiffness is desired. While unlikely to directly improve plyometric performance, high-intensity isometric training may be a valuable tool in improving tendon thickness and stiffness which may decrease injury rates, and improve performance when included as a supplement to traditional resistance training (58, 184, 187, 189).

Parallel elastic component

The effect of resistance training on the PEC and extracellular matrix is lacking, due to the methodological challenge of separating connective tissue from intrafibrillar elements to evaluate their relative contributions to force transmission (296). Subjective measures such as pain and ROM are limited in utility, as they contain confounding variables and often manifest gradually (296). However, we do know that the PEC is comprised primarily of collagen fibers (286) and that adding collagen around the myofibrils leads to an increase in stiffness and transmission of force to the passive structures of the extracellular matrix (125). Thus, it is postulated that the increase in extracellular matrix stiffness is a contributing factor to more energy-efficient eccentric muscle actions (331).

Several studies have examined resistance training and collagen formation in healthy humans (159, 172, 174, 175, 193, 218). In-situ investigations by Mass et al. (222) and Gomez et al. (130) have reported that damaged tendons and ligaments healing under tension had higher collagen contents compared to passively healing controls. It is understood that damaged tendons experience more efficient healing when factors including transforming growth-factor ß1, platelet-derived growth factor, and IGF-1 are elevated (204). Therefore, resistance training, which places a tissue under tension, increases hormonal and molecular signaling factors, providing optimal extracellular matrix maintenance in the elderly (331). Additionally, resistance training can cause exercise-induced muscle damage and increase local inflammation (72, 331). Muscle damage following unaccustomed loading has been observed to acutely increase collagen synthesis and extracellular matrix remodeling (158, 347), while chronic resistance training has resulted in increased intramuscular collagen (159). Interestingly, eccentric and concentric contractions appear equally proficient for increasing collagen synthesis when total work is equated (235). However, eccentric muscle actions enable greater force production or greater work performed at the same load (90) and therefore lead to greater adaptation when total sets and repetitions are equal (148).

In summary, EQI training theoretically offers a time and energy-efficient means of triggering morphological adaptations in all primary components of force transmission. Therefore, implementation of EQI training could likely be beneficial for increasing muscle size and improving tendon, and other connective tissue health. However, these hypotheses must be empirically tested.

Eccentric quasi-isometric contractions and neurological qualities

Eccentric quasi-isometric training could be expected to improve muscle function at low, but not high velocities. Although a few acute studies are examining and describing EQI exercise on musculotendinous (51, 210, 333, 340) and neuromuscular adaptations (7, 369), the lack of any long-term investigations makes any definitive conclusions problematic. However, there is a significant amount of research examining fatiguing contractions (229, 303), yielding isometrics (7, 122, 157, 299-301, 305), slow tempo resistance training (351, 381-383, 394), and joint angle (83, 250, 251, 303, 343) that allow conjecture and identify areas for future research.

Contraction intent

Contraction intent is an important factor to consider when evaluating the effect of resistance training (74). Although the intent of the trainee during EQIs is to maintain a movement velocity of zero, once isometric failure occurs at low velocity, lengthening follows despite maximal effort due to accumulated fatigue (238, 316). Though a variety of isometric training and exercise methods have been described (122, 157, 305), the vast majority of experiments have utilized maximal contractions against an immovable object. While maximal isometrics serves as a valuable and highly reliable means of evaluating neuromuscular function (91, 266), results from these studies are difficult to apply to EQI exercise. Recently, researchers have demonstrated that "yielding" (resisting an external force) isometrics, with the intent of preventing eccentric muscle action, create different fatigue and neuromuscular characteristics compared to "pushing" (exerting force against an immovable object) isometrics (122, 157, 299-301, 305). Hunter et al. (157) compared time to task failure and neuromuscular function when maintaining a constant force (pushing) of 15% of MVIC, or by supporting an equivalent inertial load while maintaining a constant joint angle (holding). Pushing resulted in significantly greater time to failure (1402 ± 728 s) than holding (702 ± 582 s) (157). Similarly, Schaefer et al. (305) examined pushing and holding isometric actions at 80% of MVIC and found that subjects could maintain the target force for twice as long when pushing (41 ± 24 s vs 19 ± 8 s). Hunter et al. (157), Schaefer et al. (305), and other investigators (122, 299-301) have also demonstrated that agonist activation at failure is greater when pushing, while co-activation of antagonist and synergist muscles are greater when holding (122, 299-301, 305). While the increased co-activation during position tasks are a likely cause of the decreased endurance time (122, 157, 300, 305), it is plausible that position task training may lead to superior joint stabilization and thus carry value in rehabilitative settings (299). Additionally, several activities and sporting actions involve bracing to avoid dynamic muscle action (199, 371). Therefore, while pushing isometrics likely allow for greater morphological adaptations, due to larger forces and time under tension, training with the intent to maintain specific positions instead of exerting force against an immovable object may provide improved carry over to specific tasks that involve maintaining specific joint angles or postures due to the similarity of neural characteristics (199, 372).

Ballistic and ramp contractions are additional means of distinguishing movement intent (268). When comparing the result of several isometric training studies directly comparing contraction intents, Oranchuk et al. (268) determined that training with ballistic intent resulted in constantly greater improvements in muscular activation (3/4 studies) (1.04-10.5%$\cdot$week^{-1}, ES = 0.02-0.31 vs 1.64-5.53%$\cdot$week^{-1}, ES$\cdot$week^{-1} = 0.03-0.20) and rapid (0-150 ms) force production (3/3 studies) (1.2-13.4%$\cdot$week^{-1}, ES$\cdot$week^{-1} = 0.05-0.61 vs 1.01-8.13%$\cdot$week^{-1}, ES$\cdot$week^{-1} = 0.06-0.22). Furthermore, Behm and Sale (41) compared the effects of isometric contractions performed with ballistic intent, and high angular velocity (240°$\cdot$s^{-1}) concentric contractions. Both concentric and isometric training lead to similar (all $p < 0.01$) improvements in peak isometric force, rate of force development and relaxation and peak torque at 14.9°$\cdot$s^{-1}, 29.8°$\cdot$s^{-1}, 59.6°$\cdot$s^{-1}, 88.8°$\cdot$s^{-1}, 173°$\cdot$s^{-1} and 240°$\cdot$s^{-1} (41). These results highlight the importance of contraction intent, and not necessarily movement velocity, on neurological qualities and performance alterations. Although comparing the above results with EQI training is difficult, given that EQIs are non-ballistic, it is reasonable to suggest that they would be unlikely to improve explosive neuromuscular performance. Thus, a progressive resistance training program to improve explosive performance would avoid incorporating EQIs in late training cycles; they may be best positioned early in a periodized plan, likely as an adjunct to traditional resistance training.

Contraction intensity

While research on isometric contraction intensity is emerging, the only long-term training investigations examining neurological adaptations utilize traditional, pushing isometrics. Investigations directly comparing isometric training intensity have determined that little difference in morphological or performance adaptations exists if the total volume is equated (268). While little evidence exists regarding different isometric contraction intensities on neurological adaptations, the wealth of data on dynamic contractions may provide insight. High load dynamic training has been found to increase coordination (358) and reduce neuromuscular inhibition (2), which is valuable when optimal performance is desired (74). Additionally, a significant portion of the existing literature has determined that high-intensity dynamic resistance training is superior for improving neuromuscular function and sports performance when compared to lower intensity methods (74).

Joint angle

Motor-unit activation and muscle inhibition are strongly affected by the joint angle (249, 303, 343). The strain sensing organelles of the Golgi tendon organ and muscle spindles undergo different levels of stimulation at varying muscle-tendon lengths (249, 303). For example, Suter and Herzog (343) examined muscle inhibition and joint angle by comparing voluntary force and force produced by superimposed femoral nerve stimulation at 15°, 30°, 45°, 60°, and 90° of knee flexion. While muscle inhibition was present at all assessed joint angles, the largest superimposed twitches were present at LMLs (343). Greater muscular stretch, patellofemoral pressure, and ligament strain at knee angles between 45° and 60° of flexion are theorized to underpin the greater degree of muscle inhibition (343); however, these observations are not necessarily applicable for all joints or movements to differing tendon structural properties, fascicle lengths and co-contraction dynamics (15, 46, 139, 170, 197, 392). Although muscle inhibition is necessary for extreme situations, improving muscular activity is important when returning to activity or when optimizing performance (74, 249).

Advantages of LML isometric training for improving muscle size and force production throughout a full ROM exist (9, 35, 188, 250, 251, 268, 353). Interestingly, studies investigating the effect of restricted ROM resistance training have determined that limiting dynamic contractions to LML does not result in meaningful changes in the length-tension relationship (363, 364). While EQI contractions utilize a full ROM, they are inherently low velocity. Therefore, EQI training should be implemented early in a yearly training plan to improve morphology and improve position-specific functions.

Applications to performance and rehabilitation

Performance

Performance in sport is dependent on a variety of physical qualities. As such, training methodologies have differing utility and value depending on the type of sport, proximity to competition, individual training age, and a multitude of additional factors. With few exceptions (199, 372, 378), quasi-isometric and EQI contractions have not been widely utilized in training plans. However, although no direct investigations on EQI contraction or training exist, relevant research, (e.g., isometric, eccentric, time under tension, blood flow restriction) suggest that EQIs may have a place in intelligently designed programs. The theoretical potential of EQIs concerning dynamic (eccentric and concentric), eccentric only, and isometric resistance training are summarized in Table 5 (based on (342)).

Table 5. Theoretical potential of dynamic, eccentric, isometric, and eccentric quasi-isometric resistance training to benefit musculotendinous morphology and performance

Training outcome	Training method	Contractile element	Series elastic component	Parallel elastic component
Morphology	Dynamic	++++	+	+
	Eccentric	+++++	++	++
	Isometric	++	++	+
	EQI	++++	++	++
Endurance	Dynamic	++++	+	+
	Eccentric	++	+++	++
	Isometric	+++	++	+
	EQI	+++++	++	++
Strength	Dynamic	+++	+	+
	Eccentric	+++++	+++	++
	Isometric	++++	++	+
	EQI	+++	++	++
Power	Dynamic	+++++	+	+
	Eccentric	++++	++	++
	Isometric	++	++	+
	EQI	+	+	++

Ranked on a scale from + (low potential) to +++++ (high potential). Adapted from Suchomel et al., (342) . EQI = eccentric quasi-isometric.

Muscular endurance

A systematic increase in the exposure to the total volume that a muscle or muscle-group undergoes is a common means of improving muscular endurance (178, 378). Training with EQIs may have the potential to provide a unique stimulus for promoting muscular endurance, as a primary aim is to increase the amount of time that the prescribed position is maintained. Additionally, while a high volume of submaximal dynamic contractions is commonly employed to improve muscular endurance, the constant muscular tension present in isometric and quasi-isometric contractions can alter blood flow and muscle oxygenation (7, 333). Although far from conclusive, this mild, and temporary alteration in oxygenation may lead to alterations in aerobic and anaerobic enzymes and significant, yet temporary increases in several anabolic signaling factors (237, 349). Furthermore, muscular endurance training may lead to adaptations to the t-tubule structure and increase Ca^{2+} re-uptake (78), therefore offering a protective effect from delayed onset muscle soreness and short-term performance decrements that may occur from future high-load training (67, 69).

Eccentric quasi-isometric training may also offer a novel sport-specific training stimulus to athletes that undergo regular, sustained quasi-isometric contractions. While actual sports participation offers the greatest level of sport-specific adaptation, utilizing quasi-isometric or EQI contractions in a controlled environment such, as a weight-room, offers the ability to apply focused overload. For example, a speed skater wishing to increase lower-body muscular endurance in a skating specific ROM, via morphological adaptations, may wish to experiment with quasi-isometric or EQI training by utilizing a leg-press (Figure 8).

Figure 8. The initial quasi-isometric hold and final position after a maximal eccentric contraction in the single-leg leg press.

Hypertrophy

Muscle mass is highly related to strength (126) and is, therefore, an important factor in sports performance. While heavy loading, including supra-maximal eccentric training, offers a strong stimulus, total work and training volume are the most important determinants of hypertrophic adaptation (196, 236, 308, 312). While moderate resistance training allows for a time-efficient means of accumulating volume, EQIs may be superior in specific circumstances. Depending on the intensity, initial joint angle, and other factors, EQI contractions can expose a muscle group to a substantial total load in a relatively short period. Eccentric quasi-isometric contractions also offer a likely advantage over dynamic training when it comes to accumulating volume as shortening contractions are less energetically and mechanically efficient (236). While a non-linear, inverse relationship exists between intensity and time under tension (178, 378), exclusion of the less efficient concentric phase allows for higher intensities throughout a set duration, or more work at the same intensities (89, 236). Therefore, a single EQI contraction would likely impart greater time under tension than a similarly loaded set of dynamic contractions when both are taken to failure. Likewise, similar set durations could be met with a greater external load applied to an EQI contraction compared to a dynamic alternative. Additionally, EQIs are likely to reduce muscle oxygenation and metabolite clearance (7, 333) which may lead to preferential recruitment of type-II muscle fibers with increased capacity to increase cross-sectional area and force production, and signal anabolic hormones known to contribute to the hypertrophic response (208, 314, 349).

Strength and power

A variety of morphological and neurological factors including muscle size, muscle fiber type, and motor-unit recruitment characteristics determine strength and power (13, 74, 75, 89, 98, 116, 199, 249, 342, 360, 383, 398). While EQI contractions may be a viable tool for improving total hypertrophy, an abundance of evidence supports the use of high-velocity contractions and maximal to supra-maximal loads for preferentially targeting type-II muscle fibers (116, 270). From a neurological perspective, the ability to express maximal force and power is contingent on several factors. While isometric and eccentric resistance training can lead to the neurological and neuromuscular adaptations of rate-coding, agonist, antagonist, and synergist activation and co-activation, the adaptations above are highly specific (2). As EQI contractions are inherently submaximal and intentionally low velocity, it is likely that direct carry over to high threshold activities would be minimal. However, the slow, relatively high accumulated loading synonymous with EQI contractions, may potentially lead to improved rates of collagen synthesis and stiffness of the SEC and PEC (174, 193, 218). There is reason to believe that these morphological adaptations may improve force transmission by decreasing the electromechanical delay, therefore improving the rate of force development and stretch-shortening cycle function (125, 218). Quasi-isometric and EQI contractions are postulated to build position-specific strength and potentially reduce injury risk (371, 372). Verkhoshansky and Siff (378), described weightlifters utilizing EQI training to strengthen key positions in their weightlifting pulls. For example, a weightlifter who struggles to maintain an ideal position throughout the "first pull" (339) may wish to experiment with EQI contractions (Figure 9).

Figure 9. The initial quasi-isometric hold and final position after a maximal eccentric contraction in the snatch pull.

Rehabilitation

Injuries to any of the three components of force transmission require mechanical overload at some point in the rehabilitation process (218). Isometric and quasi-isometric exercises are already commonplace in the initial phases of muscular and tendon rehabilitation protocols as they enable tight control over ROM and intensity (128, 178, 293-295, 357). Sustained submaximal isometric contractions avoid large peak forces and acutely reduce tendon pain, potentially allowing for periods of pain-free dynamic exercise (294, 295, 357). Furthermore, while progressive mechanical tension is crucial (172, 174), slow movement velocities should be prescribed to stimulate damaged fibers (22). Therefore, the combined static and lengthening phases of EQI contractions may provide an analgesic effect while stimulating connective tissue reformation. In the case of serious injuries, such as bone fractures or severe connective tissue strains, patients may undergo a period of full or partial immobilization. These periods of immobilization often result in significant muscle atrophy and fascicle shortening (345). Eccentric quasi-isometric exercise may offer a submaximal means of improving tendon morphology, work capacity, muscle thickness, and neuromuscular function while returning fascicles to a normal length (218). Eccentric quasi-isometric contractions can be performed with a wide range of loads and can be easily implemented through a specific ROM. For example, a patient may experiment with EQI contractions by performing an EQI elbow flexion, with the torso inclined, until the elbow reaches the end ROM (Figure 9). At this point, a second EQI with a focus on the shoulder flexors can be initiated to impart further mechanical loading, metabolic stress to the target tissues (Figure 10). While currently highly speculative, a hypothetical training plan including EQIs for an athlete recovering from patellar tendonitis is provided in table 6.

Figure 10. Eccentric quasi-isometric incline biceps curl.

Table 6. Hypothetical resistance training program for an athlete recovering from patellar tendonitis

Day 1					Day 2				
Exercise	**Sets x Reps**	**Intensity**	**Tempo**	**ROM**	**Exercise**	**Sets x Reps**	**Intensity**	**Tempo**	**ROM**
Phase 1: Pain and load management									
Isometric Wall-squat	4 x 30-60s	BW	N/A	30-60º	Isometric knee extension	4 x 30-60s	70% MVIC	N/A	30-60º
Mini-band hip-thrust	3 x 15-20	BW	2-1-2-1	Full	1-leg DB Romanian deadlift	3 x 10-12	Moderate	3-0-1-0	Full
Clam shells	3 x 10-15	Band	2-1-2-1	Full	Mini-band side shuffle	3 x 10-15	Band	1-0-1-0	0-30º
EQI knee extension	2 x 60-90s	50-60% 1-RM	N/A	Pain free	EQI knee extension	2 x 60-90s	50-60% 1-RM	N/A	Pain free
Phase 2: Morphological restoration									
1-leg hip-thrust	3 x 10-20	BW	2-0-2-1	Full	1-leg back extension	3 x 10-20	BW	2-0-1-1	Full
Hamstring curls	3 x 8-12	Heavy	3-0-2-0	Full	ECC 1-leg decline squat	3 x 10-15	BW	4-0-1-0	0-75º
Knee extensions	3 x 8-12	70-80% 1-RM	2-0-2-1	Full	1-leg press	3 x 15-20	60-70% 1-RM	2-0-1-1	Full
EQI knee extension	3 x 30-60s	70-80% 1-RM	N/A	15-90º	EQI 1-leg press	2 x 30-60s	70-80% 1-RM	N/A	45-90º
Phase 3: Strength and functional improvement									
Mini-band march	2 x 20	Band	1-0-1-0	Full	BB hip-thrust	3 x 8-10	Heavy	2-1-2-1	Full
BB back squat	4 x 6-8	Heavy	3-1-3-1	Full	BB front squat	4 x 5-6	Heavy	3-1-3-1	Full
Glute-ham raise	4 x 6-8	BW	3-0-1-0	Full	BB Romanian deadlift	4 x 8-10	Heavy	2-0-1-1	Full
EQI skater squat	3 x 15-30s	Moderate	N/A	75º-floor	EQI DB Bulgarian split squat	3 x 15-30s	Moderate	N/A	45º-floor

Each phase = 2-3 weeks. Tempo = eccentric-pause-concentric-pause. Reps = repetitions. ROM = range of motion. BW = bodyweight. N/A = not applicable. MVIC = maximal voluntary isometric contraction. EQI = eccentric quasi-isometric. s = seconds. 1-RM = one-repetition maximum. DB = dumbbell. ECC = eccentric. BB = barbell.

Limitations

Due to the lack of any long-term investigations regarding EQI or quasi-isometric resistance training, limitations are abundant in this review. Like many methods of resistance training, EQIs can be applied with an endless combination of variables including intensity, contraction duration, repetitions, sets, rest periods, frequencies, and exercise selection. Any adjustment to the aforementioned parameters will alter the resemblance of EQI to traditional methods. Similarly, much is left to be determined regarding established training methods such as isometrics. For example, while the characteristics of "pushing" and "holding" isometric contractions differ (122, 157, 299-301, 305), there is a paucity of research examining long-term consequences to such altered loading parameters. Researchers and practitioners need to progress the knowledge and understanding of the acute and short-term neuromuscular, biomechanical, and metabolic effects of quasi-isometric and EQI contractions (122, 157, 299-301, 305). Furthermore, long-term investigations are needed to compare the potential structural and functional adaptations to established training methods.

Practical applications

It is common for "novel" training methods to precede evidence-based practice. While there are limited data on long-term adaptations, short-term investigations, anecdotal evidence, and relevant scientific knowledge make a strong case for the investigation of EQI loading and training. Based on the existing literature, the value of EQIs appears to relate most strongly to triggering morphological rather than neuromuscular adaptations and are likely best applied early in a periodized training plan, distal to high threshold neuromuscular work. Quasi-isometric and EQI training may also hold value in pre and rehabilitation contexts to modify muscle-tendon structures, provide analgesic effects, and closely match functional movements from a neurological perspective. Finally, EQIs appear to have the potential to provide an efficient means of increasing total load and volumes in specific positions.

Examination of EQI muscle actions and training is required due to the complete lack of direct empirical evidence investigating this area. As such, several foci for potential research exist. From an acute standpoint, EQI contractions may involve unique neuromuscular activation and muscular contraction dynamics that would be worthy of investigation. Researchers may also wish to compare the short-term effects of EQI exercise with volume equated modalities such as dynamic or isokinetic contractions on neuromuscular fatigue, delayed onset muscle soreness, or the repeated bout effect. Furthermore, long-term training studies are required to determine optimal loading parameters and exercise selection, as well as whether adaptation is population specific.

Section 2 – Methodological considerations

Chapter 4 - Variability of regional quadriceps architecture in trained men assessed by B-mode and extended field-of-view ultrasonography

Reference

Oranchuk DJ, Nelson AR, Storey AG, and Cronin JB. Variability of regional quadriceps architecture in trained men assessed by B-mode and extended field-of-view ultrasonography. *Int J Sports Physiol Perform* 15: 430-436, 2020.

Author contribution

Oranchuk DJ, 80%; Nelson AR, 5%; Storey AG, 5%; Cronin JB, 10%.

Prelude

Ultrasound evaluated muscle thickness, pennation angle, and fascicle length were commonly utilized measures identified in chapters two and three. Additionally, evaluating these measures of muscle morphology and architecture in different regions (proximal, middle, and distal) of a muscle are increasingly common, and show dichotomous adaptations following different exercises modes including contraction type and range of motion, and are therefore highly relevant to eccentric quasi-isometric exercise and training. However, little is known about the variability of regional muscle thickness, pennation angle and fascicle length measurements in the rectus femoris, vastus lateralis and anterior and lateral vastus intermedius; thus, quantifying this variability provides the purpose of chapter four.

Introduction

Ultrasonographic examination of skeletal muscle architecture in different regions (i.e., proximal, middle, distal) has become common as a non-invasive means to assess physiological adaptations (111, 221, 250, 268). While the links with performance remain unclear, architectural evaluations of muscle thickness (MT), pennation angle (PA) and fascicle length (FL) have several uses that may be important to researchers and practitioners (6, 190, 268). For example, Abe et al. (6) and Kumagi et al. (190) found significant ($p < 0.05$) relationships between 100-meter sprint performances and FL of the lower body musculature in male (r = 0.43-0.57) and female (r = 0.44-0.51) sprinters, respectively. Similarly, while not interchangeable (109), MT, muscle volume, and cross-sectional area of specific muscles were found to be correlated with maximal voluntary isometric force production in several cross-sectional investigations (r = 0.45-0.77) of untrained or recreationally trained participants (13, 48, 360). Additionally, differing regional architectural adaptations have been found following resistance training with specific contraction types (eccentric vs concentric) and ranges of motion, with eccentric and full range training, preferentially increasing distal MT and force production at long muscle lengths (108, 111, 250, 268, 317).

Two-dimensional B-mode ultrasonography is commonly utilized to assess MT and PA, and calculate FL. Additionally, the extended field of view (EFOV) function; where a panoramic view of a muscle is formed, is becoming an increasing common means of assessing FL (110, 250). However, variability data is spread across several populations, muscles and methods (6, 13, 48, 190, 360). For example, of the previously cited publications, only two examined more than a single quadriceps head (13, 360), while Trezise et al. (360) was the only group to utilize the EFOV function. Additionally, the sample sizes were relatively small (N = 11-22) (6, 13, 48, 190) in all but one investigation (360), and no researchers have used resistance trained populations. Furthermore, while one study had more than two sessions, only intraclass correlation coefficients (ICC) were reported (360), which raise some issues. For example, while it is the most commonly reported reliability statistic, the ICC is overly reliant on between-subject variability, whereas typical error of measure (TEM) and coefficient of variation (CV) are minimally affected by this (149, 285). Additionally, there is a dearth of information regarding the reliability of quadriceps architecture at different regions (191). Considering this information, this paper aims to address these limitations by quantifying the test-retest variability associated with region-specific MT, PA, and FL ultrasonographic measurements, with a large sample of homogeneous, well-trained participants, over multiple testing occasions using a full statistical analysis including ICC, CV, and TEM.

Methods

Experimental design

Using a repeated measures design, we examined quadriceps muscle architecture at proximal, middle, and distal regions of the vastus lateralis, rectus femoris and the anterior and lateral vastus intermedius using B-mode and EFOV ultrasonography. Each participant was tested on three separate occasions, separated by 5-8 days and the ICC, TEM and CV were used to provide insight into the variability of the measurements.

Participants

Twenty-six healthy, resistance-trained males (28.8 ± 4.8 years, 180.2 ± 7.7 cm, 81.8 ± 11.8 kg) volunteered. To minimize training effects from the testing procedures, all subjects were required to have at least six months (4.9 ± 3.8 years, range = 0.75 – 16 years) of at least twice weekly resistance training experience (2.53 ± 0.76 sessions·week^{-1}, range = 2-6 sessions·week^{-1}), and be free of musculoskeletal injuries in the three months before data collection. Participants were instructed to maintain their current level of physical activity throughout the data collection period. The Auckland University of Technology Research Ethics Committee approved the study (18/232), and all participants gave informed consent. All participants were instructed to refrain from strenuous physical activity and avoid alcohol, caffeine, and other ergogenic aids for at least 72 hours before each session.

Testing procedures

Muscle architecture

Participants were positioned in a supine position on a massage table for 15 minutes, to allow for inter- and intra-cellular fluid re-distribution with knees and hips fully extended with a foot strap used to prevent excessive external rotation (250). A certified ISAK Level-2 anthropometrist measured the length of the lateral and anterior aspect of the thigh, per the instructions of Noorkoiv et al. (250). Thigh lengths were recorded, and markings were made with an indelible pen, at 30% (proximal), 50% (middle) and 70% (distal) of the lateral and anterior distances, respectively (221). The vastus medialis was excluded as it can be further broken down into the obliquus and longus portions, with deep and superficial fiber bundles (63).

In vivo muscle architecture was determined via 2-dimensional B-mode ultrasonography (Figure 11A) using an ultrasound transducer and built-in software (45 mm linear array, 12 MHz; GE Healthcare, Vivid S5, Chicago, IL, USA). The following trigonometric equation calculated muscle FL (119): $FL = MT \times (\sin \theta)^{-1}$. Fascicle length was also measured by the EFOV function as detailed extensively elsewhere (110, 250). In brief, the ultrasound probe is moved across a muscle, while a texture mapping algorithm merges the sequence of images into a composite image (Figure 11B) (110). A water-soluble gel was applied to the scanning head of the ultrasound probe to achieve acoustic coupling, with care taken to avoid deformation of muscle architecture. The probe was oriented perpendicular to the skin and parallel to the estimated fascicle direction (110). On each occasion, two samples were captured and averaged to give mean MT, PA, and FL.

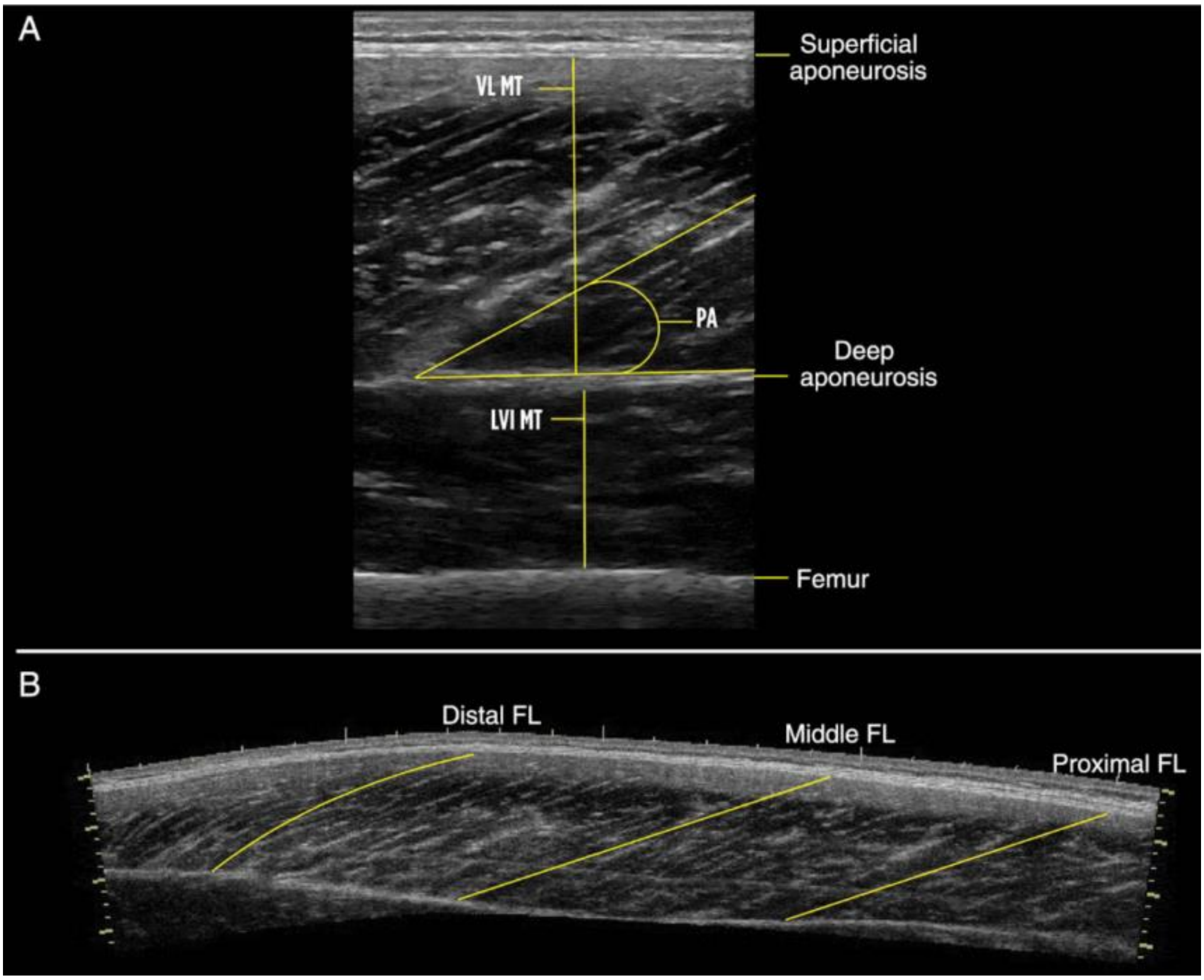

Figure 11. (A) B-mode ultrasound image of the mid VL and LVI. (B) Extended field-of-view image of the VL. VL = vastus lateralis; LVI = lateral vastus intermedius; MT = muscle thickness; PA = pennation angle; FL = fascicle length.

Data processing and analysis

Images were analyzed via digitizing software (ImageJ; National Institutes of Health, USA). Muscle thickness (cm) was defined as the perpendicular distance between the deep and superficial aponeurosis, and PA was defined as the angle of the fascicles relative to the deep aponeurosis (110). Due to the depth of the muscle, the fascicles of the vastus intermedius were not consistently visible. Therefore, PA and FL were not recorded for the lateral and anterior vastus intermedius. As the rectus femoris is complex, in that there are distinctly different directions of pennation, only 24/52 of distal rectus femoris measurements were able to be determined (97, 250). Additionally, a single participant suffered a quadriceps injury during the data collection period. Therefore, a total of 51 limbs were analysed.

Statistical analysis

Mean, and standard deviation (SD) are reported for all variables. All data were log-transformed to correct for heteroscedastic effects and analysed using an Excel spreadsheet. Intersession analysis was performed on the session mean for each variable. The ICC and CV were used to explore relative and absolute variability. An ICC < 0.67 and CV > 10% were deemed as having large variability, moderate variability was determined from either an ICC > 0.67 or a CV < 10%, but not both, and an ICC > 0.67 and CV < 10% were deemed as having small variability (201). Variability was also examined via TEM to provide the reader with a practical inference of the magnitude of error expected for any change in the mean, therefore reflecting the smallest worthwhile effect. Magnitudes for variability effects were calculated by doubling the TEM result (201, 328) with thresholds of 0.2-0.6 (small), 0.6-1.2 (moderate), 1.2-2.0 (large), 2.0-4.0 (very large) and > 4.0 (extremely large) (152, 201).

Results

Means, SDs, and variability data of MT measurements for all quadriceps muscles and regions are found in Table 7, while PA data of the vastus lateralis and rectus femoris are found in Table 8. Data for both calculated and EFOV derived FL are presented in Table 9.

Table 7. Test-retest variability of ultrasonographic derived muscle thickness over three repeated measures.

Region	Mean muscle thickness (cm)			Days 1 - 2						Days 2 - 3					
	Day 1	Day 2	Day 3	TEM	TEM x 2	TEM inference	CV	ICC	CV/ICC inference	TEM	TEM x 2	TEM inference	CV	ICC	CV/ICC inference
Vastus lateralis															
Proximal	2.5 ± 0.35	2.5 ± 0.35	2.51 ± 0.36	0.23	0.46	Small	3.1	0.95	Small	0.26	0.52	Small	3.4	0.94	Small
Middle	2.78 ± 0.43	2.8 ± 0.43	2.79 ± 0.41	0.15	0.30	Small	2.4	0.98	Small	0.20	0.40	Small	3.0	0.96	Small
Distal	2.22 ± 0.37	2.21 ± 0.36	2.19 ± 0.35	0.22	0.44	Small	3.8	0.96	Small	0.23	0.46	Small	3.8	0.95	Small
Mean				**0.20**	**0.40**	**Small**	**3.1**	**0.96**	**Small**	**0.23**	**0.46**	**Small**	**3.4**	**0.95**	**Small**
Rectus femoris															
Proximal	2.75 ± 0.3	2.78 ± 0.3	2.74 ± 0.29	0.24	0.48	Small	2.7	0.95	Small	0.24	0.48	Small	2.7	0.95	Small
Middle	2.69 ± 0.32	2.70 ± 0.32	2.67 ± 0.32	0.23	0.46	Small	2.7	0.95	Small	0.27	0.54	Small	3.2	0.93	Small
Distal	1.98 ± 0.33	1.97 ± 0.3	1.96 ± 0.32	0.47	0.94	Moderate	3.7	0.95	Small	0.26	0.52	Small	4.1	0.94	Small
Mean				**0.31**	**0.62**	**Moderate**	**3.0**	**0.95**	**Small**	**0.26**	**0.52**	**Small**	**3.3**	**0.93**	**Small**
Lateral vastus intermedius															
Proximal	2.01 ± 0.5	2.04 ± 0.52	2.03 ± 0.49	0.37	0.72	Moderate	9.3	0.88	Small	0.30	0.60	Moderate	7.7	0.92	Small
Middle	2.07 ± 0.55	2.09 ± 0.51	2.06 ± 0.56	0.17	0.34	Small	4.3	0.97	Small	0.17	0.34	Small	4.2	0.97	Small
Distal	1.92 ± 0.5	1.89 ± 0.51	1.89 ± 0.49	0.14	0.28	Small	3.5	0.98	Small	0.16	0.32	Small	3.9	0.98	Small
Mean				**0.23**	**0.46**	**Small**	**5.7**	**0.94**	**Small**	**0.21**	**0.42**	**Small**	**5.3**	**0.96**	**Small**
Anterior vastus intermedius															
Proximal	3.0 ± 0.48	3.0 ± 0.45	3.0 ± 0.45	0.19	0.38	Small	3.0	0.97	Small	0.18	0.36	Small	2.8	0.97	Small
Middle	2.28 ± 0.5	2.29 ± 0.48	2.3 ± 0.51	0.25	0.50	Small	5.7	0.94	Small	0.21	0.42	Small	5.0	0.96	Small
Distal	1.84 ± 0.41	1.84 ± 0.4	1.83 ± 0.41	0.20	0.40	Small	3.1	0.95	Small	0.18	0.36	Small	3.4	0.94	Small
Mean				**0.21**	**0.42**	**Small**	**4.5**	**0.96**	**Small**	**0.19**	**0.38**	**Small**	**4.0**	**0.97**	**Small**

TEM = typical error of measure. CV = coefficient of variation (%). ICC = intraclass correlation coefficient.

Table 8. Test-retest variability of ultrasonographic derived pennation angle over three repeated measures.

	Mean pennation angle (°)			Days 1 - 2						Days 2 - 3					
Region	**Day 1**	**Day 2**	**Day 3**	**TEM**	**TEM x 2**	**TEM inference**	**CV**	**ICC**	**CV/ICC inference**	**TEM**	**TE M x 2**	**TEM inference**	**CV**	**ICC**	**CV/ICC inference**
						Vastus lateralis									
Proximal	16.9 ± 3.35	16.7 ± 3.3	17 ± 2.75	0.42	0.84	Moderate	8.0	0.85	Small	0.42	0.84	Moderate	7.1	0.86	Small
Middle	20.6 ± 3.04	20.5 ± 2.65	20.5 ± 2.58	0.75	1.50	Large	8.8	0.65	Moderate	0.71	1.42	Large	7.6	0.67	Small
Distal	22.2 ± 3.16	22.5 ± 2.62	23.1 ± 3.75	0.83	1.66	Large	3.8	0.96	Small	0.66	1.32	Large	3.3	0.95	Small
Mean				**0.67**	**1.34**	**Large**	**6.9**	**0.82**	**Small**	**0.60**	**1.20**	**Moderate**	**6.0**	**0.83**	**Small**
						Rectus femoris									
Proximal	18.8 ± 3.78	18.9 ± 3.69	18.9 ± 3.43	0.63	1.26	Large	11.4	0.73	Moderate	0.73	1.46	Large	12.0	0.66	Large
Middle	14.3 ± 2.97	14.7 ± 1.53	15.3 ± 2.9	0.61	1.22	Large	11.4	0.74	Moderate	1.29	2.58	Very large	17.3	0.38	Large
Distal	10.1 ± 2.41	10.1 ± 2.50	10.7 ± 2.27	0.71	1.42	Large	15.6	0.67	Moderate	0.91	1.82	Large	18.5	0.55	Large
Mean				**0.65**	**1.30**	**Large**	**12.8**	**0.71**	**Moderate**	**0.98**	**1.96**	**Large**	**15.9**	**0.53**	**Large**

TEM = typical error of measure. CV = coefficient of variation (%). ICC = intraclass correlation coefficient.

Table 9. Test-retest variability of ultrasonographic derived calculated and extended field-of-view fascicle length over three repeated measures.

	Mean fascicle length (cm)			Days 1 - 2						Days 2 - 3					
Region	**Day 1**	**Day 2**	**Day 3**	**TEM**	**TEM x 2**	**TEM inference**	**CV**	**ICC**	**CV/ICC inference**	**TEM**	**TEM x 2**	**TEM inference**	**CV**	**ICC**	**CV/ICC inference**
						Vastus lateralis calculated									
Proximal	8.82 ± 1.77	8.96 ± 1.89	8.73 ± 1.5	0.44	0.88	Moderate	7.5	0.84	Small	0.46	0.92	Moderate	7.5	0.83	Small
Middle	8.02 ± 1.47	8.06 ± 1.2	8.03 ± 1.18	0.64	1.28	Large	9.3	0.71	Small	0.55	1.10	Moderate	7.4	0.77	Small
Distal	5.91 ± 0.93	5.8 ± 0.84	5.64 ± 0.9	0.59	1.18	Moderate	8.2	0.75	Small	0.55	1.10	Moderate	7.7	0.77	Small
Mean				**0.56**	**1.12**	**Moderate**	**8.3**	**0.77**	**Small**	**0.52**	**1.04**	**Moderate**	**7.5**	**0.79**	**Small**
						Vastus lateralis EFOV									
Proximal	7.7 ± 0.69	7.84 ± 0.81	7.65 ± 0.74	0.55	1.10	Moderate	4.8	0.78	Small	0.44	0.88	Moderate	4.1	0.84	Small
Middle	8.18 ± 0.77	8.21 ± 0.86	8.11 ± 0.88	0.55	1.10	Moderate	4.9	0.78	Small	0.41	0.82	Moderate	4.1	0.86	Small
Distal	7.11 ± 0.89	7.13 ± 0.96	7.22 ± 1.01	0.39	0.78	Moderate	4.7	0.87	Small	0.54	1.08	Moderate	6.6	0.78	Small
Mean				**0.50**	**1.00**	**Moderate**	**4.8**	**0.81**	**Small**	**0.46**	**0.92**	**Moderate**	**4.9**	**0.83**	**Small**
						Rectus femoris calculated									
Proximal	8.85 ± 1.86	8.87 ± 1.83	8.66 ± 1.58	0.58	1.16	Moderate	10.7	0.75	Moderate	0.69	1.38	Large	11.6	0.69	Moderate
Middle	11.3 ± 2.48	11 ± 2.0	10.8 ± 2.39	0.62	1.24	Large	11.2	0.73	Moderate	1.33	2.66	Very large	17.9	0.37	Large
Distal	11.8 ± 2.97	11.9 ± 3.17	11 ± 2.61	0.70	1.40	Large	16.0	0.68	Moderate	0.92	1.84	Large	19	0.55	Large
Mean				**0.63**	**1.26**	**Large**	**12.6**	**0.72**	**Moderate**	**0.98**	**1.96**	**Large**	**16.2**	**0.54**	**Large**
						Rectus femoris EFOV									
Proximal	8.14 ± 0.95	8.13 ± 0.83	8.19 ± 0.73	0.52	1.04	Moderate	5.4	0.80	Small	0.54	1.08	Moderate	4.8	0.78	Small
Middle	10.2 ± 1.48	10.2 ± 1.52	9.83 ± 1.48	0.51	1.02	Moderate	7.1	0.80	Small	0.88	1.76	Large	10.5	0.57	Large
Distal	12.1 ± 2.29	12.6 ± 2.5	11.8 ± 2.41	0.26	0.52	Small	5.2	0.94	Small	0.65	1.30	Large	11.5	0.72	Moderate
Mean				**0.43**	**0.86**	**Moderate**	**5.9**	**0.85**	**Small**	**0.69**	**1.38**	**Large**	**8.9**	**0.69**	**Small**

TEM = typical error of measure. CV = coefficient of variation (%). ICC = intraclass correlation coefficient. EFOV = extended field-of-view

Magnitudes of variability were small to moderate for all measures of MT (ICC = 0.88-0.98, CV = 2.4-9.3%, TEM = 0.16-0.47). Pennation angle of the vastus lateralis was found to have small to large variabilities (ICC = 0.65-0.96, CV = 3.8-8.8%, TEM = 0.42-0.83). Conversely, rectus femoris was found to have moderate to large variability regardless of region (ICC = 0.38-0.74, CV = 11.4-18.5%, TEM = 0.61-1.29). The EFOV technique (ICC = 0.57-0.94, CV = 4.1-11.5%, TEM = 0.26-0.88) demonstrate smaller variability than trigonometrically derived (ICC = 0.37-0.84, CV = 7.4-17.9%, TEM = 0.44-1.33) measurements of FL, across all regions.

Discussion

The variability associated with regional MT, PA and calculated and EFOV-derived FL of vastus lateralis, rectus femoris and lateral and anterior vastus intermedius in resistance trained males, was important to determine given the identified limitations in the existing literature. The main findings were: 1) MT variability was small in all quadriceps muscle heads and regions, 2) only rectus femoris PA and FL measurements were found highly variable; and 3) the EFOV technique should be utilized to assess FL where possible.

The MT of all measured quadriceps heads, at all regions, had low variability (ICC = 0.88-0.98, CV = 2.4-9.3%, TEM = 0.16-0.47). These results are similar to previous findings that report low variability of ultrasound-derived MT (13, 110, 221). Therefore, it would seem MT is a stable measurement and can be used with confidence by researchers and practitioners, at least over a period of 5-8 days.

In terms of PA, rectus femoris was found to have moderate to large variability regardless of region (ICC = 0.38-0.74, CV = 11.4-18.5%, TEM = 0.61-1.29). However, more than half of the distal rectus femoris images were unusable, dramatically lowering statistical power, and likely contributing to the large variabilities. The variability of the PA for the vastus lateralis regions was found to be acceptable (ICC = 0.65-0.96, CV = 3.3-8.8%, TEM = 0.42-0.83). These findings support the proclivity of researchers exclusively evaluating PA in the vastus lateralis (6, 48, 190).

The EFOV technique (ICC = 0.57-0.94, CV = 4.1-11.5%, TEM = 0.26-0.88) was found to have less variability than trigonometrically-derived (ICC = 0.37-0.84, CV = 7.4-17.9%, TEM = 0.44-1.33) measurements of FL, across all muscles and regions, which was similar to previous reports (110). Calculated vastus lateralis FL demonstrated reasonably low variability, suggesting that vastus lateralis FL can be consistently derived via trigonometric calculation when the EFOV function is not available. However, it must be noted that while both show acceptable variability, distal vastus lateralis FL measures were dissimilar between the trigonometric and EFOV methods. This can be attributed to irregular pennation angle and muscle thickness changes, and to the fact that the trigonometric equation neglects curvature. Conversely, calculated rectus femoris FL had moderate to very large variability.

Practical applications

The results of this study provide insight regarding which ultrasound-derived regional quadriceps architectural measures can be studied with confidence. While MT can be relied upon for all muscles and regions, PA of all muscles and regions, and rectus femoris FL should be interpreted with caution. Furthermore, while both EFOV and trigonometric methods resulted in acceptable variabilities of regional vastus lateralis FL, the two methods should not be used interchangeably as both reliability and validity are required before a measurement technique can be deemed useful.

While the report fulfils its primary purpose, limitations and future research direction exist. Firstly, between-practitioner experience and technical training may result in differing degrees of variability (110). Similarly, different equipment specifications, including probe size could most certainly alter variability (110). Muscle architecture variability should be examined in other homogenous populations, including resistance-trained women.

Conclusions

When evaluating muscle architecture, researchers and practitioners can be confident in MT assessments regardless of quadriceps head or region. However, PA and FL of the rectus femoris had consistently larger TEMs, CVs and smaller ICCs when compared to the vastus lateralis. Therefore, larger changes to the architecture of rectus femoris are required for practitioners to be confident that training-induced adaptation has occurred. Finally, the EFOV function should be the method of choice when evaluating FL in the proximal, middle, or distal regions of the vastus lateralis and rectus femoris.

Chapter 5 - Variability of regional quadriceps echo intensity in active young men with and without subcutaneous fat correction

Reference

Oranchuk DJ, Stock MS, Nelson AR, Storey AG, and Cronin JB. Variability of regional quadriceps echo intensity in active young men with and without subcutaneous fat correction. *Appl Physiol Nutr Metab* 45: 745-752, 2020.

Author contribution

Oranchuk DJ, 80%; Stock MS, 8%; Nelson AR, 4%; Storey AG, 4%; Cronin JB, 4%.

Prelude

While chapter four focused on the most traditional measures of muscle morphology and architecture, the relatively novel ultrasonographic measure of echo intensity, a proposed measure of muscle quality, is becoming increasingly popular. In brief, echo intensity refers to the brightness of an ultrasound image and as fat infiltrates, metabolic waste products and connective tissues are known to increase brightness, it is likely that regional echogenicity may provide an interesting means of evaluating and comparing the effects of eccentric quasi-isometric resistance-training, and other contraction types. Additionally, long-term adaptations may relate to acute echo intensity changes. However, the variability of regional (proximal, middle, distal) echo intensity of the vastus lateralis, rectus femoris, and lateral and anterior vastus intermedius had yet to be determined. Furthermore, the effect of adjusting echo intensity for an individual's subcutaneous fat thickness required further examination.

Introduction

Ultrasonographic evaluations are widely reported and utilized to assess acute (67) and long-term effects of training (221), the ageing process (240), and the relationship between muscular qualities and performance (60, 63, 336). While most ultrasonographic evaluations focus on architectural measures such as thickness, pennation angle and fascicle length, echo intensity (EI) has become commonly utilized (60, 67, 77, 253, 336). While not yet conclusive, EI is thought to be a non-invasive means of evaluating the current quality of a muscle, as elevated echogenicity is related to muscle damage (67, 253), collagen (282), fat infiltration (395), and oedema (62).

The examination of regional (proximal, middle, distal) muscle architecture has become increasingly common (263) as specific modes of resistance training may result in region-specific adaptations (111, 221, 250, 268). Furthermore, correlations of muscle architecture and morphology to performance differ based on the assessed region (360). However, with few exceptions (221, 395), EI evaluation in different regions has not yet been widely adopted by researchers or practitioners, leaving a fascinating area for future investigation. For example, different modes of exercise may cause acute, region-specific alterations in hormonal and metabolic factors that may correlate to long-term adaptations (112, 346); which could aid in further understanding the underlying mechanisms of region-specific morphological alterations. Furthermore, muscles tend to increase in collagen with age and injury (400); therefore, evaluating regional EI may provide insight into the ageing process without resorting to invasive methods such as biopsies.

Several recent reports have examined the reliability, interchangeability of methods, and optimal collection procedures of EI (62, 80, 356, 374-376). However, many studies examining EI report no reliability data (60, 253), while others report the coefficient of variation (CV) (67) or intraclass correlation coefficient (ICC) in isolation (77, 240), which raises some issues. For example, while it is the most commonly reported reliability statistic, the ICC is overly reliant on between-subject variability, whereas typical error of measure (TEM) and CV are minimally affected by this (285). Additionally, no studies have examined the variability of EI over more than two testing sessions. Moreover, while subcutaneous fat tissue can affect the quality of ultrasonographic imaging and reduce the ability of EI to predict muscle function (338), studies examining regional muscle EI have not adjusted for fat thickness (221), and/or have not examined the deep musculature of the vastus intermedius (221, 395). Similarly, the single study comparing the reliability of EI with and without subcutaneous fat correction only examined the middle region of the vastus lateralis, during a single session i.e., within session reliability (374). Therefore, the primary purpose of this study was to robustly determine the variability of EI, with and without correction for subcutaneous fat thickness, assessed over three sessions, in three distinct regions (proximal, middle, distal) of the superficial and deep knee extensor muscles. Furthermore, we aimed to compare corrected EI in different regions of each quadriceps muscle.

Methods

Experimental design

Using a repeated measures design, we examined quadriceps muscle EI at proximal, middle, and distal regions of the vastus lateralis, rectus femoris and the anterior and lateral vastus intermedius using B-mode ultrasonography, collected in the longitudinal plane, with and without subcutaneous fat thickness corrections. Each participant was tested on three separate occasions, separated by seven days and the ICC, TEM, and CV were used to provide insight into the intersession variability of the measurement. The interchangeability of each muscle region was also examined.

Participants

Twenty healthy, resistance-trained males (26.9 ± 5.2 years, 1.78 ± 0.07 m, 80.5 ± 10.7 kg, 25.2 ± 5.2 kg/m^2) volunteered. As determined via questionnaire, all participants were required to have at least six months (4.1 ± 3.5 years, range = 1.2 – 16 years) of resistance training experience (2.71 ± 0.56 sessions·week^{-1}, range = 2-5 sessions·week^{-1}) and were free of musculoskeletal injuries in the three months before data collection. Participants were instructed to maintain their current level of physical activity throughout the data collection period. The Auckland University of Technology Research Ethics Committee approved the study (18/232), and all participants gave informed consent. All participants were instructed to refrain from strenuous physical activity for at least 48 hours before each session.

Testing procedures

During the initial visit to the laboratory, the subjects' height and body mass were recorded using a stadiometer (Holtain Ltd, Crymych, United Kingdom) and a digital scale

(Weightec, Auckland, New Zealand). At each session, participants were positioned in a supine position on a massage table for 10 minutes, to allow for inter- and intra-cellular fluid re-distribution (356) with knees and hips fully extended with a foot strap used to prevent excessive external rotation (250). A certified ISAK Level-2 anthropometrist measured the length of the lateral and anterior aspect of the thigh, per the instructions of Noorkoiv et al. (250). The length of the lateral aspect of the thigh was determined by measuring the distance from the superior border of the greater trochanter to the inferior border of the lateral condyle of the femur. The anterior aspect of the thigh was determined by measuring the distance between the superior border of the patella and the inferior border of the anterior, superior iliac spine. Thigh lengths were recorded, and markings were made with an indelible pen, at 30% (proximal), 50% (middle) and 70% (distal) of the lateral and anterior distances, respectively (221). The vastus lateralis and lateral vastus intermedius (Figure 12A), and rectus femoris and anterior vastus intermedius (Figure 12B) were collected in the same image, respectively. The vastus medialis was excluded as it can be further broken down into the obliquus and longus portions, with deep and superficial fiber bundles (63).

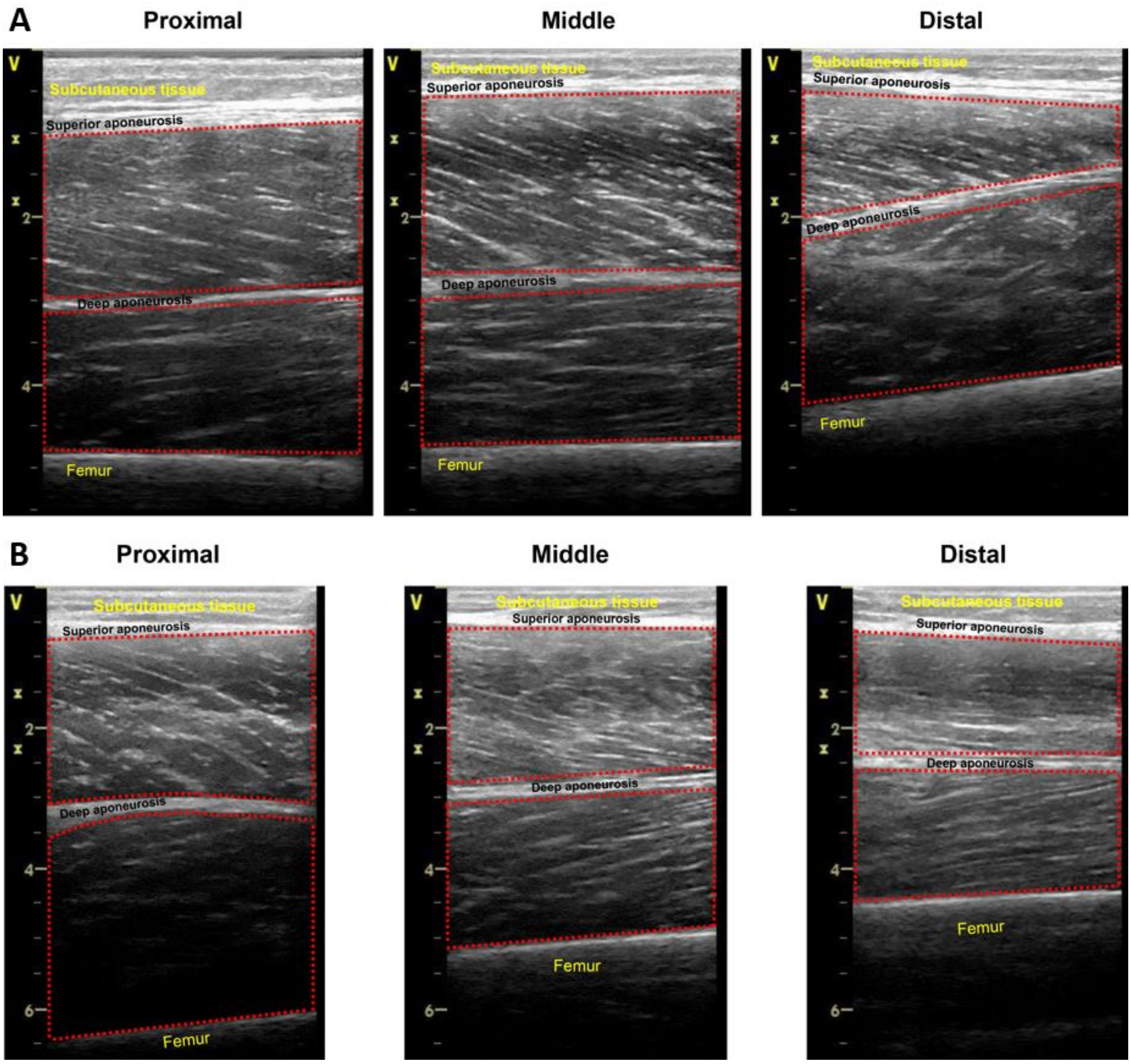

Figure 12. Representative B-mode ultrasound image of the proximal, middle, and distal vastus lateralis (top muscle) and lateral vastus intermedius (bottom muscle) (A). Representative B-mode ultrasound image of the proximal, middle, and distal rectus femoris (top muscle) and anterior vastus intermedius (bottom muscle) (B). The area inside of the dotted line represents the region of interest for each region and muscle.

In-vivo muscle EI of both limbs was determined via 2-dimensional B-mode ultrasonography using an ultrasound transducer and built-in software (45 mm linear array, 12 MHz; GE Healthcare, Vivid S5, Chicago, IL, USA). All assessments were performed by the same experienced sonographer. A water-soluble gel was applied to the scanning head of the ultrasound probe to achieve acoustic coupling, with care taken to avoid the deformation of muscle architecture (62). The sonographer was careful to avoid any transducer tilt (80), and the transducer was always positioned in the longitudinal plane to increase ease and reduce the time required to collect ultrasound images (376). The order of testing was always the same (i.e., right lateral, proximal, middle, distal; right anterior, proximal, middle, distal; left lateral, proximal, middle, distal; left anterior, proximal, middle, distal). While supine rest time may alter muscle architecture and radiological density of muscle (44), the difference in EI between right and left limbs were considered small (ES = 0.13) and the values were highly correlated (r = 0.98). Two consecutive scans were acquired for each muscle and region. The two images were averaged for further analysis. Ultrasound settings (Frequency: 12MHz, Brightness: maximum, gain: 60 dB, dynamic range: 70) were kept consistent across participants. Due to large differences in muscle thickness, scanning depth was individualized for each participant, muscle and region, and recorded and maintained through all collections (62).

Data processing and analysis

Images were analyzed via digitizing software (ImageJ; National Institutes of Health, USA). The region of interest was defined as the perpendicular distance between the deep and superficial aponeurosis of each muscle (Figure 12) and extended to each end of the B-mode image (62, 375). The polygon function was utilized to define the region of interest. Great care was taken to ensure the largest possible region of interest was captured, without the inclusion of aponeurosis or bone (62, 375). The straight-line function was utilized to assess the subcutaneous fat thickness of each image. Subcutaneous fat thickness was determined from the average of the proximal, middle and distal values of each image (302). All images were inspected and analysed by the sonographer. Corrected EI was calculated as uncorrected EI + (subcutaneous fat thickness [cm] × 40.5278) (395).

Statistical analysis

Mean, and standard deviation (SD) were reported for all variables. All data were log-transformed to correct for heteroscedastic effects and analysed using an Excel spreadsheet (149). The test-retest analysis was performed on the session mean for each variable. Sessions one-two, two-three and one-three were compared. The ICC (type 3,1) and CV were used to explore relative and absolute variability. An ICC < 0.67 and CV > 10% were deemed as having large variability, moderate variability was determined from either an ICC > 0.67 or a CV < 10%, but not both, and an ICC > 0.67 and CV < 10% were deemed as having small variability (263). Variability was also examined via TEM to provide the reader with a practical inference of the magnitude of error expected for any change in the mean (263). Magnitudes for variability effects were calculated by doubling the TEM result with thresholds of 0.2-0.6 (small), 0.6-1.2 (moderate), 1.2-2.0 (large), 2.0-4.0 (very large) and > 4.0 (extremely large) (152, 263).

The following statistical analyses were performed using the SPSS statistical analysis software (Version 25, IBM Corporation, Armonk, NY). An initial statistical analysis showed nearly identical corrected EI values for the dominant and non-dominant limbs ($p = 0.273$, ES = 0.071, $r = 0.973$). As such, data from both limbs were combined to create a single variable. A two-way (muscle [vastus lateralis, lateral vastus intermedius, rectus femoris, anterior vastus intermedius] × location [proximal, middle, distal]) repeated-measures analysis of variance (ANOVA) was used to detect differences in EI values among the regions and muscles, with the mean of the three sessions utilized for analysis. In the event of a significant ($p < 0.05$) two-way interaction, the data were further decomposed into separate repeated measures ANOVAs across muscle and location. Significant main effects were further evaluated with Bonferroni pairwise comparisons. Cohen's *d* effect size (ES) were calculated to measure the magnitude of effect using these criteria: trivial < 0.2, small = 0.2-0.49, moderate = 0.5-0.79, and large > 0.8 (115). To determine interchangeability and quantify the degree of shift in muscle EI along the length of each muscle, a correlational analysis was performed between each adjacent region (proximal vs middle, middle vs distal) using a Pearson (r) product-moment correlation test. Correlation coefficients of 0.10-0.29, 0.30-0.49, 0.50-0.69, 0.70-0.89 and ≥ 0.90 were considered small, moderate, large, very large and nearly perfect, respectively (152). Individual participant data were displayed using previously published Excel templates (387).

Results

For uncorrected EI, statistically significant differences were found for all four muscles ($p < 0.001$). Apart from the proximal and middle regions of the lateral vastus intermedius ($p = 0.676$), all regional comparisons were significant ($p \leq 0.004$) and showed that EI values increased as the measurement sites moved distally (proximal < middle < distal; Figure 13). The effect sizes for the proximal-to-middle comparisons were as follows: vastus lateralis ES = 0.19 (trivial); rectus femoris ES = 0.33 (small); lateral vastus intermedius ES = 0.10 (trivial); anterior vastus intermedius ES = 0.88 (large). The middle-to-distal comparisons were: vastus lateralis ES = 0.50 (moderate); rectus femoris ES = 0.22 (small); lateral vastus intermedius ES = 0.58 (moderate); anterior vastus intermedius ES = 0.82 (large). Very large to nearly perfect correlations were found between all adjacent regions of each muscle (r = 0.78-0.96).

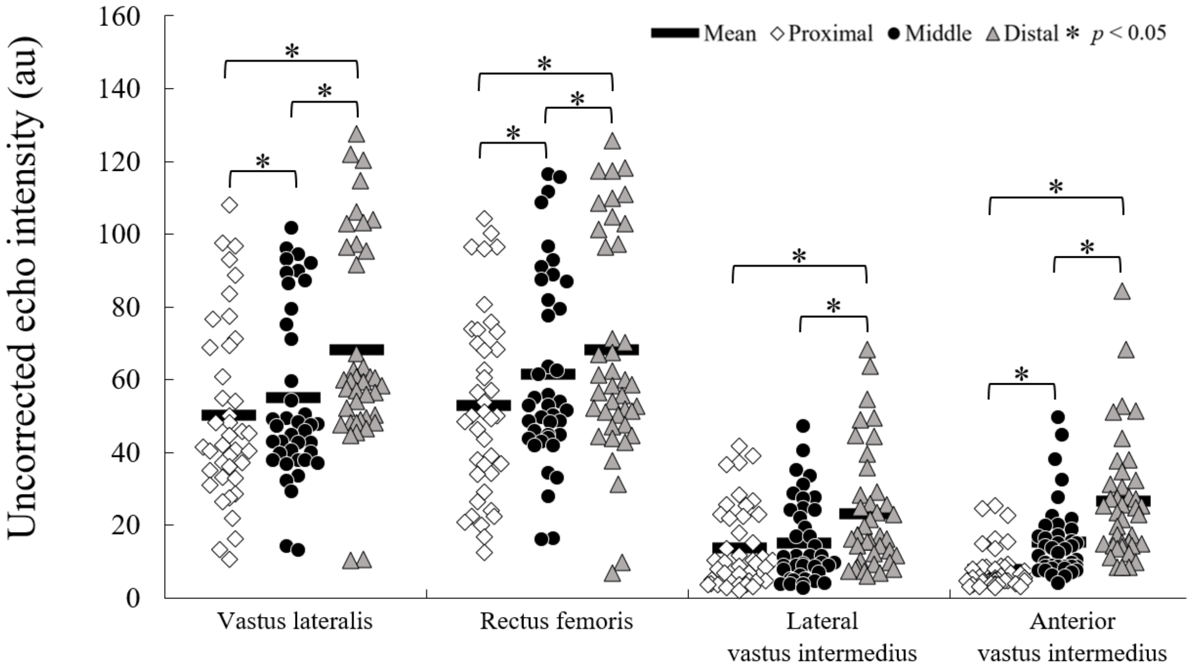

Figure 13. Individual regional uncorrected echo intensity of the quadriceps.

The results of the two-way repeated-measures ANOVA indicated that there was a significant muscle × location interaction ($p < 0.001$) for corrected EI. Follow-up analyses demonstrated that, for a given region, there were significant differences among all four muscles ($p < 0.026$, ES = 0.22-2.29), with the only exception being a non-significant difference at the proximal regions of the rectus femoris and vastus lateralis ($p = 1.0$, ES = 0.07). However, differences among locations for each muscle were more variable (Figure 14). Whereas the vastus lateralis, lateral vastus intermedius, and anterior vastus intermedius all showed differences among the proximal, middle, and distal regions, the rectus femoris displayed similar corrected EI values along its length ($p = 0.143$, ES = 0.02-0.11). For the vastus lateralis, corrected EI was lower at the middle than both the proximal ($p < 0.001$, ES = 0.43) and distal ends ($p < 0.001$, ES = 0.38). The lateral vastus intermedius displayed significant differences ($p \leq 0.038$, ES = 0.35-0.82) among all locations (proximal > distal > middle). For the anterior vastus intermedius, similar corrected EI values were found at the proximal and middle ends (ES = 0.11), while both regions were significantly lower than the distal end ($p < 0.001$, ES = 0.54-0.63). Finally, corrected EI of adjacent regions (e.g., middle, and distal vastus lateralis) were very large to nearly perfectly correlated ($r = 0.89$-0.96) for the vastus intermedius and rectus femoris, and moderate to very large for the lateral and anterior vastus intermedius ($r = 0.61$-0.79).

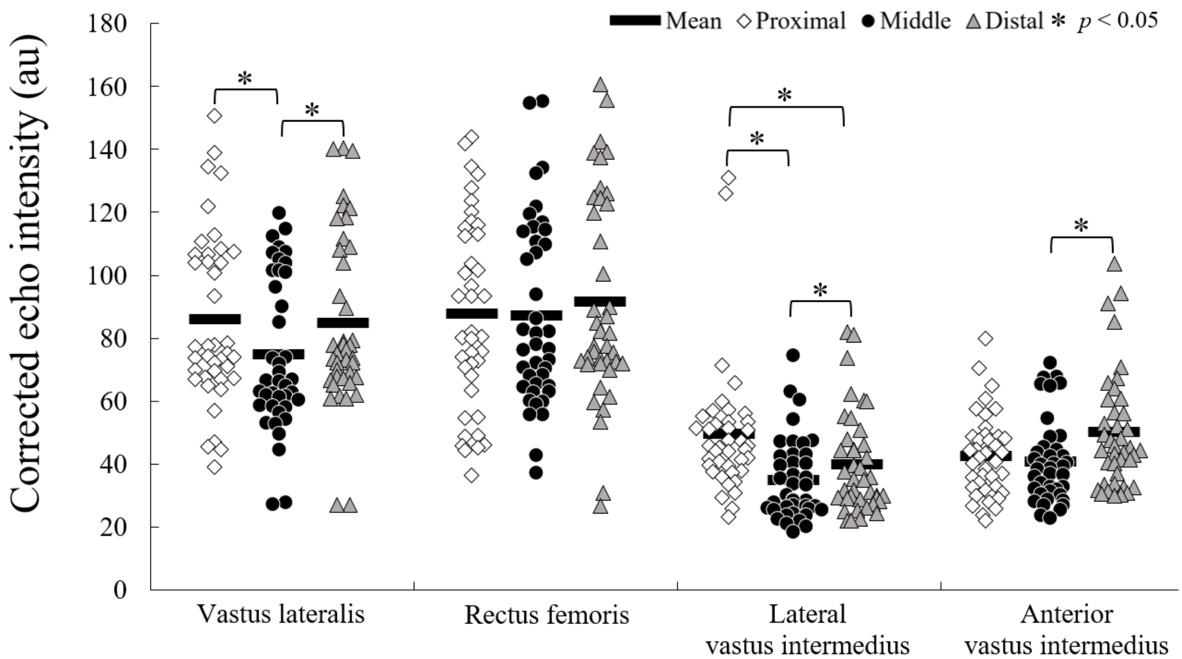

Figure 14. Individual regional subcutaneous fat thickness corrected quadriceps echo intensity of the quadriceps.

Session means and SD, and intersession variability data of uncorrected EI measurements for all quadriceps muscles and regions are found in Table 10. Small to moderate variability was found in all regions of the vastus lateralis, rectus femoris, lateral vastus intermedius, and proximal and middle portions of the anterior vastus intermedius (ICC = 0.83-0.98, CV = 7.7-41.7%, TEM = 0.14-0.47). However, distal anterior vastus intermedius had moderate to large variability (ICC = 0.69-0.85, CV = 32.8-42.7%, TEM = 0.45-0.68).

Table 10. Test-retest variability of regional quadriceps uncorrected echo intensity over three repeated measures.

Region	Echo intensity (au)			Days 1 - 2						Days 2 - 3						Days 1-3					
	Day 1	Day 2	Day 3	TEM	TEM x 2	TEM inference	CV	ICC	CV/ICC inference	TEM	TEM x 2	TEM inference	CV	ICC	CV/ICC inference	TEM	TEM x 2	TEM inference	CV	ICC	CV/ICC inference
Vastus lateralis																					
Proximal	50.3 ± 11.9	50.1 ± 12.2	50.7 ± 12.3	0.23	0.46	Small	12.7	0.95	Moderate	0.26	0.52	Small	15	0.94	Moderate	0.21	0.42	Small	11.9	0.96	Moderate
Middle	54.4 ± 10.5	55.6 ± 11.2	54.8 ± 11.3	0.27	0.54	Small	12.9	0.94	Moderate	0.26	0.52	Small	13.2	0.94	Moderate	0.22	0.44	Small	11.6	0.95	Moderate
Distal	67.7 ± 13.7	68.9 ± 13.8	67.9 ± 13.7	0.14	0.28	Small	7.7	0.98	Small	0.17	0.34	Small	9.1	0.97	Small	0.15	0.30	Small	8.4	0.98	Small
Mean				**0.21**	**0.42**	**Small**	**11.1**	**0.96**	**Moderate**	**0.23**	**0.46**	**Small**	**12.4**	**0.95**	**Moderate**	**0.19**	**0.38**	**Small**	**10.6**	**0.96**	**Moderate**
Rectus femoris																					
Proximal	52.6 ± 16.3	53.7 ± 16	52.6 ± 16	0.24	0.48	Small	13.1	0.95	Moderate	0.29	0.58	Small	16.8	0.92	Moderate	0.20	0.40	Small	12	0.96	Moderate
Middle	61.5 ± 13.8	61.8 ± 13.8	61.3 ± 12.9	0.22	0.44	Small	10.8	0.96	Moderate	0.15	0.30	Small	10.8	0.98	Moderate	0.16	0.32	Small	7.9	0.98	Small
Distal	68.2 ± 15.7	67.2 ± 16.3	68.6 ± 16	0.24	0.48	Small	15.5	0.95	Moderate	0.21	0.42	Small	12.8	0.96	Moderate	0.25	0.50	Small	15.7	0.95	Moderate
Mean				**0.23**	**0.46**	**Small**	**13.1**	**0.95**	**Moderate**	**0.22**	**0.44**	**Small**	**13.5**	**0.90**	**Moderate**	**0.20**	**0.41**	**Small**	**11.9**	**0.96**	**Moderate**
Lateral vastus intermedius																					
Proximal	13.9 ± 11.1	13.8 ± 10.2	14.5 ± 10.9	0.35	0.70	Moderate	35.1	0.90	Moderate	0.42	0.84	Moderate	41.7	0.86	Moderate	0.32	0.64	Moderate	31	0.91	Moderate
Middle	15.1 ± 11.3	15 ± 10.1	15.4 ± 12.2	0.44	0.88	Moderate	39.3	0.84	Moderate	0.32	0.64	Moderate	30	0.91	Moderate	0.44	0.88	Moderate	40.8	0.85	Moderate
Distal	23.7 ± 12.5	23.4 ± 10	23 ± 10.1	0.31	0.62	Moderate	22.9	0.92	Moderate	0.37	0.74	Moderate	27.1	0.88	Moderate	0.36	0.72	Moderate	27.6	0.89	Moderate
Mean				**0.37**	**0.74**	**Moderate**	**32.4**	**0.89**	**Moderate**	**0.37**	**0.74**	**Moderate**	**32.9**	**0.88**	**Moderate**	**0.37**	**0.75**	**Moderate**	**31.1**	**0.88**	**Moderate**
Anterior vastus intermedius																					
Proximal	7.9 ± 5.3	7.8 ± 6.8	7.8 ± 5.5	0.39	0.78	Moderate	26.3	0.87	Moderate	0.38	0.76	Moderate	24.9	0.88	Moderate	0.42	0.84	Moderate	26.9	0.86	Moderate
Middle	15.4 ± 7.7	14.9 ± 7.2	15.5 ± 7.6	0.41	0.82	Moderate	26.6	0.86	Moderate	0.47	0.94	Moderate	30.5	0.83	Moderate	0.49	0.98	Moderate	30.5	0.82	Moderate
Distal	26.4 ± 9.1	28.1 ± 12.5	25.5 ± 7	0.55	1.10	Moderate	37.5	0.77	Moderate	0.68	1.36	Large	42.7	0.69	Moderate	0.45	0.72	Moderate	32.8	0.85	Moderate
Mean				**0.45**	**0.90**	**Moderate**	**30.1**	**0.83**	**Moderate**	**0.51**	**1.02**	**Moderate**	**32.7**	**0.80**	**Moderate**	**0.42**	**0.85**	**Moderate**	**26.7**	**0.86**	**Moderate**

au = arbitrary units. TEM = typical error of measure. CV = coefficient of variation (%). ICC = intraclass correlation coefficient. All statistics are log-transformed.

Session means and SD, and intersession variability data of corrected EI measurements for all quadriceps muscles and regions are found in Table 11. Small variability was found in all regions of the vastus lateralis and rectus femoris (ICC = 0.95-0.98, CV = 4.5-8.3%, TEM = 0.13-0.24). Small to moderate intersession variability was found in the lateral and anterior vastus intermedius (ICC = 0.81-0.95, CV = 7.1-16.8%, TEM = 0.23-0.49).

Table 11. Test-retest variability of regional quadriceps corrected echo intensity over three repeated measures.

	Echo intensity (au)			Days 1 - 2						Days 2 - 3						Days 1-3					
Region	**Day 1**	**Day 2**	**Day 3**	**TEM**	**TEM x 2**	**TEM inference**	**CV**	**ICC**	**CV/ICC inference**	**TEM**	**TEM x 2**	**TEM inference**	**CV**	**ICC**	**CV/ICC inference**	**TEM**	**TEM x 2**	**TEM inference**	**CV**	**ICC**	**CV/ICC inference**
Vastus lateralis																					
Proximal	85.3 ± 27.1	86.1 ± 28.3	86.2 ± 28.1	0.18	0.36	Small	5.9	0.97	Small	0.24	0.48	Small	8.2	0.95	Small	0.23	0.46	Small	7.7	0.95	Small
Middle	73.7 ± 24.5	75.6 ± 24.8	74.7 ± 24.9	0.22	0.44	Small	7.7	0.96	Small	0.23	0.46	Small	8.2	0.95	Small	0.22	0.44	Small	8.2	0.95	Small
Distal	84.1 ± 28.3	85.3 ± 27.9	84.8 ± 28.5	0.17	0.34	Small	6.2	0.97	Small	0.18	0.36	Small	6.8	0.97	Small	0.18	0.36	Small	6.5	0.97	Small
Mean				**0.19**	**0.38**	**Small**	**6.6**	**0.97**	**Small**	**0.22**	**0.44**	**Small**	**7.7**	**0.96**	**Small**	**0.21**	**0.42**	**Small**	**7.5**	**0.96**	**Small**
Rectus femoris																					
Proximal	86.9 ± 30.9	88.1 ± 29.9	87.7 ± 31.8	0.20	0.40	Small	7.6	0.96	Small	0.24	0.48	Small	9.1	0.95	Small	0.19	0.38	Small	7.4	0.97	Small
Middle	87.1 ± 29	87.5 ± 30.3	86.9 ± 30.1	0.19	0.38	Small	6.6	0.97	Small	0.15	0.30	Small	5.1	0.98	Small	0.13	0.26	Small	4.5	0.98	Small
Distal	91.6 ± 33.2	90.6 ± 33.8	92.2 ± 33.2	0.20	0.40	Small	8.3	0.96	Small	0.20	0.40	Small	7.9	0.97	Small	0.19	0.38	Small	7.5	0.97	Small
Mean				**0.20**	**0.40**	**Small**	**7.5**	**0.96**	**Small**	**0.20**	**0.40**	**Small**	**7.4**	**0.97**	**Small**	**0.17**	**0.34**	**Small**	**6.5**	**0.97**	**Small**
Lateral vastus intermedius																					
Proximal	48.8 ± 21	49.8 ± 21.2	50 ± 21.5	0.26	0.52	Small	8.9	0.94	Small	0.26	0.52	Small	8.9	0.94	Small	0.23	0.46	Small	8	0.95	Small
Middle	34.4 ± 13.2	35 ± 13.5	35.3 ± 12.8	0.33	0.66	Moderate	11.9	0.90	Moderate	0.28	0.56	Small	9.6	0.93	Small	0.27	0.54	Small	9.6	0.93	Small
Distal	40.1 ± 17.5	39.7 ± 16.1	39.9 ± 15.3	0.29	0.58	Small	11.3	0.93	Moderate	0.36	0.72	Moderate	12.8	0.89	Small	0.38	0.76	Moderate	14.7	0.88	Moderate
Mean				**0.29**	**0.58**	**Small**	**10.7**	**0.92**	**Moderate**	**0.30**	**0.60**	**Moderate**	**10.4**	**0.92**	**Moderate**	**0.29**	**0.58**	**Small**	**10.8**	**0.92**	**Moderate**
Anterior vastus intermedius																					
Proximal	42.1 ± 13.1	42.2 ± 13.4	42.9 ± 13.5	0.25	0.50	Small	7.8	0.94	Small	0.23	0.46	Small	7.1	0.95	Small	0.29	0.58	Small	8.9	0.93	Small
Middle	41 ± 14.6	40.6 ± 13.1	41 ± 13.4	0.31	0.62	Moderate	9.8	0.92	Small	0.32	0.64	Moderate	10.1	0.91	Moderate	0.27	0.54	Small	8.8	0.92	Small
Distal	49.8 ± 20	51.4 ± 20.4	49.1 ± 18	0.47	0.94	Moderate	11.3	0.83	Moderate	0.49	0.98	Moderate	16.8	0.81	Moderate	0.40	0.80	Moderate	13.2	0.85	Moderate
Mean				**0.38**	**0.76**	**Moderate**	**6.9**	**0.90**	**Small**	**0.35**	**0.70**	**Moderate**	**11.3**	**0.86**	**Moderate**	**0.32**	**0.64**	**Moderate**	**10.3**	**0.90**	**Moderate**

au = arbitrary units. TEM = typical error of measure. CV = coefficient of variation (%). ICC = intraclass correlation coefficient. All statistics are log-transformed.

Discussion

A comprehensive analysis of the intersession variability associated with EI at multiple regions of the superficial and deep quadriceps femoris musculature was previously lacking. Additionally, no studies had examined the effect of subcutaneous fat thickness correction on intersession variability of EI. The present investigation's primary findings were: 1) that intersession variability of regional quadriceps EI was reasonably low in all muscles and regions except of the distal anterior vastus intermedius; 2) intersession variability of regional EI was substantially reduced following subcutaneous fat correction and, 3) with the exception of the rectus femoris, corrected EI nearly always increased as measurements moved away from the mid-region. Therefore, correction for subcutaneous fat thickness should be utilized before EI measures can be used with confidence; additionally, careful delineation of muscular regions is necessary.

The most pertinent finding of the present investigation was that intersession variability was considerably lower in corrected (ICC = 0.81-0.98, CV = 4.5-16.8%, TEM = 0.13-0.49) versus raw (ICC = 0.69-0.98, CV = 7.7-42.7%, TEM = 0.14-0.68) EI values; a finding that has not been previously reported. While the lack of previous research on regional differences make direct, region-to-region comparison difficult, EI variability in the middle region of a variety of muscles have been reported (62, 67, 221, 240, 384). In this study, the superficial muscles (vastus lateralis and rectus femoris) were observed to have small to moderate variability with raw EI (ICC = 0.92-0.98, CV = 7.7-16.8%, TEM = 0.15-0.29) and small variability once corrected (ICC = 0.95-0.98, CV = 4.5-9.1%, TEM = 0.13-0.25). These findings are similar to those of previous studies that reported CVs ranging from 6.8-7.4% and correlations between 0.74-0.97 in the superficial quadriceps or elbow-flexors (62, 67, 221, 240, 384). However, it should be noted that only Mota and Stock (240) corrected for subcutaneous fat.

While subcutaneous fat correction slightly reduced intersession variability of the superficial compartments, a more dramatic improvement was present in the vastus intermedius. When examining raw EI values, the ICC (0.84-0.94) and TEM (0.31-0.47) were reasonably acceptable in the proximal and middle vastus intermedius, while CVs were notably greater (26.3-30.5%) than the superficial musculature. Additionally, larger variabilities were found for the distal anterior vastus intermedius (ICC = 0.69-0.85, CV = 32.8-42.7%, TEM = 0.45-0.68). However, once corrected for subcutaneous fat thickness, intersession variability of the lateral and anterior vastus intermedius were small to moderate (ICC = 0.81-0.95, CV = 7.1-16.8%, TEM = 0.23-0.49) regardless of region. Unfortunately, to our knowledge, the only investigation reporting vastus intermedius EI variability did not include TEM or CV statistics. Additionally, variability was only determined within a session, making a direct comparison to our study difficult; however, the variability reported (ICC ≥ 0.95) is similar to our data (77). Additionally, Cruz-Montecinos et al. (77) reported lower (p = 0.048) EI in the anterior vastus intermedius when compared to the rectus femoris, in agreement with the present findings.

When examining the corrected EI values, apart from the proximal vastus lateralis (85.5 ± 27.4) and proximal rectus femoris (87.6 ± 30.4), there were significant (p < 0.026, ES = 0.22-2.29) between-muscle differences for a given location (proximal, middle, distal). Additionally, EI was always lower in the deep musculature of the lateral and anterior vastus intermedius when compared to the more superficial vastus lateralis and rectus femoris, in agreement with Cruz-Montecinos et al. (77) who reported lower (p = 0.048) EI in the anterior vastus intermedius when compared to the rectus femoris. While corrected EI of the rectus femoris did not differ between regions p = 0.143, ES = 0.02-0.11), the opposite was true for the vastus muscles. Corrected EI at proximal and distal regions was greater than the middle for both the vastus lateralis and lateral vastus intermedius, while the distal anterior vastus intermedius was greater than the middle. In contrast, raw EI nearly always increased as the measurements approached the knee, most likely due to noticeably different subcutaneous fat thickness at the proximal (lateral = 0.88 ± 0.6 cm; anterior = 0.85 ± 0.34 cm), middle (lateral = 0.49 ± 0.29; anterior = 0.63 ± 0.22), and distal (lateral = 0.41 ± 0.15 cm; anterior = 0.58 ± 0.2 cm), regions. As such, image quality was likely degraded by larger magnitudes as measures approached the hip, highlighting the importance of correcting for subcutaneous fat thickness when assessing the echogenicity of multiple regions of a muscle, or throughout a longitudinal intervention where changes in fat thickness are expected. To our knowledge, this is the first study to demonstrate increasing EI towards the proximal and distal portion of a muscle. However, this finding can be supported as muscles tend to gradually increase in collagen content as they approach and transition to the myotendinous junctions (341).

While the primary aim of this investigation was achieved, readers should be aware of several limitations and directions for future research. Firstly, differences in machine specifications and brightness, gain, depth, and dynamic range settings do not allow for the utilization of EI as normative data. Additionally, readers should be aware that we collected our images in the longitudinal, and not the transverse plane, which is not interchangeable (p = 0.002) despite being largely correlated (r = 0.68) (376). Readers should also be cognisant that the present study only examines physically active males, therefore our results may not translate to elderly, obese or clinical populations. Furthermore, muscular glycogen and hydration status may alter echogenicity, thus intersession variability may be improved by tightly controlling physical activity and fluid intake before EI assessments. Finally, while precedence exists for the specific inference cut-offs in this article (201, 263, 265, 269, 328), it is important to note that consensus to such thresholds is not universal (149, 285). Consequently, readers may wish to apply their own inferences based on their specific contexts. Future research should examine the variability of regional EI in other muscle groups. Furthermore, researchers may wish to examine the effects of specific modes of exercise on the EI of different regions. Finally, long-term tracking of regional EI may lead to new insights into the ageing process.

Conclusions

This was the first paper to examine the variability, and absolute differences in EI collected in different regions of the quadriceps femoris. Corrected quadriceps EI was substantially more consistent than non-corrected EI, especially in the vastus intermedius. Therefore, researchers should adjust for subcutaneous fat thickness, even in acute, or cross-sectional study designs. Additionally, EI almost always increases as the measures approach the proximal or distal regions, and therefore, cannot be used interchangeably, likely due to an increase in fibrous content towards the myotendinous junctions of each muscle.

Chapter 6 - Variability of concentric angle-specific isokinetic torque and impulse assessments of the knee extensors

Reference

Oranchuk DJ, Neville JG, Nelson AR, Storey AG, and Cronin JB. Variability of concentric angle-specific isokinetic torque and impulse assessments of the knee extensors. *Physiol Meas* 41: 01NT02, 2020.

Author contribution

Oranchuk DJ, 80%; Neville JG, 8%; Nelson AR, 4%; Storey AG, 4%; Cronin JB, 4%.

Prelude

While peak torque and optimal angle are commonly reported in the relevant literature, chapters two and three highlighted the importance of evaluating muscle function throughout the entire range of motion. This observation is especially true when examining the acute effects and long-term adaptations of different modes of resistance-training including eccentric quasi-isometrics, eccentric contractions, or contractions at different muscle lengths. However, little is known about the variability of isokinetic measurements besides peak torque and optimal angle. Therefore, Chapter 6 examined the variability of angle-specific concentric torque and impulse.

Introduction

Isokinetic assessments are frequently utilized in a variety of settings, including sports performance (85), rehabilitation (165, 355) and musculoskeletal and neuromuscular research (52, 96, 251, 280, 393). For example, determining the optimal angle (i.e., the angle of peak torque) via isokinetic assessments has been proposed as a proxy for changes in muscle fascicle length and injury prediction (355), as many injuries occur at, or near, full knee extension (100, 211), and end-range of motion (ROM) strength is a strong indicator of recovery following anterior cruciate ligament reconstruction (64). Additionally, the concentric optimal angle has been widely used as a non-invasive means of estimating exercise-induced muscle damage (52, 280, 393). For instance, Philippou et al. (280) reported that 50 maximal eccentric knee extensions caused significant shifts towards longer quadriceps muscle lengths, lasting up to 16 days, using concentric optimal angle assessment. Similarly, Yeung and Yeung (393) reported greater increases in quadriceps optimal angle and soreness, and reductions in peak torque, in the eccentric vs concentric limb following a bout of step-ups.

While the peak torque and the optimal angle have traditionally been the focus of isokinetic assessments, the optimal angle may have high variability and is a poor predictor of performance or injury risk (355). Alternatively, multiple-angle maximal voluntary isometric contractions allow for reliable and robust length-tension assessments and the quantification of the rate of force development and impulse (269). Additionally, isometric assessments are commonly utilized to examine muscular activation and the variability of maximal and submaximal motor outputs (195, 258, 332). However, obtaining a full isometric length-tension profile requires an extensive number of contractions (250, 268). For example, Noorkoiv et al. (250) evaluated knee-extension force at eight angles, totalling 16 maximal isometric contractions per limb, with one and two minutes of rest between contractions and joint-angles, respectively. While robust, the aforementioned evaluation may be excessively time-consuming (~23 minutes per limb after warmup), thereby limiting practicality, and potentially inducing a training stimulus (134).

A potential solution to the limitations with isometric length-tension assessments would be to implement angle-specific isokinetic (torque-angle) evaluations throughout the ROM). Additionally, the angular impulse may provide better diagnostic information to the practitioner, and therefore deliver more informative programming information for athletic and clinical populations. However, while concentric peak torque is highly reliable (355), little is known regarding the between-session variability of angle-specific torque outputs. For example, recent studies examining angle-specific torque reported no reliability data (85, 96), while others report the coefficient of variation (CV) (165) or intraclass correlation coefficient (ICC) (23) in isolation, which fail to provide a robust assessment of variability as the ICC is overly reliant on between-subject variability, whereas typical error of measure (TEM) and CV are minimally affected by this (149, 285). Finally, to the authors' knowledge, there are currently no reports outlining the variability of angle-specific impulse measures. Therefore, the primary purpose of this note was to determine isokinetic derived angle-specific concentric torque and angular impulse intersession variability, through the entire knee-joint ROM, and determine the need for familiarization.

Methods

Experimental design

Using a repeated measures design, isokinetic concentric peak torque, angle of peak torque, torque at 10° increments from 100-10º of knee flexion (0º = full extension), total contraction impulse, and impulse in 10° bands from 100-10º were quantified. Both limbs of each subject underwent unilateral testing on three separate occasions, 5-8 days (6.9 ± 0.9 days) apart. Intersession variability of each torque and impulse measure were examined via ICC, CV, and TEM.

Subjects

Thirty-two healthy, resistance-trained males (27.9 ± 5.3 years, 179.1 ± 7.5 cm, 81.5 ± 11.2 kg) volunteered. To minimize training effects from the testing procedures, all subjects were required to have at least six months (4.2 ± 3.9 years, range = 0.5 – 16 years) of at least twice weekly resistance training experience (2.54 ± 0.79 sessions·week^{-1}, range = 2-6 sessions·week^{-1}) and be free of musculoskeletal injuries in the three months before data collection. Participants were instructed to maintain their current level of physical activity throughout the data collection period apart from refraining from strenuous physical activity in the 48 hours before each session. Additionally, participants were instructed to avoid alcohol, caffeine, and other ergogenic aids for at least 24 hours before each session. The Auckland University of Technology Research Ethics Committee approved the study (18/232), and all subjects gave written informed consent after being informed of the risks and benefits of participation. A total of 63 limbs were tested and analysed due to a knee injury unrelated to the study.

Testing procedures

Concentric knee-extension performance

Subjects warmed up by cycling at low to moderate resistance using a self-selected pace for five minutes. Subjects were seated upright on the isokinetic dynamometer (CSMi; Lumex, Ronkonkoma, NY, USA) at a hip angle of 85º, with shoulder, waist, and thigh straps to reduce body movement during contractions. The shin-pad was positioned ~5 cm superior to the medial malleolus of each limb. To standardize body position, subjects were required to hold handles at the sides of the chair, while the non-working limb was positioned behind a restraining pad. Knee alignment was determined by visual inspection and unloaded knee extensions to ensure proper joint tracking and comfort. Dynamometer settings were recorded and matched for subsequent sessions.

Once fitted to the dynamometer, subjects underwent a series of extensions and flexions of the knee to determine safety stop positions and calibrate gravity correction. Subjects then completed a standardized warmup of a single concentric contraction of 30%, 50%, 70%, 85% and 100% of perceived maximal voluntary contraction, respectively. One minute after the completion of the warmup contractions, subjects completed five maximal concentric knee extensions in immediate succession at $60º \cdot s^{-1}$. Each contraction was initiated and terminated at 105° and 5° of knee flexion, respectively. Subjects were given strong verbal encouragement along with visual feedback of the torque-time tracing during each maximal contraction.

Data processing and analysis

Data were analyzed via a customized MATLAB (MathWorks, Natick, MA) script. Each isokinetic contraction was analyzed by detecting and identifying the maximum (105°) and minimum (5°) angle that signified the start and end of each contraction. Torque outputs at ten angles (100°, 90°, 80°, 70°, 60°, 50°, 40°, 30°, 20°, 10°) were recorded. Peak torque was detected as the highest instantaneous torque between 105°, and 5° of knee flexion, with the corresponding angle, recorded. The angular impulse was calculated as the area under the torque-time curve between each of the ten angles. Thus, total angular impulse throughout the entire ROM and between nine bands (100-90°, 90-80°, 80-70°, 70-60°, 60-50º, 50-40°, 40-30°, 30-20°, 20-10°) was calculated.

Statistical analysis

Mean, and standard deviation are reported for all variables. All data were analysed using an Excel (version 2016; Microsoft Corporation, Redmond, WA) spreadsheet from sportsci.org (149), utilizing log-transformation to correct for heteroscedastic effects. Intersession analysis was performed on the mean results of the variables for each session. The ICC (type 3,1) and CV were used to explore relative and absolute variability. An ICC < 0.67 and CV > 10% were deemed as having large variability, moderate variability when either the ICC > 0.67 or the CV < 10%, but not both, and small variability when ICC > 0.67 and CV < 10% (263, 269, 328). Variability was also examined via the standardized TEM to provide a practical interpretation of the magnitude of error expected for any change in the mean. Magnitudes for effects were calculated by doubling the TEM result (263, 328) and applying thresholds of 0.2-0.6 (small), 0.6-1.2 (moderate), 1.2-2.0 (large), 2.0-4.0 (very large) and > 4.0 (extremely large) (263, 269).

Results

Isokinetic peak torque, optimal angle, and angle-specific torque data are presented in Table 12. Peak torque was found to have small intersession variability (ICC = 0.94-0.95, CV = 6.2-7.4%, TEM = 0.22-0.26), whereas optimal angle was found to have moderate to large variability (ICC = 0.58-0.64, CV = 7.3-8%, TEM = 0.76-0.86). Angle-specific torque was observed to have small to moderate variability (ICC = 0.79-0.94, CV = 6.4-14.1%, TEM = 0.25-0.51) except for at the most extreme angles of 10° and 100° (ICC = 0.57-0.83, CV = 12.9-42.9%, TEM = 0.40-0.89).

Table 12. Test-retest variability of Isokinetic (60º·s^{-1}) knee extension torque production over three repeated measures.

	Mean			Days 1 - 2						Days 2 - 3					
	Day 1	**Day 2**	**Day 3**	**TEM**	**TEM × 2**	**TEM inference**	**CV**	**ICC**	**CV/ICC inference**	**TEM**	**TEM × 2**	**TEM inference**	**CV**	**ICC**	**CV/ICC inference**
							Peak torque (Nm)								
	211.3 ± 53	217.8 ± 53.2	213.1 ± 52	0.26	0.52	Small	7.4	0.94	Small	0.22	0.44	Small	6.3	0.95	Small
							Optimal angle (º)								
	69.2 ± 8	68.9 ± 8.3	69.3 ± 7.5	0.86	1.72	Large	8.0	0.58	Moderate	0.76	1.52	Large	7.3	0.64	Moderate
							Angle-specific torque (Nm)								
Joint angle															
100º	113 ± 40.6	121.5 ± 43.5	113.9 ± 39	0.89	1.78	Large	42.9	0.57	Large	0.68	1.36	Moderate	27.7	0.67	Large
90º	168.8 ± 43.9	176.8 ± 45.2	173 ± 42.7	0.35	0.70	Moderate	10	0.88	Moderate	0.34	0.68	Moderate	8.3	0.91	Small
80º	193.3 ± 48.2	198.8 ± 50.3	196.6 ± 48.2	0.25	0.50	Small	6.4	0.94	Small	0.29	0.58	Small	7.9	0.92	Small
70º	203.3 ± 51.7	207.3 ± 53.1	204.5 ± 51	0.30	0.60	Moderate	8.2	0.93	Small	0.27	0.56	Small	8.0	0.92	Small
60º	198.9 ± 54.6	202.3 ± 52.7	199.7 ± 52	0.35	0.70	Moderate	10.7	0.88	Moderate	0.28	0.59	Small	8.5	0.91	Small
50º	180.8 ± 52.8	183.7 ± 51.3	181.4 ± 50.2	0.37	0.74	Moderate	12.3	0.85	Moderate	0.30	0.60	Moderate	9.9	0.88	Small
40º	156.4 ± 47.5	158.5 ± 45.4	156.8 ± 45.7	0.40	0.80	Moderate	10.4	0.83	Moderate	0.32	0.64	Moderate	10.4	0.87	Moderate
30º	128.8 ± 40	129.9 ± 37.7	129.5 ± 39.6	0.45	0.90	Moderate	13.2	0.80	Moderate	0.37	0.74	Moderate	11.2	0.86	Moderate
20º	101.1 ± 32.4	100.7 ± 29.1	101.4 ± 32.8	0.51	1.02	Moderate	14.1	0.79	Moderate	0.39	0.78	Moderate	11.9	0.85	Moderate
10º	71.6 ± 23.5	71.9 ± 21.4	72.7 ± 24.4	0.65	1.30	Large	17.5	0.73	Moderate	0.40	0.80	Moderate	12.9	0.83	Moderate
Mean				**0.45**	**0.90**	**Moderate**	**14.5**	**0.82**	**Moderate**	**0.36**	**0.72**	**Moderate**	**11.7**	**0.86**	**Moderate**

TEM = standardized typical error of measure. CV = coefficient of variation (%). ICC = intraclass correlation coefficient. Nm = newton-meters. All reliability statistics are log-transformed.

The isokinetic angular impulse data can be observed in Table 13. The variability of total impulse through the entire ROM was found to be small to moderate (ICC = 0.93-0.97, CV = 6.4-8.1%, TEM = 0.20-0.31). Like angle-specific torque, the variability of all angular impulse bands was found to be small to moderate (ICC = 0.78-0.96, CV = 6.6-13.6%, TEM = 0.27-0.53), except for the most extreme angles (100-90° and 20-10°) (ICC = 0.75-0.85, CV = 11-16.5%, TEM = 0.36-0.60).

Table 13. Test-retest variability of Isokinetic (60º·s^{-1}) knee extension angular impulse over three repeated measures.

	Mean			**Days 1 - 2**						**Days 2 – 3**					
	Day 1	**Day 2**	**Day 3**	**TEM**	**TEM × 2**	**TEM inference**	**CV**	**ICC**	**CV/ICC inference**	**TEM**	**TEM × 2**	**TEM inference**	**CV**	**ICC**	**CV/ICC inference**
							Total (100-10º) impulse (Nm·s)								
	240.1 ± 63.1	246 ± 61.7	242.2 ± 62.2	0.31	0.62	Moderate	8.1	0.93	Small	0.20	0.40	Small	6.4	0.96	Small
							Angle-specific impulse (Nm·s)								
Joint angle															
100-90º	24.9 ± 6.9	26.4 ± 7.1	25.5 ± 6.6	0.58	1.16	Large	16.5	0.76	Moderate	0.36	0.72	Moderate	11	0.85	Moderate
90-80º	30.5 ± 7.8	31.7 ± 8	31.2 ± 7.7	0.28	0.56	Small	6.6	0.94	Small	0.30	0.60	Moderate	7.5	0.92	Small
80-70º	32.8 ± 9.2	33.5 ± 9.6	32 ± 10.7	0.27	0.54	Small	7	0.96	Small	0.28	0.56	Small	7.8	0.92	Small
70-60º	33.8 ± 8.9	34.4 ± 8.8	33.9 ± 8.6	0.32	0.64	Moderate	9.1	0.90	Small	0.27	0.54	Small	8.1	0.93	Small
60-50º	31.9 ± 9	32.3 ± 8.7	31.9 ± 8.5	0.36	0.72	Moderate	11.8	0.85	Moderate	0.31	0.62	Moderate	9	0.90	Small
50-40º	28.2 ± 8.4	28.7 ± 8.1	28.3 ± 8	0.50	1.00	Moderate	12.9	0.82	Moderate	0.35	0.70	Moderate	9.9	0.88	Small
40-30º	23.9 ± 7.3	24.1 ± 6.9	23.9 ± 7.1	0.51	1.02	Moderate	13.5	0.80	Moderate	0.42	0.84	Moderate	12.8	0.86	Moderate
30-20º	19.2 ± 6	19.3 ± 5.6	19.3 ± 6.1	0.53	1.06	Moderate	13.6	0.78	Moderate	0.41	0.82	Moderate	11.3	0.85	Moderate
20-10º	14.5 ± 4.7	14.4 ± 4.2	14.5 ± 4.8	0.60	1.20	Large	15.3	0.75	Moderate	0.41	0.82	Moderate	12	0.84	Moderate
Mean				**0.44**	**0.88**	**Moderate**	**11.8**	**0.84**	**Moderate**	**0.34**	**0.68**	**Moderate**	**9.9**	**0.88**	**Small**

TEM = standardized typical error of measure. CV = coefficient of variation (%). ICC = intraclass correlation coefficient. Nm·s = newton-meter seconds. All reliability statistics are log-transformed.

Discussion

A comprehensive understanding of the variability associated with isokinetic torque and angular impulse across multiple angles, in a homogenous resistance-trained population, was previously lacking. As such, the main purpose of the study was to examine the intersession variability of traditional isokinetic assessments (i.e., peak torque, optimal angle), and the potentially more consistent diagnostic metrics of angle specific torque and angular impulse. Our primary findings were: 1) variability was minimal for isokinetic peak torque and total impulse throughout the quadriceps ROM: 2) optimal angle demonstrates moderate to large variability and, 3) angle-specific isokinetic torque and angular impulse were found to have small to moderate variability, except for the ends of ROM.

Minimal variability was associated with concentric peak torque (ICC = 0.94-0.95, CV = 6.3-7.4%, TEM = 0.22-0.26), enabling the use of this metric without necessarily reporting optimal angle (251, 268). Interestingly, while the mean optimal angle was nearly identical between sessions, moderate to large viabilities were found (ICC = 0.58-0.64, CV = 7.3-8.0%, TEM = 0.76-0.86), likely due to between-subject changes in rank-order. The aforementioned result question the common practice of analysing the optimal angle, especially as it is likely that clinical populations would have greater biological variability than the population of resistance-trained men used in this study. Furthermore, this finding may explain the generally lack of substantial optimal angle changes in longitudinal investigations and highlights the need for researchers to determine their own test-retest variability. The much less studied angle-specific isokinetic torque was found to be small to moderate in variability at 90-20° of knee flexion (ICC = 0.79-0.94, CV = 6.4-14.1%, TEM = 0.25-0.51) while 100° and 10° were more variable (ICC = 0.57-0.83, CV = 12.9-42.9%, TEM = 0.40-0.89). These results suggest that even healthy, resistance-trained subjects may have difficulty in consistently initiating and completing isokinetic contractions. These findings are important to consider as peak anterior cruciate ligament loading typically occurs between 10-30° of knee flexion (100). While a direct investigation is required, it would be expected that rehabilitative populations would have greater difficulty consistently initiating and completing contractions (64), thus resulting in more variable torque and impulse outputs near end ROM. Therefore, isometric contractions, with lower movement variability, may prove a more reliable measurement of injured populations.

Variabilities reported here are similar to those of Arnold, Perrin, and Hellwig (23) (ICC = 0.83-0.87) and are more consistent when compared to Kannus and Yasuda (165) (CV = 35-47%); although these authors report across two sessions at only 30°, 60° and 75°, and 15° and 75° of knee-flexion, respectfully. Furthermore, to our knowledge, this is the first paper reporting angle-specific angular impulse, the reliability of which was more consistent (mean ICC = 0.84-0.88, CV = 9.9-11.8%, TEM = 0.34-0.44) as compared to angle-specific torque (mean ICC = 0.82-0.86, CV = 11.7-14.5%, TEM = 0.36-0.45). Additionally, all angular impulse brackets held small to moderate variabilities between sessions two and three, suggesting that only a single familiarization session is required to confidently evaluate the entire length-tension relationship. Alternatively, while the variability of angle-specific torque was more consistent for sessions two-three (mean ICC = 0.88, CV = 9.9%, TEM = 0.38) versus one-two (mean ICC = 0.84, CV = 11.8%, TEM = 0.44), variation at 100º remained moderate to large, suggesting that more than one familiarization session may be required to adequately detect small changes at long muscle lengths. Thus, we recommend utilizing bracketed ranges over torque at a single point in the ROM when practitioners must be sure that a change has occurred, especially when evaluating the knee extensors near full extension or flexion.

While the primary aim of this paper was accomplished, it is important to note limitations and directions for future research. We did not account for limb dominance, which may have altered intersession variability. However, it is common practice to evaluate both limbs in research (e.g., within-participant parallel conditions) and clinical (e.g., inter-limb asymmetry) settings. A complex relationship between fatigue, adaptations, and performance exists. As such, it is possible that each testing session could have led to small adaptations and/or resulted in residual fatigue, potentially affecting our results. However, while familiarization effects can be conferred in fewer than 10 maximal contractions (134), it is unlikely that noticeable levels of fatigue remained by the second and third testing sessions as even high responders have been shown to recover upwards of 80% of maximal voluntary isometric contraction just four days following 50 maximal eccentric contractions in untrained participants (154).

This study only examined the knee extensors; therefore, muscle groups such as the knee flexors, or humeral rotators must be directly examined before researchers and practitioners can understand the utility of angle-specific torque or impulse measurements at other muscle groups and joints. Furthermore, the utility of assessing agonist/antagonist strength ratios via angle-specific torque or impulse analyses remains unknown. Similarly, studies examining the variability of submaximal and maximal motor-outputs and muscle activation during non-isometric contractions should be undertaken. Additionally, the reader needs to be cognizant that only males with substantial resistance training experience were recruited for this investigation. Thus, the response of untrained, youth, elderly, female and rehabilitative populations could be different. Future researchers will also need to determine the variability of eccentric contractions and contractions at different velocities to gain a full understanding of the utility of these measures in a comprehensive torque-angle profile. Most importantly, future researchers should determine the validity of angle specific torque and impulse to predict injury and monitor recovery processes. Finally, while precedence exists for the specific inference cut-offs in this article (263, 269, 328), it is important to note that consensus to such thresholds is not universal (149, 285). Consequently, readers may wish to apply their own inferences based on their specific contexts.

Conclusions

Isokinetic concentric torque and angular impulse have low to moderate variability at all but extreme joint angles. Additionally, angle-specific angular impulse intersession variability at long muscle length is relatively low, and therefore could be used instead of angle-specific torque when multiple familiarization sessions are not practical and/or different diagnostic information is sought. Depending on the methodological purpose, researchers and practitioners can utilize angle-specific concentric torque or angular impulse as a time-efficient evaluation of contractile and neuromuscular qualities when the quantification of the rate of force development is not required.

Chapter 7 - Variability of multiangle isometric force-time characteristics in trained men

Reference

Oranchuk DJ, Storey AG, Nelson AR, Neville JG, and Cronin JB. Variability of multiangle isometric force-time characteristics in trained men. *J Strength Cond Res* Ahead of print, 2019.

Author contribution

Oranchuk DJ, 80%; Storey AG, 8%; Nelson AR, 4%; Neville JG, 4%; Cronin JB, 4%.

Prelude

While Chapter 6 established the intersession variability of concentric muscle function, isometric contractions allow for truer measures of peak contractile force, and the evaluation of rate of force development and impulse. All of these variables may be important in determining the effects of eccentric quasi-isometric training. However, little is known about the variability of these measurements at multiple angles, over repeated testing occasions in a homogenous, resistance-trained population. Thus, determining the intersession variability of multi-angle isometric force-time characteristics provided the purpose of this chapter.

Introduction

Traditionally, the evaluation of the length-tension relationship has been completed via isokinetic derived angle of peak torque (i.e., optimal-angle) (355). However, in Chapter 6 we determined that the optimal angle holds relatively high variability, even in resistance-trained men (265). Additionally, dynamic contractions do not allow for reliable rate of force development (RFD) metrics to be calculated, and eccentric evaluations require extensive familiarization and may be excessively strenuous if regular testing is required (355). As such, isometric evaluations of force, RFD and impulse are popular in general (268), athletic (92, 266), and rehabilitative (16, 70, 181) populations due to the ease of use and a high degree of safety (390). Additionally, isometric evaluations are regularly utilized to gain insight regarding neural drive and pain-induced inhibition via the rapid application of force (215), which is valuable in a variety of contexts (16, 92, 181, 390). For example, Angelozzi et al. (16) reported that while peak force returned to baseline six-months after anterior cruciate ligament reconstruction, early-stage (from contraction onset to a pre-determined time interval; e.g., 0-30 ms, 0-50 ms, 0-90 ms) RFD remained measurably depressed 12 months post reconstruction. Furthermore, late-stage (100-200 ms) RFD is a more sensitive means of indirectly evaluating exercise-induced muscle damage than peak force, providing value in research settings (276).

Isometric contractions at multiple joint angles are commonly included in testing batteries (49, 188, 250) as morphological and functional adaptations to training appear to be joint angle specific (268). For example, Kubo et al. (188) observed that isometric training at long muscle lengths resulted in significantly improved isometric force from 40-110° of knee-flexion, whereas short muscle length training only improved force production from 40-80°. Thus, no between-group differences would have been detected if force production had been evaluated at a single joint angle of ≤ 80° (188). Furthermore, strength and rapid force production at specific joint angles may provide beneficial information to athletic and rehabilitative populations. For instance, many knee and hamstring injuries occur at, or near, full extension (100), and strength near the end-range of motion is a strong indicator of recovery (64). Alternatively, high force outputs at long muscle lengths critical to performance for athletes such as weightlifters (339). Therefore, isometric evaluation of muscle properties should take place at multiple angles, i.e., whole muscle length-tension relationship (355).

While multi-angle isometric assessments have the potential to be useful in athletic and rehabilitation settings, several limitations have been identified by researchers. For example, nine of 26 papers included in a recent systematic review of isometric resistance training included multi-angle isometric assessments (268). However, only six reported reliability, and in three, variability was only derived from a single session (i.e., within-trial variation) (268), which has limited application to test-retest methodologies. Additionally, each study in the review (268), and the earlier cited lack original reliability statistics (70, 181, 266, 276), or report only a single statistic, with a mixture of intraclass coefficient correlation (ICC) (16, 49), or the coefficient of variation (CV) (188, 250). Moreover, while peak force was highly reliable (ICC = 0.80-0.99) across seven accepted studies, a systematic review of closed-chain isometric assessments (92) only reported pooled ICCs, which raises some issues. For example, while it is the most commonly reported reliability statistic, the ICC is overly reliant on between-subject variability, which minimally affects typical error of measure (TEM) and CVs (149, 285). Another limitation was the distinct lack of resistance-trained subjects as none of the papers included in the aforementioned systematic review included subjects with any substantial strength training history (268). Furthermore, the variability of RFD and impulse are seldom reported (16, 49). Therefore, the primary purpose of this technical report is to provide a comprehensive analysis of the variability of a multi-angle isometric knee extension assessment over three testing sessions in resistance-trained subjects. The findings of this report will provide greater insight into isometric measures that can be used with confidence in test-retest methodologies that are quantifying longitudinal changes.

Methods

Experimental approach to the problem

Isometric force-time characteristics of the knee extensors were examined using a repeated measures study design. Subjects were tested on three separate occasions, with 5-8 days between sessions. Each session followed identical sequencing of testing including a series of isometric contractions at short (40º), medium (70º), and long (100º) muscle lengths (0º=full extension). Intersession variability of peak force, early (0-50 ms) and late-stage (0-100 ms, 0-200 ms, 100-200 ms) RFD and impulse were examined via ICC, CV, and TEM.

Subjects

Twenty-six healthy, resistance-trained males (28.8 ± 4.8 years, 180.2 ± 7.7 cm, 81.8 ± 11.8 kg) volunteered. To minimize training effects from the testing procedures, all subjects were required to have at least six months (4.9 ± 3.8 years, range = 0.75 – 16 years) of at least twice weekly resistance training experience (290) (2.53 ± 0.76 sessions·week^{-1}, range = 2-6 sessions·week^{-1}), and be free of musculoskeletal injuries in the three months before data collection. Participants were instructed to maintain their current level of physical activity throughout the data collection period apart from refraining from strenuous physical activity in the 72 hours before each session. Additionally, participants were instructed to avoid alcohol, caffeine, and other ergogenic aids for at least 24 hours before each session. The Auckland University of Technology Research Ethics Committee approved the study (18/232), and all subjects gave written informed consent after being informed of the risks and benefits of participation.

Testing procedures

Isometric testing

Participants warmed up by cycling at a low to moderate resistance using a self-selected pace for five minutes. Participants were seated upright on the isokinetic dynamometer (CSMi; Lumex, Ronkonkoma, NY, USA) at a hip angle of 85º, with shoulder, waist, and thigh straps to reduce body movement during contractions. The shin-pad force was ~5 cm superior to the medial malleoli. Participants were required to hold the handles at the sides of the chair, and the non-working limb was positioned behind a restraining pad. Knee alignment was determined by visual inspection, and unloaded knee extensions were performed by the subjects to ensure proper joint tracking. Dynamometer settings were recorded and matched for all subsequent sessions.

Once fitted to the dynamometer, participants performed a series of extensions and flexions of the knee to determine the safety stop positions and calibrate to the gravity correction. Participants then completed a standardized warmup of submaximal concentric contractions of 30%, 50%, 70%, 85% and 100% of perceived maximal voluntary contraction. Each warm-up contraction was initiated and terminated at 105° and 5° of knee flexion, respectively. Sixty seconds after the completion of the isokinetic warm-up, the participants' knee was positioned at 40º of flexion where one familiarization isometric knee extension at 50% of maximal voluntary isometric contraction (MVIC) was performed. Subsequently, two

MVICs lasting four seconds were completed with 30 seconds separating each contraction. Participants were instructed to contract "as fast and hard as possible" following a countdown of "3-2-1-go!" (215). All athletes were given strong verbal encouragement along with visual feedback of the force-time tracing during each trial (215). Participants were also instructed to avoid any pre-tension and countermovement of the knee extensors while the live force-time trace was carefully inspected by the examiner leading up to each contraction (215). The cut-off for pre-tension was set at 10 N. Any contractions with a clear countermovement or an unsteady baseline were rejected and repeated (215). The subjects then completed the same series at 70º and 100º of knee flexion with 60 seconds of rest between angles. The isometric contractions were always performed in series from short to long muscle lengths to avoid greater muscle damage and fatigue synonymous with contractions at long muscle lengths (250). Following the final isometric contraction, the isokinetic warm-up and isometric assessment were repeated on the opposite limb. Limb order was randomized throughout the three testing sessions and counterbalanced over the sample. All isokinetic and isometric contractions were collected, without filtering, via a custom-made software (LabVIEW; National Instruments, New Zealand) sampling at 2000 Hz (215).

Data processing and analysis

Data were analyzed via a customized MATLAB (MathWorks, Natick, MA) script. All force data were divided by the length of the lever arm, in meters, to normalize the difference in shank length between subjects. Following an initial manual inspection of the raw data, isometric forces over 200 N were identified to signify a full contraction and eliminate false contractions. A peak detection algorithm was implemented to detect and identify the instantaneous peak force of each contraction. The on-set of effort was determined via visual inspection and a manual section of each force-time curve (215). The same researcher determined on-set of effort by visually detecting the last trough before force deflected above the range of the baseline noise (215). Rate of force development and impulse were calculated for 0-50 ms, 0-100 ms, 0-200 ms, and 100-200 ms, based on the manual onset of effort detection (215).

Statistical analysis

Mean, and standard deviation was calculated for all variables. All data were log-transformed to correct for heteroscedastic effects and analysed using an Excel (version 2016; Microsoft Corporation, Redmond, WA) spreadsheet (149, 263). Intersession analysis was performed on the mean results of the variables for each session. The ICC and CV were used to explore relative and absolute variability, respectively. An ICC < 0.67 and CV > 10% were deemed as having large variability, moderate variability when either the ICC > 0.67 or the CV < 10%, but not both, and small variability when ICC > 0.67 and CV < 10% (201, 263). Variability was also examined via TEM to provide the reader with a practical interpretation of the magnitude of error expected for any change in the mean (201, 263). Magnitudes for effects were calculated by doubling the TEM result (201, 263) with thresholds of 0.2-0.6 (small), 0.6-1.2 (moderate), 1.2-2.0 (large), 2.0-4.0 (very large) and > 4.0 (extremely large) (152, 201, 263).

Results

Variability data for multi-angle isometric force, RFD and impulse measures are found in Table 14.

Table 14. Test-retest variability of isometric knee extension force production over three repeated measures.

Joint angle	Mean			Days 1 – 2						Days 2 - 3					
	Day 1	Day 2	Day 3	TEM	TEM × 2	TEM inference	CV	ICC	CV/ICC inference	TEM	TEM × 2	TEM inference	CV	ICC	CV/ICC inference
Peak Force (N)															
40º	611.5 ± 140	601.3 ± 134	603.6 ± 133	0.45	0.90	Moderate	10.8	0.84	Moderate	0.39	0.78	Moderate	9.6	0.87	Small
70º	790 ± 201	807.2 ± 174	805.5 ± 188	0.36	0.72	Moderate	9.2	0.88	Small	0.49	0.98	Moderate	11.5	0.80	Moderate
100º	669 ± 151	679.2 ± 153	682.7 ± 149	0.28	0.56	Small	6.7	0.93	Small	0.38	0.76	Moderate	8.5	0.88	Small
Mean				**0.36**	**0.62**	**Moderate**	**8.9**	**0.88**	**Small**	**0.42**	**0.84**	**Moderate**	**9.9**	**0.85**	**Small**
RFD 0-50 ($N \cdot s^{-1}$)															
40º	3894 ± 1227	3739 ± 967	3635 ± 1053	0.64	1.28	Large	22.4	0.71	Moderate	0.82	1.64	Large	23.5	0.60	Large
70º	3245 ± 1255	3003 ± 1304	2940 ± 1121	0.74	1.48	Large	32.2	0.66	Large	0.66	1.32	Large	27.2	0.70	Moderate
100º	1690 ± 998	1577 ± 827	1670 ± 1024	0.67	1.34	Large	31.9	0.70	Moderate	0.70	1.40	Large	33.7	0.68	Moderate
Mean				**0.68**	**1.36**	**Large**	**28.8**	**0.69**	**Moderate**	**0.73**	**1.46**	**Large**	**28.1**	**0.66**	**Large**
RFD 0-100 ($N \cdot s^{-1}$)															
40º	3401 ± 980	3179 ± 846.8	3142 ± 868	0.57	1.14	Moderate	18.7	0.76	Moderate	0.60	1.20	Moderate	19.9	0.71	Moderate
70º	3264 ± 1061	3025 ± 1007	2977 ± 939	0.48	0.96	Moderate	18.8	0.82	Moderate	0.57	1.14	Moderate	20.1	0.76	Moderate
100º	2334 ± 761	2258 ± 471.6	2293 ± 830	0.51	1.02	Moderate	19.4	0.80	Moderate	0.57	1.14	Moderate	21.7	0.76	Moderate
Mean				**0.52**	**1.04**	**Moderate**	**19**	**0.79**	**Moderate**	**0.58**	**1.16**	**Moderate**	**20.6**	**0.74**	**Moderate**
RFD 0-200 ($N \cdot s^{-1}$)															
40º	2459 ± 631	2340 ± 607.7	2297 ± 611	0.55	1.10	Moderate	15.9	0.78	Moderate	0.53	1.06	Moderate	15.6	0.79	Moderate
70º	2804 ± 790	2643 ± 755.3	2618 ± 728	0.43	0.86	Moderate	14	0.85	Moderate	0.47	0.94	Moderate	14.9	0.82	Moderate
100º	2271 ± 575	2224 ± 584	2266 ± 637	0.39	0.78	Moderate	11.8	0.87	Moderate	0.43	0.86	Moderate	13	0.85	Moderate
Mean				**0.46**	**0.92**	**Moderate**	**13.9**	**0.83**	**Moderate**	**0.48**	**0.96**	**Moderate**	**14.5**	**0.82**	**Moderate**
RFD 100-200 ($N \cdot s^{-1}$)															
40º	1534 ± 460	1501 ± 446.6	1452 ± 459	0.74	1.48	Large	21.5	0.67	Moderate	0.53	1.06	Moderate	17.1	0.79	Moderate
70º	2344 ± 649	2261 ± 634.6	2259 ± 637	0.45	0.90	Moderate	13.9	0.84	Moderate	0.46	0.92	Moderate	15	0.83	Moderate
100º	2207 ± 560	2190 ± 557.1	2240 ± 558	0.39	0.78	Moderate	10.9	0.87	Moderate	0.37	0.74	Moderate	10.4	0.88	Moderate
Mean				**0.53**	**1.06**	**Moderate**	**15.4**	**0.79**	**Moderate**	**0.45**	**0.90**	**Moderate**	**14.2**	**0.83**	**Moderate**
Impulse 0-50 ($N \cdot s$)															
40º	10.6 ± 5.7	9.38 ± 4.3	9.19 ± 4.6	0.51	1.02	Moderate	32.9	0.80	Moderate	0.57	1.14	Moderate	32.9	0.76	Moderate
70º	8.15 ± 6	7.26 ± 5.8	6.8 ± 4.4	0.70	1.40	Large	56.2	0.68	Moderate	0.57	1.14	Moderate	42.5	0.76	Moderate
100º	2.93 ± 3.5	2.52 ± 2.6	2.86 ± 3.6	0.66	1.32	Large	61	0.70	Moderate	0.70	1.40	Large	63.1	0.68	Moderate
Mean				**0.62**	**1.24**	**Large**	**50**	**0.73**	**Moderate**	**0.61**	**1.22**	**Large**	**46.2**	**0.73**	**Moderate**
Impulse 0-100 ($N \cdot s$)															
40º	21.9 ± 10.6	27.3 ± 12.3	16.8 ± 12.9	0.52	1.04	Moderate	36.3	0.79	Moderate	0.52	1.04	Moderate	33.1	0.79	Moderate
70º	30.8 ± 17.4	26.7 ± 15.6	25.7 ± 14	0.43	0.86	Moderate	33.8	0.85	Moderate	0.52	1.04	Moderate	37	0.80	Moderate
100º	16.8 ± 9.2	15.7 ± 8.7	16.5 ± 10.6	0.49	0.98	Moderate	38.4	0.81	Moderate	0.53	1.06	Moderate	42.1	0.79	Moderate
Mean				**0.48**	**0.96**	**Moderate**	**36.2**	**0.82**	**Moderate**	**0.52**	**1.04**	**Moderate**	**37.4**	**0.79**	**Moderate**

							Impulse 0-200 (N·s)								
40º	64.5 ± 28.7	58.7 ± 26.6	57 ± 27.1	0.51	1.02	Moderate	30.7	0.80	Moderate	0.44	0.88	Moderate	27	0.85	Moderate
70º	87.4 ± 43.9	78.1 ± 39.4	76.4 ± 38.9	0.41	0.82	Moderate	27.6	0.86	Moderate	0.45	0.90	Moderate	29.6	0.84	Moderate
100º	58.2 ± 26.1	56.2 ± 25.4	58.7 ± 30.7	0.38	0.76	Moderate	23.6	0.88	Moderate	0.41	0.82	Moderate	25.9	0.86	Moderate
Mean				**0.43**	**0.86**	**Moderate**	**27.3**	**0.85**	**Moderate**	**0.43**	**0.86**	**Moderate**	**27.5**	**0.85**	**Moderate**
							Impulse 100-200 (N·s)								
40º	33.9 ± 15.9	31.4 ± 15.2	30.3 ± 15.1	0.56	1.12	Moderate	33.1	0.77	Moderate	0.41	0.82	Moderate	25.8	0.86	Moderate
70º	56.5 ± 27.9	51.3 ± 25	50.6 ± 24.9	0.41	0.82	Moderate	26.9	0.86	Moderate	0.44	0.88	Moderate	29.2	0.84	Moderate
100º	41.4 ± 18.5	40.4 ± 17.8	42.2 ± 21	0.36	0.72	Moderate	21.5	0.89	Moderate	0.38	0.76	Moderate	23.1	0.88	Moderate
Mean				**0.44**	**0.88**	**Moderate**	**27.2**	**0.84**	**Moderate**	**0.41**	**0.82**	**Moderate**	**26**	**0.86**	**Moderate**

TEM = typical error of measure. CV = coefficient of variation (%). ICC = intraclass correlation coefficient. RFD = rate of force development. $N·s^{-1}$ = newtons per second. N·s = newton seconds. All reliability statistics are log-transformed.

Small to moderate variabilities were found for isometric peak force (ICC = 0.80-0.93, CV = 6.7-11.5%, TEM = 0.28-0.49) while late-stage (0-100, 100-200, 0-200 ms) RFD (ICC = 0.67-0.88, CV = 10.4-21.5%, TEM = 0.37-0.74) and impulse (ICC = 0.77-0.89, CV = 21.5-42.1%, TEM = 0.36-0.56) were moderately variable regardless of angle between sessions one-two and two-three. However, moderate to large variability were found for early-stage (0-50 ms) RFD (ICC = 0.60-0.71, CV = 22.4-33.7%, TEM = 0.64-0.82) and impulse (ICC = 0.68-0.80, CV = 32.9-63.1%, TEM = 0.51-0.70).

Discussion

A comprehensive analysis of the variability associated with isometric peak force, RFD, and impulse at multiple angles during knee extension, in a homogenous resistance-trained population was previously lacking. This study addressed these limitations with the primary findings being: 1) peak force is minimally variable, 2) late-stage RFD and impulse are moderately variable, and 3) early-stage RFD and impulse hold moderate to large variability.

Small to moderate variability (ICC = 0.80-0.93, CV = 6.7-11.5%, TEM = 0.28-0.49) was associated with isometric peak force regardless of joint angle, meaning that practitioners and researchers can be confident in using this metric across angles. Our findings corroborate previous reports, in that late (ICC = 0.67-0.89, CV = 10.4-42.1%, TEM = 0.36-0.74), but not early-stage (ICC = 0.60-0.80, CV = 22.4-63.1%, TEM = 0.51-0.82) RFD and impulse, are relatively stable between testing occasions regardless of joint angle (215, 271). For example, Palmer, Pineda, and Durham (271) recently reported highly reliable peak force (ICC = 0.84-0.90, CV = 6.6-12%) and late-stage RFD (ICC = 0.81, CV = 12.3-19.4%), while peak and early-stage RFD (ICC = 0.55-0.85, CV = 17.3-55.9%) were much less consistent across two sessions in a multi-angle isometric squat (271). No systematic bias was observed between sessions one-two, indicating a negligible learning effect and that the assessments need very little familiarisation in trained subjects.

From the findings of this technical report, reporting early-stage RFD (16, 276) would seem questionable, supporting the decisions of researchers who have declined to include rapid force production earlier than a 100 ms threshold (49). However, it is important to note that large intersession variability does not necessarily preclude early-stage RFD or impulse from holding value if the smallest detectable change is known. For example, Krafft (181) and

Angelozzi (16), reported relatively large improvements in peak (98.4-103.6%, Cohen's d = 0.58-1.06) and early-stage RFD (20.3-41.7%, d = 0.35-0.44) throughout recovery from anterior cruciate ligament reconstruction, which may have surpassed the smallest detectable change. However, neither study reported the information required to calculate the smallest detectable change in their population. Alternatively, well-trained athletic populations are unlikely to experience large enough improvements in early-stage RFD and impulse to overcome the moderate to large intersession variability (290).

While the primary aim of this report was achieved, readers should be cognizant of the limitations. While two contractions per angle, per session was selected to avoid neuromuscular adaptations and reduce assessment time, a greater number of contractions is often recommended to improve measurement reliability (215). Furthermore, the variability of peak force, and RFD and impulse would have likely been improved by performing ramp, and brief rapid contractions, respectively. (215). All contractions were performed in a commercial dynamometer, where deformation of the seat and tissues of the subject may result in small shifts in the prescribed joint angle when compared to custom-made apparatus (20, 215). While the slight deviation in joint angle should not affect intersession variability, practitioners should be aware that the reported force, RFD and impulse data may not be interchangeable with other equipment set-ups (20, 215). Future research should examine other movements (e.g., knee flexion, dorsiflexion) and populations (e.g., females, elderly, untrained, rehabilitative) to have a full understanding of the utility and reproducibility of multi-angle isometric force-time characteristics. Finally, while precedence exists for the specific statistical inference cut-offs in this article (201, 263), it is important to note that universal consensus is not possible (285, 386). Therefore, readers may wish to apply their own inferences based on their specific contexts.

Practical applications

This was the first study to undertake a comprehensive analysis of knee extension force-time variability across multiple joint angles and testing occasions. Peak force, and late-stage RFD and impulse were the most stable measures at all assessed angles, indicating that the whole muscle length-tension relationship can be determined for knee extension. However, practitioners should avoid reporting early-stage (0-50 ms) RFD and impulse, due to moderate to large intersession variability. Additionally, practitioners should be aware that outcome measures with moderate to large variability require larger training-induced adaptations before they can be sure that real changes have occurred. It also appears that there is minimal learning involved with the testing, so familiarisation and assessment can occur in the same session with well-trained individuals. Readers may wish to calculate the smallest worthwhile change from table 14; however, it is critical to realize that these data are only applicable to a resistance-trained male population. In summary, isometric peak force, and late-stage RFD and impulse have low to moderate variability regardless of joint angle and therefore, can be used with confidence to demonstrate the force capability of knee extensors.

Section 3 – Correlational analyses

Chapter 8 - The effect of regional quadriceps anatomical parameters on angle-specific isometric torque expression

Reference

Oranchuk DJ, Hopkins WG, Nelson AR, Storey AG, and Cronin JB. The effect of regional quadriceps anatomical parameters on angle-specific isometric torque expression. *Appl Physiol Nutr Metab* 46: 368-378, 2021.

Author contribution

Oranchuk DJ, 80%; Hopkins WG, 10%; Nelson AR, 4%; Storey AG, 3%; Cronin JB, 3%.

Prelude

Chapters 4 to 7 examined the intersession variability of several measures of muscle morphology, architecture, and function, while Chapters 2 and 3 presented several studies examining the correlations between anatomical features and muscular performance. However, the relationships between the primary measures of the thesis have not been examined in detail. More specifically, the association between regional muscle structure and the length-tension relationship required elucidation. Understanding these associations allows for further understanding of what morphological and architectural parameters are most important for joint-angle-specific neuromuscular performance; enabling a potential reduction in the number of ultrasonic variables required to be collected in subsequent studies. Furthermore, understanding the aforementioned relationships could aid in the interpretation of future findings. Therefore, this chapter examined the relationship between the region and muscle-specific muscle thickness, pennation angle and fascicle length, and angle specific maximal isometric torque using several linear regression models.

Introduction

The relationship of specific anatomical properties (muscle thickness (MT), volume, cross-sectional area, pennation angle (PA), fascicle length (FL)) to performance indices of several sports have been examined (6, 177, 190, 247, 368). Likewise, the assessment of muscle mass and architecture has been extensively utilized to model in-vivo muscle function during isometric and isokinetic contractions (13, 48, 73, 213, 359, 360, 379). For example, Blazevich et al. (48) reported quadriceps muscle volume to be the best predictor of maximal isometric force (R^2 = 0.60) and slow (30$^{o}\cdot s^{-1}$) concentric torque (R^2 = 0.74), while the combination of physiological cross-sectional area and FL was reported as a moderate predictor (R^2 = 0.59) of high-velocity (300$^{o}\cdot s^{-1}$) concentric contractions. Similarly, MT, muscle volume, and cross-sectional area of specific muscles were found to be moderately to very largely correlated with isometric and isokinetic force or torque production in both cross-sectional (r = 0.45-0.904) (13, 48, 213, 360, 379) and longitudinal investigations (r = 0.53-0.89) (33, 99, 250, 359) in untrained or recreationally trained participants.

While muscle size and structure are linked to force production, controversy remains regarding the relative contribution of regional quadriceps muscle anatomical variables at different joint angles and angular velocities. Ando et al. (13) examined the relationship between architecture of the vastus lateralis, rectus femoris, vastus medialis, and lateral and anterior vastus intermedius, and maximal knee extension force. The authors reported that while MT and PA of all four muscles were positively correlated (r = 0.19-0.74) with maximal force production, only MT of the anterior vastus intermedius (r = 0.74) and PA of the lateral vastus intermedius (r = 0.68) reached statistical significance (13). Additionally, multiple linear regression showed that 91% of the variation in force could be accounted for by the anterior vastus intermedius MT and lateral vastus intermedius PA (13). However, Ando et al. (13) only assessed force at 90° of knee flexion and included a relatively small sample of 11 participants.

The examination of muscle size, quality, and architecture in different regions (proximal, middle, distal) of a muscle has become popular in contemporary research (110, 213, 250, 264, 267, 337, 359, 360). While conflicting results exist, several groups have found that eccentric resistance training, or training at long muscle lengths, results in preferential hypertrophy of the distal region, and leads to substantial increases in FL (250, 268). The superior adaptations to the distal region following eccentric and long muscle length resistance training are accompanied by preferential improvements in force and torque outputs at long muscle lengths, and throughout the entire range of motion (111, 268). Yet, these observations are countered by Trezise et al. (359), who reported that proximal quadriceps cross-sectional area was the best predictor of isometric (R^2 = 0.59) and concentric (R^2 = 0.58) torque production. Additionally, a recent investigation reported that the increase in proximal vastus lateralis cross-sectional area and PA was the best, albeit weak (R^2 = 0.27), predictor for the increase in isometric torque following 10 weeks of resistance training (359).

While the aforementioned findings are fascinating, most correlational studies do not examine force throughout the range of motion (13, 33, 73, 99), or only report peak concentric torque (48, 360). These limitations leave many questions unanswered as understanding force production at specific joint angles is required for optimal performance or injury prevention (100, 211); which is among the reasons why assessing force production at short, medium, and long muscle lengths have become increasingly common (265, 268, 360). Additionally, other factors, including FL and PA, are often missing from analyses (33, 99). One potential reason for the lack of length-tension, torque-angle, and complete regional muscle size and architectural assessments included in correlational investigations is the noticeable lack of data providing multiple reliability statistics over several sessions. Furthermore, to our knowledge, none of the previously cited correlational analyses have utilized a homogenous resistance-trained population. Given the aforementioned research and limitations, the purpose of this study was two-fold; 1) to determine the intersession reliability of regional quadriceps anatomy, and multi-angle maximal voluntary isometric torque (MVIT), and 2) investigate the ability of regional quadriceps MT, PA, and FL to predict MVIT at three knee joint angles in resistance-trained men.

Materials and Methods

Experimental design

Using a repeated measures design, we examined measures of regional quadriceps anatomical parameters and MVIT at a range of joint angles. At each session, an ultrasonographic assessment of regional quadriceps MT, PA, and FL, followed by an isometric assessment of MVIT at 40º, 70º, and 100º of knee flexion (0º = full extension) was completed. Each participant was tested on three separate occasions, separated by 5-8 days.

Participants

Twenty-four healthy males (28.5 ± 4.7 years, 180.1 ± 7.7 cm, 81.6 ± 11.8 kg) volunteered for this study. All participants were required to have at least six months of resistance training experience (6.73 ± 4.83, range = 1-18 years) with at least two weekly sessions of lower-body resistance training (2.54 ± 0.75, range = 2-4 sessions·week^{-1}) and be free of any musculoskeletal injuries for at least three months before data collection. Participants were instructed to maintain their current level of physical activity throughout the data collection period apart from refraining from strenuous physical activity, alcohol, caffeine, and other ergogenic aids for at least 48 hours before each session. The Auckland University of Technology Research Ethics Committee approved the study (18/232), and all subjects provided written informed consent.

Testing procedures

Ultrasonography

All ultrasound images were collected using the same transducer and built-in software (45 mm linear array, GE Healthcare, Vivid S5, Chicago, IL). Ultrasound settings (frequency, 12 MHz; brightness, maximum; gain, 60 dB; dynamic range, 70; depth, individualized) were recorded and kept consistent across all sessions. All assessments were performed by the same sonographer with ~3 years of experience. Upon arrival, participants were positioned in a supine position on a massage table for 15 minutes, to allow for fluid re-distribution (374). The participants remained in a supine position with knees and hips fully extended with a foot strap used to prevent excessive external rotation (267). During this period, the participants had each thigh measured and marked by an ISAK level-2 anthropometrist. The length of the lateral aspect of the thigh was determined by measuring the distance from the superior border of the greater trochanter to the inferior border of the lateral condyle of the femur. The anterior aspect of the thigh was determined by measuring the distance between the superior border of the patella and the inferior border of the anterior, superior iliac spine (250). Thigh lengths were recorded, and markings were made at 30% (proximal), 50% (middle), and 70% (distal) of the lateral and anterior distances, respectively (267). The vastus lateralis was marked by determining the most lateral aspect of the thigh (Figure 15A). Participants were instructed to briefly tense the quadriceps so that the researcher could mark the rectus femoris (Figure 15B). Pilot testing with our resistance-trained male cohort determined that extended field-of-view scans of the vastus intermedius were not consistently clear. Thus, scanning depths were adjusted to only capture the vastus lateralis and rectus femoris muscles. The vastus medialis was excluded as it can be further broken down into the obliquus and longus portions, with deep and superficial fiber bundles (63). Furthermore, MT of the vastus medialis oblique and longus have substantially smaller correlations with magnetic resonance imaging derived cross-sectional area when compared to the vastus lateralis or rectus femoris (124). MT and PA of the vastus lateralis and lateral vastus intermedius, and the rectus femoris and anterior vastus intermedius were collected in the same snap-shot images, respectively. Typical proximal, middle, and distal lateral and anterior images are provided in Figure 16.

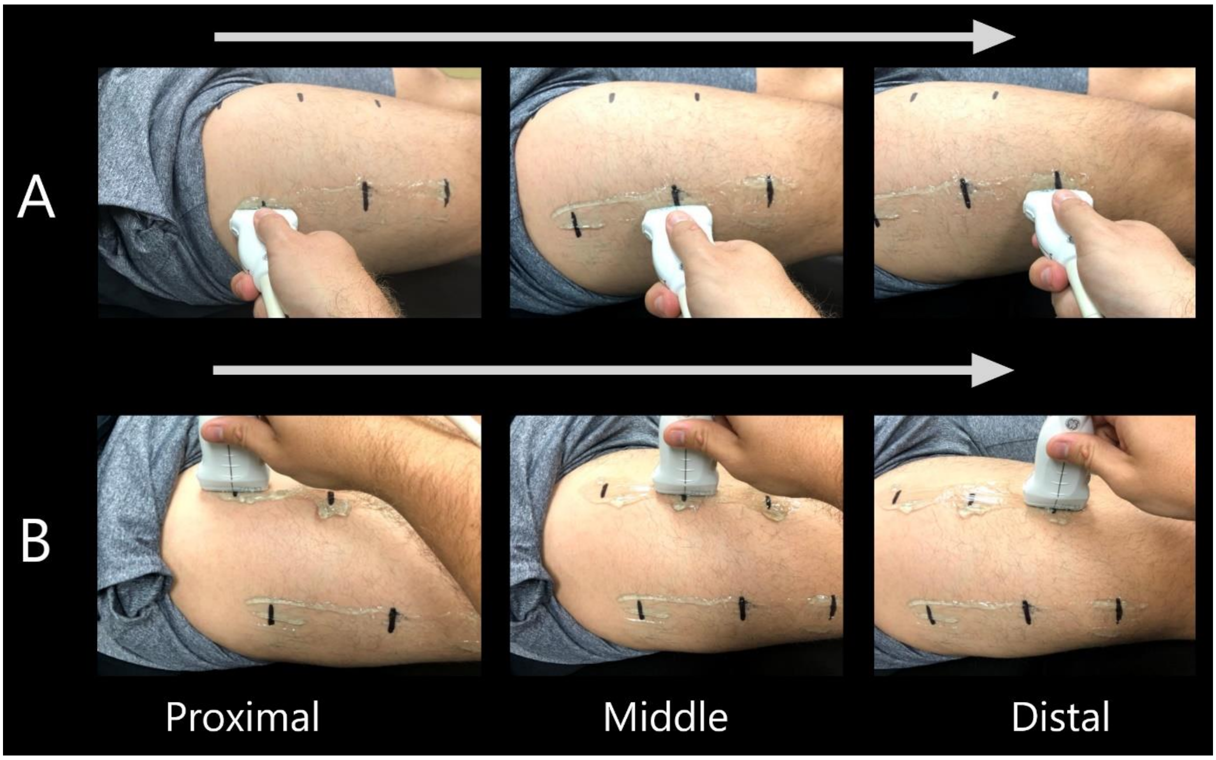

Figure 15. Markings and scanning probe position for the lateral (panel A) and anterior (panel B) quadriceps femoris. Arrows illustrate the direction of extended field-of-view probe sweep. Images provided courtesy of Dr. Matt Stock (University of Central Florida).

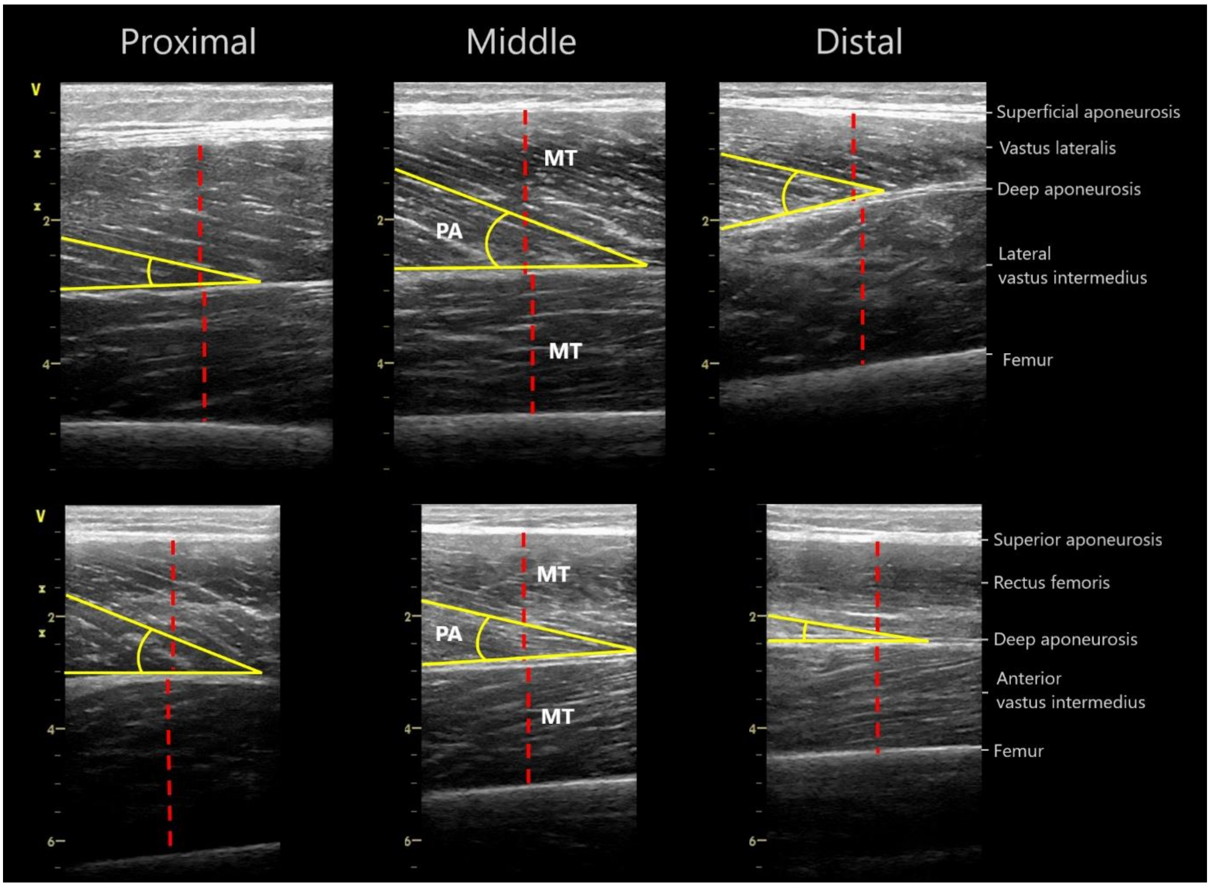

Figure 16. Representative proximal, middle, and distal B-mode ultrasound images of the lateral (top) and anterior (bottom) quadriceps muscles. MT = muscle thickness. PA = pennation angle.

Fascicle length was measured by the extended field-of-view function as extensively detailed previously (252, 263). The ultrasound probe was moved across a muscle, while a texture mapping algorithm merged the sequence of images into a composite image (110, 252). A water-soluble gel was applied to the scanning head of the ultrasound probe to achieve acoustic coupling, with care taken to avoid tissue deformation (110, 252, 263). The probe was oriented perpendicular to the skin and parallel to the estimated fascicle direction (110, 252, 263). Two images were captured for each region or extended field-of-view scan. Two measures (MT, PA, FL) were quantified for each image and averaged. The mean from both images was averaged to give a mean MT, PA, and FL for subsequent analysis (263).

Isometric dynamometry

Following the ultrasonographic assessment, participants warmed up by cycling at low to moderate resistance using a self-selected pace for five minutes (269). Subjects were seated on the isokinetic dynamometer (CSMi; Lumex, Ronkonkoma, NY) at a hip angle of 85°, with shoulder, waist, and thigh straps to reduce body movement during contractions (265, 269). The shin-pad was positioned ~5 cm superior to the ankle joint malleoli (269). Subjects were required to hold handles at the sides of the chair, while the non-working limb was positioned behind a restraining pad (269). Knee alignment was determined by visual inspection and unloaded knee extensions. Dynamometer settings were recorded and matched for subsequent sessions.

Once fitted to the dynamometer, subjects underwent a series of extensions and flexions of the knee to determine safety stop positions and calibrate gravity correction (269). Subjects then completed a standardized warmup of concentric contractions of 30%, 50%, 70%, 85%, and 100% of perceived MVIT (269). One minute after the completion of the warmup contractions, the participants' knee was positioned at 40º of flexion, where one familiarization isometric knee extension at 50% of perceived MVIT was performed (269). Sixty seconds later, two maximal contractions lasting four seconds were completed with 30 seconds separating each contraction (269). Participants were instructed to contract "as fast and hard as possible," following a countdown of "3-2-1-go!" (215, 269). All participants were given strong verbal encouragement along with visual feedback of the force-time tracing during each trial (215, 269). Participants were instructed to avoid any pre-tension and countermovement of the knee extensors, while the live force-time trace was carefully inspected by the examiner leading up to each contraction (215, 269). The cut-off for pre-tension was set at 10 N (269). Any contractions with a countermovement or an unsteady baseline were rejected and repeated (215, 269). The participants then completed the same series at 70º and 100º of knee flexion. The isometric contractions were always performed in series from 40º to 100º to avoid greater muscle damage and fatigue synonymous with long muscle length contractions (250). Ten minutes following the final isometric contraction, the concentric warm-up, and isometric assessments were repeated on the opposite limb. Limb order was randomized throughout the testing sessions and counterbalanced over the participant group. All contractions were collected, without filtering, via a custom-made software (LabVIEW; National Instruments, New Zealand) sampling at 2000 Hz (215, 269).

Data processing and analysis

Ultrasonography

Images were stored and analyzed via digitizing software (ImageJ; National Institutes of Health). Muscle thickness (cm) was defined as the perpendicular distance between the deep and superficial aponeurosis, and PA was defined as the angle of the fascicles relative to the deep aponeurosis (110, 263). Due to the depth of the muscle, the fascicles on the lateral and anterior vastus intermedius were not consistently visible (263). Therefore, PA and FL were not recorded for the lateral and anterior vastus intermedius. As the rectus femoris is complex, in that there are distinctly different directions of pennation (250), only 23/48 of distal rectus femoris FL measurements were able to be determined. Representative vastus lateralis and rectus femoris extended field-of-view images are illustrated in Figure 17A and B, respectfully. Anatomical variables were averaged across all sessions to reduce errors arising from sonography or participant variability.

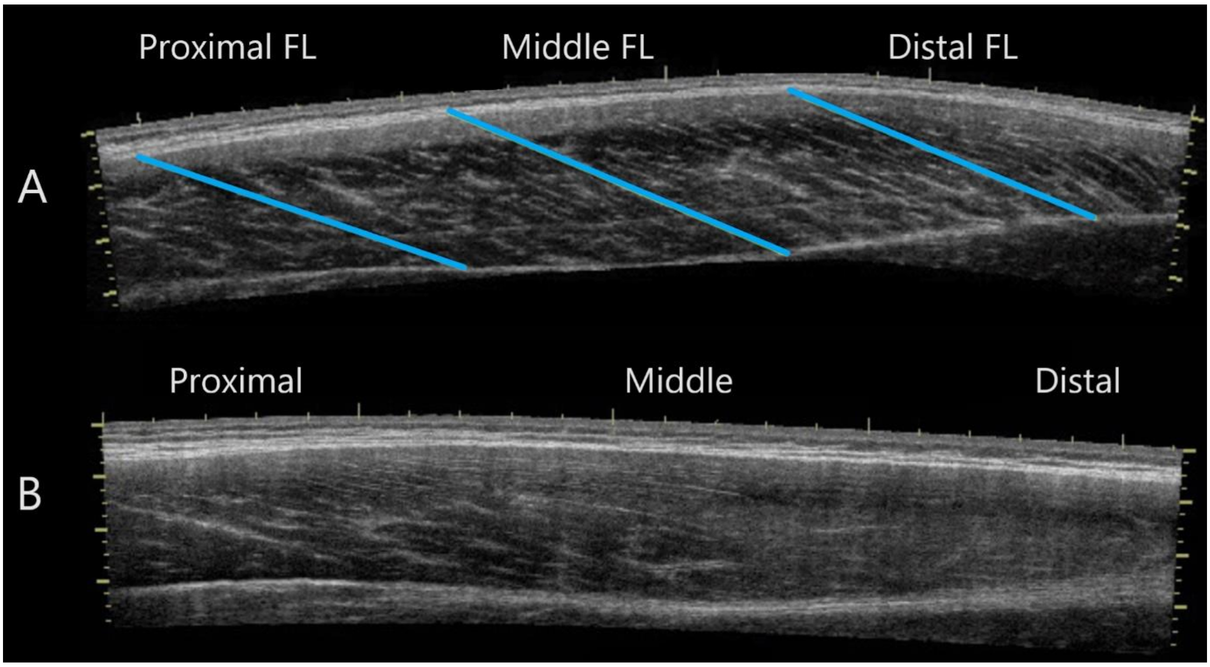

Figure 17. Representative extended field-of-view images of the vastus lateralis with proximal, middle, and distal fascicle lengths (A). Typical extended field-of-view image of the rectus femoris (B); note the lack of discernible fascicles towards the distal region. FL = fascicle length.

Isometric dynamometry

Data were analyzed via a customized MATLAB (MathWorks, Natick, MA) script. As the moment arm substantially affects isometric outputs (133, 374), all torque data were divided by the length of the dynamometer arm, in meters, to normalize the difference in shank length between participants (269). Thus, all MVIT data are reported in newtons (N). Normalized MVITs over 200 N were identified to signify a full contraction and eliminate false contractions (269). A peak detection algorithm was implemented to detect and identify the instantaneous peak torque of each contraction (269). The contraction with the highest instantaneous peak torque was analyzed to minimize issues of voluntary activation. The maximum values of MVIT across the three sessions were utilized to reduce error arising from submaximal voluntary activation.

Statistical analysis

Reliability

Measures of MVIT, MT, and FL were log-transformed before analysis to reduce non-uniformity of error (149, 152) and analyzed with an Excel spreadsheet (150). To reduce bias in the correlations between variables, only measures with sufficiently high intersession reliability were included in the correlational analysis. Since the mean or maximum of the three sessions was used in the correlation analysis, the relevant measure of reliability was the square root of the intraclass correlation coefficient (√ICC) of the mean of the three sessions (152). A value of √ICC > 0.90 (corresponding to between-session ICC > 0.60) was considered sufficiently reliable since any correlation with the variable would be biased downward by a factor of 0.90 at most (152). For comparison with other studies, the between-session typical error of measurement (TEM) was also analyzed and expressed as a percentage for MVIT, MT, and FL (149, 152). TEM is expressed in degrees for PA, as there is an upper limit of 90º, and unlike other measures, it would not be expected for error to change with increasing or decreasing values (149, 152).

While not a primary aim of the study, the variability of intra-image measures (e.g., the variability of two proximal vastus lateralis FL measures in the same image) was performed to determine variations in quadriceps anatomy across regions and muscles. The same procedure and interpretation as the intrasession reliability analysis. Intra-image variability statistics were not analyzed for MVIT as the greatest value, regardless of contraction or session were utilized for the correlational analysis.

Correlational analysis

As the primary goal of this study was to examine the effects of regional quadriceps anatomy on MVIT, a measure was included only if it was sufficiently reliable in all three regions (proximal, middle, distal) and knee joint angles (40º, 70º, 100º). Simple linear regressions were used to predict angle specific MVIT with anatomical parameters in isolation (e.g., distal vastus lateralis MT). Multiple linear regressions were used to predict MVIT with anatomical variables from a single muscle and region (e.g., distal vastus lateralis MT + distal vastus lateralis PA + distal vastus lateralis FL), with lateral or anterior compartments (e.g., distal vastus lateralis MT + distal vastus lateralis PA + distal vastus lateralis FL + distal lateral vastus intermedius MT), and finally, with region across all muscles (e.g., distal vastus lateralis MT + distal vastus lateralis PA + distal vastus lateralis FL + distal lateral vastus intermedius MT + distal rectus femoris MT+distal anterior vastus intermedius MT).

All regression analyses were performed with Proc Reg in the Statistical Analysis Software (University Edition of SAS Studio, version 9.4, SAS Institute, Cary NC). Measures of the ability of the regression models to predict torque were the multiple R (the correlation between observed and predicted values), $\sqrt{R^2}$ (equivalent to the absolute value of Pearson's *r* for a single predictor), and the adjusted multiple R (the square-root of the R-squared, $\sqrt{adjR^2}$, adjusted for degrees of freedom). The adjustment removes the upward bias in the R-squared that occurs when any predictor is added to a model with a finite sample size. Negative values of $adjR^2$ were expressed as negative correlations by changing the sign before taking the square root. Effects (adjusted multiple R, their means, and their differences) are presented with the qualitative magnitude of their observed (sample) value and interpreted as trivial, small, moderate, large, very large, and extremely large for values < 0.10, ≥ 0.10, ≥ 0.30, ≥ 0.50, ≥ 0.70, and ≥ 0.90 respectively (152).

Sampling uncertainty in the estimates of effects is presented as 90% compatibility limits (90%CL), which were estimated from percentiles of the effects in 10,000 bootstrapped samples (152). The bootstrapped effects were estimated initially by performing multiple linear regression with each bootstrapped sample, but the median values of the effects were substantially higher than those in the original sample. Therefore, values in the bootstrapped samples were derived as follows: the regression coefficients in the original sample were used to predict the dependent variable in each bootstrapped sample; the correlation between the predicted and observed values of the dependent variable in each sample was squared and adjusted for degrees of freedom; the square root of this adjusted R-squared then provided values of adjusted multiple R, which showed close agreement between the original and bootstrapped median values. As a further check on the adequacy of this bootstrap method, the analyses were performed on simulated data with a sample size of 24 and population simple correlations between a dependent variable and two predictor variables in two limbs. One hundred analyses each of 10,000 bootstrap samples were performed for correlations ranging from 0.00 to 0.70. Observed and median adjusted multiple R showed a downward bias of 0.05 to 0.10 for true correlations of 0.00-0.30, 0.04 for true correlations of 0.50, and only 0.02 for true correlations of 0.70. Despite the bias, 90%CLs showed less than the 10% expected error rate in their coverage of low values of true correlations and a slightly higher error rate (~12%) for true correlations of 0.50 and 0.70. The bootstrapping was therefore judged to be trustworthy (152).

The non-clinical version of magnitude-based decisions with a minimally informative prior was used to interpret the uncertainty in effect magnitudes (151). Chances that the true magnitude was a substantial negative value, a trivial value, and a substantially positive value were derived directly from the bootstrapped samples as the proportion of sample values with those magnitudes. Effects were deemed to be clear (to have adequate precision) if the chances of one or other substantial true values were < 5% (i.e., the 90%CLs did not include substantial positive and negative values). Clear effects are reported with a qualitative descriptor for the magnitude with chances > 25% using the following scale: > 25%, possibly (*); > 75%, likely (**); > 95%, very likely (***); and > 99.5%, most likely (****) (152). When the chances of a substantial or trivial magnitude were > 95%, the magnitude itself is described as clear. Effects with inadequate precision are described as unclear. Effects with adequate precision defined by 99% compatibility intervals are highlighted in **bold** in tables and figures; the overall error rate for coverage of 10 independent true values with such intervals is that of a single effect with a 90%CL, and interpretation of outcomes are focused on these effects.

Results

Reliability

Intersession

Assessments of the thickness of all muscles were reliable (√ICC = 0.97-1.00, TEM = 1.9-6%), regardless of limb or region. Similarly, vastus lateralis PA was reliable (√ICC = 0.90-0.92, TEM = 1.1-2.3º) regardless of limb or region. However, rectus femoris PA showed large variability at the distal region of both limbs (√ICC = 0.88-0.89, TEM = 1.5-1.9º) and in the middle of the dominant limb (√ICC = 0.87, TEM = 2.4º). Therefore, rectus femoris PA was not included in the correlational analysis. Vastus lateralis FL was reliable (√ICC = 0.95-0.97, TEM = 3.9-7.7%), regardless of limb or region. However, rectus femoris FL could only be confidently identified in 11 of 24 participants in all limbs and regions across all three sessions.

Therefore, intra-image and intersession statistics were not calculated, and rectus femoris FL was not included in the correlational analysis. Finally, MVIT was reliable (√ICC = 0.94-0.98, TEM = 6.8-12.1%), across all limbs and joint angles.

Intra-image

Intra-image MT were nearly identical (√ICC = 0.98-1.00, TEM = 0.8-1.9%), regardless of limb, muscle, or region. When comparing two fascicles per image vastus lateralis PAs were similar (√ICC = 0.94-0.98, TEM = 2.2-4.7º) regardless of limb or region. However, intra-image rectus femoris PA was increasingly variable as measures moved distally (proximal: (√ICC = 0.94-0.96, TEM = 2.4-5.4º; middle: √ICC = 0.91-0.94, TEM = 2.6-5.0º; distal: √ICC = 0.87-0.90, TEM = 2.0-3.9º), regardless of limb. Conversely, intra-image vastus lateralis FL was more variable at the proximal (√ICC = 0.87-0.90, TEM = 7.8-9.2%) and distal (√ICC = 0.89-0.93, TEM = 6.7-8.9%) regions when compared to the middle (√ICC = 0.93-0.94, TEM = 5.5-8.0%).

Correlational analysis

Mean regional anatomical measures are summarized in **Appendix 5**. Peak normalized MVIT for the dominant and non-dominant limbs were 684±129 N and 644 ± 142 N at 40º, 910 ± 205 N and 855 ± 180 N at 70º, and 740 ± 184 N and 714 ± 133 N at 100º, respectively. All between-limb differences in predictive ability were unclear, or possibly small; therefore, all correlations are presented after pooling dominant and non-dominant limbs.

Simple linear regressions

Correlations and bootstrapped 90%CLs of individual measures of regional muscle anatomy with MVIT at 40º, 70º, and 100º of knee flexion are presented in Figure 18. Vastus lateralis MT ($\sqrt{adjR^2}$ = 0.18-0.64) and FL ($\sqrt{adjR^2}$ = 0.29-0.60) had small to large correlations, while PA had trivial to small ($\sqrt{adjR^2}$ = -0.08-0.34) correlations with MVIT, regardless of joint angle. Correlations between MVIT and rectus femoris ($\sqrt{adjR^2}$ = -0.01-0.49) lateral ($\sqrt{adjR^2}$ = 0.23-0.58) and anterior vastus intermedius MT ($\sqrt{adjR^2}$ = 0.06-0.32) were trivial to moderate, small to large, and trivial to moderate, respectively. The largest simple correlation was between middle vastus lateralis MT and MVIT at 100° of knee flexion ($\sqrt{adjR^2}$ = 0.64), with distal vastus lateralis MT having the greatest mean correlation with MVIT ($\sqrt{adjR^2}$ = 0.61 ± 0.05).

Conversely, proximal vastus lateralis PA had the smallest mean correlation with MVIT ($\sqrt{adjR^2}$ = -0.05 ± 0.03).

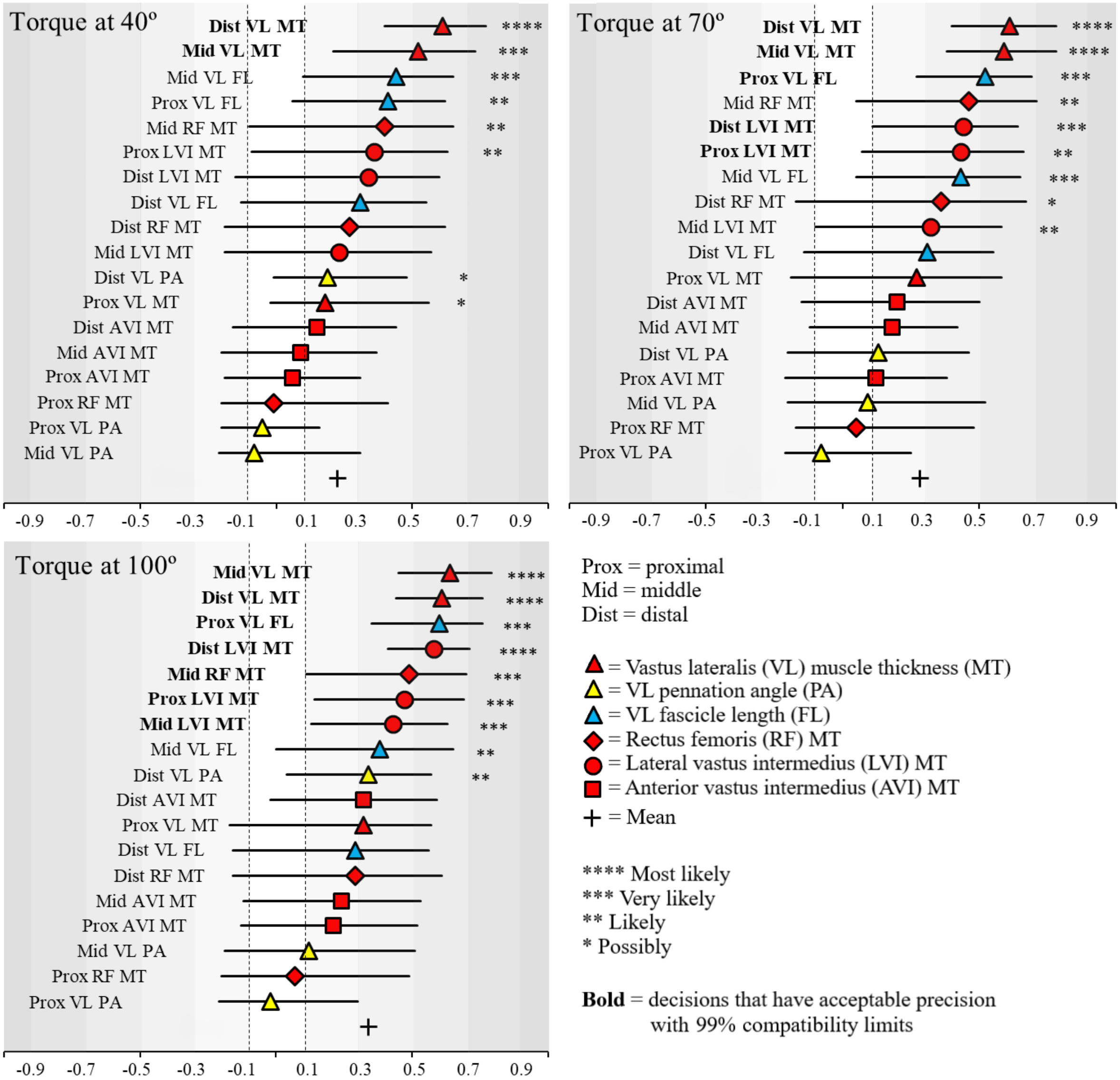

Figure 18. Adjusted simple correlations with bootstrapped 90% compatibility limits of normalized maximal voluntary isometric torque at 40°, 70°, and 100° of knee flexion with regional quadriceps architecture.

Between-region differences in simple correlations are presented in **Appendix 6**. Distal and middle vastus lateralis MT had likely or very likely higher correlations with MVIT than proximal vastus lateralis MT ($\Delta\sqrt{adjR^2}$ = 0.29-0.43). Distal vastus lateralis PA had a likely greater correlation with MVIT at 100° than proximal PA ($\Delta\sqrt{adjR^2}$ = 0.37). Conversely, proximal vastus lateralis FL had a likely greater correlation with MVIT at 100° than distal FL ($\Delta\sqrt{adjR^2}$ = 0.31). Middle rectus femoris MT had likely greater correlations with MVIT than proximal rectus femoris MT (Δ√adjR^2 = 0.41-0.43). Distal lateral vastus intermedius MT had a likely greater correlation with MVIT at 100º than middle vastus intermedius MT (Δ√adjR^2 = 0.15). All other between-region differences were unclear, or possibly small.

Multiple linear regressions

Between-region differences in multiple linear regression correlations with angle-specific MVIT are presented in **Appendix 7**.

All multiple linear regressions of the vastus lateralis MT, PA, and FL combination were likely, very likely, or most likely moderate to large (√adjR^2 = 0.41-0.66) (Table 15). The largest correlation was always found in the distal region; however, substantial between-region differences were only likely between distal and proximal regions at 40º (Δ√adjR^2 = 0.25), with all other comparisons being unclear, or possibly small (Δ√adjR^2 = 0.03-0.19).

Table 15. Multiple correlations (√R^2) and adjusted multiple correlations (√adjR^2), with compatibility limits and magnitude-based decisions, between normalized maximal voluntary isometric torque and combined regional quadriceps measures (MT + PA + FL).

Joint angle	Region	√R^2	√adjR^2 (90%CL)	Decision
40º	Proximal	0.53	0.41 (-0.06, 0.65)	Moderate**
	Middle	0.67	0.59 (0.20, 0.76)	Large***
	Distal	0.71	0.66 (0.44, 0.82)	**Large******
70º	Proximal	0.57	0.47 (0.05, 0.68)	Moderate**
	Middle	0.66	0.58 (0.19, 0.75)	Large***
	Distal	0.69	0.65 (0.41, 0.81)	**Large******
100º	Proximal	0.61	0.56 (0.16, 0.76)	Large***
	Middle	0.67	0.62 (0.36, 0.77)	**Large*****
	Distal	0.68	0.65 (0.50, 0.78)	**Large******

MT = muscle thickness. PA = pennation angle. FL = fascicle length. 90%CL = 90% compatibility limits. * = possibly. ** = likely. *** = very likely. **** = most likely substantial. Decisions in **bold** have acceptable precision with 99% CLs.

Multiple linear regressions of lateral quadriceps anatomy were always greatest in the distal region (Table 16). Distal had likely larger correlations with MVIT at 40º and 70º than the proximal region (Δ√adjR^2 = 0.20-0.25), while all other between-region comparisons were unclear or possibly small (Δ√adjR^2 = 0.05-0.18).

Table 16. Multiple correlations (√R^2) and adjusted multiple correlations (√adjR^2), with compatibility limits and magnitude-based decisions, between normalized maximal voluntary isometric torque and combined regional quadriceps measures (VLMT + PA + FL + LVIMT).

Joint angle	Region	√R^2	√adjR^2 (90%CL)	Decision
40°	Proximal	0.56	0.40 (-0.15, 0.66)	*Moderate*
	Middle	0.68	0.58 (0.13-0.76)	**Large*****
	Distal	0.72	0.65 (0.02-0.73)	Large**
70°	Proximal	0.60	0.48 (0.03, 0.70)	Moderate**
	Middle	0.68	0.58 (0.14, 0.76)	**Large*****
	Distal	0.73	0.68 (0.48, 0.83)	**Large******
100°	Proximal	0.65	0.59 (0.26, 0.77)	**Large*****
	Middle	0.72	0.64 (0.39, 0.78)	**Large******
	Distal	0.73	0.69 (0.55, 0.81)	**Large******

VL = vastus lateralis. LVI = lateral vastus intermedius. MT = muscle thickness. PA = pennation angle. FL = fascicle length. CL = compatibility limits. * = possibly. ** = likely. *** = very likely. **** = most likely substantial. Decisions in **bold** have acceptable precision with 99% CLs. *Italicized* decisions are unclear.

The combinations of lateral, and anterior quadriceps MT are presented in Table 17. Distal lateral MT was always largely correlated to MVIT (√adjR^2 = 0.59-0.68) and had likely greater correlations with MVIT than proximal lateral MT at all three joint-angles (Δ√adjR^2 = 0.20-0.23). Conversely, middle anterior MT was likely moderately correlated with MVIT at 70º and 100º (√adjR^2 = 0.42-0.49), while all other correlations were unclear. Middle anterior MT had likely moderate-largely greater correlations than proximal anterior MT when predicting MVIT at 40º (Δ√adjR^2 = 0.56), 70º (Δ√adjR^2 = 0.46), and 100º (Δ√adjR^2 = 0.35). Comparisons between lateral and anterior MT are presented in **Appendix 8**. Lateral MT had likely moderate-largely greater correlations with MVIT at 40º ($\Delta\sqrt{adjR^2}$ = 0.57 (proximal) and 0.42 (distal)), 70º ($\Delta\sqrt{adjR^2}$ = 0.47 (proximal) and 0.33 (distal)), and 100º ($\Delta\sqrt{adjR^2}$ = 0.35 (distal)) than anterior MT.

Table 17. Multiple correlations (√R^2) and adjusted multiple correlations (√adjR^2), with compatibility limits and magnitude-based decisions, between normalized maximal voluntary isometric torque and combined regional muscle thickness.

Lateral (VLMT + LVIMT)				
Joint angle	Region	√R^2	√adjR^2 (90%CL)	Decision
40°	Proximal	0.48	0.36 (-0.07, 0.62)	Moderate**
	Middle	0.57	0.49 (0.12, 0.72)	**Moderate*****
	Distal	0.64	0.59 (0.34, 0.76)	**Large*****
70°	Proximal	0.54	0.43 (0.01, 0.66)	Moderate**
	Middle	0.64	0.58 (0.37, 0.75)	**Large*****
	Distal	0.67	0.63 (0.42, 0.78)	**Large******
100°	Proximal	0.59	0.48 (0.08, 0.70)	**Moderate****
	Middle	0.70	0.65 (0.46, 0.80)	**Large******
	Distal	0.72	0.68 (0.52, 0.81)	**Large******
Anterior (RFMT + AVIMT)				
Joint angle	Region	√R^2	√adjR^2 (90%CL)	Decision
40°	Proximal	0.22	-0.21 (-0.30, 0.37)	*Small*
	Middle	0.44	0.35 (-0.25, 0.62)	*Moderate*
	Distal	0.33	0.17 (-0.29, 0.59)	*Small*
70°	Proximal	0.24	-0.04 (-0.28, 0.41)	*Trivial*
	Middle	0.49	0.42 (-0.07, 0.79)	Moderate**
	Distal	0.39	0.30 (-0.28, 0.64)	*Moderate*
100°	Proximal	0.34	0.14 (-0.27, 0.45)	*Small*
	Middle	0.54	0.49 (0.07, 0.70)	Moderate**
	Distal	0.41	0.32 (-0.25, 0.64)	*Moderate*

VL = vastus lateralis. LVI = lateral vastus intermedius. RF = rectus femoris. AVI = anterior vastus intermedius.MT = muscle thickness. CL = compatibility limits. * = possibly. ** = likely. *** = very likely. **** = most likely substantial. Decisions in **bold** have acceptable precision with 99% CLs. *Italicized* decisions are unclear.

When combining all variables by region the greatest correlations were exclusively found at the distal region, with likely small differences between the distal and proximal regions at 40º ($\Delta\sqrt{adjR^2}$ = 0.37) and 70º ($\Delta\sqrt{adjR^2}$ = 0.25) (Table 18).

Table 18. Multiple correlations ($\sqrt{R^2}$) and adjusted multiple correlations ($\sqrt{adjR^2}$), with compatibility limits and magnitude-based decisions, between normalized maximal voluntary isometric torque and combined regional quadriceps measures (VLMT + PA + FL + LVIMT + RFMT + AVIMT).

Joint angle	Region	$\sqrt{R^2}$	$\sqrt{adjR^2}$ (90%CL)	Decision
40°	Proximal	0.56	0.26 (-0.39, 0.61)	*Small*
	Middle	0.68	0.51 (-0.12, 0.73)	*Large*
	Distal	0.73	0.63 (0.21, 0.81)	**Large*****
70°	Proximal	0.62	0.41 (-0.10, 0.67)	*Moderate*
	Middle	0.69	0.53 (0.01, 0.74)	Large**
	Distal	0.74	0.66 (0.42, 0.82)	**Large*****
100°	Proximal	0.67	0.54 (0.07, 0.75)	**Large******
	Middle	0.72	0.61 (0.23, 0.76)	**Large*****
	Distal	0.74	0.66 (0.49, 0.80)	**Large******

VL = vastus lateralis. LVI = lateral vastus intermedius. RF = rectus femoris. AVI = anterior lateral vastus intermedius. MT = muscle thickness. PA = pennation angle. FL = fascicle length. CL = compatibility limits. * = possibly. ** = likely. *** = very likely. **** = most likely substantial. Decisions in **bold** have acceptable precision with 99% CLs. *Italicized* decisions are unclear.

Finally, regardless of model, single, and multiple correlations were greatest for MVIT at 100º ($\sqrt{adjR^2}$ = 0.35 ± 0.19, $\sqrt{R^2}$ = 0.63 ± 0.12, $\sqrt{adjR^2}$ = 0.55 ± 0.15), and decreased at 70º ($\sqrt{adjR^2}$ = 0.30 ± 0.20, $\sqrt{R^2}$ = 0.60 ± 0.14, $\sqrt{adjR^2}$ = 0.49 ± 0.18) and 40º ($\sqrt{adjR^2}$ = 0.25 ± 20, $\sqrt{R^2}$ = 0.57 ± 0.15, $\sqrt{adjR^2}$ = 0.43 ± 0.23). However, the differences were either unclear or possibly-likely trivial-small, except for a moderate likely higher correlation between proximal anterior MT and MVIT at 100º versus 40º ($\Delta\sqrt{(adjR^2)}$ = 0.35; 90%CL = 0.03, 0.69).

Discussion

While several studies have examined the relationship between anatomy and performance, none have investigated the role of regional quadriceps anatomical parameters on isometric muscle function at more than one joint angle. Additionally, none of the relevant literature has reported measurement reliability over multiple sessions. Therefore, we aimed to determine intersession reliability and investigate the role of regional quadriceps MT, PA, and FL on MVIT at multiple joint angles. The main findings were: 1) while MT had high intersession reliability regardless of muscle, region, or limb dominance, PA and FL could only be confidently assessed in the vastus lateralis; 2) the middle and distal regions of the quadriceps had larger correlations to MVIT than the proximal region with regards to predicting MVIT, especially at 40º; 3) the lateral quadriceps MT had larger correlations with MVIT at all angles when compared to anterior quadriceps MT; and, 4) the ability of quadriceps anatomy to predict MVIT increased as muscle length increased. While not a primary aim, we determined that the proximal and distal vastus lateralis FLs had greater intra-region variability compared to the middle regions, while intra-region rectus femoris PA was greatest at the distal region.

To be confident in our correlational findings, intersession reliability determination of our measures was a priority. While MT was highly reliable regardless of muscle, region, or limb, only vastus lateralis PA and FL could be included in our models. Additionally, MVIT had low intersession reliability at all joint angles in both dominant and non-dominant limbs. Several correlational studies have reported intrasession (6, 48, 73, 177, 247) or intersession reliability (13, 213, 360), while others fail to report any test-retest data (190, 368). Furthermore, none have reported all measures, over three sessions, with their full sample size. For example, while Trezise, Collier, and Blazevich (360) examined an impressive sample size of 56 men, only 10 returned for a re-test. Similarly, nine participants were tested a second time by Ando et al. (13). More importantly, both studies reported the pooled intersession ICC for all muscles and regions, making it impossible to know the test-retest statistics of each variable (13, 360), adding uncertainty to their primary results. It must be noted intersession reliability of ultrasonographic measurements relates primarily to technician-related error and that our results should not be applied to other studies.

Middle and distal quadriceps anatomy generally had greater simple and multiple correlations to MVIT when compared to the proximal region (see Appendices 6 and 7), except for proximal and middle vastus lateralis FL having a likely greater correlation with MVIT at 100º than distal FL (*r* = 0.31). With regards to region, our finding is similar to Ando et al. (13) who found the middle anterior vastus intermedius (*r* = 0.74) to be the only MT measurements to reach large, or very large correlations with knee extensor force at 90º. However, the investigation of Ando et al. (13) should be interpreted with caution due to a sample of N = 11 (106). Conversely, our results conflict with Trezise, Collier, and Blazevich (360) who reported "proximal" quadriceps cross-sectional area have the single largest correlation (*r* = 0.77) to maximal concentric and MVIT, with slightly lower correlations at "middle" (*r* = 0.72) and "distal" (*r* = 0.69) regions. It is important to note that quadriceps cross-sectional area was obtained at 50% (proximal), 40% (middle), and 30% (distal) of thigh-length by these authors (360), making their "proximal" region more comparable to our mid-region. It is also worth considering that the one-dimensional measure of MT does not account for muscle shape, whereas cross-sectional area accounts for shape in two-dimensions. Trezise, Collier, and Blazevich's (360) sample was a mixture of endurance runners, weightlifters, recreationally-trained, and untrained participants, whereas the present cohort was only resistance-trained men. While Maden-Wilkinson et al. (213) recently reported little difference in the percent of the maximal cross-sectional area across regions of the thigh between trained and untrained participants, several interventions have shown greater hypertrophy at the distal or middle, versus proximal regions of muscle following resistance-training (110, 268, 359). Therefore, the larger correlations in the middle and distal versus proximal regions in our study could be partially explained by training history.

Another key finding of this study was the substantially greater correlations between lateral MT and MVIT versus the anterior musculature (see Appendix 8). These findings align with Ando et al. (13), who reported a greater correlation between isometric force with the MT of the vastus lateralis (*r* = 0.43) than the rectus femoris (*r* = 0.19). However, Coratella et al. (73) recently reported similar correlations between mid-region vastus lateralis (*r* = 0.214) and rectus femoris (*r* = 0.211) MT, and late-stage rate of force development at 90º of knee flexion. Unfortunately, correlations with peak force were not reported, making direct comparison difficult (73). Furthermore, the vastus lateralis accounts for a substantially greater portion of the total quadriceps size than the rectus femoris (177, 213, 250, 337), almost certainly leading to greater contribution to knee-extension performance. However, explaining the large discrepancy between lateral and anterior vastus intermedius correlation with MVIT is more difficult. Most of the related literature either pool multiple quadriceps muscles (177, 250, 360), utilize the total cross-sectional area (359), or do not specify if the vastus intermedius was scanned from the coronal or sagittal plane (73). Additionally, the only study reporting both lateral and anterior vastus intermedius MT had contradictory results to ours, with the anterior portion ($r = 0.74$) having a greater correlation to knee-extension force than the lateral ($r = 0.37$) (13). Other than the small sample size, Ando et al.'s (13) results may differ from ours as they assessed the quadriceps with the knee flexed at 90º. It is plausible that a difference in lateral and anterior vastus intermedius MT with a flexed knee may alter the relationship between structure and function (374).

While not changing with different joint angles, proximal vastus lateralis FL was more highly correlated with MVIT than distal FL. Although the regions examined by Trezise and colleagues (359, 360) differed from ours, they still reported increasing correlation coefficients between MVIT and FL as the measurements moved proximally, in agreement with the present findings. Conversely, Trezise, and colleagues (359, 360) found that vastus lateralis PA had greater correlations as the measures moved proximally, in conflict with the present study. Additionally, numerous studies have reported PA to be strongly correlated with sport or contractile performance (177, 359, 360, 379), whereas PA had only trivial to moderate correlations in ours. The reason for this discrepancy is difficult to determine as our inter-session and intra-image measures were highly repeatable. However, the substantial resistance training experience of our volunteers could have altered the relationships between regional vastus lateralis PA and knee-extension performance. Finally, minimal improvements in the regression models were found when examining vastus lateralis MT or cross-sectional area, with the incorporation of PA (359, 360); a phenomenon likely explained by PA tending to increase with MT; making its inclusion somewhat redundant.

The correlations between MVIT and quadriceps anatomy became larger as the joint angle increased from 40º, 70º, and 100º of knee flexion. Interestingly, vastus intermedius MT was one of the primary contributors to the observation (Figure 18). Indeed, Saito and Akima (303) examined the electrical activity of the four major quadriceps muscles during isometric contractions at 30º, 60º, and 90º of flexion and determined that vastus intermedius activation significantly increased with each joint angle, while vastus lateralis, rectus femoris and vastus medialis activity did not greatly differ throughout the range of motion (303). On a related note, researchers have suggested that the vastus intermedius undergoes greater mechanical strain and damage when compared to the vastus lateralis during lengthening contractions (12, 121), likely due to the vastus intermedius fascicles directly attaching to the bone, whereas the vastus lateralis fascicles attach to the intermuscular aponeurosis (14). The exclusion of the vastus medialis is another potential reason for smaller correlations at 40º, as the vastus medialis has been shown to exhibit its greatest electrical activity during the final 60º of knee extension (324). Thus, the inclusion of the vastus medialis into our regression models may have resulted in more homogenous correlations between the assessed joint angles. While exhibiting only trivial to moderate correlations, vastus lateralis PA was another noticeable contributor to the greater correlations at increased joint angles, whereas the relationship between FL and MVIT did not change throughout the range of motion despite small to large simple correlations. This observation is difficult to explain as longer fascicles are theorized to increase shortening velocity and contractile force at longer muscle lengths (6, 190, 247), whereas, to the authors' knowledge, no studies have found PA to differentially affect performance at different joint angles. However, variable fascicle gearing theory and three-dimensional models of muscle contraction (27, 28, 297) may help in understanding the present findings. For example, Azizi and Roberts (28) report increased fascicle rotation, and architectural gearing ratios during lengthening versus shortening contractions. More simply, increases in muscle-tendon unit length were almost completely accommodated by PA increases, with minimal change in FL (28).

While not the primary intention of this study, several practical applications can be found. First, simple, and multiple correlations were consistently greater at 70º and 100º compared to 40º. The lateral musculature also had greater correlations with MVIT when compared to the anterior musculature. Similarly, middle, and distal anatomy had greater correlations when compared to the proximal region. As such, time and resource-poor researchers may wish to evaluate only the middle and distal regions of the lateral quadriceps when aiming to predict function.

Limitations and future research directions

While the aims of this study were achieved, there are several limitations to consider. Firstly, the use of surface or needle electromyography to determine individual muscle activation at different joint angles was not utilized; yet similar examinations have reported electromyography to have trivial to moderate correlations to isometric (359, 360) and cycling performance (177), and/or contributed little to multiple regression models (133, 359, 360). Similarly, we could only evaluate the voluntary efforts of our participants, and not the maximal potential of the quadriceps musculature through peripheral or transcranial stimulation techniques (176, 194). To partially address this we used the greatest MVIT outputs over the three collection sessions, and note that the literature has consistently reported isometric voluntary activation of the knee extensors of > 90% in healthy young men (176, 298, 360), with little difference in voluntary activation or electromyography amplitude with at different knee joint angles (20, 194). While the aforementioned strategy to maximize voluntary activation removes many limitations, the lack of joint angle order randomization may have led to the accumulation of non-trivial fatigue levels as contractions progressed from 40º to 100º of flexion.

Future research could include the knee joint moment arm, which can change through the range of motion (48, 360). Likewise, compression of the dynamometer padding means that the joint angles reported were likely overestimated. While the joint angles still corresponded to relatively short, medium, and long muscle lengths, researchers could utilize motion-capture or goniometric measurements to more precisely evaluate joint angles (20). Researchers may also wish to scan the quadriceps in the same position as the isometric strength assessment to better represent joint angle specific architecture. Though highly correlated with MT (109), assessments of cross-sectional area or muscle volume via magnetic resonance imaging, or panoramic or three-dimensional ultrasound may further uncover the relationship between form and function. More experienced sonographers could have consistently produced extended field-of-view rectus femoris and vastus intermedius FLs, allowing for further elucidation of the relationship between regional quadriceps anatomy and angle-specific torque. Similarly, performing several, smaller extended field-of-view scans may have allowed for improved rectus femoris imaging, and reduced intra-image variability of proximal and distal vastus lateralis FL. While several studies have examined inhomogeneous morphological and architectural adaptations, very few have evaluated more than two regions of an individual muscle (397). Therefore, we recommend that future investigations examine three or more regions to further illuminate the effect of training, or disuse on region specific muscle adaptations. Finally, similar research examining the effect of regional muscle anatomy in other populations, or on dynamic contractions, at several velocities, through a full range of motion, would be of interest.

Conclusions

This was the first study to examine the effect of regional quadriceps anatomy on the length-tension relationship. Our data demonstrated that the relative contribution of regional anatomical parameters to MVIT does not change at different joint angles. However, middle, and distal quadriceps characteristics were the strongest predictors of MVIT, apart from vastus lateralis FL, where proximal and mid-regions were greater. Researchers can utilize our findings to streamline evaluations of knee extensor performance and anatomy.

Section 4 – Short-term effects and biomechanical profiling of eccentric quasi-isometric resistance-exercise

Chapter 9 – Short-term neuromuscular, morphological, and architectural responses to eccentric quasi-isometric muscle actions

Reference

Oranchuk DJ, Nelson AR, Storey AG, Diewald SN, and Cronin JB. Short-term neuromuscular, morphological, and architectural responses to eccentric quasi-isometric muscle actions. *Eur J Appl Physiol* 121: 141-158, 2021.

Author contribution

Oranchuk DJ, 80%; Nelson AR, 6%; Storey AG, 4%; Diewald SN, 5%; Cronin JB, 5%.

Prelude

The literature reviews and methodological based chapters aimed to accumulate data and understand the effects of eccentric quasi-isometric adjacent exercise and training. However, to this point, there are no studies directly examining the physiological effects, or alterations in performance due to eccentric quasi-isometric loading. Therefore, the present chapter represents a culmination of the knowledge acquired throughout the previous sections of the thesis to robustly compare the short-term physiological effects of the novel isotonically loaded EQI contraction with the commonly employed isokinetic eccentric contraction.

Introduction

Novel volumes, intensities, and modes of exercise lead to muscle damage, characterized by acute reductions in neuromuscular output, delayed onset muscle soreness (DOMS), muscular swelling, and altered muscular mechanical properties (112, 275, 276, 280, 393). In addition to higher than normal volumes and intensities, fatigue, DOMS, and edema are highly dependent on contraction type as eccentric contractions have greater neurological and energy efficiency (93), and induce higher levels of muscle damage when compared to concentric or isometric muscle actions (69, 90, 275). The differential adaptations between eccentric and isometric and concentric contractions are probably due, at least in part, to the greater absolute and cumulative mechanical loading (i.e., force) that can be imparted on the musculotendinous unit (90). The excessive and unaccustomed loading induces a disruption in muscle cell membranes and individual sarcomeres (111) that may contribute to reduced neuromuscular outputs (90). For example, Peñailillo et al. (276) reported significantly greater reductions in peak force and rate of force development following eccentric vs concentric cycling. Similarly, ultrasound derived muscle thickness (MT) and echo intensity (EI) increased dramatically following eccentric exercise (62, 68, 69), and several studies have reported acute and chronic shifts in the torque-angle and length-tension relationships following eccentric loading (280, 322, 393).

In addition to large acute shifts in morphology, architecture, and neuromuscular function, eccentric resistance training is a time and energy-efficient means of triggering substantial chronic adaptations (90). For example, when compared to concentric contractions, maximal and submaximal eccentric resistance training may result in earlier recruitment of high threshold motor units (90, 93, 246) and increase fascicle length (FL) (111); theoretically underpinning greater maximal force expression and shifting the length-tension and torque-angle relationships to longer muscle lengths. However, while contraction mode appears to be an important factor in the aforementioned adaptations (111), a proposed mechanism whereby eccentric training induces greater neuromuscular adaptation is by allowing greater mechanical loading per contraction (90, 93). Thus, practitioners regularly search for practical and context-specific means to impart mechanical loading.

Isometric contractions can be performed at a variety of intensities and angles within a range of motion (ROM) and can be maintained for long periods (268). Thus, isometric resistance training is a safe, time-efficient, and effective means of imparting mechanical loading (268). However, adaptations from isometric training have a questionable transfer to dynamic tasks (268). Likewise, there are clear differences in neural control between traditional "pushing" (imparting force against an immovable object) and "holding" (resisting an external load) isometrics, also known as "yielding" or "quasi" isometrics (157, 299, 305, 333). For example, Schaefer et al. (305) examined pushing and holding isometric actions at 80% of maximal voluntary isometric torque (MVIT) and found that subjects could substantially increase their duration at the target force when pushing (41 ± 24 s vs 19 ± 8 s). Additionally, agonist activation at failure is greater when pushing (299), while co-activation of antagonist and synergist muscles is greater when holding (299, 305). However, holding isometrics are unlikely to trigger substantial morphological adaptations as the contractions are terminated at task-failure (157, 299, 305, 333). A contraction that involves both a holding isometric and eccentric type muscle activity has been termed eccentric quasi-isometric (EQI) (262, 378).

To perform an EQI contraction, an individual initiates a holding isometric muscle action and attempts to maintain the joint position for as long as possible, or for a prescribed duration, before voluntarily or non-voluntarily moving to another joint-angle or cessation of effort (262, 378). When holding a position as long as possible, fatigue accumulates whereby the isometric action transitions to an eccentric; this is then resisted as much as possible throughout the specified ROM (262). The extended time-under-tension, combined with slow velocities (65) and few total contractions theoretically allows for large quantities of muscular loading with reduced joint stress and DOMS (262, 378). While exercise variations, such as isometric (268), dynamic, eccentric, and concentric only training (65, 111, 275) at different velocities (65) and ROM (363) have been studied, the authors are unaware of any research examining EQI contractions. Therefore, we aimed to be the first to objectively determine EQI kinetics and compare the acute effects of a single bout of EQI and eccentric resistance exercise on DOMS, muscle morphology, and architecture and neuromuscular performance.

Methods

Experimental design

A within-participant, parallel conditions with repeated measures design was implemented to compare the acute effects and recovery from eccentric and EQI contractions on DOMS, muscle morphology, architecture, and neuromuscular performance. One week following a familiarization session, eccentric (ECC) and EQI conditions were unilaterally allocated to the right or left limb in a randomized and counterbalanced manner. Regional (proximal, middle, distal) quadriceps DOMS, muscle architecture, EI, and isokinetic torque-angle and multi-angle MVIT-time characteristics were evaluated via pressure-pain threshold, ultrasonography, and concentric and isometric dynamometry, respectively. All dependent variables were evaluated at seven time points; familiarization, immediately pre- and post-exercise (PRE and POST, respectively), and 24 h, 48 h, 72 h, and 7 d after exercise).

Participants

G*Power (v 3.1.9.4) was utilized to determine a priori sample size using a difference between two independent means statistical test with two tails. As such a minimum sample size of 13 limbs per condition was calculated to detect an effect size of 1.15, where $\alpha = 0.05$ and $1-\beta = 0.80$ based on the between-condition, PRE to POST decrements in MVIT published by Alemany et al. (10) and Doguet et al. (88). As we expected smaller between-condition changes, a total of 15 healthy, resistance-trained, males (26.4 ± 5.2 years, 179 ± 7.8 cm, and 81.5 ± 12.1 kg) were recruited, for this study. All participants had at least six months of resistance training experience (5.21 ± 4.1, range = 2-12 years) performing at least two weekly sessions of lower-body resistance training (2.48 ± 0.68 sessions$\cdot$week^{-1}; range = 2-4 sessions$\cdot$week^{-1}) and were free of any musculoskeletal injuries for at least three months before data collection. The Auckland University of Technology Research Ethics Committee approved the study (18/232), and all participants provided informed consent. All participants were instructed to refrain from strenuous physical activity, anti-inflammatory medication, recovery supplements, and practices such as foam rolling or heat or cold application throughout the single week study period. Additionally, alcohol, caffeine, and other ergogenic aids were forbidden in the 48 hours leading up to each session.

Testing procedures

All testing procedures were performed at each time point apart from the pressure-pain threshold, which was not evaluated POST. Testing was always performed in the same order (pressure-pain threshold, ultrasonography, and concentric and isometric dynamometry). The study and individual session timelines are summarized in Figure 19.

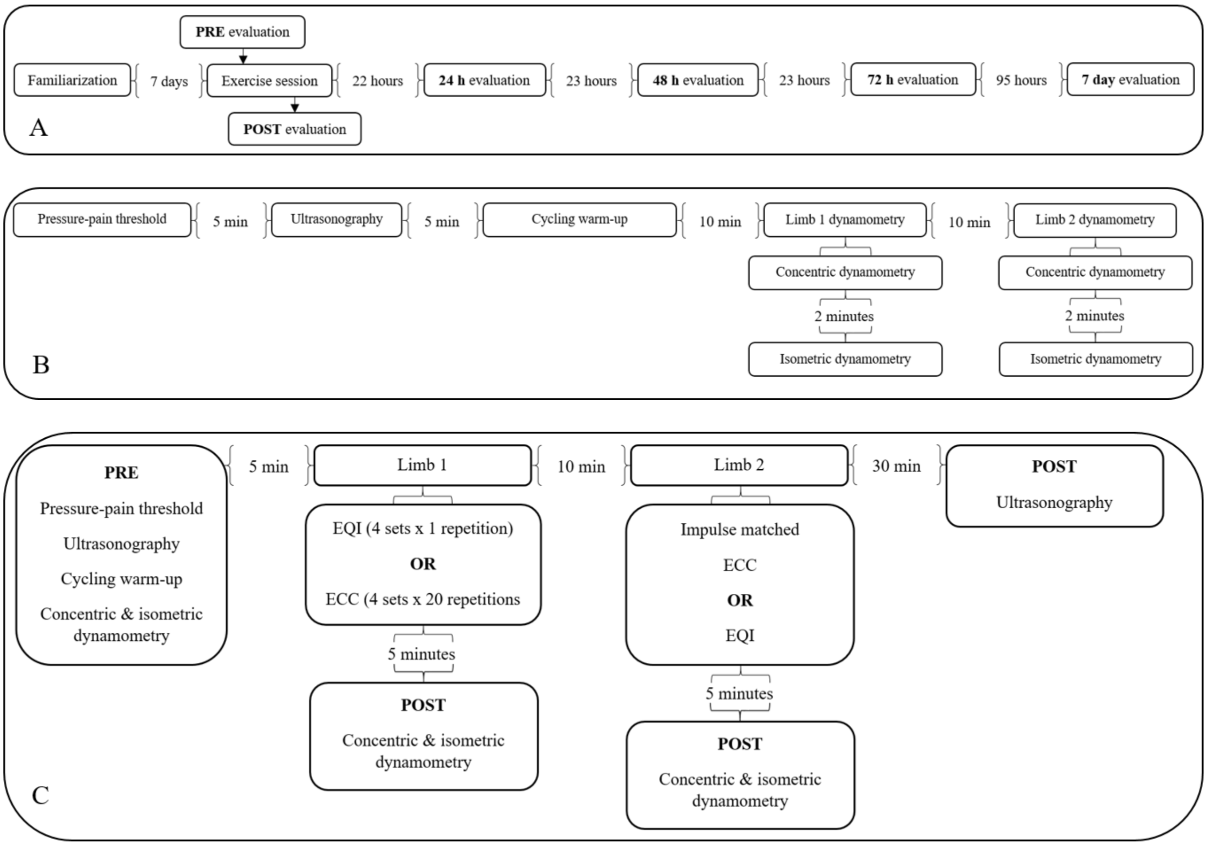

Figure 19. (A) Study timeline. (B) Evaluation session timeline. (C) Exercise session timeline.

Pressure-pain threshold

Upon arrival, participants were positioned supine on a massage table, with a foot strap used to prevent excessive leg external rotation (221). Each thigh was measured and marked by a certified ISAK level-2 anthropometrist. The length of the lateral aspect of the thigh was determined by measuring the distance from the superior border of the greater trochanter to the inferior border of the lateral condyle of the femur. The anterior aspect of the thigh was determined by measuring the distance between the superior border of the patella and the inferior border of the anterior, superior iliac spine. Thigh lengths were recorded, and markings were made at 30% (proximal), 50% (mid), and 70% (distal) of the lateral and anterior distances, respectively (221). A semi-permanent marker was used for markings, which participants were instructed to reapply each day. The sites were rechecked at each visit. The pressure-pain threshold was determined by an analog pressure algometer (FB5K, Imada CO, LTD, Japan), with a custom made 1.25 cm diameter head. The order of testing was always the same (i.e., right lateral, proximal, middle, distal; right anterior, proximal, middle, distal; left lateral, proximal, middle, distal; left anterior, proximal, middle, distal). The head of the algometer was gradually applied to each location until the participant verbally indicated when a sensation of pressure shifted into the slightest onset of pain, explained as a one on a ten-point visual analog scale (113). Each site was tested four times, separated by 10 seconds, before moving to the next site. Each of the four algometer applications was averaged. The intersession coefficient of variation (CV) of the proximal, middle, and distal vastus lateralis were 13.1%, 9.2%, and 8.5%, respectively; and proximal, middle, and distal rectus femoris were 10.2%, 9.1%, and 9.8%, respectively.

Ultrasonography

In-vivo regional MT and EI of the vastus lateralis, rectus femoris, and anterior and lateral vastus intermedius, and pennation angle (PA) of the vastus lateralis were determined via 2-dimensional B-mode snapshots using an ultrasound transducer (45 mm linear array, 12 MHz; GE Healthcare, Vivid S5, Chicago, IL). Regional FL was measured by the extended field-of-view function as detailed extensively elsewhere (110, 252). In brief, the ultrasound probe is moved across a muscle, while a texture mapping algorithm merges the sequence of images into a composite image. The same experienced sonographer performed all assessments. A water-soluble gel was applied to the scanning head of the ultrasound probe to achieve acoustic coupling, with care taken to avoid the deformation of muscle architecture. For all ultrasonographic assessments, the probe was oriented perpendicular to the skin and parallel to the estimated fascicle direction with care to avoid transducer tilt. The transducer was always positioned in the longitudinal plane to reduce the time required to collect ultrasound images, and as EI collected in the longitudinal and sagittal planes are highly correlated (376). Brightness, depth, gain, and dynamic range was recorded and simulated for each participant through all collections (62). On each occasion, two samples were captured and averaged to give a mean MT, PA, FL, and EI.

Concentric dynamometry

Following the ultrasonographic assessment, participants warmed up by cycling at low to moderate resistance using a self-selected pace for five minutes. Participants were seated upright on the isokinetic dynamometer (CSMi; Lumex, Ronkonkoma, NY, USA) at a hip angle of 85º, with shoulder, waist, and thigh straps to reduce body movement during contractions. The shin-pad was positioned ~5 cm superior to the medial ankle joint malleoli. Participants were required to hold handles at the sides of the chair, while the non-working limb was positioned behind a restraining pad. Knee alignment was determined by visual inspection, participant feedback, and unloaded knee extensions to ensure proper joint tracking. Dynamometer settings were recorded and matched for subsequent sessions.

Once fitted to the dynamometer, participants underwent a series of extensions and flexions of the knee to determine safety stop positions and calibrate gravity correction. Participants then completed a standardized warmup of concentric contractions of 30%, 50%, 70%, 85%, and 100% of perceived maximal voluntary contraction (265). One minute after the completion of the warmup contractions, participants completed five maximal concentric knee extensions in immediate succession at $60^{o}\cdot s^{-1}$ (265). Each contraction was initiated and terminated at 105° and 5° of knee-flexion (0º = full extension), respectively. Participants were given strong verbal encouragement along with visual feedback of the torque-time tracing during each maximal contraction.

Isometric dynamometry

Two minutes after the completion of the isokinetic assessment, the participants' knee was positioned at 40º of flexion, where one familiarization isometric knee extension at 50% of MVIT was performed (269). Following another 60 seconds of rest, two maximal isometric contractions lasting four seconds were completed with 30 seconds separating each contraction (269). Participants were instructed to contract "as fast and hard as possible," following a countdown of "3-2-1-go!" with strong verbal encouragement and visual feedback of the torque-time tracing during each trial (215). Participants were also instructed to avoid any pre-tension and countermovement of the knee extensors while the live torque-time trace was carefully inspected by the examiner leading up to each contraction. The cut-off for pre-tension was set at 10 Nm (269). Any contractions with a clear countermovement or an unsteady baseline were rejected and repeated (215). The participants then completed the same series at 70º and 100º of knee-flexion. The isometric contractions were always performed in series from short to long muscle length to avoid greater muscle damage and fatigue reported with contractions at long muscle length (250). Following the final isometric contraction, the isokinetic and isometric assessments were repeated on the opposite limb. Limb order was randomized throughout the three testing sessions and counterbalanced over the participant group. All isokinetic and isometric contractions were collected, without filtering, via a custom-made software (LabVIEW; National Instruments, New Zealand) sampling at 2000 Hz (215).

Exercise procedures

Both the ECC and EQI exercise protocols were performed on the same dynamometer as the evaluations. Five minutes after the isometric evaluations, participants began with either the ECC or EQI bout. Eccentric and EQI bouts were allocated to the participants' limbs in a randomized and counterbalanced manner. The exercise order was also randomized and counterbalanced. Five minutes after each exercise protocol was completed, the same limb performed the isokinetic and isometric evaluations. Ten minutes after the POST evaluation on the first limb, the second exercise protocol was initiated on the opposite limb. The POST ultrasonographic evaluation of each respective limb was performed 30 minutes after the completion of the isometric evaluation.

Eccentric contractions

Eccentric contractions were initiated and terminated at 30º and 110º of knee-flexion, respectively. Pilot testing established that approximately 20 maximal eccentric contractions were required to impulse-match a single EQI contraction. Thus, participants performed four sets of 20 maximal ECC contractions, with 180 seconds of rest between sets, when allocated before the EQI bout. When allocated after the EQI bout, ECC contractions were prescribed in sets of 20 contractions and continued with 180 seconds of rest between sets until the same total angular impulse (integral of knee extension torque over time; Nm·s) was matched to the EQI bout (322). The angular impulse was calculated in real-time by a custom-made software (LabVIEW; National Instruments, New Zealand) sampling at 500 Hz. The dynamometer was set at $60^{o} \cdot s^{-1}$, and each contraction was initiated when the participant achieved 30% of their MVIT at 40º from the PRE evaluation (322). Therefore, each contraction was started with proper pre-activation and muscle force (322). After each ECC contraction, the participant performed an unloaded concentric contraction to return to the 30º starting position. Participants performed five ECC contractions on each limb during the familiarization.

Eccentric quasi-isometric contractions

Eccentric quasi-isometric contractions were initiated and terminated at 30º and 110º of knee-flexion, respectively. Based on pilot testing, participants performed four EQI contractions when allocated before the ECC bout. When allocated after the ECC bout, EQI contractions were repeated until the same total angular impulse was matched to the ECC bout. The dynamometer was set to isotonic mode, and a load equivalent to 70% of each participants' highest MVIT at PRE, regardless of joint angle, was applied based on pilot testing and previously recommended (262). The isotonic load was gradually applied over two seconds. The participants were instructed not to exert enough effort as to cause a concentric contraction, but instead attempt to "brace" and "maintain joint position throughout the ROM" (262). Once the load was reached, the participant held the initial position until isometric failure, at which point slow and brief changes in joint angle occurred with the participant maintaining maximal effort throughout each contraction. While highly variable, many participants had several periods of near-zero changes in knee flexion, followed by periods of joint angle changes until the entire ROM was completed. After each EQI contraction, the participant rested for 180 seconds before performing an unloaded concentric contraction to return to the 30º starting position and initiate the subsequent contraction. Participants performed a single EQI contraction on each limb during the familiarization session.

Data processing and analysis

Ultrasonography

Images were stored and analyzed via digitizing software (ImageJ; National Institutes of Health, USA). Muscle thickness (cm) was defined as the perpendicular distance between the deep and superficial aponeurosis, and PA was defined as the angle of the fascicles relative to the deep aponeurosis (110, 263). Due to the depth of the muscle, the fascicles on the lateral and anterior vastus intermedius were not consistently visible (263). Therefore, PA and FL were not recorded for the lateral and anterior vastus intermedius. Additionally, PA and FL were not recorded for the rectus femoris due to large test-retest variability (263). Extended field-of-view FL was determined by meaning two fascicles from the most proximal, middle, and most distal portion of each scan. A typical PRE-POST extended field-of-view scan of the vastus lateralis is provided in Figure 20. For EI, the region of interest was defined as the perpendicular distance between the deep and superficial aponeurosis of each muscle and extended to each end of the B-mode image (62, 375). The polygon function was utilized, and great care was taken to ensure the broadest possible region of interest, without the inclusion of aponeurosis or bone (62, 375). The caliper function was utilized to assess the subcutaneous fat thickness of each image. Subcutaneous fat thickness was determined from the average of the proximal, middle, and distal values of each image (267). All images were inspected and analyzed by the sonographer. Corrected EI was calculated as uncorrected EI + (subcutaneous fat thickness [cm] × 40.5278) (395).

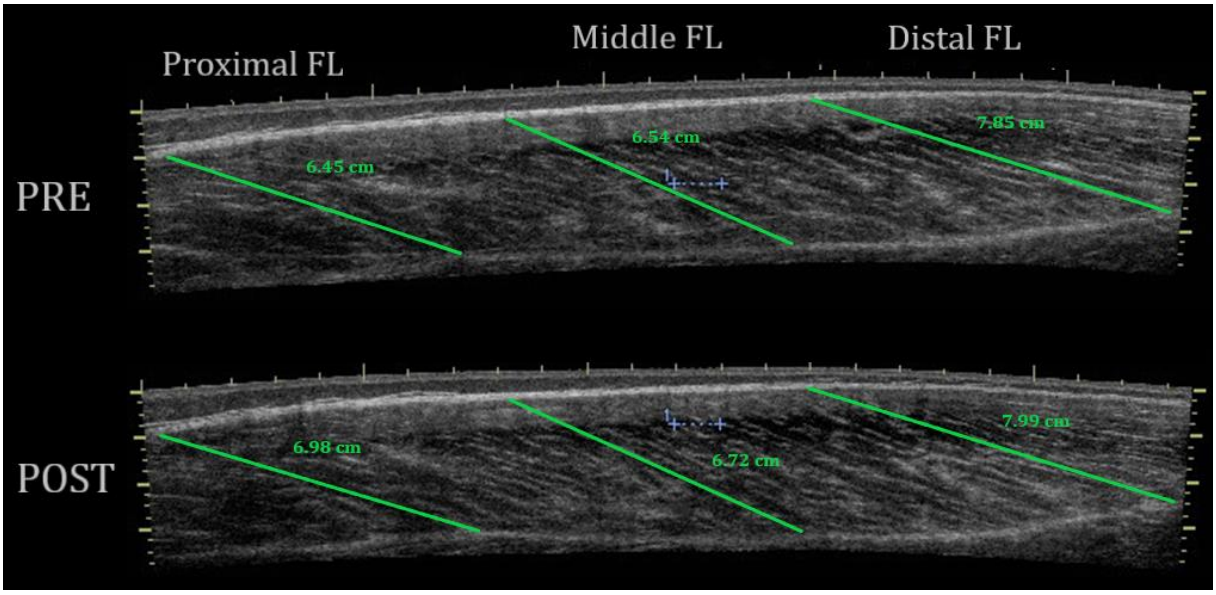

Figure 20. Representative extended field-of-view ultrasound evaluation of regional vastus lateralis fascicle length PRE and POST eccentric quasi-isometric condition. The dotted marker at the center of the images represents 1 cm.

We previously determined the intersession variability of ultrasound-derived measures in a similar population of resistance-trained men over three weeks in Chapters 4 and 5 (263, 267). For MT, the intersession CV of the respective proximal, middle, and distal regions of each muscle were: vastus lateralis = 3.1-3.4%, 2.4-3.0%, 3.8%; lateral vastus intermedius = 7.7-9.3%, 4.2-4.3%, 3.5-3.9%; rectus femoris = 2.7%, 2.7-3.2%, 3.7-4.1%; and anterior vastus lateralis = 2.8-3.0%, 5.0-5.7%, 3.1-3.4%. For vastus lateralis PA: 7.1-8.0%, 7.6-8.8%, and 6.0-6.9%, respectively. For vastus lateralis FL: 4.1-4.8%, 4.1-4.9%, and 4.7-6.6%, respectively. For corrected EI: vastus lateralis = 5.9-8.2%, 7.7-8.2%, 6.2-6.8%; lateral vastus intermedius = 8.0-8.9%, 9.6-11.9%, 11.3-14.7%; rectus femoris = 7.4-9.1%, 4.5-6.6%, 7.5-8.3%; and anterior vastus lateralis = 7.1-8.9%, 8.8-10.1%, 6.9-11.3%.

Concentric dynamometry

Data were analyzed via a customized MATLAB (MathWorks, Natick, MA) script. All torque data were divided by the length of the lever arm, in meters, to normalize the difference in shank length between participants (265). Each isokinetic contraction was analyzed by detecting and identifying the maximum (105°) and minimum (5°) angle that signified the start and end of each contraction. Peak concentric torque was detected as the highest instantaneous torque during the isovelocity phase between 105° and 5° of knee-flexion. The angular impulse was calculated as the area under the torque-time curve between each of the eight angles. Thus, total angular impulse throughout the entire ROM and between nine bands (100-90º, 90-80°, 80-70°, 70-60°, 60-50°, 50-40°, 40-30°, 30-20°, 20-10º) were calculated (265). Data from Chapter 6 had previously determined intersession (one week apart) variability of the aforementioned concentric evaluation following a familiarization session (265). Briefly, intersession CV of concentric peak torque and total concentric impulse was 6.3-7.4%, and 6.4-8.1%, respectively. The intersession CV of the nine aforementioned impulse bands were: 11%, 7.5%, 7.8%, 8.1%, 9%, 9.1%, 12.8%, 11.3%, and 12%, respectively.

Isometric dynamometry

Data were analyzed via a customized MATLAB (MathWorks, Natick, MA) script. Isometric torques over 200 Nm were identified to signify a full contraction and eliminate false contractions (269). A peak detection algorithm was implemented to detect and identify the instantaneous MVIT of each contraction (269). The onset of effort was determined via visual inspection and a manual section of each torque-time curve (215, 269). The same researcher determined the onset of effort by visually detecting the last trough before torque deflected above the range of the baseline noise (215, 269). Rate of torque development was calculated for 0-200 ms (RTD_{0-200}), based on the manual onset of effort detection (215, 269, 276). We had previously determined intersession (one week apart) variability of the isometric evaluation following familiarization (269). Chapter 7 determined the intersession CV of MVIT at 40º, 70º and 100º were 9.6%, 11.5%, and 8.5%, respectively. While intersession CV of RTD_{0-200} at 40º, 70º, and 100º were 15.6%, 14.9%, and 13%.

Eccentric contractions

Data were analyzed via a customized MATLAB (MathWorks, Natick, MA) script. Peak and mean eccentric torque, and total and angle specific angular impulse throughout each contraction and set were quantified. Changes in torque and impulse outputs throughout the ECC protocol were also quantified.

Eccentric quasi-isometric contractions

Data were analyzed via a customized MATLAB (MathWorks, Natick, MA) script. The EQI contractions were quantified by calculating the mean velocity throughout the ROM and in the ROM brackets of 30-40º, 40-50º, 50-60º, 60-70º, 70-80º, 80-90º, 90-100º and 100-110º.

Statistical analysis

Raw data are presented as mean and standard deviation. For comparisons, reference Bayesian inference with a uniform dispersed prior (magnitude-based decisions, MBD) was utilized (272). Between-condition changes were analyzed using a pre-post parallel-group trial spreadsheet (272). All variables were log-transformed for analysis, then back-transformed to express effects as factors, after adjustment for the modifying effects of the total impulse of each exercise condition. Change scores of the ECC and EQI conditions were compared at POST, 24 h, 48 h, 72 h, and 7 d post-exercise for all dependent variables. Uncertainty in the effects was expressed as 95% compatibility intervals (95%CI). Non-clinical MBD was used since neither ECC nor EQI contractions can be regarded as best-practice training. Magnitudes of the changes were assessed using standardized changes (Cohen's *d* effect size (ES)) of 0-0.20, 0.20-0.60, 0.60-1.20, 1.20-2.0 and 2.0-4.0 for small, moderate, large, very large and extremely large, respectively (152). Effects with 95%CIs overlapping both a substantial increase and decrease were deemed unclear; for clear effects, the likelihood that the true effect was substantial and/or trivial was indicated with the following scale: 25-75%, possibly (*); 75-95%, likely (**); 95-99.5%, very likely (***); > 99.5%, most likely (****) (152). Apart from group comparison at baseline, only between-condition differences where the 95%CI for the change score does not cross zero are reported in-text, due to the many dependent variables and time points. Between-condition % and ES differences with 95%CIs and the smallest important difference are presented in appendices.

Results

Thirteen participants completed all sessions, while two participants could not attend testing at the 72-h time point. Therefore, changes at 72 h included only individuals that were present at all time points.

Exercise sessions

Nearly identical (ES = 0.02) total impulses were observed for the ECC (32887 ± 16987 Nm·s) and EQI (33229 ± 17358 Nm·s) protocols, despite large inter-participant variability (Figure 21).

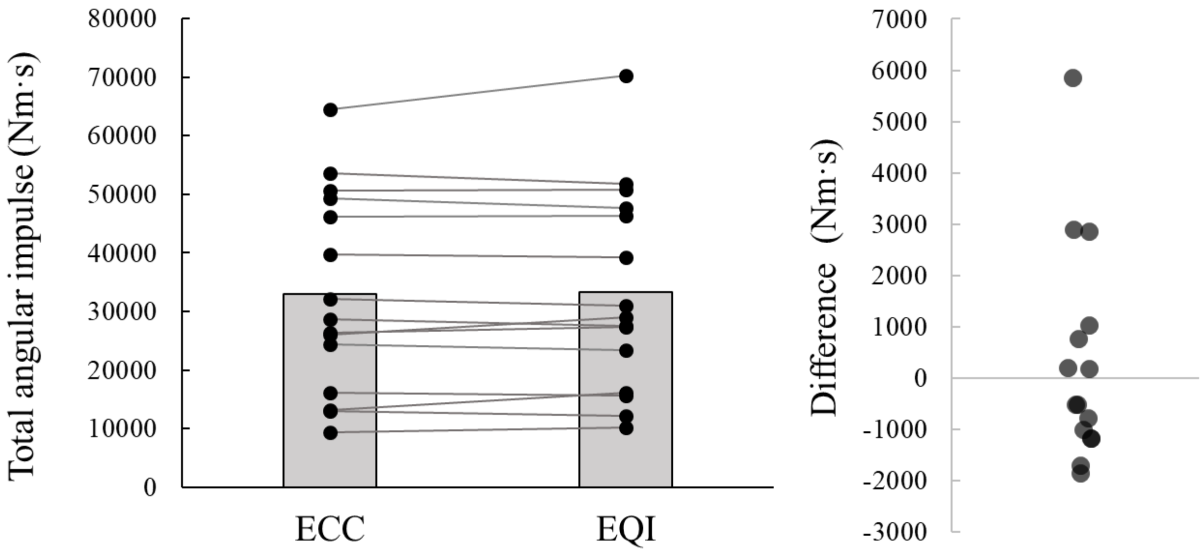

Figure 21. Individual participant total angular impulse for each exercise condition, and the impulse difference between conditions.

Eccentric protocol

Each participant completed 100.8 ± 54 eccentric contractions across 4.8 ± 2.5 (range = 2-10) sets. The mean set duration was 57 ± 7.5 seconds. Including the 180 second intra-set rest periods, the ECC protocol lasted 17.6 ± 8.3 (range = 5.2-31.3) minutes. Mean peak torque through all contractions were 215 ± 54 Nm. The total time-under-tension was 135 ± 72 s. Mean total angular impulse distribution across the ROM brackets is shown in Figure 22.

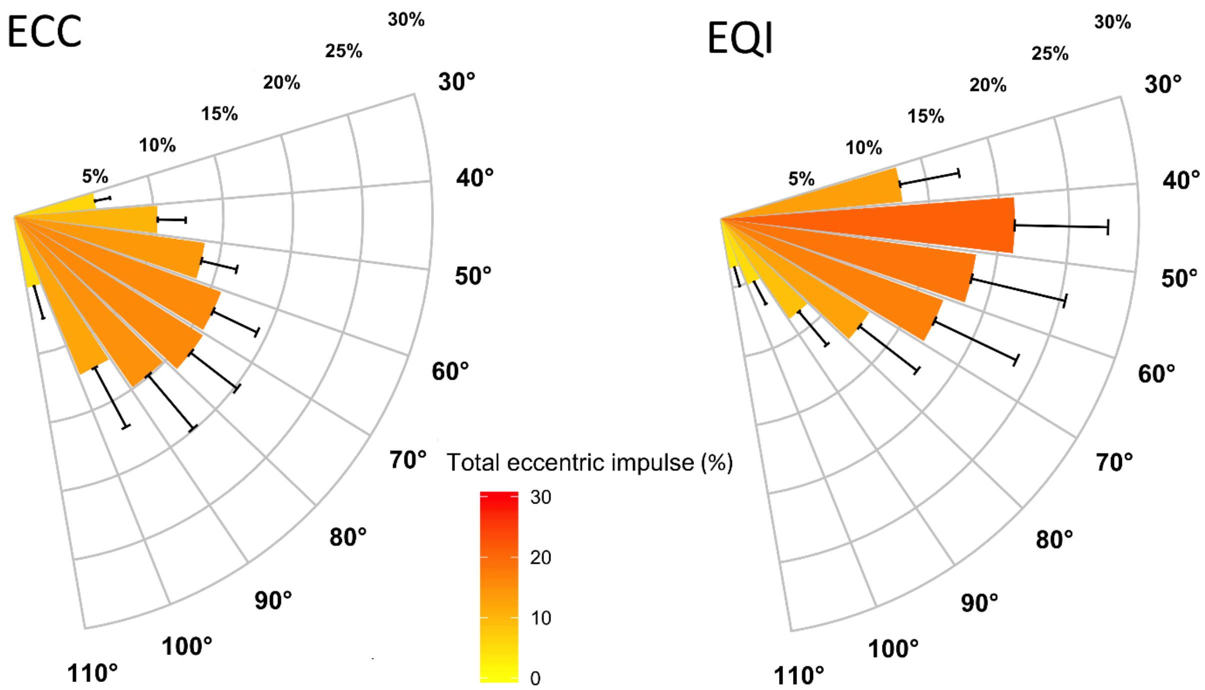

Figure 22. Mean percentage of total angular impulse through eight range of motion brackets during the eccentric (ECC) and eccentric quasi-isometric (EQI) bouts. Error bars denote the standard deviation.

Eccentric quasi-isometric protocol

Participants completed 3.85 ± 1.1 (range = 1-8) EQI contractions, isotonically loaded to 172 ± 41.5 Nm, with an average angular velocity of 1.29°·s^{-1}. Mean contraction duration was 62.1 ± 38 seconds with the longest and shortest contraction durations of 140 (the respective participants' first contraction) and 5.5 seconds (the respective participants' eighth contraction), respectively. Including 180-second intra-set rest periods, the EQI protocol lasted 13 ± 9.5 (range = 3.5-28.2) minutes. EQI mean duration across ROM brackets were: 30-40°: 8.9 ± 10.8 s; 40-50°: 14.6 ± 11.9 s; 50-60°: 11.1 ± 8.3 s; 60-70°: 9.3 ± 7.1 s; 70-80°: 7.0 ± 5.5 s; 80-90°: 5.6 ± 4.5 s; 90-100°: 3.5 ± 2.8 s; and 100-110°: 2 ± 2.4 s. The total time-under-tension was 242 ± 132 s. Mean total angular impulse distribution across the ROM brackets is shown in Figure 22.

Acute effects and recovery

Pressure-pain threshold

Six of 15 participants reported no pain at baseline with the maximum possible pressure. Therefore, these six individuals were not included in the statistical analysis for pressure-pain threshold as no baseline values were present Between-condition differences in pressure-pain threshold with 95%CIs are presented in **Appendix 9**. Except for the middle rectus femoris, possibly, likely, or very likely substantial differences in pressure-pain threshold were found at all muscles and regions except for the mid rectus femoris, with ECC resulting in greater reductions relative to EQI (Figure 23A-F).

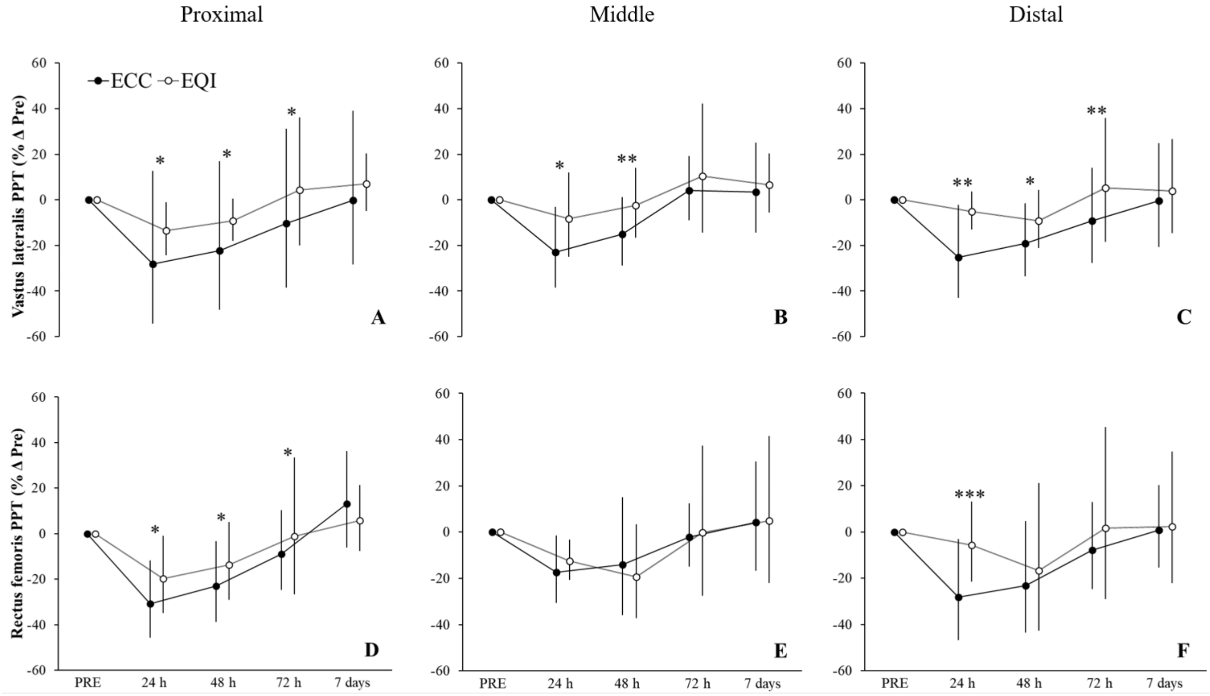

Figure 23. The region-specific pressure-pain threshold (PPT) of the vastus lateralis (panels A-C) and rectus femoris (panels D-F), before and following eccentric or eccentric quasi-isometric exercise. Likelihood of a substantial between-condition difference is indicated as *possibly; **likely; ***very likely; ****most likely. Error bars represent standard deviations.

Relative to EQI, the ECC condition resulted in small reductions in pressure-pain threshold for middle vastus lateralis at 24 h (*16.5%, ES = 0.32) and 48 h (**17.7%, ES = 0.33) (Figure 23B); distal vastus lateralis at 24 h (**25.9%, ES = 0.40) and 72 h (**15.8%, ES = 0.26) (Figure 23C); and distal rectus femoris at 24 h (***30.4%, ES = 0.54) (Figure 23F).

Muscle architecture

Between-condition differences in vastus lateralis MT with 95%CIs are presented in **Appendix 10**, and between-condition differences in PA and FL with 95%CIs presented in **Appendix 11**.

There were no clear substantial between-condition differences in the middle or distal vastus lateralis, distal lateral vastus intermedius, rectus femoris, or anterior vastus intermedius (Figure 24A-L). Relative to ECC, there were small increases in proximal lateral vastus intermedius MT with EQI at POST (**6.8%, ES = 0.28), 48 h (**7.1%; ES = 0.29), and 72 h (*5.1%, ES = 0.22) (Figure 24D).

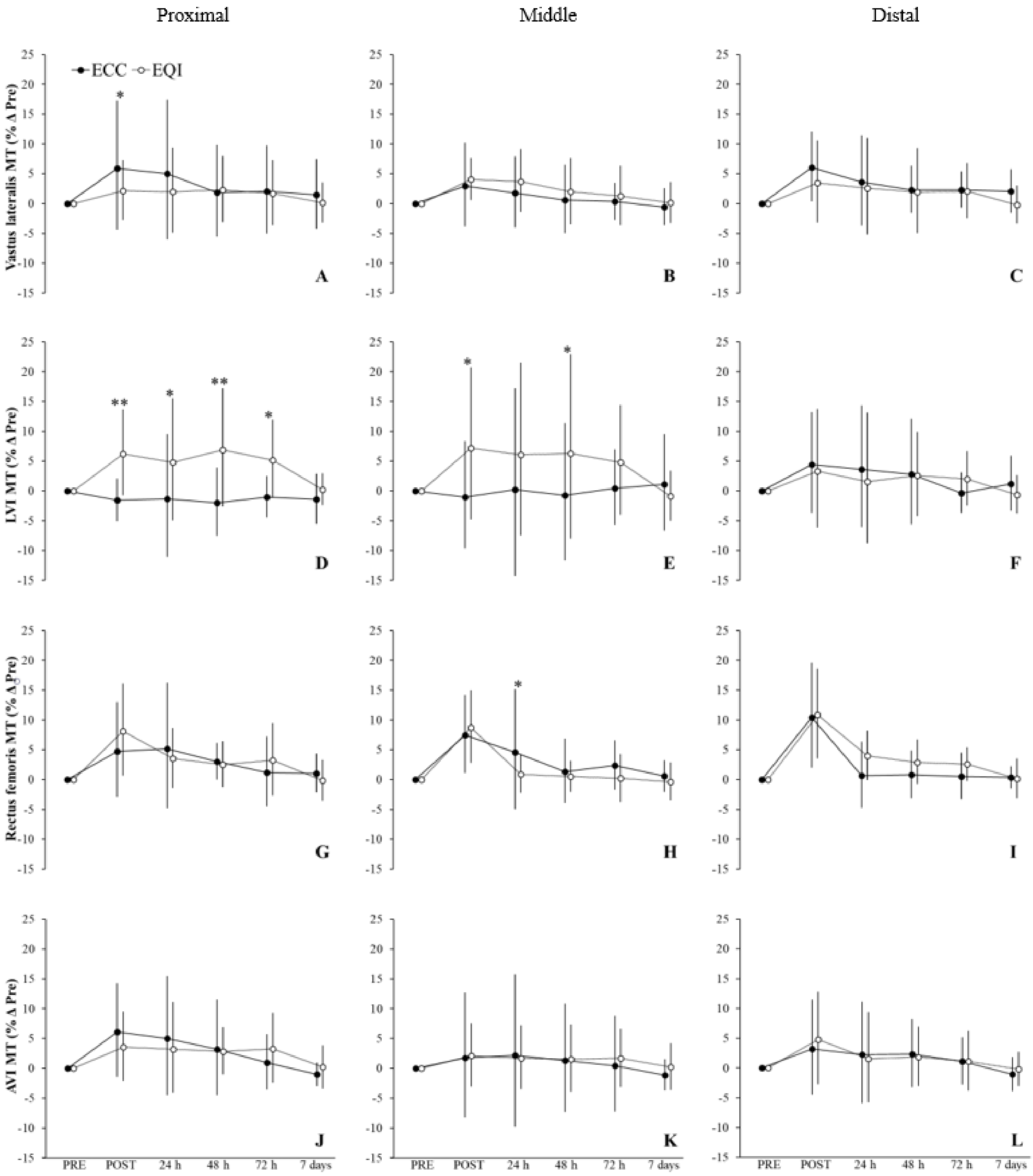

Figure 24. Region-specific muscle thickness (MT) of the vastus lateralis (panels A-C), lateral vastus intermedius (panels D-F), rectus femoris (panels G-I), and anterior vastus intermedius (panels J-L), before and following eccentric or eccentric quasi-isometric exercise. Likelihood of a substantial between-condition difference is indicated as *possibly; **likely; ***very likely; ****most likely. Error bars represent standard deviations.

Relative to ECC, there was a small decrease in distal vastus lateralis PA with EQI at POST (**8.7%, ES = 0.49). Relative to ECC, there were small to moderate decreases in proximal vastus lateralis fascicle length at POST (**6.2%, ES = 0.49) and 24 h (***8.3%, ES = 0.66), respectively. Conversely, EQI led to an increase in proximal rectus femoris FL at POST (***11%, ES = 0.64) and 24 h (**6%, ES = 0.36).

Echo intensity

Between-condition differences in EI with 95%CIs are presented in **Appendix 12**. There were possible to very likely greater EI increases following ECC versus EQI in 3/12 regions with a very likely increase in distal rectus femoris EI with ECC at POST (***8.3%, ES = 0.55).

Concentric performance

Between-condition differences in peak concentric torque, total angular impulse, and angle-specific torque with 95%CIs are presented in **Appendix 13**.

Relative to EQI, the ECC condition resulted in small to moderate reductions at POST in: peak torque (**8.7%, ES = 0.50) (Figure 25A); total angular impulse (**8.3%, ES = 0.45) (Figure 25B); and impulse 100-90º (***19.7%, ES = 0.57) (Figure 26C), 90-80º (***15.6%, ES = 0.60) (Figure 26D), 80-70º (**11.7%, ES = 0.56) (Figure 26E), 70-60º (**10.7%, ES = 0.58) (Figure 26F); and 60-50º (**10.5%, ES = 0.62) (Figure 26G).

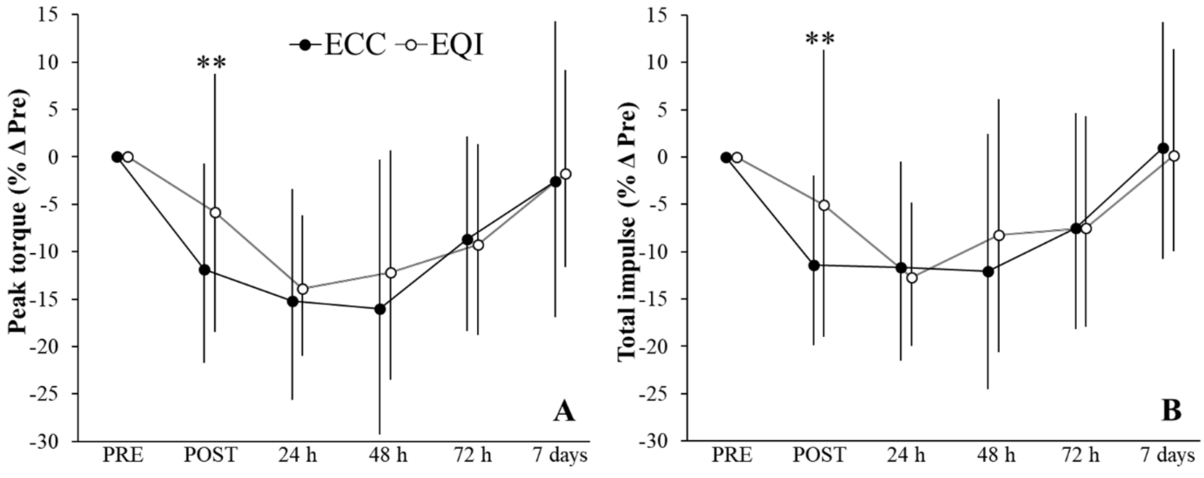

Figure 25. Concentric peak torque (panel A) and total concentric impulse (panel B) before and following eccentric or eccentric quasi-isometric exercise. Likelihood of a substantial between-condition difference is indicated as *possibly; **likely; ***very likely; ****most likely. Error bars represent standard deviations.

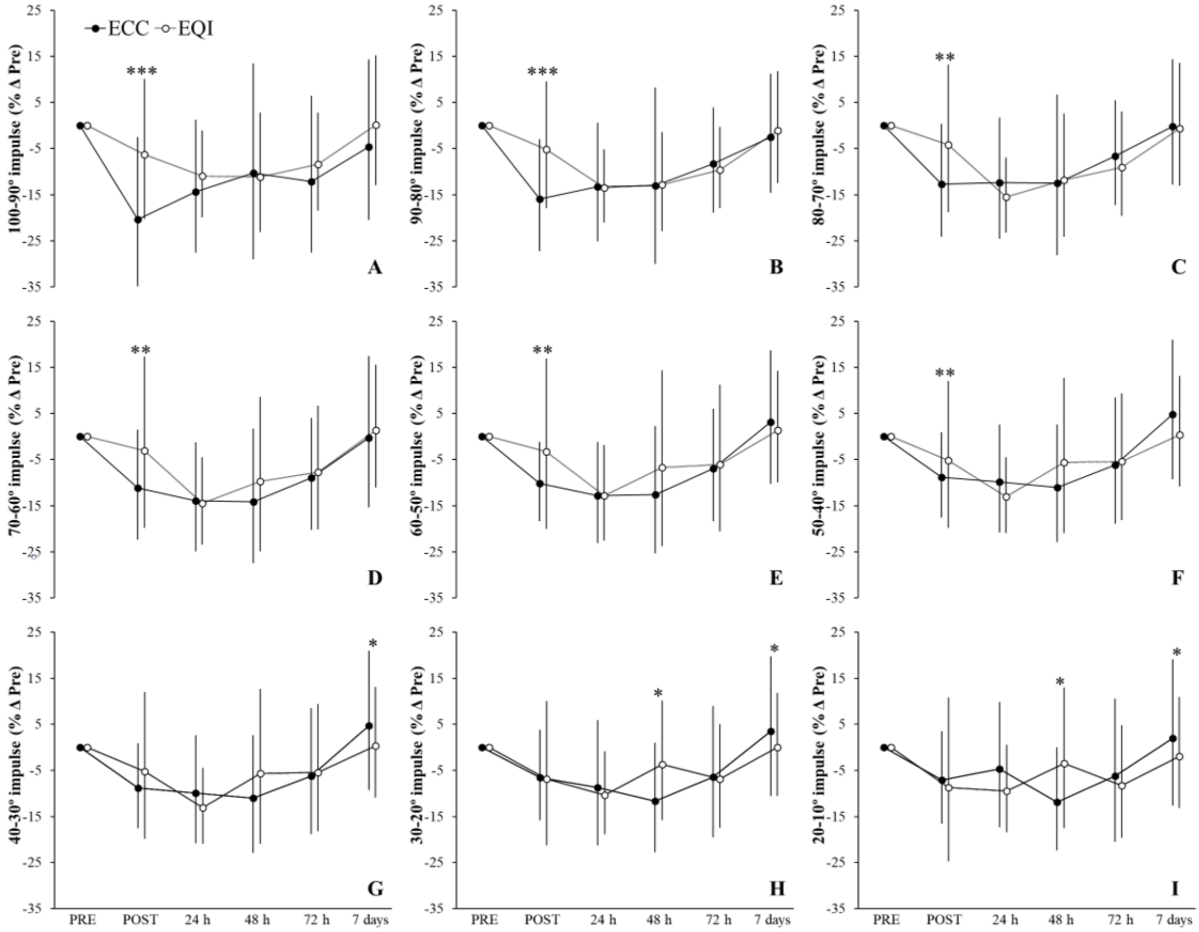

Figure 26. Concentric angle-specific impulse before and following eccentric or eccentric quasi-isometric exercise. Likelihood of a substantial between-condition difference is indicated as *possibly; **likely; ***very likely; ****most likely. Error bars represent standard deviations. Panels A, B, C, D, E, F, G, H and I, represent changes in concentric angular impulse from 100-90º, 90-80º, 80-70º, 70-60º, 60-50º, 50-40º, 40-30º, 30-20º, and 20-10º, respectively.

Isometric performance

Between-condition differences in MVIT and RTD_{0-200} with 95%CIs are presented in **Appendix 14**.

Relative to EQI, the ECC condition resulted in small reductions in MVIT at 70º (**10.4%, ES = 0.35) (Figure 27B) and 100º (**9.8%, ES = 0.39) (Figure 27C) at POST. Eccentric also resulted in small to moderate reductions in RTD_{0-200} at 70º at POST (****32.3%, ES = 0.70) (Figure 27E); and 100º at POST (**15.3%, ES = 0.42) (Figure 27F), relative to EQI.

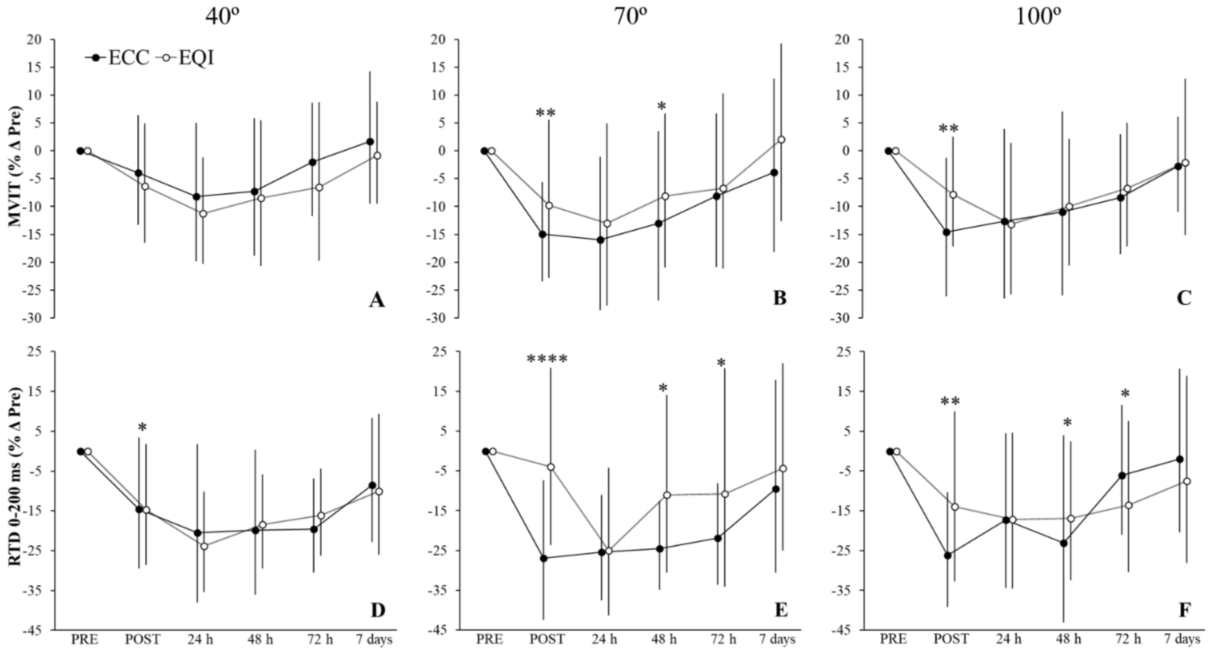

Figure 27. Joint-angle specific maximal voluntary isometric torque (MVIT) (panels A-C) and rate of torque development (RTD 0-200) (panels D-F), before and following eccentric or eccentric quasi-isometric exercise. Likelihood of a substantial between-condition difference is indicated as *possibly; **likely; ***very likely; ****most likely. Error bars represent standard deviations.

Discussion

The purposes of this investigation were to determine the kinetic characteristics of EQI contractions, and if bouts of EQI and ECC exercise, equated by angular impulse, resulted in different acute changes in pain, muscle architecture and morphology, and neuromuscular performance. The main findings were: 1) the majority (56%) of the EQI contraction time and impulse took place between 30-60º, as compared to the identical time spent at each ROM bracket with the isokinetic eccentric condition; 2) DOMS and EI were substantially greater with the ECC condition, especially at the distal region of the rectus femoris; 3) muscle swelling and architectural shifts were variable depending on the assessed muscle and region; and, 4) while concentric and isometric torque and RTD decreased similarly at shorter muscle lengths, decreases in voluntary outputs at long muscle lengths were greater following ECC.

Exercise conditions

Despite matched total angular impulse, EQIs distribute impulse quite differently to widely utilized isokinetic ECC contractions. While previous studies have compared the acute effects of isotonic and isokinetic contractions, to our knowledge, all previous investigations utilized isotonic loads that were more than 100% of maximal voluntary contraction (10, 88, 307). As such, the extremely low-velocity (1.29°·s^{-1}), submaximal (70% MVIT) EQI condition has a unique impulse distribution (Figure 22) making a direct comparison to other research difficult. Alemany et al. (10) and Doguet and colleagues (88) compared isokinetic and isotonic contractions loaded to 110% of MVIT and 150% of concentric maximum, respectively. While Alemany et al. (10) reported greater changes in markers of muscle damage (DOMS, MVIT, creatine kinase) following the isotonic condition, Doguet et al. (88) found no between-condition difference in DOMS, force output, creatine kinase, or invoked H-reflex and M-wave characteristics. These dichotomous findings demonstrate that acute neuromuscular and damage marker responses to different contraction modes are not simple to predict despite the efforts of researchers to equate repetitions and velocity.

Eccentric resistance training is often employed as a time-efficient means of exposing the neuromuscular system to high quantities of mechanical loading, leading to substantial morphological, architectural, and neuromuscular adaptations in healthy and well-trained populations (90). Relative to ECC, the EQI condition was slightly shorter in duration (13 ± 9.5 and 17.6 ± 8.3 minutes) with lower peak torques, demonstrating its practicality of imparting total impulse in a relatively brief period. Time-under-tension was equal through the ROM in the ECC condition with the majority of the angular impulse being expressed at moderate muscle lengths, whereas the majority of time-under-tension, and thus angular impulse (and likely fatigue accumulation), was at short to moderate muscle lengths with the EQIs; with these between-condition differences likely effecting regional morphology (90, 322) and angle specific neuromuscular performance (322, 363, 365) at these lengths. It may also be speculated that differences in velocity, impulse distribution, and possible load sharing by the series and parallel elastic components (125), could lead to dichotomous long-term adaptations in muscle morphology, musculotendinous stiffness, and fascial structure (158, 171). Additionally, fascicle mechanics/dynamics of the EQI contraction were not determined. As such it is impossible to know if true eccentric lengthening was occurring, or if there were brief periods of little tension interspersed with isometric contractions.

Muscle soreness

The EQI condition was associated with lesser DOMS in the 48 h post-exercise, compared to the ECC condition, evidenced by small reductions in the PPT of some quadriceps muscles with EQI at 24 hr (distal rectus femoris and vastus lateralis, middle vastus lateralis), and 72 hr (middle and distal vastus lateralis) of ~15-30% (Figure 23A-F). The aforementioned findings are not surprising given the literature on eccentric contraction velocity and muscle soreness and damage markers (65). Chapman et al. (65) examined the elbow flexors and found that high velocity (120°·s^{-1}) ECC led to greater muscle soreness and creatine kinase concentrations for up to 96 hours when compared to a slow (30°·s^{-1}) ECC protocol. In the present study, mean velocities throughout the ROM were 60°·s^{-1} and 1.29°·s^{-1} for ECC and EQI groups, respectively. While speculative, the lesser DOMS associated with the EQI condition could suggest that EQIs are predominantly isometric with brief periods of low tension causing small changes in joint angle, opposed to any true eccentric muscle action (90, 206). Finally, while differences in DOMS were consistent, between-condition differences were often smaller than the intra-session CV, placing a degree of uncertainty on our results.

Interestingly, there were no apparent between-condition differences in the pressure-pain threshold at the proximal vastus lateralis or the middle rectus femoris (though only nine participants were included, limiting the ability to determine clear results). This suggests that muscle damage may be most prevalent in the distal region of the quadriceps muscles, regardless of contraction mode. Contrary to our findings, Baker, Kelly, and Eston (29) found that DOMS was greatest towards the myotendinous junction (proximal and distal) of the quadriceps. However, it must be noted that they utilized a down-hill running protocol to induce soreness, suggesting that compound movements, with a stretch-shortening cycle, may lead to different patterns of DOMS when compared to single-joint isolation movements. Taken together with the findings of Baker et al. (29), it appears that multiple regions should be assessed when determining the effects of an intervention on DOMS.

Muscle morphology and architecture

Changes in MT, PA, and FL are difficult to decipher due to differential findings between the regions assessed. Firstly, while most between-condition differences in MT (swelling) were minimal, the EQI condition resulted in substantially greater increases at POST, 24 h and 48 h at the proximal (4.8-7.1%, ES = 0.20-0.29) and at POST and 48 h at the middle (4.8-5.9%, ES = 0.21-0.26) lateral vastus intermedius (Figure 24D-E). Interestingly, the observation is not matched in the anterior portion of the vastus intermedius (Figure 24J-L) or the vastus lateralis or rectus femoris. It might be speculated that EQI contractions may induce greater recruitment of the vastus intermedius muscle; however, this is unlikely as the femoral nerve innervates all the knee extensor muscles, and several studies have demonstrated that preferential recruitment of the quadriceps muscles is subtle at best (329). However, it should be noted that all studies in the aforementioned review utilized standard surface electromyography (329), while high density (334), or needle electromyography (230) may elucidate the possibility of preferential, or regional recruitment further. Interestingly, researchers have recently suggested that the vastus intermedius undergoes greater mechanical strain and damage when compared to the vastus lateralis during ECC contractions (12, 120), likely due to fascicles directly attaching to the bone, whereas the vastus lateralis fascicles attach to the intermuscular aponeurosis (14). While purely speculative, the greater mechanical strain of the vastus intermedius fascicles may be exacerbated with EQI contractions. Another possible explanation for our findings is that the vastus intermedius has a substantially different fiber type profile than the rectus femoris or vastus lateralis, as different fiber types are preferentially activated based on contraction velocity (71). As a related possibility, sustained EQI contractions are likely to induce substantial blood occlusive effects (84) potentially leading to increased activation and swelling of type 1 fibers (47). Regardless, intra-contraction fascicle tracking and needle electromyography of the vastus intermedius are required to fully elucidate the between-condition differences.

Between-condition differences in vastus lateralis PA exist depending on the assessed region, with the EQI condition resulting in a substantial decrease in PA at the distal vastus lateralis, whereas the opposite was found in the mid-region. However, all differences were trivial or small (0.1-8.7%, ES = 0.0-0.49). Contrastingly, several likely and very likely between-condition differences were found when examining FL of the proximal vastus lateralis at POST and 24 h (6.2-8.3%, ES = 0.49-0.66), and middle vastus lateralis at 24 h, 48 h and 72 h (4-5.6%, ES = 0.31-0.43) vastus lateralis. ECC resulted in an acute increase in proximal vastus lateralis FL, whilst EQI increased FL in the middle portion. Alternatively, EQI led to moderate and small FL increases at the proximal rectus femoris at POST (11%, ES = 0.64) and 24 h (6%, ES = 0.36), relative to ECC. These differences in resting FL length led us to speculate that differing magnitudes of fascicle strain/stretch were present between the proximal and middle regions of the vastus lateralis and that the EQI condition preferentially strains the fascicles of the rectus femoris. However, intra-contraction fascicle tracking would be needed to confirm this theory. Comparing our findings to previous works is difficult as most previous investigations utilize trigonometric equations to estimate FL, and/or only measure FL at a single region. Also, cross-sectional area or three-dimensional imaging may have allowed for additional clarity as changes in fluid distribution or muscle shape could have contributed to the complex alterations in regional MT, PA, and FL. As a final note, while the reported between-condition changes were always larger than the smallest important difference, the custom effects for middle PA and FL were slightly smaller than previously reported intersession variabilities (263).

The ECC condition resulted in greater increases in EI at POST at the middle (5.5%, ES = 0.21) and distal (11.9%, ES = 0.54) rectus femoris and distal lateral vastus intermedius (15.1%, ES = 0.26), relative to EQI. Additionally, EI increased by the largest magnitude following the ECC condition in 10 of the 12 assessed sites (though only three were possible or very likely substantial), in line with the findings of Chapman et al. (65). Furthermore, researchers have determined that the distal rectus femoris is increasingly activated as the knee angle increases (380), likely explaining the large between-condition difference in echogenicity. Except for the anterior vastus intermedius, EI increased most noticeably in the distal region of all muscles; which is supported by researchers citing that metabolic and hormonal markers were acutely elevated predominantly at the distal portion with ECC exercise (112, 346). Tabuchi et al. (346) recently examined calpains and calcium ion accumulation throughout rat muscle fibers following ECC contractions and found substantially greater accumulation at the distal region of single muscle fibers in-vitro. Franchi et al. (112) examined the acute and chronic effects of ECC and concentric contractions on hormonal and metabolic markers with morphological, architectural, and functional adaptations in the vastus lateralis in-vivo. The researchers determined that ECC training resulted in substantially greater phosphorylation of focal adhesion kinase at the distal region of the vastus lateralis (112), which may be a factor in the preferential increase in FL and distal MT following ECC resistance training (111). Interestingly, EI nearly exclusively peaked at POST and returned to or near baseline by 24 h, whereas other researchers have reported elevated EI up to five days post-exercise (68, 287). However, in contrast to the previous studies (68, 287), we utilized well-trained participants, likely reducing muscle damage and metabolite accumulation.

Neuromuscular performance

Relative to EQI, the ECC condition resulted in similar or greater acute reductions in concentric peak torque (8.7%, ES = 0.50), total impulse (8.3%, ES = 0.45) (Figure 25) and impulse at most of the assessed joint angles (Figure 26). However, differences were largest at the longest (100-70º) muscle lengths (11.7-19.7%, ES = 0.56-0.60), and became smaller towards medium (70-40º) (8-10.7%, ES = 0.45-0.62) and short muscle lengths (40-10º) (4.7-7.5%, ES = 0.25-0.32). While it is difficult to determine the underlying mechanisms, the ECC condition involved a considerably greater percentage of each contraction at long muscle length when compared to EQI. The differences in the percentage of time-under-tension and angular impulse contributing to joint-angle specific reductions in concentric torque are likely neurological as all between-group differences were unclear or trivial past 24 h. Based on underlying fatigue mechanisms (30), it is plausible that the ECC contraction resulted in greater central fatigue, while both ECC and EQI contractions led to similar levels of disruption distal to the neuromuscular junction. For similar reasons, the largest decreases in torque and RTD were typically observed at POST following ECC, whereas reductions in performance were often delayed to 24 h or 48 h in the EQI limb. This may be, in part, due to the within-participant design resulting in cumulative fatigue affecting the whole human. While subsequent studies employing techniques such as femoral nerve and transcranial magnetic stimulation would be needed to determine exact mechanisms of fatigue, chronic ECC loading would likely result in greater, and more uniform changes over the entire torque-angle relationship, whereas EQI loading would result in greater improvements at shorter muscle lengths (322). It is also important to recognize that all participants performed both conditions in the same session and that any residual central fatigue would affect both limbs throughout the 7-d recovery period.

Similar to the concentric assessment, trivial between-condition differences in MVIT were found at the short muscle length, whereas small reductions were observed with ECC at medium (POST; 10.4%, ES = 0.35; and 48 h; 7.9%, ES = 0.27) and long (POST; 9.8%, ES = 0.39) muscle lengths, relative to EQI. The ECC condition also resulted in considerably larger reductions in RTD_{0-200} (6.3-38.6%, ES = 0.33-1.39) at medium and long muscle lengths, relative to EQI. Additionally, RTD_{0-200} remained depressed longer following the ECC condition, aligning with the concentric performance reduction at POST with ECC, compared to a delayed reduction at long muscle lengths following EQI. These findings are consistent with Peñailillo et al. (276), who found RTD to be a more sensitive metric to estimate muscle damage and track recovery than MVIT. A potential explanation for greater torque reductions at larger joint angles may be due to the greater intramuscular pressure synonymous with stretched muscles (114, 330). This greater pressure may have increased the sensation of DOMS, reducing neural drive at longer muscle lengths (114, 330). Interestingly, the between-condition differences in RTD_{0-200} mirror shifts in muscle architecture. Acute changes in FL following contraction are due to an altered sarcomere resting length, which could increase or decrease shortening velocity, and therefore alter RTD (111). In the current investigation, it is plausible that the relative increase in FL at the proximal vastus lateralis with a relative decrease in FL at the middle vastus lateralis contributed to the conflicting RTD_{0-200} alterations at 40º, 70º, and 100º of knee flexion.

Limitations and directions for future research

Although there have been several studies and reviews of quasi-isometric and EQI contractions (157, 262, 305, 333), this was the first to investigate the kinetic characteristics and short-term effects of EQI resistance exercise. While we determined the short-term effects of EQIs on regional muscle soreness, morphology and architectural, and isometric and concentric performance through the length-tension relationships, there are several limitations and directions for future research. Employing peripheral and central nervous system stimulation is required to elucidate neuromuscular fatigue etiology. Similarly, more invasive methodologies including blood analyses and muscle biopsies are required to directly evaluate the acute and chronic hormonal and morphological alterations induced by EQI exercise. Analysis of intra-contraction electromyography and fascicle tracking are also required to understand contraction dynamics. There were large between-participant differences in total impulse due to wide-spanning individual abilities to perform EQI and ECC contractions. While this discrepancy was factored into our statistical analysis as a modifying prior effect, future studies may consider performing all EQI contractions before a contrasting contraction. Future analyses could also examine the amount of time and impulse accumulated isometrically and eccentrically during EQI contractions. Additionally, while within-participant parallel designs have many benefits (212), cross-education effects remain a valid methodological concern. Specifically, the potential cross-over effect may have contributed to comparatively smaller between-condition differences versus comparable study designs (10, 88, 276), suggesting that the present study was underpowered despite a sample size larger than the aforementioned works. Inline, it should be noted that a few ‘likely’ effects were smaller than previously determined intersession variabilities (see Appendices 10, 11 and 13). Therefore, readers may wish to focus on the ‘very likely’ or ‘most likely’ substantial effects. As fatigue was likely accumulated between 30-60º in the EQI condition, perhaps restricting the conditions to longer muscle lengths, equating by mean velocity, or comparing EQIs with impulse distribution matched traditional isometrics would have made for more comparable conditions. Most importantly, practitioners need to know how medium to long-term EQI training would translate to musculoskeletal health and performance in a variety of populations; and if EQI may be superior to more traditional training in specific contexts.

As a brief aside, this study demonstrates the importance of assessing morphological and architectural shifts in multiple muscles and regions and evaluating isokinetic and isometric performance at multiple joint angles (260). We are one of the first to evaluate changes in EI in multiple regions (221, 337), while past studies have demonstrated the importance of multi-angle isokinetic and isometric evaluations (250, 322). Future research must determine the potential relationship between acute shifts in the measured variables, and long-term adaptations.

Practical applications

While suggesting applications based on a single short-term study is difficult, several hypotheses can be made. Firstly, EQIs resulted in less severe DOMS compared to ECC exercise, a finding that may be important for practitioners aiming to optimize client adherence and prescribe resistance training around other activities. While it should not be assumed that short-term responses will manifest into long term adaptations, based on the acute responses observed in the present study, it may be hypothesised that EQI resistance training might promote vastus intermedius hypertrophy, whereas EQI and ECC training might promote similar architectural adaptations. It is likely that EQIs, as employed in this study, would predominantly improve neuromuscular outputs at short to moderate muscle lengths due to most of the impulse, and acute performance reductions occurring between 30-60º of flexion. Alternatively, the ECC condition appears more likely to lead to improved torque and RTD throughout the ROM. While not measured in the present study, it could be hypothesized that the 'holding' EQI contraction could be useful for improving intermuscular coordination, and result in larger cardiovascular responses (e.g., heart rate, blood pressure), due to greater agonist and synergist muscle activation (299, 305). Ultimately, EQI contractions might be best suited to special or injured populations, or general preparatory, unloading, or transition phases of athletic populations due to the relatively low number of joint movements, modest torques, and time-efficiency relative to ECC contractions. However, the application of EQI contractions must be evaluated on a case-by-case basis due to large inter-individual variabilities in duration, total impulse, and impulse distribution.

Conclusions

While the short-term effects of both conditions were mostly similar, ECC resulted in relatively greater increases in DOMS, and larger reductions in concentric and isometric performance at medium and long muscle lengths. Eccentric quasi-isometric training may be a viable alternative to traditional modes of resistance training in individuals suffering from, or susceptible to musculoskeletal injury due to the relatively low peak torques and the total number of repetitions required to achieve substantial neuromuscular overload. Further comparisons and longitudinal interventions are required.

Chapter 10 – Kinetic and kinematic profile of eccentric quasi-isometric loading

Reference

Oranchuk DJ, Diewald SN, McGrath JW, Nelson AR, Storey AG, and Cronin JB. Kinetic and kinematic profile of eccentric quasi-isometric loading. *Sports Biomech* Ahead of print, 2021.

Author contribution

Oranchuk DJ, 80%; Diewald SN, 8%; McGrath WJ, 4%, Nelson AR, 2%; Storey AG, 2%; Cronin JB, 4%.

Prelude

Chapter 9 examined the short-term effects of eccentric quasi-isometric resistance exercise and compared it to an impulse equated bout of eccentric contractions. One of the key findings was that eccentric quasi-isometric contractions predominantly overloaded the initial half of the range of motion; closely mirrored by acute and short-term reductions at short muscle lengths when compared to isokinetic eccentric loading. However, while providing a robust evaluation of short-term physiological effects, the biomechanical profile of eccentric quasi-isometric loading of the knee extensors requires greater analysis, including between contraction joint-angle-specific changes in angular impulse, time-under-tension, and angular velocity. Understanding these kinetic and kinematic variables, and the between contraction performance reductions are key to planning and interpreting future acute and short-term studies. Additionally, greater knowledge regarding the biomechanics of eccentric quasi-isometric and how fatigue and learning affect the profile is required to inform training prescription.

Introduction

Examining loading variables (e.g., intensity; contraction type) (196, 268) and schemes (e.g., failure, inter-set co-contraction) (105, 311) have become increasingly common as researchers and practitioners look to optimize resistance-training induced adaptations. Among the novel training modes, eccentric quasi-isometric (EQI) contractions have gained recent interest in the scientific literature (248, 262, 264, 268, 366). As discussed in Chapter 3, one of the reasons behind the surge in EQI interest is the proposed benefit and utility in rehabilitative populations (due to slow contraction velocities) (45, 174, 248, 262, 366), and specificity to sports that require long contraction durations or quasi-isometric muscle action, such as sprinting, sailing, grappling, skiing or skating (262, 306, 333, 370).

While a modest number of studies have examined yielding/quasi-isometric contractions (300, 305), one study has directly investigated the physiological effects of EQI exercise (264). Oranchuk et al. (264) reported that a bout of EQI exercise resulted in less muscle soreness, smaller increases in echo intensity (a proposed measure of muscle damage and intra and intercellular metabolite accumulation), and smaller reductions in isometric and concentric torque at long muscle lengths, when compared to an impulse-equated bout of eccentric contractions (264). Both conditions, however, resulted in a similar decrease in voluntary torque at shorter muscle lengths, likely due to joint-angle-specific fatigue (264). Whilst Oranchuk et al. (264) presented an initial profile of the short-term physiological effects, the biomechanical description of EQIs was simple and did not include contraction-by-contraction changes. By comparison, the kinetic and kinematic characteristics (and inter-set changes) of traditional eccentric and concentric contractions have been regularly examined (53, 135, 280). Understanding these contraction dynamics, and the between-set changes is important for both practitioners and researchers. For example, strength and conditioning, and rehabilitation professionals need to understand the contraction characteristics, so that EQIs can be best used to produce the desired musculotendinous adaptation. Likewise, researchers need to understand the between-contraction changes so that EQIs can be compared with other contraction types in longitudinal examinations. Therefore, the purpose of this study was to describe the kinetics and kinematics associated with a bout (four maximal repetitions) of EQI contractions. Based on the existing literature, it was hypothesized that the majority of angular impulse (integral of knee extension torque over time; Nm·s) would be distributed in the initial half of the range of motion (ROM).

Methods

Experimental design

A cross-sectional design was implemented to determine the biomechanical characteristics of EQI contractions via a single bout of four contractions. During a familiarization session, each participant performed a single EQI knee extension on a single randomly selected limb, to failure, following a detailed explanation and demonstration. Five to seven days later, each participant performed four EQI contractions to failure separated by 180 seconds of rest with the same limb as used in the familiarization session. Time-normalized angle-time characteristics, and absolute angular impulse, velocity, and time-under-tension, were determined through the entire ROM, and through eight ROM brackets. Changes in the variables were compared across the four contractions (C1, C2, C3, C4) during the session.

Participants

A total of 14 healthy, resistance-trained males (age: 27.9 ± 5.1 years, height: 179.4 ± 7.1 cm, mass: 80.5 ± 10.8 kg) volunteered for this study. All participants had at least six months of resistance training experience (6.42 ± 3.96, range = 1.5-10 years) performing at least two weekly sessions of lower-body resistance training (2.28 ± 0.82 sessions·week^{-1}, range = 2-4 sessions·week^{-1}) and were free of any musculoskeletal injuries for at least three months before data collection. The ethical committee of the Auckland University of Technology (18/232) and Victoria University (HRE19-110) approved this study, and all participants provided informed consent. All participants were instructed to refrain from strenuous physical activity, anti-inflammatory medication, recovery supplements, and practices such as foam rolling or heat or cold application in the days between the familiarization and experimental session. Additionally, alcohol, caffeine, and other ergogenic aids were forbidden in the 48 hours leading up to each session.

Testing procedures

Warmup and load determination

All warm-up and dynamometric procedures before the EQI contraction testing were explained in detail by Oranchuk and colleagues (264). In brief, after cycling at a low to moderate resistance for 5 minutes, participants were positioned upright on the isokinetic dynamometer (CSMi; Lumex, Ronkonkoma, NY, USA) at a hip angle of 85º, with shoulder, waist, and thigh straps affixed to reduce body movement during contractions. The shin-pad was positioned ~5 cm superior to the medial malleoli of the ankle. Participants were required to hold handles at the sides of the chair, while the non-working limb was positioned behind a restraining pad. The handles were held as pilot testing found that the torso displaced upwards (altering knee angles) when performing contractions while holding the straps or positioning the hands across the chest. Knee alignment was determined by visual inspection, participant feedback, and unloaded knee extensions to ensure proper joint tracking, and dynamometer settings were recorded and matched for the subsequent session. Participants underwent a series of extensions and flexions of the knee to determine safety stop positions and calibrate gravity correction, followed by a standardized warmup of concentric contractions ranging from 30-100% of maximal perceived effort from 105° and 5° of knee-flexion (260, 264). Two minutes after the completion of the concentric contractions the participants performed two maximal isometric contractions at 40º, 70º, and 100º of knee flexion. The dynamometer was then set to isotonic mode, and per previous recommendations (262, 264), a load equivalent to 70% of each participant's highest maximal voluntary isometric contraction was used for the EQI contractions.

Eccentric quasi-isometric contractions

Similar to Chapter 9, EQI contractions were initiated and terminated at 30º (Figure 28A) and 100º (Figure 28B) of knee-flexion, respectively. To allow for pre-activation, and thus improve adaptive force/torque (306), the isotonic load was gradually applied from 35% to 70% of maximal voluntary isometric contraction torque over two seconds. The load then remained at 70% of maximal voluntary isometric contraction torque for the remainder of the contraction. The participants were instructed not to exert enough effort as to cause a concentric contraction, but instead attempt to "brace" and "maintain joint position throughout the ROM" (262, 264). Once the load was reached, the participant held the initial position until isometric failure, at which point, slow and brief changes in joint-angle occurred with the participant maintaining maximal effort throughout each contraction. While highly variable, many participants had several periods of near-zero changes in knee flexion, followed by periods of joint angle changes until the entire ROM was completed. As torque was held constant, the participants' ability to maintain a constant torque output throughout the ROM was the quality of interest. To avoid pacing, participants were not told how many contractions/sets they would perform. Strong verbal encouragement was provided during each set.

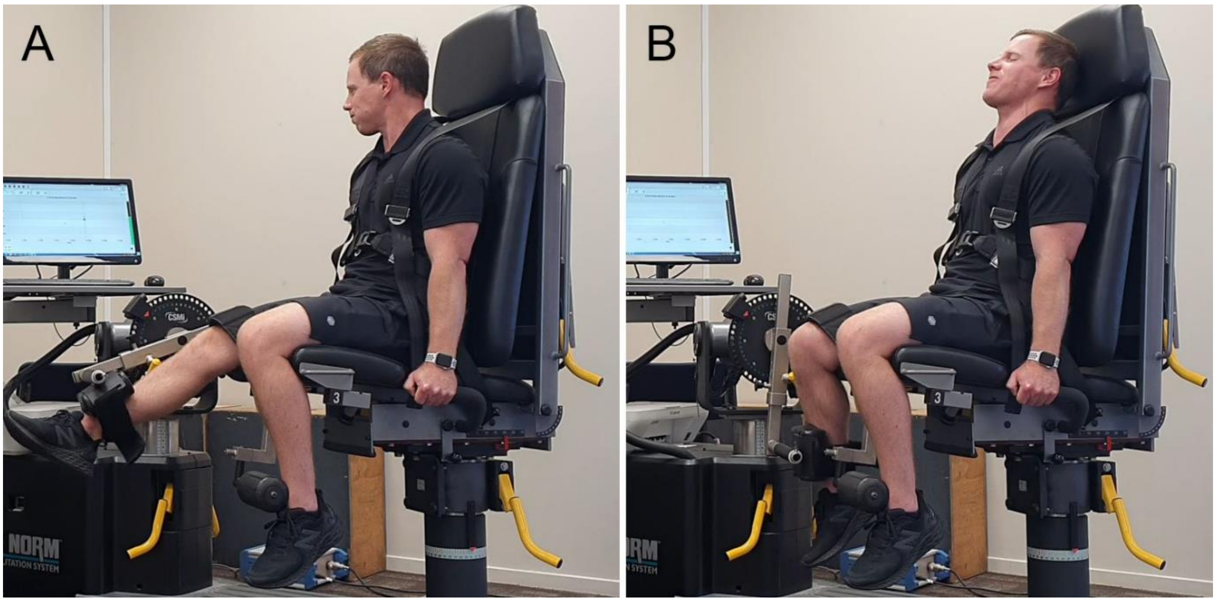

Figure 28. Start (panel A) and end (panel B) position for the eccentric quasi-isometric contractions.

Like Chapter 9, the participant rested for 180 seconds after each EQI before performing an unloaded concentric contraction to return to the 30^{o} starting position and initiate the next EQI (264). The exercise prescription was based on the results of Oranchuk et al., (264) who reported reductions in concentric and isometric performance following 3.85 ± 1.1 EQI contractions. The 180 second rest period was determined during piloting to be sufficient in maintaining both performance and time-efficiency. Additionally, Oranchuk et al. (264) determined that the total angular impulse of ~four EQI contractions was equal to ~100 eccentric contractions performed at $60^{o} \cdot s^{-1}$; a loading scheme known to result in substantial reductions in neuromuscular outputs and increased markers of muscle damage (234, 264, 352). Due to their non-ballistic nature, EQI data were collected at 100 Hz.

Data processing and analysis

Data were analyzed via a customized MATLAB (2020a, MathWorks, Natick, MA) script. The MATLAB script processed the data at 100 Hz with no filter. Position, torque, and velocity data were taken from the raw dynamometer software, and angular impulse was calculated using the trapezoidal method of the torque curve for each ROM band. Each EQI contraction was analyzed by detecting and identifying the minimum (30°) and maximum (100°) angle that signified the start and end of each contraction. To quantify differences throughout the ROM, angular impulse (Nm·s), angular velocity ($^{o} \cdot s^{-1}$), and time-under-tension (sec) were calculated for the entire ROM, and between eight bands (30-40°, 40-50°, 50-60°, 60-70°, 70-

80°, 80-90°, and 90-100°) (264, 265). For this study, short, medium, and long muscle lengths refer to 30-50º, 50-80º, and 80-100º of flexion, respectively.

Statistical analysis

Time-normalized torque-time kinetics

Statistical parametric mapping (SPM) was utilized to compare angle-time characteristics between contractions. One dimensional SPM (25) uses random field theory to objectively identify field regions that co-vary significantly with the experimental design (274). Statistical parametric mapping analysis was performed and tracings of the joint angle-time curves with 95% compatibility limits visually examined. If visual between-condition differences were apparent, a two-tailed, paired-sample t-test was performed on the time-normalized data to determine the magnitude of precision of the between-condition differences. The SPM analyses were implemented in MATLAB (MathWorks, Natick, MA) using the open-source package located at http://www.spm1d.org/ (274).

Absolute torque-angle characteristics

Statistical analyses of the absolute torque-angle characteristics were performed with RStudio, version 1.4.869. Shapiro-Wilk tests and visual assessments of normality probability plots were conducted on kinetic and kinematic data. The assumption for the equality of variances was checked via Levene's tests. Inter-contraction differences were evaluated via one-way analyses of variance (ANOVAs) with Bonferroni adjusted post-hoc contrasts for angular impulse, time-under-tension, and velocity, respectively. The initial strength level, as defined by MVIT at 70º, was utilized as a between-subject factor. An alpha level of 0.05 was used to determine statistical significance with Omega squared (ω^2) ['formula 2' (115)] used to characterize the effect size of each ANOVA. Due to the limited sample size, qualitative descriptors of paired Hedges' *g* effect sizes (ES) (192) were assessed as: trivial < 0.2, small = 0.2-0.49, moderate = 0.5-0.79, large > 0.8 (115). ESs are reported with 95% compatibility limits to provide readers with the magnitudes of difference while also providing statistical significance with a cut-off of $p < 0.05$ (38, 292). All reported *p*-values are Bonferroni adjusted. Data are reported as mean ± standard deviation unless otherwise stated.

Results

Time-normalized angle-time kinetics

Compatibility limits overlapped throughout each contraction for the time-normalized curves; however, 95%CIs nearly delineated between ~15-30% of contraction duration when comparing C1 and C4 (Figure 29). Between-contraction differences increased throughout the four EQI contractions (Figure 30). Most notably, the initial increase in the joint angle from ~30-50º (Figure 29) (~0-15%, Figure 30) tended to occur earlier as the loading protocol progressed, while joint angle changes from 50-100º remained similar.

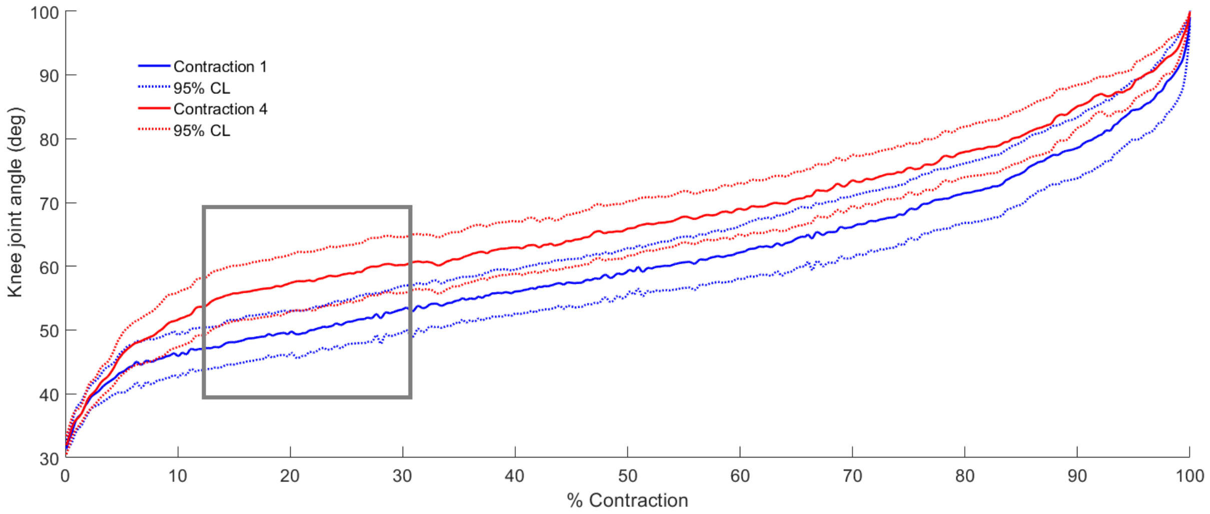

Figure 29. Time normalized angle-time curve comparison of eccentric quasi-isometric contractions one, and four. The knee angle is presented in degrees with 95% compatibility limits. The grey box highlights a near lack of compatibility limit overlap.

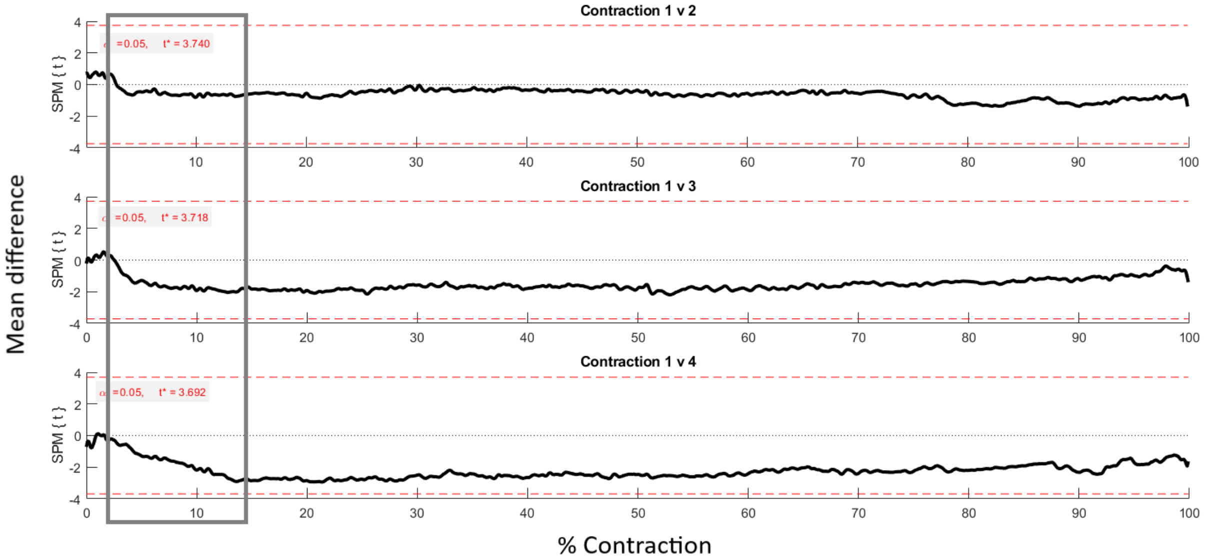

Figure 30. Mean difference in time normalized angle-time curves. The red dotted line represents cut off for statistical significance (p = 0.05). The grey box highlights the time-normalized kinematic changes occurring during the first ~15% of each contraction.

Absolute torque-angle characteristics

All data were normally distributed (p > 0.05). There were no significant (p < 0.05) interaction effects between strong and weak participants (above and below the group mean for MVIC at 70º, respectively); therefore, all proceeding results are presented with all participants pooled.

EQIs were isotonically loaded to 184 ± 31 Nm, with an average angular velocity of 1.34 ± 2.9º·s^{-1}. Mean time-under-tension was 53.7 ± 26 (range = 16.1-140) seconds. EQI mean contraction velocity and duration across ROM brackets were: 30-40º: 4.35 ± 4.2º·s^{-1} (2.3 ± 2.4 s); 40-50º: 1.03 ± 1.1º·s^{-1} (9.7 ± 9.1 s); 50-60º: 0.70 ± 1.0º·s^{-1} (14.3 ± 10.2 s); 60-70º: 0.78 ± 1.2º·s^{-1} (12.8 ± 8.1 s); 70-80º: 1.09 ± 1.3º·s^{-1} (9.2 ± 7.6 s); 80-90º: 1.59 ± 1.6º·s^{-1} (6.3 ± 6.4 s); and 90-100º: 3.85 ± 3.9º·s^{-1} (2.6 ± 2.6 s).

There were significant main effects for total angular impulse ($F_{(1.49,\ 17.9)}$ = 16.5, p < 0.001, ω^2 = 0.11), and angular impulse from 30-40º ($F_{(3.0,\ 36.0)}$ = 3.18, p < 0.036, ω^2 = 0.04), and 40-50º ($F_{(1.49,\ 17.9)}$ = 0.006, ω^2 = 0.18). As they are derived from the same data, near identical effects were found for total time-under-tension and mean velocity (F = 12.7-12.8, $p \leq$ 0.003, ω^2 = 0.07-0.08), and time-under-tension and velocity from 40-50º (F = 8.12-8.16, $p \leq$ 0.010, ω^2 = 0.15-0.17). All other interactions were non-significant (p = 0.057-0.830, ω^2 = 0.01-0.04).

Mean ± SD data, Hedges' *g* ESs with 95% compatibility limits and %Δ for angular impulse, time-under-tension, and angular velocity is provided in **Appendices 15, 16, and 17**, respectively. Briefly, between-contraction decreases in total angular impulse (Figure 31) and time-under-tension and increases in velocity were observed (ES = 0.36 ± 0.26, 22.2 ± 10.9%) (see Appendices). Furthermore, the largest reduction in angular impulse and time-under-tension (increase in velocity) was nearly exclusively found between 30-40º (ES = 0.35 ± 0.26, 46.0 ± 42.1%), and 40-50º (ES = 0.63 ± 0.27, 73.5 ± 58.1%), with smaller changes generally found through the 50-100º ROM brackets (ES = 0.10 ± 0.26, 14.3 ± 24.6%) (see Appendices). The changes in total angular impulse and impulse distribution over the four contractions are illustrated in Figures 31 and 32, respectively. While varying in levels of significance (see Appendix 15), increases in relative (% of total) angular impulse are apparent when examining 60-70° from C2 to C3 and C4, 70-80° from C2 to C3, and in 80-90° from C3 to C4; resulting in a shift in relative impulse from short towards medium to long muscle lengths (Figure 32).

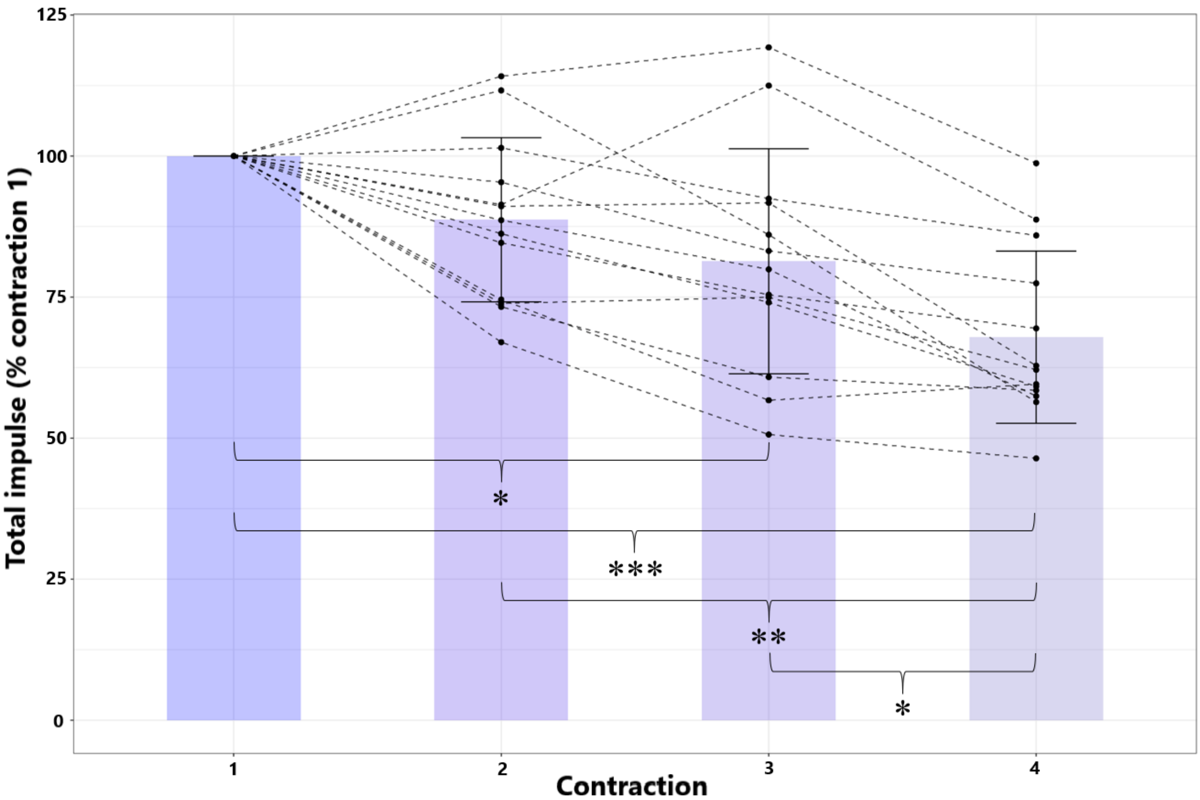

Figure 31. Change in total angular impulse between contractions. **p* < 0.05, ***p* < 0.01, ****p* < 0.001. Error bars denote the standard deviations.

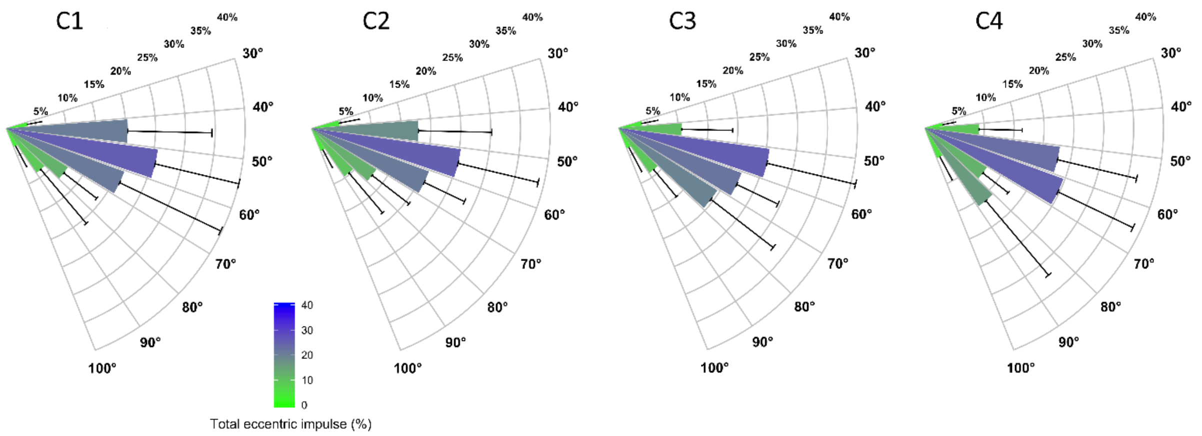

Figure 32. Angle-specific eccentric quasi-isometric impulse from contraction one (C1), contraction two (C2), contraction three (C3) and contraction four (C4). Error bars denote the standard deviations.

Discussion

The biomechanical characteristics of EQI knee-extensions and the kinematic changes throughout a bout of contractions were quantified. Our primary findings were that most of the angular impulse and time-under-tension took place towards short to moderate muscle lengths, consistent with our hypothesis. There was also a decrease in the angular impulse of ~11-18% between contractions. We also determined that the relative proportion of angular impulse and time-under-tension shifted towards moderate to long muscle lengths as the number of contractions increased. The potential physiological and practical implications for practitioners and researchers are discussed herewith.

It appears that EQI knee-extensions predominantly load the first half of the ROM, which corresponds to the fatigue-induced decreases in concentric and isometric torque and rate of torque development at shorter muscle lengths following similar bouts of EQIs (264). However, in this study, a shift in angular impulse and time-under-tension from short to medium, to medium to long muscle lengths as repetition number increased was observed (Figure 32). For example, from C1 to C4, angular impulse from 30-60º showed small to large decreases (ES = 0.30-0.90, 38.2-74.1%), whereas angular impulse from 60-100º (ES = -0.19-0.41, -22.8-33.8%) remained relatively constant, and in some cases, increased through the contractions (see Appendix 15). This finding is relevant as the joint-angle specific effects of resistance-exercise have been previously discussed (135, 195, 322, 365) with multiple reviews concluding that training through a full ROM or at longer muscle lengths is superior to short muscle length training when increases in muscle size and increased dynamic performance are desired (268, 310).

Other unique aspects of EQIs are the extremely slow velocities/long contraction durations at modest external torques. When compared to maximal strength training, explosive intent results in greater improvements in the rate of force/torque development due to increases in neural drive characteristics (354), and adaptations to a plethora of tendon and aponeurosis functional qualities (32, 225). However, the isometric training literature suggests that training-induced improvements in muscle size and maximal strength are not differentially affected by contraction intent (32, 216, 225, 268, 354). Alternatively, the duration of contraction has notable effects on training-induced morphological adaptations (262, 268, 314). For example, Schott, McCully, and Rutherford (1995) compared time-under-tension equated isometric training utilizing contractions of 3 or 30 s. While both groups experienced similar maximal force increases, only the 30-second contraction group increased quadriceps cross-sectional area, suggesting increased metabolite accumulation during the sustained contractions as a plausible mechanism (314). Indeed, several studies have demonstrated a reduction in blood flow and muscle oxygenation during sustained contractions (83, 146, 261) with some researchers suggesting that contraction-induced muscle deoxygenation and metabolite accumulation could promote muscle growth, primarily by altering muscle activation, leading to earlier recruitment of type-II motor units (82). On a related note, it appears that substantial blood flow restriction is possible with contractions as low as 25% of maximal voluntary contraction (333), far below the 70% utilized in our study. Finally, as EQI loading includes an eccentric portion through the ROM, the contraction could be maintained for substantially longer than a fatiguing isometric contraction in isolation. Therefore, an EQI may result in greater metabolic signalling due to greater, or at least more sustained muscle deoxygenation and metabolite accumulation when compared to holding isometrics.

While contraction intensity (% of maximum) is questionably important for muscle hypertrophy (268) so long as a minimum threshold is reached (196), contractions ≥ 70% may be necessary to increase tendon stiffness and cross-sectional area (50, 268). However, the literature also suggests that slow, or sustained contractions are at least as beneficial to tendon remodeling and function as higher velocity, or rapid contractions (45, 174, 262, 268).

Slow contractions, synonymous with EQIs may be better tolerated by populations with tendon pain (45, 174, 262), despite, to our best knowledge, no studies confirming this hypothesis, likely due to the difficulty in recruiting a meaningful sample of participants with homogenous tendon issues/qualities. Therefore, EQI contractions would likely be valuable in rehabilitative settings as contraction intensities ≥ 70% can be applied while maintaining low contraction velocities (248, 262, 366). While not completely elucidated, it is also likely that the slow eccentric portion of EQIs is especially beneficial in the rehabilitation of tendinopathies (137, 172). Of note, it is unlikely that moderate-intensity contractions taken to failure, synonymous with EQIs, would be as effective as briefer, high-intensity contractions for improving the rate of motor unit activation (232). However, the study of Miller et al. (232) included isometric contractions in isolation, and the effects of including an eccentric phase (as in EQIs) may result in alternative findings (93). Also, the difference in the effectiveness of high versus moderate-intensity contractions to longitudinally increase central nervous system activation remains to be determined.

Limitations and directions for future research

While both the joint-angle-specific characteristics and between-contraction changes were determined there are several limitations and directions for future research. From a biomechanical standpoint, intra-contraction fascicle and tendon-aponeuroses tracking are required to better understand the contraction mechanics and the potential load sharing of active and passive components through the ROM (147, 286). Similarly, electromyography would be required to elucidate the relative contribution of each quadriceps muscle and region over different velocities and joint angles. Likewise, peripheral, and/or transcranial magnetic stimulation would be required to determine the etiology of the observed fatigue. Also, the variability and quantification of the individual isometric and eccentric phases were not quantified in the present study. Thus, future research may wish to determine exactly what proportion of the angular impulse was produced via static or lengthening contractions, perhaps utilizing novel measuring systems (304). Finally, while it is highly likely that substantial blood flow restriction and muscle de-oxygenation occurred during the EQI contractions (261, 333), near-infrared spectroscopy is required to confirm this and examine the effects of rapid, small amplitude changes in ROM that may allow for very brief periods of muscle relaxation and thus increased substrate exchange and metabolite clearance (305). Likewise, several researchers have examined muscle oxygenation during fatiguing isometric contractions (7, 83, 176, 261, 327), but none have determined the oxygenation kinetics of a subsequent eccentric phase.

Researchers must also directly determine the tolerability of specific joint angles as well as contraction velocity and intensity in participants with tendon or joint pain. Researchers may wish to utilize SPM analyses to easily compare the kinematic qualities of contrasting contraction types or relative intensities or velocities.

Conclusions

Total angular impulse and time-under-tension decreased by ~15% from contraction to contraction. Additionally, most kinetic and kinematic between-contraction changes occurred at short to moderate muscle lengths, effectively shifting the angular impulse distribution to longer muscle lengths throughout the protocol. Researchers must be mindful of the between-set drop-offs observed with EQI exercise and determine the same characteristics of a comparative contraction type when attempting to match conditions over a training study. Additionally, researchers could employ SPM analysis to compare a plethora of loading variables (e.g., isotonic vs isokinetic; high vs low intensity; eccentric vs concentric). As training at longer muscle lengths is beneficial for hypertrophy and strength throughout the range of motion, it could be recommended that an EQI contraction be initiated at moderate to long muscle lengths to avoid imparting a large proportion of the total angular impulse at shorter muscle lengths. Practitioners could alter the impulse distribution to longer muscle lengths by prescribing a greater number of contractions, reducing rest periods, or implementing EQI contractions towards the end of a traditional training session where fatigue may be present (262). The large standard deviations and compatibility limits in cumulative loading and loading distribution (see Appendices 15, 16 and 17) highlight the need to prescribe EQI contractions on an individual basis. Based on related findings it is plausible that EQIs could be utilized to load abnormal (e.g., damaged, tendinopathic) tendon, alter muscle morphology, or improve performance in similar tasks, while other training methods are likely superior for reducing electromechanical delay and explosive performance enhancement. Of course, longitudinal examinations are required to confirm this line of thought.

Section 5 – Conclusions

Chapter 11 – Summary, practical applications, limitations, and future research directions

Summary

The primary question of the thesis was "What are the acute, and long-term effects of eccentric quasi-isometric (EQI) loading on muscle form and function?" The basis for the overarching question was determined by reviewing quasi-isometric and EQI contractions in the literature, and recognizing a paucity of scientific evidence to support their use; despite seemingly logical anecdotal evidence supporting EQI loading in rehabilitation and sport performance contexts. To answer the overarching question, a systematic series of literature reviews, cross-sectional and intervention studies were performed. Thus, the following sections form the thesis: Section 1) systematic and narrative reviews of literature; Section 2) several methods-based investigations; Section 3) correlational analysis of muscle structure and function; Section 4) acute and short-term investigations; and Section 5) summary.

Key findings

Section 1

As no literature directly examining EQI contractions existed, a systematic review of isometric training interventions in humans was performed (Chapter 2), and a narrative review of EQI adjacent biomechanical, physiological, biological, and practical literature was also completed (Chapter 3). In Chapter 2 several important loading parameters were identified, including muscle length/joint angle, and contraction intensity, duration, and intent. Isometric training at longer muscle lengths produced greater muscular hypertrophy and dynamic performance improvements than equal volumes of shorter muscle length training, while ballistic intent resulted in greater neuromuscular activation and rapid force production (268). Substantial improvements in muscular hypertrophy and maximal force production were possible regardless of training intensity, however, intensities greater than 70% were required for improving tendon structure and function (268). In Chapter 3 it was determined that EQIs may provide a practical means of increasing total volume and metabolic and hormonal outputs (262). At the same time, EQIs likely allow for a safe and time-efficient application of large quantities of mechanical tension (262). However, in Chapter 3 it was also concluded that given neuromuscular specificity it was unlikely that EQI adaptations were beneficial to power or speed-based movements (262).

Section 2

Section 2 consisted of four chapters, each determining the variability of extensive evaluations of regional quadriceps muscle morphology and architecture, and joint-angle-specific knee-extension performance that was partially identified in Section 1. Chapter 4 determined that regional quadriceps muscle thickness was a highly reliable measure, whereas greater caution was required when examining quadriceps pennation angle, or fascicle length, especially in the rectus femoris (263). Additionally, the extended field-of-view technique offered greater confidence than trigonometric estimations of vastus lateralis fascicle length (263). Key findings from Chapter 5 were that echo intensity could be relied upon in all regions of the quadriceps muscles, however, intersession variability was reduced when utilizing a mathematical correction for subcutaneous fat thickness (267). Furthermore, it was determined that fat corrected echo intensity increased towards the myotendinous junctions (267). Chapter 6 examined the variability of concentric isokinetic measures of torque and impulse throughout the range of motion (265). Key findings were that the optimal angle was highly variable, and that impulse brackets were the most reliable means of determining the concentric torque-angle relationship (265). Finally, in Chapter 7 the variability of short, medium, and long quadriceps muscle length isometric evaluations were examined (269). Intersession variability of peak torque and rate of torque development from 0-200 ms could be used with confidence, regardless of joint angle (269). However, the rate of torque development and impulse in smaller time frames should be utilized and interpreted with caution (269).

Section 3

Within Section 3 a single chapter was used to determine the relationship between several of the most reliable measures found in Section 2. These correlational analyses were performed to better understand the relationship between form and function, and therefore inform researchers to which measures should be focused on during longitudinal interventions. In Chapter 8 it was determined that the middle and distal regions of the vastus lateralis and lateral vastus intermedius were the best predictors of isometric torque production, regardless of the joint angle (260). Additionally, correlations between muscle architecture and isometric torque increased at longer muscle lengths (260).

Section 4

Section 4 was comprised of two acute/short-term studies examining the biomechanical profile and physiological effects of EQI loading. Chapter 9 was a within-participant design exposing each quadriceps to impulse-matched bouts of isotonic EQI or isokinetic eccentric loading (264). Though several of the outcome variables were similar between-conditions, the eccentric limb experienced greater muscle soreness, and middle-distal muscle echo intensity, with larger reductions in concentric and isometric performance throughout the length-tension relationship (264). Conversely, greater vastus intermedius muscle swelling occurred in the EQI limb with similar reductions in torque outputs at shorter muscle lengths (264). While it was found in Chapter 9 that the majority of angular impulse in the EQI contraction occurred at shorter muscle lengths (264), Chapter 10 aimed to thoroughly define the kinetics and kinematics of EQI loading over a series of contractions. Chapter 10 confirmed that most of the angular impulse and time-under-tension occurred early in the range of motion, however, the proportion of loading shifts from short to moderate muscle lengths as the number of contractions increases (259).

Practical applications

Strength and conditioning, and rehabilitation practitioners are constantly searching for safe, time-efficient, and effective means of imparting mechanical tension and improving muscle size and function. Therefore, one of the aims of the thesis was to inform practitioners of the potential benefits and drawbacks of EQI loading. Some of the main practical findings were:

- Isometric resistance training can be utilized to induce morphological adaptations including muscle hypertrophy and increased tendon stiffness (268).
- While isometric performance improvements are joint-angle-specific, practitioners should prescribe isometric contractions at longer muscle lengths when increasing muscle size, and improving performance through the range of motion is desired (268).
- Practitioners aiming to improve tendon stiffness should prescribe contractions exceeding 70% of maximal voluntary contraction (268).
- EQI loading is a time-efficient means of imparting high mechanical tension, with minimal delayed onset muscle soreness or short-term performance reductions (262).
- A high degree of inter-participant variability exists, therefore, EQI loading should be applied on a case-by-case basis (259, 264).
- EQI training is likely a valuable tool for improving or maintaining muscle size and joint-angle-specific strength (262, 264). However, EQI training is unlikely to lead to improvements in ballistic movements (262, 264).

- EQIs may possibly be best implemented near the end of a resistance training session when overloading the entire range of motion is desired (259, 262).
- Training with EQIs is likely most beneficial in rehabilitation settings as a bridge between static and dynamic movements (262).

Additionally, our thesis findings can drive better methodological understanding and practice in several areas:

- Researchers can confidently evaluate muscle thickness of all muscles and regions of the quadriceps, however, pennation angle and calculated fascicle length should be interpreted with caution, especially in the rectus femoris (263).
- Researchers should utilize the extended field-of-view technique to estimate vastus lateralis fascicle length (263).
- Echo intensity can be relied upon at all regions and muscles of the quadriceps; however, subcutaneous fat correction improves intersession reliability (267).
- Impulse brackets are a more reliable means of evaluating the torque-angle relationship of isokinetic concentric knee-extensions than the optimal angle, or angle-specific torque (265).
- Isometric peak torque can be tested with high reliability across knee joint angles; however, early-stage rate of torque development and impulse should be interpreted with caution (269).
- Researchers may wish to focus on middle and distal lateral quadriceps architecture when examining training or unloading induced adaptations (260).
- Angular impulse distribution should be considered when comparing between-condition loading (264).
- Multiple points in the range of motion and regions of muscle should be evaluated to thoroughly evaluate between-condition changes in morphological and neuromuscular variables (259, 264).
- Statistical parametric mapping may be a simple means of comparing joint-angle specific loading during single-joint contractions (259).

Limitations and directions for future research

This thesis was the first to directly examine EQIs, however, two planned investigations could not be completed due to the COVID-19 lockdowns particularly in Melbourne where I was collecting data. Complicating this was the fact that I was unable to return to New Zealand as the borders were closed to all non-citizens or permanent residents. Thus, several limitations and future research directions exist.

- As knee-extension and the knee extensors were the examined movement and muscle group of interest, future research could examine EQIs in other movements and muscle groups.
- Similarly, resistance-trained males were the population of focus. Therefore, females and rehabilitative populations should be examined.
- While the kinetic and kinematic profile of EQI contractions were determined, intra-contraction fascicle tracking and region and muscle-specific electromyographical measures are required to elucidate neural and contractile characteristics.
- Peripheral nerve and transcranial magnetic stimulation techniques could be employed to delineate the short-term performance reductions from EQI and comparative contraction types.
- A profile of metabolic and hormonal disruptions and muscle damage through blood and biopsy analysis is required to understand the underlying mechanisms of the short- or long-term effects of EQI loading.
- The largest limitation is the lack of any longitudinal investigation. Therefore, any potential applications of EQI training are speculative. Long-term effects of EQI resistance training must be determined to understand the regional muscle and joint-angle-specific adaptations possible in a variety of contexts.

Conclusions

This thesis was the first to perform academic research on EQI loading, with a focus on morphological, architectural, and contractile performance alterations in resistance-trained men. While muscle physiologists and neuromuscular researchers can find points of value, the thesis is most relevant to strength and conditioning and rehabilitation focused practitioners. Although extensive future research is required to understand underlying mechanisms and long-term adaptations, the thesis provided novel and original information on the biomechanical profile and acute and short-term physiological effects of EQI loading. Ultimately, EQI training is likely best applied to special or injured populations. EQI loading could play a role in general preparatory, unloading, or transition phases of high-performance populations due to the low number of joint movements, modest muscle soreness, and high time efficiency.

Section 6 – References and appendices

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Appendices

Appendix 1. Study quality scoring system

No.	Item	Score
1	Inclusion criteria stated	0-2
2	Random allocation of subjects to groups	0-2
3	Independent and dependent variables were clearly stated	0-2
4	Groups were tested for similarity at baseline	0-2
5	A control group was utilized	0-2
6	Interventions were volume equated	0-2
7	Assessments were practically useful	0-2
8	Intervention duration was practically useful	0-2
9	Statistical analysis was appropriate	0-2
10	Evaluation methods are valid and reliable	0-2

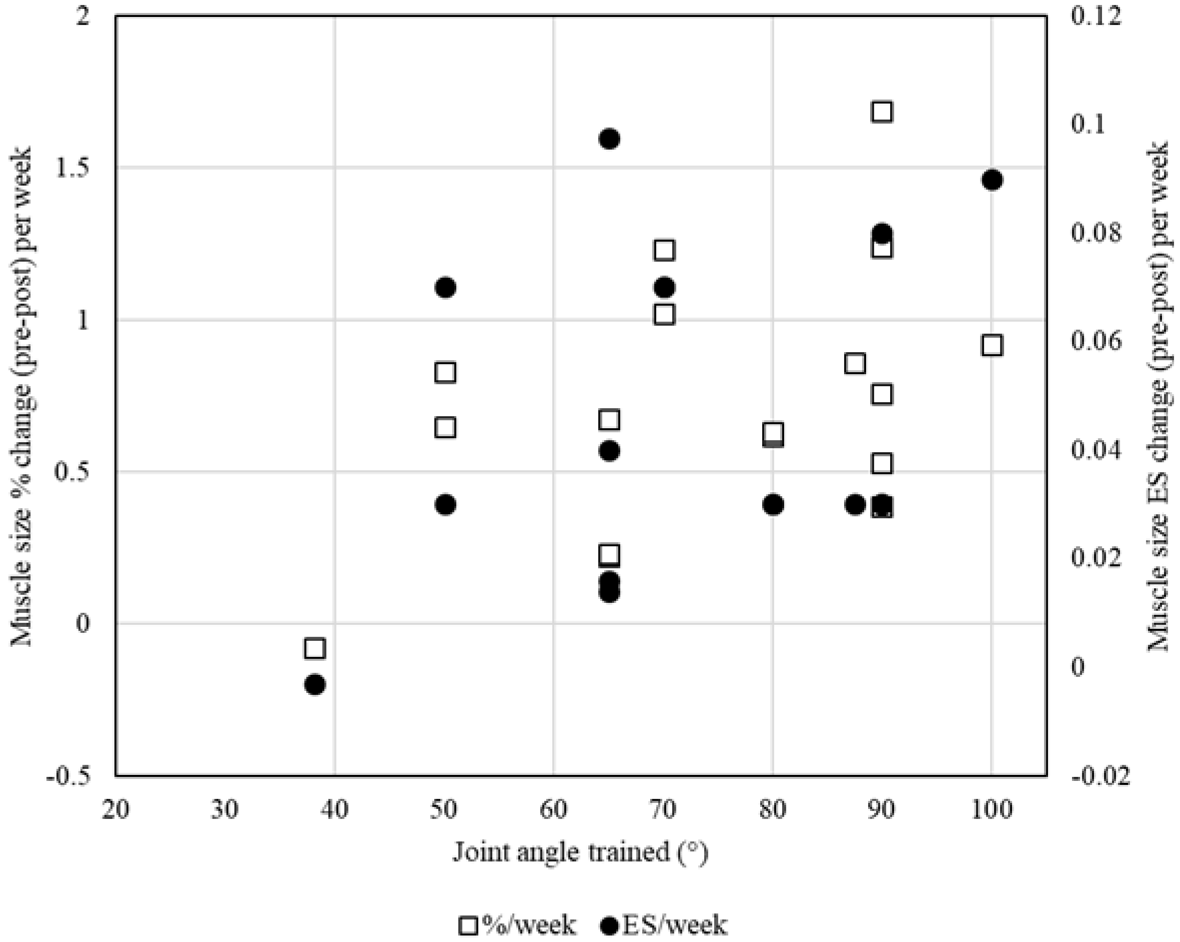
Adapted from Brughelli et al. (56)

Appendix 2. Study quality ratings

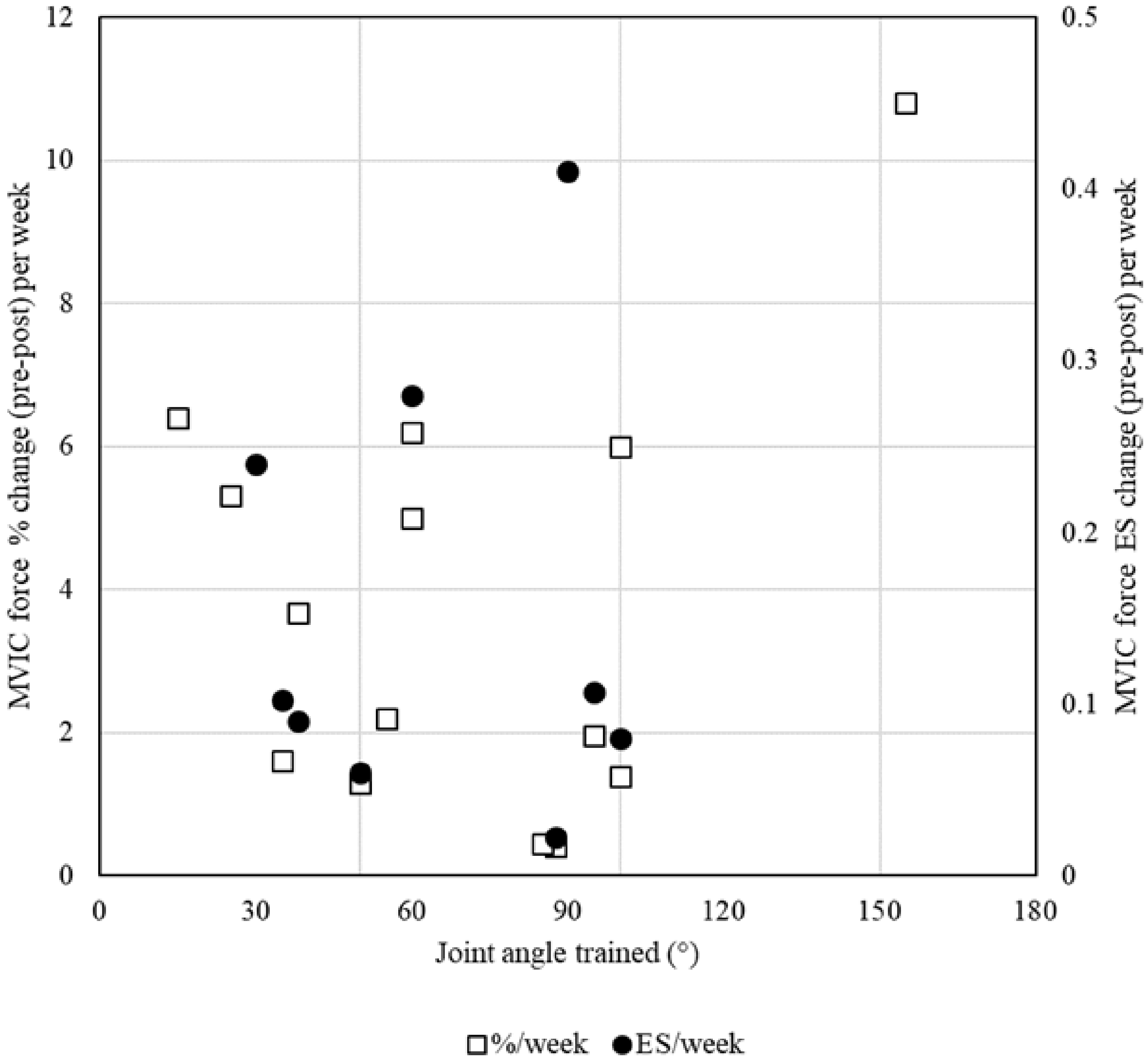
Author	N	Mean age	Training status	Volume equated	Non-exercise control	QS
Alegre et al. (9)	29	19.3	Untrained	Yes	Yes	18/20
Bandy & Hanten (35)	107	23.9	Untrained	Yes	Yes	18/20
Massey et al. (225)	42	25	Untrained	No	Yes	18/20
Maffiuleti & Martin (216)	21	Unknown	Untrained	No	Yes	17/20
Noorkoiv et al. (250)	16	23.7 ± 4	Untrained	Yes	No	17/20
Noorkoiv et al. (251)	16	23.7 ± 4	Untrained	Yes	No	17/20
Sterling (335)*	120	Unknown	Active	Yes	Yes	17/20
Balshaw et al. (32)	48	Unknown	Untrained	No	Yes	16/20
Kanesha et al. (164)	12	27.5	Untrained	Yes	No	16/20
Ullrich et al. (362)	10	24.4 ± 3.2	Active	Yes	No	16/20
Williams (389)*	23	22.8	Active	No	Yes	16/20
Bogdanis et al. (49)	15	21.5 ± 2.1	Active	Yes	No	15/20
Arampatzis et al. (21)	21	28	Untrained	Yes	No	14/20
Arampatzis et al. (19)	11	23.9	Untrained	Yes	Yes	14/20
Kubo et al. (185)	8	22.6	Untrained	Yes	No	14/20
Waugh et al. (385)	14	30	Active	Yes	No	14/20
Lindh (205)	10	26.5	Active	Yes	No	13/20
Meyers (231)	29	Unknown	Untrained	No	Yes	13/20
Rasch & Pierson (289)	29	Unknown	Untrained	Yes	No	13/20
Tillin & Folland (354)	19	20.5	Active	No	No	12/20
Young et al. (396)	4	20.5	Active	Yes	No	12/20
Khouw & Herbert (169)	51	Unknown	Untrained	No	No	11/20
Kubo et al. (188)	9	24 ± 1	Active	Yes	No	11/20
Szeto et al. (344)	18	Unknown	Active	No	No	11/20
Thepaut-Mathieu et al. (353)	24	31.8	Untrained	Yes	Yes	11/20
Schott et al. (314)	7	22.7	Untrained	No	No	10/20

QS = quality score. *Unpublished doctoral dissertation.

Appendix 3. Isometrically trained joint angle and hypertrophic adaptations (multiple comparisons; n = 9)



Appendix 4. Isometrically trained joint angle and strength adaptations (multiple comparison. n = 7)



Appendix 5. Regional quadriceps architecture averaged over three sessions

Muscle	Measurement	Limb	Proximal	Middle	Distal
Vastus lateralis	MT (cm)	Dominant	2.54 ± 0.36	2.81 ± 0.43	2.21 ± 0.34
		Non-dominant	2.44 ± 0.33	2.74 ± 0.41	2.20 ± 0.37
	PA (°)	Dominant	17.1 ± 3.2	20.6 ± 2.6	22.7 ± 2.7
		Non-dominant	16.3 ± 2.7	20.2 ± 2.1	22.5 ± 2.8
	FL (cm)	Dominant	7.73 ± 0.68	8.18 ± 0.83	7.16 ± 0.83
		Non-dominant	7.70 ± 0.73	8.16 ± 0.72	7.12 ± 0.90
Rectus femoris	MT (cm)	Dominant	2.80 ± 0.26	2.69 ± 0.33	1.96 ± 0.30
		Non-dominant	2.76 ± 0.33	2.69 ± 0.31	1.99 ± 0.31
Lateral vastus intermedius	MT (cm)	Dominant	2.02 ± 0.44	2.04 ± 0.54	1.93 ± 0.44
		Non-dominant	2.01 ± 0.51	2.03 ± 0.53	1.84 ± 0.42
Anterior vastus intermedius	MT (cm)	Dominant	2.94 ± 0.46	2.24 ± 0.47	1.88 ± 0.42
		Non-dominant	2.96 ± 0.47	2.36 ± 0.49	1.78 ± 0.37

MT = muscle thickness. PA = pennation angle. FL = fascicle length. Data are mean ± SD.

Appendix 6. Differences in adjusted simple correlations (√adjR^2), with compatibility limits and magnitude-based decisions, between normalized maximal voluntary isometric torque and regional quadriceps measures

Joint angle	Region comparison	Δ √adjR^2 (90%CL)	Decision
Vastus lateralis muscle thickness			
40º	Distal-Proximal	0.43 (0.06, 0.65)	**Moderate****
	Distal-Middle	0.09 (-0.12, 0.31)	*Trivial*
	Middle-Proximal	0.35 (0.03, 0.54)	Moderate**
70º	Distal-Proximal	0.35 (0.04, 0.80)	Moderate**
	Distal-Middle	0.02 (-0.17, 0.21)	*Trivial*
	Middle-Proximal	0.32 (0.09, 0.70)	**Moderate****
100º	Distal-Proximal	0.29 (0.00, 0.78)	Small**
	Distal-Middle	-0.03 (-0.22, 0.17)	*Trivial*
	Middle-Proximal	0.32 (0.13, 0.68)	**Moderate*****
Vastus lateralis pennation angle			
40º	Distal-Proximal	0.25 (-0.10, 0.63)	*Small*
	Distal-Middle	0.23 (-0.17, 0.60)	*Small*
	Middle-Proximal	0.02 (-0.27, 0.38)	*Trivial*
70º	Distal-Proximal	0.20 (-0.23, 0.60)	*Small*
	Distal-Middle	0.03 (-0.52, 0.50)	*Trivial*
	Middle-Proximal	0.17 (-0.18, 0.59)	*Small*
100º	Distal-Proximal	0.37 (-0.06, 0.69)	Moderate**
	Distal-Middle	0.22 (-0.20, 0.60)	*Small*
	Middle-Proximal	0.15 (-0.24, 0.54)	*Small*
Vastus lateralis fascicle length			
40º	Distal-Proximal	-0.11 (-0.56, 0.28)	*Small*
	Distal-Middle	-0.13 (-0.52, 0.22)	*Small*

	Middle-Proximal	0.03 (-0.28, 0.32)	*Trivial*
70º	Distal-Proximal	-0.22 (-0.67, 0.10)	*Small*
	Distal-Middle	-0.13 (-0.50, 0.23)	*Small*
	Middle-Proximal	-0.09 (-0.45, 0.18)	Trivial
100º	Distal-Proximal	-0.31 (-0.72, 0.01)	Small**
	Distal-Middle	-0.09 (-0.45, 0.26)	*Trivial*
	Middle-Proximal	-0.21 (-0.59, 0.08)	Small*
Rectus femoris muscle thickness			
40º	Distal-Proximal	0.28 (-0.32, 0.67)	*Small*
	Distal-Middle	-0.13 (-0.51, 0.22)	*Small*
	Middle-Proximal	0.41 (0.00, 0.62)	Moderate**
70º	Distal-Proximal	0.31 (-0.31, 0.65)	*Moderate*
	Distal-Middle	-0.11 (-0.49, 0.23)	*Small*
	Middle-Proximal	0.41 (0.01, 0.59)	Moderate**
100º	Distal-Proximal	0.23 (-0.35, 0.64)	*Small*
	Distal-Middle	-0.20 (-0.59, 0.15)	*Small*
	Middle-Proximal	0.43 (0.08, 0.64)	**Moderate****
Lateral vastus intermedius muscle thickness			
40º	Distal-Proximal	-0.02 (-0.31, 0.21)	*Trivial*
	Distal-Middle	0.11 (-0.08, 0.32)	Small*
	Middle-Proximal	-0.13 (-0.42, 0.10)	Small*
70º	Distal-Proximal	0.01 (-0.22, 0.23)	*Trivial*
	Distal-Middle	0.13 (-0.01, 0.32)	Small*
	Middle-Proximal	-0.11 (-0.40, 0.09)	Small*
100º	Distal-Proximal	0.12 (-0.10, 0.40)	Small*
	Distal-Middle	0.15 (0.05, 0.32)	**Small****

	Middle-Proximal	-0.04 (-0.26, 0.19)	*Trivial*
Anterior vastus intermedius muscle thickness			
40º	Distal-Proximal	0.09 (-0.20, 0.49)	*Trivial*
	Distal-Middle	0.06 (-0.19, 0.36)	*Trivial*
	Middle-Proximal	0.03 (-0.19, 0.34)	*Trivial*
70º	Distal-Proximal	0.08 (-0.24, 0.55)	*Trivial*
	Distal-Middle	0.02 (-0.01, 0.26)	*Trivial*
	Middle-Proximal	0.06 (-0.22, 0.35)	*Trivial*
100º	Distal-Proximal	0.16 (-0.18, 0.56)	*Small*
	Distal-Middle	0.08 (-0.05, 0.36)	*Trivial*
	Middle-Proximal	0.03 (-0.22, 0.37)	*Trivial*

CL=compatibility limits. *=possibly. **=likely. ***=very likely substantial. Decisions in **bold** have acceptable precision with 99% CLs. *Italicized* decisions are unclear.

Appendix 7. Differences in adjusted multiple correlations (√adjR^2), with compatibility limits and magnitude-based decisions, between normalized maximal voluntary isometric torque and regional quadriceps measures

Joint angle	Region comparison	Δ √adjR^2 (90%CL)	Decision
VL MT + VL PA + VL FL			
40º	Distal-Proximal	0.25 (0.00, 0.69)	Small**
	Distal-Middle	0.06 (-0.17, 0.42)	*Trivial*
	Middle-Proximal	0.19 (-0.06, 0.56)	Small*
70º	Distal-Proximal	0.18 (-0.07, 0.57)	Small*
	Distal-Middle	0.07 (-0.16, 0.40)	*Trivial*
	Middle-Proximal	0.11 (-0.10, 0.38)	*Small*
100º	Distal-Proximal	0.08 (-0.11, 0.43)	*Trivial*
	Distal-Middle	0.03 (-0.11, 0.23)	*Trivial*
	Middle-Proximal	0.05 (0.16, 0.35)	*Trivial*
VL MT + VL PA + VL FL + LVI MT			
40º	Distal-Proximal	0.25 (0.02, 0.73)	Small**
	Distal-Middle	0.07 (-0.16, 0.47)	*Trivial*
	Middle-Proximal	0.18 (-0.09, 0.62)	Small*
70º	Distal-Proximal	0.20 (0.00, 0.60)	Small**
	Distal-Middle	0.10 (-0.10, 0.48)	Small
	Middle-Proximal	0.10 (-0.15, 0.44)	Small
100º	Distal-Proximal	0.10 (-0.04, 0.37)	Small*
	Distal-Middle	0.05 (-0.07, 0.25)	*Trivial*
	Middle-Proximal	0.05 (-0.16, 0.31)	*Trivial*
VL MT + LVI MT			
40º	Distal-Proximal	0.23 (0.04, 0.53)	**Small****
	Distal-Middle	0.10 (-0.11, 0.38)	*Small*

	Middle-Proximal	0.13 (-0.09, 0.42)	Small*
70º	Distal-Proximal	0.20 (0.04, 0.49)	Small**
	Distal-Middle	0.04 (-0.13, 0.22)	*Trivial*
	Middle-Proximal	0.16 (-0.02, 0.48)	Small*
100º	Distal-Proximal	0.20 (0.00, 0.54)	Small**
	Distal-Middle	0.03 (-0.13, 0.19)	*Trivial*
	Middle-Proximal	0.17 (0.00, 0.47)	**Small***
RF MT + AVI MT			
40º	Distal-Proximal	0.38 (-0.34, 0.74)	*Moderate*
	Distal-Middle	-0.18 (-0.61, 0.26)	*Small*
	Middle-Proximal	0.56 (-0.01, 0.69)	Large**
70º	Distal-Proximal	0.34 (-0.34, 0.72)	*Moderate*
	Distal-Middle	-0.12 (-0.60, 0.28)	*Small*
	Middle-Proximal	0.46 (0.02, 0.67)	Moderate**
100º	Distal-Proximal	0.18 (-0.32, 0.65)	*Small*
	Distal-Middle	-0.17 (-0.61, 0.14)	*Small*
	Middle-Proximal	0.35 (0.04, 0.71)	Moderate**
VL MT + VL PA + VL FL + RF MT + LVI MT + AVI MT			
40º	Distal-Proximal	0.37 (0.02, 0.94)	Moderate**
	Distal-Middle	0.11 (-0.15, 0.69)	*Small*
	Middle-Proximal	0.25 (-0.18, 0.77)	*Small*
70º	Distal-Proximal	0.25 (0.01, 0.70)	Small**
	Distal-Middle	0.13 (-0.09, 0.61)	Small*
	Middle-Proximal	0.11 (-0.31, 0.53)	*Small*
100º	Distal-Proximal	0.12 (-0.07, 0.53)	Small*
	Distal-Middle	0.05 (-0.08, 0.33)	Trivial*

Middle-Proximal	0.07 (-0.22, 0.48)	*Trivial*

CL=compatibility limits. VL=vastus lateralis. LVI=lateral vastus intermedius. RF=rectus femoris. AVI=anterior vastus intermedius. MT=muscle thickness. PA=pennation angle. FL=fascicle length. *=possibly. **=likely substantial. Decisions in **bold** have acceptable precision with 99% CLs. *Italicized* decisions are unclear.

Appendix 8. Differences in adjusted multiple correlations (√adjR^2), with compatibility limits and magnitude-based decisions, between lateral (vastus lateralis + lateral vastus intermedius) and anterior (rectus femoris + anterior vastus intermedius) quadriceps muscle thickness

Joint angle	Region	Δ √adjR^2 (90%CL)	Decision
40º	Proximal	0.57 (-0.09, 0.79)	Large**
	Middle	0.14 (-0.15, 0.64)	*Small*
	Distal	0.42 (-0.01, 0.88)	Moderate**
70º	Proximal	0.47 (-0.10, 0.70)	Moderate**
	Middle	0.17 (-0.05, 0.56)	Trivial*
	Distal	0.33 (-0.02, 0.88)	Moderate**
100º	Proximal	0.33 (-0.13, 0.72)	*Moderate*
	Middle	0.15 (-0.08, 0.48)	Small*
	Distal	0.35 (0.00, 0.87)	Moderate**

CL=compatibility limits. *=possibly. **=likely substantial. *Italicized* decisions are unclear.

Appendix 9. Raw pressure-pain threshold values at each time-point with custom effect of between-condition deltas

		Condition	PRE	24 hours	48 hours	72 hours	7 days
Vastus lateralis							
	Proximal						
		ECC	3.4 ± 1.5	2.6 ± 1.4	2.7 ± 1.3	3.0 ± 1.4	3.4 ± 1.3
		EQI	3.2 ± 1.4	2.8 ± 1.5	3.0 ± 1.5	3.4 ± 1.6	3.4 ± 1.3
		Custom effect (%)		12.9% (-6.7, 36.3)	14.9% (-6.9, 41.8)	14% (-1.3, 31.8)	3.8% (-11.6, 21.8)
		Custom effect (ES)		*↑ 0.25 (-0.15, 0.66)	*↑ 0.29 (-0.15, 0.73)	*↑ 0.28 (-0.03, 0.58)	0.08 (-0.26, 0.41)
	Middle						
		ECC	2.9 ± 1.3	2.3 ± 1.3	2.4 ± 1.3	2.9 ± 1.3	3.0 ± 1.3
		EQI	3.0 ± 1.3	2.9 ± 1.6	3.0 ± 1.5	3.3 ± 1.4	3.1 ± 1.3
		Custom effect (%)		16.5% (3.7, 31.2)	17.7% (10.3, 25.5)	8.1% (-1.2, 18.3)	1.9% (-12.1, 18.1)
		Custom effect (ES)		*↑ 0.32 (0.07, 0.56)	**↑ 0.33 (0.2, 0.47)	0.16 (-0.02, 0.34)	0.04 (-0.26, 0.34)
	Distal						
		ECC	2.9 ± 1.6	2.3 ± 1.6	2.4 ± 1.3	2.6 ± 1.4	3.0 ± 1.6
		EQI	2.9 ± 1.5	2.7 ± 1.5	2.7 ± 1.6	3.0 ± 1.6	3.0 ± 1.4
		Custom effect (%)		25.9% (8.6, 46)	10% (-2.1, 23.6)	15.8% (9.2, 22.7)	7% (-15.5, 32.9)
		Custom effect (ES)		**↑ 0.40 (0.14, 0.66)	*↑0.17 (-0.04, 0.37)	**↑ 0.26 (0.15, 0.36)	0.12 (-0.39, 0.44)
Rectus femoris							
	Proximal						
		ECC	3.0 ± 1.3	2.2 ± 1.3	2.5 ± 1.5	2.8 ± 1.5	3.2 ± 1.3
		EQI	3.2 ± 1.4	2.6 ± 1.4	2.9 ± 1.6	3.2 ± 1.6	3.4 ± 1.4
		Custom effect (%)		13.8% (-4.8, 36)	9.9% (-1.6, 22.9)	11.4% (-3.9, 29.2)	-1.2% (-14.5, 14.2)
		Custom effect (ES)		*↑ 0.27 (-0.1, 0.65)	*↑ 0.2 (-0.03, 0.44)	*↑ 0.23 (-0.08, 0.54)	-0.03 (-0.33, 0.28)
	Middle						
		ECC	2.8 ± 1.5	2.4 ± 1.3	2.4 ± 1.4	2.7 ± 1.5	2.9 ± 1.1
		EQI	3.3 ± 1.6	2.9 ± 1.5	2.9 ± 1.8	3.4 ± 1.4	3.4 ± 1.6
		Custom effect (%)		4.9% (-6.4, 17.6)	-3.9% (-26.5, 25.7)	14.8%, (-4.4, 37.9)	0.05% (-16.6, 21)
		Custom effect (ES)		0.08 (-0.12, 0.29)	-0.07 (-0.54, 0.4)	0.24 (-0.08, 0.57)	0.01 (-0.32, 0.34)
	Distal						
		ECC	3.1 ± 1.5	2.3 ± 1.5	2.2 ± 1.2	2.7 ± 1.2	3.1 ± 1.4
		EQI	3.3 ± 1.4	3.2 ± 1.6	3.0 ± 1.9	3.4 ± 1.6	3.4 ± 1.5
		Custom effect (%)		30.4% (6.8, 59.2)	12.3% (-18.5, 54.6)	16.9% (-11.4, 54.2)	1.6% (-14.5, 20.7)
		Custom effect (ES)		***↑ 0.54 (0.13, 0.94)	0.24 (-0.41, 0.88)	0.32 (-0.25, 0.88)	0.03 (-0.32, 0.38)

ECC = Eccentric. EQI = Eccentric quasi-isometric. Custom effect = difference (%) and Cohen's *d* (ES) adjusted for individual total impulse and PRE value of the dependent variable. Data are mean ± standard deviation or the effect with (95% Compatibility intervals). Asterisks indicate substantial effects with adequate precision as follows: **possibly*, ***likely*, ****very likely*, *****most likely*. ↑ = larger effect in ECC. ↓ = larger effect in EQI. Smallest important difference for proximal/middle/distal regions were: vastus lateralis = 5%/9.7%/11%; rectus femoris = 9.4%/11.1%/9.1%.

Appendix 10. Raw muscle thickness values at each time-point with custom effect of between-condition deltas

		Condition	PRE	POST	24 hours	48 hours	72 hours	7 days
Vastus lateralis MT (cm)								
	Proximal							
		ECC	2.58 ± 0.28	2.67 ± 0.27	2.68 ± 0.29	2.60 ± 0.26	2.59 ± 0.26	2.59 ± 0.25
		EQI	2.53 ± 0.31	2.56 ± 0.27	2.59 ± 0.36	2.58 ± 0.3	2.56 ± 0.28	2.52 ± 0.27
		Custom effect (%)		-2.5% (-7.1, 2.4)	-1.9% (-6.8, 3.3)	1% (-2.2, 4.2)	-0.1% (-4.7, 4.2)	-0.9% (-4, 2.2)
		Custom effect (ES)		*↑ -0.21 (-0.61, 0.19)	-0.16 (-0.59, 0.27)	0.08 (-0.18, 0.35)	-0.01 (-0.38, 0.36)	-0.08 (-0.34, 0.18)
	Middle							
		ECC	2.83 ± 0.34	2.91 ± 0.35	2.86 ± 0.34	2.82 ± 0.32	2.8 ± 0.38	2.81 ± 0.36
		EQI	2.65 ± 0.33	2.75 ± 0.30	2.76 ± 0.32	2.71 ± 0.32	2.7 ± 0.31	2.66 ± 0.32
		Custom effect (%)		-0.4% (-2.5, 3.4)	2.2% (-1.2, 5.6)	1.4% (-2.7, 5.7)	2.1% (-0.01, 15.3)	1% (-1.4, 3.6)
		Custom effect (ES)		0.03 (-0.19, 0.26)	0.16 (-0.09, 0.42)	0.11 (-0.21, 0.42)	0.12 (-0.1, 0.28)	0.09 (-0.26, 0.32)
	Distal							
		ECC	2.17 ± 0.44	2.28 ± 0.46	2.23 ± 0.43	2.22 ± 0.44	2.22 ± 0.43	2.20 ± 0.41
		EQI	2.09 ± 0.42	2.16 ± 0.45	2.14 ± 0.41	2.12 ± 0.4	2.12 ± 0.37	2.08 ± 0.41
		Custom effect (%)		-1.6% (-6.6, 3.3)	-1% (-4.8, 3)	-1.1% (-4.9, 3)	-1.3% (-3.9, 1.4)	-2.1% (-4.9, 0.8)
		Custom effect (ES)		-0.08 (-0.31, 0.15)	-0.4 (-0.23, 0.14)	-0.05 (-0.24, 0.19)	-0.06 (-0.19, 0.06)	-0.1 (-0.23, 0.04)
Lateral vastus intermedius MT (cm)								
	Proximal							
		ECC	2.04 ± 0.46	2.00 ± 0.43	2.02 ± 0.40	2.00 ± 0.39	2.02 ± 0.43	2.01 ± 0.44
		EQI	1.95 ± 0.40	2.05 ± 0.39	2.06 ± 0.46	2.07 ± 0.43	2.04 ± 0.41	1.96 ± 0.40
		Custom effect (%)		6.8% (3.4, 10.4)	4.8% (-0.3, 10.1)	7.1% (3.2, 11.2)	5.1% (1.5, 8.9)	1.7% (-0.4, 3.8)
		Custom effect (ES)		**↓ 0.28 (0.14, 0.42)	*↓ 0.2 (-0.01, 0.41)	**↓ 0.29 (0.13, 0.46)	*↓ 0.22 (0.06, 0.37)	0.07 (-0.02, 0.16)
	Middle							
		ECC	2.34 ± 0.50	2.31 ± 0.46	2.37 ± 0.52	2.32 ± 0.50	2.35 ± 0.48	2.35 ± 0.49
		EQI	2.26 ± 0.42	2.37 ± 0.40	2.38 ± 0.52	2.37 ± 0.48	2.33 ± 0.44	2.24 ± 0.43
		Custom effect (%)		5.9% (-1.5, 13.8)	3.4% (-5.5, 13.1)	4.8% (-2.6, 12.8)	1.8% (-3.6, 7.6)	-2% (-5.8, 2.1)
		Custom effect (ES)		*↓ 0.26 (-0.07, 0.58)	0.15 (-0.26, 0.56)	*↓ 0.21 (-0.12, 0.55)	0.08 (-0.17, 0.33)	-0.09 (-0.27, 0.09)
	Distal							
		ECC	2.10 ± 0.38	2.16 ± 0.34	2.14 ± 0.34	2.13 ± 0.37	2.10 ± 0.39	2.1 ± 0.39
		EQI	2.05 ± 0.31	2.10 ± 0.29	2.08 ± 0.33	2.10 ± 0.32	2.08 ± 0.32	2.03 ± 0.30
		Custom effect (%)		-1% (-0.6, 0.43)	-1.3% (-7.7, 5.6)	0.5% (-3.9, 5.2)	1.9% (-2.3, 6.3)	-1.1% (-4, 1.8)
		Custom effect (ES)		-0.05 (-0.44, 0.3)	-0.07 (-0.56, 0.25)	0.03 (-0.22, 0.28)	0.1 (-0.13, 0.33)	-0.06 (-0.23, 0.1)
Rectus femoris MT (cm)								
	Proximal							
		ECC	2.58 ± 0.45	2.71 ± 0.44	2.73 ± 0.42	2.68 ± 0.46	2.63 ± 0.41	2.59 ± 0.42
		EQI	2.61 ± 0.51	2.79 ± 0.55	2.69 ± 0.49	2.67 ± 0.50	2.70 ± 0.49	2.61 ± 0.52
		Custom effect (%)		2.2% (-2.6, 7.2)	-2.1% (-5.6, 1.6)	-0.9% (-2.8, 1)	2% (-1.5, 5.7)	-0.3 (-2.5, 1.9)
		Custom effect (ES)		0.11 (-0.13, 0.36)	-0.11 (-0.30, 0.8)	-0.05 (-0.15, 0.05)	0.1 (-0.08, 0.29)	-0.02 (-0.13, 0.1)

	Middle							
		ECC	2.72 ± 0.34	2.96 ± 0.47	2.90 ± 0.48	2.80 ± 0.41	2.81 ± 0.35	2.76 ± 0.37
		EQI	2.71 ± 0.46	2.91 ± 0.46	2.73 ± 0.48	2.73 ± 0.48	2.73 ± 0.46	2.70 ± 0.46
		Custom effect (%)		0.5% (-2.7, 3.6)	-4.9% (-10.4, 1)	-1.9% (-5, 1.3)	-2.8% (-6.5, 1.2)	-1.7% (-4.3, 1)
		Custom effect (ES)		0.03 (-0.16, 0.23)	*↑ -0.31 (-0.68, 0.06)	-0.12 (-0.32, 0.08)	0.15 (-0.38, 0.11)	-0.1 (-0.27, 0.06)
	Distal							
		ECC	2.07 ± 0.37	2.34 ± 0.44	2.13 ± 0.41	2.10 ± 0.34	2.09 ± 0.35	2.07 ± 0.36
		EQI	2.02 ± 0.38	2.21 ± 0.42	2.08 ± 0.37	2.06 ± 0.36	2.06 ± 0.37	2.02 ± 0.36
		Custom effect (%)		-3.2% (-8, 1.8)	0.7% (-2.9, 4.5)	0.5% (-2, 3.1)	0.9% (-1.7, 3.6)	0% (-2.2, 2.4)
		Custom effect (ES)		-0.15 (-0.39, 0.09)	0.03 (-0.14, 0.21)	0.02 (-0.1, 0.15)	0.04 (-0.08, 0.17)	0 (-0.11, 0.11)
Anterior vastus intermedius MT (cm)	Proximal							
		ECC	3.37 ± 0.50	3.54 ± 0.50	3.49 ± 0.43	3.44 ± 0.47	3.41 ± 0.48	3.33 ± 0.45
		EQI	3.23 ± 0.46	3.33 ± 0.41	3.31 ± 0.47	3.3 ± 0.44	3.31 ± 0.49	3.23 ± 0.43
		Custom effect (%)		-2.4% (-5, 0.3)	-2.3% (-6.4, 1.9)	-0.4% (-3.2, 2.6)	0.8% (-2.5, 4.1)	0.8% (-0.9, 2.6)
		Custom effect (ES)		-0.15 (-0.32, 0.02)	-0.15 (-0.41, 0.12)	-0.02 (-0.21, 0.16)	0.05 (-0.16, 0.25)	0.05 (-0.06, 0.16)
	Middle							
		ECC	2.72 ± 0.38	2.79 ± 0.37	2.80 ± 0.39	2.76 ± 0.37	2.74 ± 0.36	2.70 ± 0.34
		EQI	2.68 ± 0.38	2.74 ± 0.37	2.73 ± 0.4	2.74 ± 0.36	2.75 ± 0.39	2.70 ± 0.35
		Custom effect (%)		-0.8% (-5.6, 4.2)	-1.2% (-6.3, 4.1)	0.5% (-3.6, 4.7)	1.3% (-3.2, 5.9)	1.2% (-0.4, 2.9)
		Custom effect (ES)		-0.06 (-0.4, 0.29)	-0.09 (-0.46, 0.29)	0.03 (-0.26, 0.32)	0.09 (-0.23, 0.41)	0.08 (-0.03, 0.2)
	Distal							
		ECC	2.33 ± 0.34	2.30 ± 0.28	2.29 ± 0.29	2.30 ± 0.32	2.27 ± 0.32	2.21 ± 0.28
		EQI	2.25 ± 0.32	2.35 ± 0.29	2.30 ± 0.31	2.31 ± 0.32	2.29 ± 0.32	2.24 ± 0.27
		Custom effect (%)		1.1% (-3.1, 5.4)	-0.2% (-4.2, 3.9)	-0.4% (-4.2, 3.6)	0% (-3.1, 3.2)	0.9% (-0.7, 2.4)
		Custom effect (ES)		0.07 (-0.1, 0.65)	-0.02 (-0.29, 0.26)	-0.03 (-0.29, 0.24)	0 (-0.21, 0.21)	0.06 (-0.04, 0.16)

MT = muscle thickness. cm = centimeters. ECC = eccentric. EQI = eccentric quasi-isometric. Custom effect = difference (%) and Cohen's *d* (ES) adjusted for individual total impulse and PRE value of the dependent variable. Data are mean ± standard deviation or the effect with (95% Compatibility intervals). Asterisks indicate substantial effects with adequate precision as follows: **possibly*, ***likely*, ****very likely*, *****most likely*. ↑ = larger effect in ECC. ↓ = larger effect in EQI. Smallest important difference for proximal/middle/distal regions were: vastus lateralis = 2.4%/2.6%/4.3%; lateral vastus intermedius = 4.6%/4.4%/3.6%; rectus femoris = 4.6%/3.9%/4.2%; anterior vastus intermedius = 3.2%/2.9%/3%.

Appendix 11. Raw vastus lateralis pennation angle and fascicle length values at each time-point with custom effect of between-condition deltas

		Condition	PRE	POST	24 hours	48 hours	72 hours	7 days
Vastus lateralis pennation angle (º)								
	Proximal							
		ECC	17.9 ± 3.43	17.8 ± 4.7	18.5 ± 4.3	17.9 ± 4.3	17.9 ± 4.1	17.8 ± 4.3
		EQI	18.9 ± 5.73	18.6 ± 5.0	18.8 ± 5.2	18.0 ± 4.6	17.9 ± 4.6	17.2 ± 4.2
		Custom effect (%)		2.1% (-12.5, 19.1)	-2% (-15.2, 13.2)	-2.7 (-0.14.1, 10.1)	-2.8% (-14.8, 10.8)	-3% (-12.5, 7.4)
		Custom effect (ES)		0.07 (-0.47, 0.61)	-0.07 (-0.58, 0.44)	-0.1 (-0.53, 0.34)	-0.1 (-0.56, 0.36)	-0.12 (-0.49, 0.25)
	Middle							
		ECC	23.2 ± 4.5	22.1 ± 5.1	22.0 ± 4.4	21.9 ± 3.8	22.4 ± 4.6	23.0 ± 5.1
		EQI	21 ± 3.7	21.6 ± 3.6	21.9 ± 3.2	21.2 ± 4.5	21.3 ± 5.2	21.4 ± 4.5
		Custom effect (%)		7.3% (-1, 16.2)	7.3% (-4.5, 20.5)	2.9% (-10.3, 18.1)	2.6% (-11.6, 19.1)	2.7% (-7.8, 14.4)
		Custom effect (ES)		**↓ 0.34 (-0.05, 0.72)	0.34 (-0.22, 0.89)	0.14 (-0.52, 0.8)	0.12 (-0.59, 0.84)	0.13 (-0.39, 0.65)
	Distal							
		ECC	26.5 ± 4.6	27.0 ± 4.1	25.3 ± 4.1	27.1 ± 6.0	26.7 ± 5.2	26.2 ± 5.2
		EQI	25.7 ± 4.8	24.0 ± 3.8	24.5 ± 3.5	25.2 ± 4.5	24.7 ± 4.8	25.7 ± 5.1
		Custom effect (%)		-8.7% (-15.6, -1.4)	-0.4% (-7.4, 7.1)	-4.5% (-15.7, 8.2)	-4.5% (-11.1, 2.5)	1.1% (-8, 11.1)
		Custom effect (ES)		**↑ -0.49 (-0.9, -0.07)	-0.02 (-0.41, 0.37)	-0.24 (-0.91, 0.42)	*↑ -0.25 (-0.63, 0.13)	0.06 (-0.45, 0.56)
Vastus lateralis fascicle length (cm)								
	Proximal							
		ECC	7.22 ± 1.04	7.35 ± 0.81	7.57 ± 0.83	7.26 ± 0.59	7.25 ± 0.65	7.30 ± 0.93
		EQI	7.43 ± 0.85	7.03 ± 0.73	7.13 ± 0.90	7.38 ± 0.71	7.22 ± 0.67	7.36 ± 0.93
		Custom effect (%)		-6.2% (-11, -1.2)	-8.3% (-12.6, -3.7)	-0.3% (-4.1, 3.6)	-2.4% (-4.8, 0.1)	-2.1% (-5.7, 1.6)
		Custom effect (ES)		**↓ -0.49 (-0.89, -0.09)	***↓ -0.66 (-1.04, -0.29)	-0.17 (-0.36, 0.04)	-0.16 (-0.33, 0.05)	-0.16 (-0.45, 0.12)
	Middle							
		ECC	7.42 ± 0.62	7.33 ± 0.75	7.32 ± 0.74	7.33 ± 0.70	7.43 ± 0.65	7.41 ± 0.71
		EQI	7.39 ± 1.15	7.29 ± 1.08	7.51 ± 1.02	7.65 ± 0.95	7.73 ± 0.95	7.54 ± 1.17
		Custom effect (%)		0.1% (-5, 5.4)	3.6% (-1.9, 9.3)	4.8% (-0.83, 11.1)	4.5% (0.08, 9.4)	2.2% (-3.4, 8.1)
		Custom effect (ES)		0 (-0.4, 0.41)	*↑ 0.27 (-0.15, 0.69)	**↑ 0.37 (-0.08, 0.82)	**↑ 0.34 (-0.01, 0.69)	0.17 (-0.27, 0.6)
	Distal							
		ECC	6.95 ± 0.74	6.89 ± 0.61	6.90 ± 0.58	6.77 ± 0.61	6.89 ± 0.71	6.99 ± 0.83
		EQI	6.73 ± 0.82	6.68 ± 0.65	6.79 ± 0.79	6.74 ± 0.88	6.77 ± 0.61	6.80 ± 0.67
		Custom effect (%)		-0.8% (-5.6, 4.2)	0.7% (-5.7, 7.6)	1.7% (-4.5, 8.6)	0.9% (-3.6, 5.8)	0.8% (-2.8, 4.5)
		Custom effect (ES)		-0.07 (-0.5, 0.36)	0.06 (-0.51, 0.63)	0.14 (-0.4, 0.69)	0.08 (-0.32, 0.48)	0.07 (-0.24, 0.38)

º = degrees. cm = centimeters. ECC = eccentric. EQI = eccentric quasi-isometric. Custom effect = difference (%) and Cohen's *d* (ES) adjusted for individual total impulse and PRE value of the dependent variable. Data are mean ± standard deviation or the effect with (95% Compatibility intervals). Asterisks indicate substantial effects with adequate precision as follows: **possibly*, ***likely*, ****very likely*, *****most likely*. ↑ = larger effect in ECC. ↓ = larger effect in EQI. Smallest important difference for proximal/middle/distal pennation angle were: 5.7%/4.2%/3.8%; fascicle length: 2.6%/2.6%/2.3%.

Appendix 12. Raw echo intensity values at each time-point with custom effect of between-condition deltas

		Condition	PRE	POST	24 hours	48 hours	72 hours	7 days
Vastus lateralis EI (a.u)								
	Proximal							
		ECC	70.6 ± 10.0	77.6 ± 12.1	73.2 ± 15.5	73.2 ± 12.4	68.7 ± 10.0	71.5 ± 11.9
		EQI	70.5 ± 14.2	73.7 ± 14.8	71.2 ± 12.0	71.6 ± 10.3	69.2 ± 10.8	68.5 ± 14.0
		Custom effect (%)		-4.7% (-11, 2.1)	-1.6% (-9.3, 6.8)	-1% (-5.9, 4.2)	1.1% (-3.9, 6.3)	1.1% (-5.6, 8.2)
		Custom effect (ES)		-0.2 (-0.62, 0.18)	-0.08 (-0.52, 0.35)	-0.05 (-0.32, 0.22)	0.06 (-0.21, 0.32)	0.06 (-0.3, 0.42)
	Middle							
		ECC	59.5 ± 7.9	65.9 ± 11.6	64.6 ± 12.4	62.9 ± 8.5	60.8 ± 7.9	61.2 ± 7.4
		EQI	61.4 ± 9.1	66.4 ± 9.1	63.2 ± 8.4	62.6 ± 7.4	59.8 ± 9.8	59.9 ± 8.7
		Custom effect (%)		-1.4% (-9.3, 7.2)	-4.4% (-10.9, 2.7)	-2.4% (-7.2, 2.7)	-4.4% (-12.4, 4.3)	3% (-10.1, 4.7)
		Custom effect (ES)		-0.1 (-0.67, 0.48)	-0.11 (-0.59, 0.18)	-0.14 (-0.51, 0.18)	-0.21 (-0.71, 0.29)	0.21 (-0.73, 0.32)
	Distal							
		ECC	69.1 ± 6.6	82.4 ± 9.3	70.5 ± 8.0	71.3 ± 8.0	70.3 ± 8.4	69.9 ± 9.3
		EQI	68.6 ± 8.0	79.8 ± 8.2	71.9 ± 9.5	71.9 ± 10.3	68.9 ± 6.4	67.7 ± 7.3
		Custom effect (%)		-2.5% (-7.8, 3.1)	2.5% (-2.8, 8.3)	-0.2% (-5.9, 5.8)	-1.2% (-6.3, 4.3)	0.9% (-5.3, 7.4)
		Custom effect (ES)		-0.22 (-0.72, 0.28)	0.23 (-0.26, 0.71)	-0.02 (-0.54, 0.5)	-0.1 (-0.58, 0.37)	0.08 (-0.49, 0.64)
Lateral vastus intermedius EI (a.u)								
	Proximal							
		ECC	43.3 ± 10.3	47.3 ± 10.2	44.3 ± 10.2	43.1 ± 9.2	43.4 ± 10.2	42.6 ± 9.7
		EQI	41.9 ± 11.6	44.9 ± 11.2	41.9 ± 10.1	42.6 ± 9.4	40.5 ± 9.9	41.3 ± 10.9
		Custom effect (%)		-0.5% (-6.3, 5.8)	-0.4% (-0.9, 8.9)	3.7% (-1.7, 9.5)	-1.1% (-8.1, 6.4)	4.2% (-4, 13.1)
		Custom effect (ES)		-0.02 (-0.23, 0.20)	-0.02 (-0.34, 0.31)	0.13 (-0.06, 0.32)	-0.04 (0.3, 0.22)	0.17 (-1.2, 0.56)
	Middle							
		ECC	28.6 ± 10.1	32.9 ± 13.0	30.2 ± 9.8	29.5 ± 10.0	28.1 ± 8.7	22.2 ± 12.1
		EQI	29.2 ± 8.8	32.6 ± 9.5	30.3 ± 7.9	30.9 ± 8.2	27.0 ± 5.3	28.5 ± 6.7
		Custom effect (%)		-2.1% (-12.8, 10)	-1.4% (-12.4, 11)	3.7% (-8.9, 17.9)	-4% (-9.3, 1.6)	-3.5% (-11.3, 5.1)
		Custom effect (ES)		-0.07 (-0.46, 0.32)	-0.05 (-0.44, 0.35)	0.12 (-0.31, 0.55)	-0.14 (-0.33, 0.05)	-0.12 (-0.4, 0.17)
	Distal							
		ECC	31.2 ± 11.6	36.5 ± 8.6	32.2 ± 7.4	30.6 ± 8.0	30.6 ± 8.5	30.9 ± 7.4
		EQI	31.0 ± 11.6	34.2 ± 12.0	34.3 ± 14.1	33.7 ± 13.4	31.4 ± 10.0	31.5 ± 10.7
		Custom effect (%)		-7.9% (-19.2, 5.1)	2.5% (-8.7, 15.1)	3.4% (-12.7, 19.8)	3.3% (-6.2, 13.8)	1.6% (-6, 9.8)
		Custom effect (ES)		*↑ -0.25 (-0.65, 0.15)	0.07 (-0.28, 0.43)	0.09 (-0.22, 0.28)	0.1 (-0.2, 0.39)	0.05 (-0.19, 0.28)
Rectus femoris EI (a.u)								
	Proximal							
		ECC	74.1 ± 20.6	78.2 ± 17.8	74.3 ± 18.5	75.6 ± 16.3	74.6 ± 16.2	72.3 ± 18.4
		EQI	74.7 ± 19.1	78.9 ± 16.3	77.1 ± 18.6	78.7 ± 15.2	73.9 ± 15.5	74.9 ± 19.5

		Custom effect (%)		0.4% (-4.7, 5.8)	3.1% (-3, 9.6)	4% (-2.4, 10.8)	-1.3% (-6, 3.7)	-1.1 (-8.5, 6.9)
		Custom effect (ES)		-0.04 (-0.3, 0.23)	0.1 (-0.11, 0.31)	0.11 (-0.1, 0.32)	-0.4 (-0.21, 0.12)	-0.04 (-0.3, 0.23)
	Middle							
		ECC	70.9 ± 11.4	85.6 ± 12.7	72.7 ± 11.6	70.1 ± 11.5	69.7 ± 11.0	69 ± 11.3
		EQI	69.8 ± 9.6	81.4 ± 11.2	71.0 ± 10.8	72.1 ± 8.2	69.1 ± 12.7	68.8 ± 8.3
		Custom effect (%)		-3.9% (-9.1, 1.6)	-1.1% (-7.2, 5.4)	3.2% (-2.1, 8.7)	0.1% (-8.6, 9.6)	1.3% (-4.9, 8)
		Custom effect (ES)		*↑ -0.25 (-0.6, 0.1)	-0.07 (-0.47, 0.33)	0.16 (-0.17, 0.49)	0.01 (-0.57, 0.58)	0.08 (-0.32, 0.49)
	Distal							
		ECC	72.9 ± 11.1	92 ± 11.0	75.7 ± 11.8	72.2 ± 11.9	70.2 ± 11.8	71.3 ± 11.9
		EQI	73.9 ± 9.6	85.6 ± 12.2	76.9 ± 7.8	74.0 ± 8.3	71.8 ± 10.1	75.4 ± 11.5
		Custom effect (%)		-8.3% (-5.4, -7.9)	1% (-5.4, 7.9)	2.4% (-5.2, 10.5)	1.6% (-7.3, 11.4)	-1.7% (-8.5, 5.7)
		Custom effect (ES)		***↑ -0.55 (-0.93, -0.17)	0.07 (-0.36, 0.49)	0.15 (-0.34, 0.64)	0.1 (-0.49, 0.69)	-0.11 (-0.57, 0.35)
Anterior vastus intermedius EI (a.u)								
	Proximal							
		ECC	39.4 ± 11.7	41.4 ± 11.2	40.1 ± 11.4	40.9 ± 11.2	40.0 ± 11.2	39.8 ± 11.7
		EQI	40.3 ± 11.0	40.3 ± 11.2	39.8 ± 10.9	40.0 ± 10.1	39.6 ± 11.4	40.4 ± 11.5
		Custom effect (%)		-4.3% (-9.2, -1.3)	-3.3% (-6.9, 0.5)	-4.1% (-7.3, 0.8)	-3.6% (-6.6, -1)	-2.9% (-7.5, 1.9)
		Custom effect (ES)		-0.15 (-0.3, -0.06)	-0.11 (-0.23, 0.02)	-0.14 (-0.25, -0.02)	-0.11 (-0.23, 0.03)	-0.1 (-0.25, 0.06)
	Middle							
		ECC	33.2 ± 5.2	34.6 ± 6.9	34.5 ± 6.3	34.0 ± 4.7	32.6 ± 4.1	33.0 ± 7.0
		EQI	31.8 ± 4.8	34.1 ± 6.5	33.9 ± 6.5	32.4 ± 5.0	31.7 ± 4.8	33.2 ± 7.1
		Custom effect (%)		3.2% (-1.5, 8.2)	2.3% (-6.1, 11.6)	-2.1% (-8.9, 5.2)	-0.3% (-6, 5.7)	2.2% (-2.3, 6.9)
		Custom effect (ES)		0.19 (-0.09, 0.47)	0.14 (-0.38, 0.65)	-0.13 (-0.56, 0.31)	-0.02 (-0.37, 0.33)	0.15 (-0.12, 0.41)
	Distal							
		ECC	38.0 ± 8.5	40.4 ± 7.0	39.0 ± 7.4	37.9 ± 6.3	38.0 ± 7.3	38.7 ± 9.3
		EQI	36.5 ± 7.0	36.7 ± 4.8	38.3 ± 7.6	38.0 ± 8.0	35.9 ± 6.7	36.7 ± 6.9
		Custom effect (%)		-4.9% (-10.7, 0.9)	0.9% (-5.5, 7.8)	2% (-5.8, 10.4)	-3.1% (-11.9, 6.6)	3.3% (-6.6, 14.1)
		Custom effect (ES)		-0.19 (-0.57, 0.18)	0.04 (-0.27, 0.35)	0.09 (-0.28, 0.47)	-0.15 (-0.6, 0.3)	0.15 (-0.32, 0.62)

EI = echo intensity. a.u = arbitrary units. ECC = eccentric. EQI = eccentric quasi-isometric. Custom effect = difference (%) and Cohen's *d* (ES) adjusted for individual total impulse and PRE value of the dependent variable. Data are mean ± standard deviation or the effect with (95% Compatibility intervals). Asterisks indicate substantial effects with adequate precision as follows: **possibly*, ***likely*, ****very likely*, *****most likely*. ↑ = larger effect in ECC. ↓ = larger effect in EQI. Smallest important difference for proximal/middle/distal regions were: vastus lateralis = 3.8%/3.8%/2.3%; rectus femoris = 5.9%/3.2%/3.1%; lateral vastus intermedius = 5.6%/6.0%/6.5%; anterior vastus intermedius = 6.2%/3.4%/4.2%.

Appendix 13. Raw angle specific concentric peak torque, total impulse, and angle specific impulse values at each time-point with custom effect of between-condition deltas

		Condition	PRE	POST	24 hours	48 hours	72 hours	7 days
Peak concentric torque (Nm)								
		ECC	214.2 ± 32.2	189.7 ± 41.7	181.5± 34.6	184.2 ± 35.8	196.4 ± 32.4	214.4 ± 37.0
		EQI	208.9 ± 31.9	200.7 ± 179.2	179.2 ± 27.3	186.8 ± 33.3	191.0 ± 28.9	205.9 ± 31.0
		Custom effect (%)		8.7% (0.4, 17.7)	1.5% (-4.8, 8.2)	3.5% (-8.7, 17.3)	-0.7% (-8.8, 8)	-1.9% (-9.6, 6.4)
		Custom effect (ES)		**↑ 0.5 (0.02, 0.98)	0.09 (-0.30, 0.47)	0.2 (-0.55, 0.96)	-0.04 (-0.55, 0.46)	-0.12 (-0.6, 0.37)
Total concentric impulse (Nm.s)								
		ECC	245.4 ± 39.2	216.9 ± 47.2	214.7 ± 41.3	217.7 ± 39.0	226.8 ± 49.1	249.1 ± 41.2
		EQI	239.5 ± 37.3	229.6 ± 51	210.1 ± 33.4	220.0 ± 39.3	222.5 ± 38.3	239.7 ± 36.8
		Custom effect (%)		8.3% (0.4, 0.16.9)	0.4% (-5.7, 4)	2.8% (-8.3, 15.2)	-0.2% (-8.4, 8.8)	-1.9% (-8.9, 5.7)
		Custom effect (ES)		**↑ 0.45 (0.02, 0.88)	0.02 (-0.33, 0.38)	0.15 (-0.49, 0.8)	-0.01 (-0.49, 0.47)	-0.11 (-0.52, 0.31)
Angle-specific impulse (Nm.s)								
	100-90º							
		ECC	26.7 ± 8.3	20.8 ± 6.5	22.1 ± 5.3	23.4 ± 5.5	23.0 ± 5.7	25.2 ± 5.9
		EQI	26.1 ± 5.6	24.7 ± 6.6	23.3 ± 5.4	23.2 ± 4.7	23.9 ± 5.1	26.0 ± 5.3
		Custom effect (%)		19.7% (6.2, 34.8)	5.1% (-3, 13.9)	-1% (-12, 11.5)	4.5% (-5.6, 15.8)	3.8% (-2.3, 10.4)
		Custom effect (ES)		***↑ 0.57 (0.19, 0.94)	*↑ 0.16 (-0.1, 0.41)	-0.03 (-0.41, 0.34)	0.14 (-0.18, 0.46)	0.12 (-0.07, 0.31)
	90-80º							
		ECC	31.3 ± 7.1	25.8 ± 6.2	26.9 ± 6.3	27.4 ± 6.1	28.5 ± 5.9	30.7 ± 6.1
		EQI	31.6 ± 6.0	30.2 ± 7.2	27.4 ± 5.3	27.5 ± 5.2	28.5 ± 4.7	31.2 ± 5.6
		Custom effect (%)		15.6% (-5.2, 26.9)	1.1% (-4.6, 7)	-0.4% (-11, 11.5)	-0.7% (-8, 7.3)	0.6% (-7.3, 9.2)
		Custom effect (ES)		***↑ 0.6 (0.21, 0.99)	0.04 (-0.19, 0.28)	-0.02 (-0.48, 0.45)	-0.3 (-0.35, 0.29)	0.02 (-0.32, 0.36)
	80-70º							
		ECC	33.0 ± 5.9	28.5 ± 6.7	28.7 ± 6.4	29.1 ± 6.3	30.7 ± 6.1	33.5 ± 6.6
		EQI	32.6 ± 5.6	31.6 ± 7.1	27.6 ± 4.6	28.8 ± 5.4	29.6 ± 4.4	32.4 ± 5.4
		Custom effect (%)		11.7% (1.2, 23.2)	-2.3% (-9.2, 5.1)	0.4% (-12.1, 14.6)	-2.2% (-10.5, 6.8)	-1.9% (-8.9, 5.7)
		Custom effect (ES)		**↑ 0.56 (0.06, 1.06)	-0.12 (-0.49, 0.25)	0.02 (-0.66, 0.69)	-0.11 (-0.56, 0.33)	-0.1 (-0.48, 0.28)
	70-60º							
		ECC	30.8 ± 5.6	29.8 ± 7.2	29.0 ± 5.8	29.4 ± 5.9	30.9 ± 5.7	34.4 ± 6.5
		EQI	32.2 ± 5.1	31.5 ± 7.1	27.5 ± 4.2	29.1 ± 5.3	29.6 ± 4.3	32.6 ± 5.2
		Custom effect (%)		10.7% (0.5, 0.22)	-0.07% (-8, 7.2)	2.4% (-12.1, 19.4)	-0.7% (-11.2, 11.1)	-1.4% (-11.5, 9.8)
		Custom effect (ES)		**↑ 0.58 (0.03, 1.14)	-0.04 (-0.48, 0.4)	0.14 (-0.74, 1.01)	-0.04 (-0.68, 0.6)	-0.08 (-0.7, 0.53)
	60-50º							
		ECC	32 ± 4.6	28.4 ± 6.3	27.8 ± 5.3	28.4 ± 5.6	29.9 ± 5.7	33.5 ± 6.2
		EQI	30.4 ± 4.8	29.7 ± 6.6	26.4 ± 3.9	28.5 ± 5.5	26.6 ± 5.1	30.8 ± 4.9
		Custom effect (%)		10.5% (0.5, 21.6)	-0.2% (-8, 8.4)	3.8% (-11.8, 22.1)	-0.4% (-12.5, 13.3)	-0.4% (-12.5, 13.3)

	Custom effect (ES)		**↑ 0.62 (0.03, 1.2)	-0.01 (-0.52, 0.5)	0.23 (-0.78, 1.23)	-0.03 (-0.82, 0.77)	-0.03 (-0.82, 0.77)
50-40º							
	ECC	28.7 ± 4.0	25.8 ± 5.8	25.7 ± 5.2	25.9 ± 4.8	27.1 ± 5.1	30.5 ± 5.7
	EQI	27.8 ± 4.9	26.7 ± 6.6	24.1 ± 4.0	26.4 ± 5.8	26.5 ± 6.1	28.0 ± 5.2
	Custom effect (%)		8% (-2.2, 19.3)	-2.3% (-10.5, 6.7)	4.5% (-9.9, 21.4)	0.1% (-11.2, 12.9)	-5.3% (-13.8, 4.1)
	Custom effect (ES)		**↑ 0.45 (-0.13, 1.03)	-0.13 (-0.65, 0.38)	0.26 (-0.61, 1.13)	0.01 (-0.69, 0.71)	-0.32 (-0.87, 0.23)
40-30º							
	ECC	24.3 ± 3.6	22.4 ± 5.3	22.3 ± 4.2	22.2 ± 4.0	23.4 ± 4.4	25.9 ± 4.8
	EQI	23.8 ± 4.5	22.7 ± 6.4	21.1 ± 4.3	23.0 ± 5.2	22.6 ± 5.5	23.9 ± 4.8
	Custom effect (%)		4.3% (-5.3, 14.7)	-3.4% (-11.2, 5)	4.7% (-8.4, 19.7)	-2.3% (-11.8, 8.2)	-6% (-14, 2.6)
	Custom effect (ES)		0.22 (-0.29, 0.73)	-0.19 (-0.63, 0.26)	0.25 (-0.46, 0.95)	-0.12 (-0.66, 0.42)	*↓ -0.33 (-0.8, 0.14)
30-20º							
	ECC	20.2 ± 3.6	18.5 ± 4.8	18.2 ± 3.6	17.9 ± 3.0	19 ± 3.4	21 ± 3.8
	EQI	19.5 ± 4.1	18.4 ± 5.1	17.7 ± 4.5	18.9 ± 4.5	18.3 ± 4.6	19.5 ± 4.2
	Custom effect (%)		4.2% (-5.2, 14.5)	-0.9% (-9, 8)	7.3% (-8.3, 19.6)	-2% (-10.3, 7.1)	-4.4% (-11.9, 3.6)
	Custom effect (ES)		0.19 (-0.25, 0.65)	-0.4 (-0.43, 0.35)	*↑ 0.32 (-0.18, 0.82)	-0.09 (-0.5, 0.31)	*↓ 0.21 (-0.58, 0.16)
20-10º							
	ECC	15.5 ± 3.3	14.1 ± 4.3	14.6 ± 3.2	13.8 ± 2.5	14.6 ± 2.7	15.8 ± 2.9
	EQI	15.2 ± 3.4	14.0 ± 4.0	13.8 ± 3.7	14.7 ± 3.7	14.0 ± 3.7	14.9 ± 3.6
	Custom effect (%)		3% (-5.3, 12.1)	-3.8% (-11, 4.1)	7.5% (-3.4, 19.6)	-3.9% (-11.5, 4.4)	-4.9% (-13.1, 4)
	Custom effect (ES)		0.12 (-0.21, 0.45)	-0.14 (-0.44, 0.17)	*↑ 0.28 (-0.13, 0.7)	-0.15 (-0.48, 0.17)	*↓ -0.2 (-0.55, 0.15)

Nm = newton-meters. Nm.s = newton-meter seconds. ECC = Eccentric. EQI = Eccentric quasi-isometric. Custom effect = difference (%) and Cohen's *d* (ES) adjusted for individual total impulse and PRE value of the dependent variable. Data are mean ± standard deviation or the effect with (95% Compatibility intervals). Asterisks indicate substantial effects with adequate precision as follows: **possibly*, ***likely*, ****very likely*, *****most likely*. ↑ = larger effect in ECC. ↓ = larger effect in EQI. Smallest important difference were: peak torque = 3.4%; total impulse = 3.7%; impulse from 100-90º = 6.3%; 90-80º = 4.8%; 80-70º = 4.0%; 70-60º = 3.5%; 60-50º = 3.3%; 50-40º = 3.5%; 40-30º = 3.5%; 30-20º = 4.4%; 20-10º = 5.2%.

Appendix 14. Raw angle specific maximal voluntary isometric torque and rate of torque development values at each time-point with custom effect of between-condition deltas

		Condition	PRE	POST	24 hours	48 hours	72 hours	7 days
MVIT (Nm)								
	40º							
		ECC	198.6 ± 44.3	182.7 ± 50.1	177.0 ± 42.6	180.2 ± 44.5	189.9 ± 44.9	200.2 ± 37.6
		EQI	196.8 ± 46.2	188.7 ± 54.2	173.1 ± 38.6	184.8 ± 55.3	186.3 ± 55.8	194.1 ± 42.1
		Custom effect (%)		2.5% (-6.3, 12.2)	-0.9% (-8.8, 7.7)	2.6% (-6.9, 13.1)	-2.2% (-10.1, 6.4)	-2.7% (-9.2, 4.2)
		Custom effect (ES)		0.08 (-0.28, 0.43)	-0.03 (-0.37, 0.3)	0.1 (-0.29, 0.5)	-0.09 (-0.43, 0.25)	-0.11 (-0.39, 0.16)
	70º							
		ECC	256.3 ± 68.2	209.9 ± 54.5	210.7 ± 68.4	219.4 ± 64.7	229.0 ± 63.8	244.3 ± 46.6
		EQI	245.4 ± 59.3	226.7 ± 66.3	214.1 ± 63.7	228.2 ± 67.8	226.9 ± 61.1	244.6 ± 47.7
		Custom effect (%)		10.4% (0, 21.9)	5.8% (-6.8, 20.2)	7.9% (-1.9, 18.7)	2.5% (-5.3, 10.9)	2.4% (-1.9, 6.9)
		Custom effect (ES)		**↑ 0.35 (0, 0.7)	0.2 (-0.25, 0.65)	*↑ 0.27 (-0.07, 0.61)	0.09 (-0.19, 0.37)	0.09 (-0.07, 0.24)
	100º							
		ECC	208.1 ± 44.4	175.1 ± 35.5	178.7 ± 45.3	184.1 ± 47.8	190.4 ± 43.7	203.6 ± 38.2
		EQI	211.9 ± 40.4	197.1 ± 41.8	186.9 ± 39.1	193.0 ± 44.2	196.8 ± 34	207.8 ± 30.3
		Custom effect (%)		9.8% (0.4, 20.1)	3.5% (-5.1, 12.8)	3.7% (-2.6, 10.5)	2.3% (-4.3, 9.4)	1.3% (-1.7, 4.4)
		Custom effect (ES)		**↑ 0.39 (0.01, 0.76)	0.14 (-0.22, 0.5)	0.15 (-0.11, 0.42)	0.1 (-0.18, 0.38)	0.05 (-0.07, 0.18)
RTD 0-200 ms (Nm·s^{-1})								
	40º							
		ECC	679.8 ± 191	582.8 ± 224	543.2 ± 150	542.5 ± 140	552.8 ± 177	626.4 ± 147
		EQI	681.9 ± 164	614.1 ± 222	511.0 ± 131	547.3 ± 112	570.3 ± 144	600.7 ± 137
		Custom effect (%)		5.4% (-4.8, 16.7)	-6.1% (-18.7, 8.5)	1.8% (-11.2, 16.8)	3.8% (-3.1, 11.3)	-1.1% (-10.4, 9.2)
		Custom effect (ES)		*↑ 0.18 (-0.17, 0.52)	-0.21 (-0.70, 0.27)	0.06 (-0.40, 0.52)	0.13 (-0.11, 0.36)	-0.04 (-0.37, 0.29)
	70º							
		ECC	728.0 ± 254	561.3 ± 240	548.3 ± 167	568.5 ± 180	588 ± 211	687.6 ± 212
		EQI	675.2 ± 211	632.3 ± 224	480.4 ± 180	554.8 ± 167	557.4 ± 157	584.0 ± 172
		Custom effect (%)		32.3% (15.3, 51.8)	-4.8% (-17.6, 10)	9.1% (-2.5, 22)	7.2% (-4.5, 20.2)	3.2% (-9.5, 13.6)
		Custom effect (ES)		****↑ 0.70 (0.36, 1.05)	-0.12 (-0.49, 0.24)	*↑ 0.22 (-0.06, 0.50)	*↑ 0.17 (-0.11, 0.46)	0.08 (-0.20, 0.35)
	100º							
		ECC	608.5 ± 182	461.7 ± 140	498.2 ± 140	480.2 ± 146	572.0 ± 176	606.7 ± 180
		EQI	624.3 ± 180	561.4 ± 209	518.4 ± 157	512.5 ± 148	543.1 ± 170	569.8 ± 138
		Custom effect (%)		15.3 % (0.9, 31.7)	1.4% (-9.8, 14.1)	6.3% (-4.8, 18.7)	-7.4% (-19.2, 6.1)	-2.6% (-14.2, 10.5)
		Custom effect (ES)		**↑ 0.42 (0.03, 0.82)	0.04 (-0.31, 0.39)	*0.18↑ (-0.15, 0.51)	*↓ -0.23 (-0.63, 0.18)	-0.08 (-0.46, 0.30)

Nm = newton-meters. Nm·s^{-1} = newton-meters per second. MVIT = maximal voluntary isometric torque. RTD = rate of torque development. ECC = Eccentric. EQI = Eccentric quasi-isometric. Custom effect = difference (%) and Cohen's *d* (ES) adjusted for individual total impulse and PRE value of the dependent variable. Data are mean ± standard deviation or the effect with (95% Compatibility intervals). Asterisks indicate substantial effects with adequate precision as follows: **possibly*, ***likely*, ****very likely*, *****most likely*. ↑ = larger effect in ECC. ↓ = larger effect in EQI. Smallest important difference at 40º/70º/100º were: MVIT = 5.0%/5.7%/4.8%; RTD 0-200 = 6.1%/8.0%/6.8%.

Appendix 15. Comparison of angular impulse (Nm·s^{-1}) between contractions

Comparison	Total impulse		30-40º		40-50º		50-60º		60-70º		70-80º		80-90º		90-100º	
	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ
C1	12267 ± 5233	ES = 0.30 (-0.02, 0.50)	**443 ± 480**	ES = -0.09 (-0.56, 0.39)	2925 ± 2615	ES = 0.33 (-0.06, 0.72)	3073 ± 2042	ES = 0.20 (-0.13, 0.53)	2305 ± 1810	ES = 0.03 (-0.67, 0.86)	1557 ± 1166	ES = 0.16 (-0.38, 0.70)	1076 ± 1634	ES = 0.09 (-0.79, 0.96)	**356 ± 384**	ES = -0.18 (-0.80, 0.44)
C2	10623 ± 4238	13.4%	**485 ± 459**	-9.5%	2059 ± 1903	29.6%	2658 ± 1739	13.5%	2248 ± 1208	2.5%	1367 ± 1096	12.2%	959 ± 779	10.9%	**432 ± 398**	-21.3%
C1	12267 ± 5233	ES = 0.51* (0.15, 0.85)	443 ± 480	ES = 0.17 (-0.22, 0.57)	2925 ± 2615	ES = 0.82* (0.11, 1.53)	3073 ± 2042	ES = 0.33 (-0.29, 0.95)	2305 ± 1810	ES = 0.09 (-0.67, 0.86)	**1557 ± 1166**	ES = -0.26 (-0.85, 0.35)	1076 ± 1634	ES = 0.17 (-0.65, 0.99)	356 ± 384	ES = 0.15 (-0.23, 0.52)
C3	9517 ± 3592	22.4%	360 ± 303	18.7%	1043 ± 1113	64.3%	2403 ± 1716	21.8%	2154 ± 1117	6.6%	**1935 ± 1555**	-24.3%	857 ± 621	20.4%	299 ± 274	16.0%
C1	12267 ± 5233	ES = 0.72*** (0.40, 1.04)	443 ± 480	ES = 0.30 (-0.01, 0.60)	2925 ± 2615	ES = 0.90** (0.23, 1.57)	3073 ± 2042	ES = 0.60 (-0.02, 1.21)	2305 ± 1810	ES = 0.16 (-0.63, 0.94)	1557 ± 1166	ES = 0.41 (-0.08, 0.74)	**1076 ± 1634**	ES = -0.09 (-0.94, 0.76)	**356 ± 384**	ES = -0.19 (-0.68, 0.31)
C4	8119 ± 3415	33.8%	221 ± 145	50.1%	757 ± 774	74.1%	1900 ± 1550	38.2%	2041 ± 1330	11.5%	1030 ± 674	33.8%	**1220 ± 1336**	-13.4%	**437 ± 434**	-22.8%
C2	10623 ± 4237	ES = 0.25 (-0.02, 0.47)	485 ± 459	ES = 0.25 (-0.04, 0.53)	2059 ± 1903	ES = 0.53* (0.10, 0.96)	2658 ± 1739	ES = 0.13 (-0.37, 0.64)	2248 ± 1208	ES = 0.08 (-0.24, 0.39)	**1367 ± 1096**	ES = -0.37 (-0.81, 0.07)	959 ± 779	ES = 0.12 (-0.14, 0.39)	432 ± 398	ES = 0.35 (-0.21, 0.92)
C3	9517 ± 3592	11.6%	360 ± 303	34.7%	1043 ± 1113	49.3%	2403 ± 1716	9.6%	2154 ± 1117	4.2%	**1935 ± 1555**	-41.6%	857 ± 621	10.6%	299 ± 274	30.8%
C2	10623 ± 4237	ES = 0.53** (0.32, 0.74)	485 ± 459	ES = 0.52 (-0.07, 0.97)	2059 ± 1903	ES = 0.69* (0.16, 1.22)	2658 ± 1739	ES = 0.43 (-0.04, 0.90)	2248 ± 1208	ES = 0.15 (-0.46, 0.76)	1367 ± 1096	ES = 0.34 (-0.28, 0.95)	**959 ± 779**	ES = -0.16 (-0.43, 0.11)	**432 ± 398**	ES = -0.01 (-0.61, 0.59)
C4	8119 ± 3415	23.6%	221 ± 145	54.4%	757 ± 774	63.2%	1900 ± 1550	28.5%	2041 ± 1330	9.2%	1030 ± 674	24.7%	**1220 ± 1336**	-27.2%	**437 ± 434**	-1.2%
C3	9517 ± 3592	ES = 0.37* (0.19, 0.55)	360 ± 303	ES = 0.43 (-0.02, 0.85)	1043 ± 1113	ES = 0.24 (-0.06, 0.54)	2403 ± 1716	ES = 0.28 (-0.01, 0.54)	2154 ± 1117	ES = 0.08 (-0.25, 0.42)	1935 ± 1555	ES = 0.67 (-0.05, 1.40)	**857 ± 621**	ES = -0.18 (-0.42, 0.05)	**299 ± 274**	ES = -0.32 (-0.75, 0.11)
C4	8119 ± 3415	14.7%	221 ± 145	38.6%	757 ± 774	27.4%	1900 ± 1550	20.9%	2041 ± 1330	5.5%	1030 ± 674	87.9%	**1220 ± 1336**	-42.4%	**437 ± 434**	-46.2%

Δ = decrease. C1 = contraction 1. C2 = contraction 2. C3 = contraction 3. C4 = contraction 4. SD = standard deviation. ES = paired Hedges' *g* effect size. Brackets show 95% compatibility limits of the ES. **Bold** = increase between sets. *$p < 0.05$. **$p < 0.01$. ***$p < 0.001$. (*p*-values are Bonferroni corrected).

Appendix 16. Comparison of time-under-tension (seconds) between contractions

	Total duration		30-40º		40-50º		50-60º		60-70º		70-80º		80-90º		90-100º	
Comparison	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ
C1	64.7 ± 32.5	ES = 0.22 (-0.01, 0.45)	**2.83 ± 3.25**	ES = -0.07 (-0.61, 0.47)	16.1 ± 13.8	ES = 0.33 (-0.09, 0.74)	17.5 ± 12.5	ES = 0.18 (-0.17, 0.52)	13.6 ± 10.8	ES = 0.05 (-0.61, 0.70)	10.8 ± 8.78	ES = 0.29 (-0.25, 0.83)	6.42 ± 8.55	ES = 0.07 (-0.77, 0.91)	**2.56 ± 2.99**	ES = -0.04 (-0.56, 0.48)
C2	57.1 ± 27.8	11.8%	**3.08 ± 3.48**	-8.8%	11.6 ± 10.6	8.0%	15.3 ± 9.90	12.6%	13.2 ± 8.10	2.9%	8.32 ± 7.44	23.0%	5.92 ± 4.55	7.8%	**2.67 ± 2.39**	-4.3%
C1	64.7 ± 32.5	ES = 0.42 (-0.10, 0.75)	2.83 ± 3.25	ES = 0.24 (-0.21, 0.68)	16.1 ± 13.8	ES = 0.78* (0.13, 1.42)	17.5 ± 12.5	ES = 0.36 (-0.20, 0.91)	13.6 ± 10.8	ES = 0.06 (-0.70, 0.83)	**10.8 ± 8.78**	ES = -0.08 (-0.38, 0.24)	6.42 ± 8.55	ES = 0.14 (-0.64, 0.94)	2.56 ± 2.99	ES = 0.16 (-0.15, 0.46)
C3	50.3 ± 22.6	22.3%	2.07 ± 1.98	26.9%	6.40 ± 7.15	60.3%	13.3 ± 9.11	24.0%	13.1 ± 6.60	3.7%	**11.6 ± 10.2**	-7.41%	5.36 ± 4.15	16.5%	2.06 ± 2.00	19.5%
C1	64.7 ± 32.5	ES = 0.61** (0.31, 0.92)	2.83 ± 3.25	ES = 0.39* (0.02, 0.77)	16.1 ± 13.8	ES = 0.88** (0.26, 1.49)	17.5 ± 12.5	ES = 0.52 (-0.02, 1.02)	13.6 ± 10.8	ES = 0.24 (-0.54, 1.01)	10.8 ± 8.78	ES = 0.58 (-0.05, 1.11)	**6.42 ± 8.55**	ES = -0.14 (-0.96, 0.69)	**2.56 ± 2.99**	ES = -0.12 (-0.53, 0.29)
C4	42.6 ± 21.4	34.2%	1.22 ± 0.98	56.9%	4.57 ± 4.98	71.6%	11.2 ± 9.24	36.0%	11.4 ± 6.86	16.2%	5.90 ± 3.83	45.4%	**7.66 ± 8.37**	-19.3%	**2.96 ± 3.15**	-15.6%
C2	57.1 ± 27.8	ES = 0.20 (-0.05, 0.35)	3.08 ± 3.48	ES = 0.28 (-0.10, 0.65)	11.6 ± 10.6	ES = 0.49* (0.09, 0.89)	15.3 ± 9.9	ES = 0.20 (-0.22, 0.62)	13.2 ± 8.10	ES = 0.01 (-0.46, 0.48)	**8.32 ± 7.44**	ES = -0.33 (-0.77, 0.12)	5.92 ± 4.55	ES = 0.12 (-0.16, 0.40)	2.67 ± 2.39	ES = 0.26 (-0.25, 0.76)
C3	50.3 ± 22.6	11.9%	2.07 ± 1.98	32.8%	6.40 ± 7.15	44.8%	13.3 ± 9.11	13.1%	13.1 ± 6.6	0.76%	**11.6 ± 10.2**	39.4%	5.36 ± 4.15	9.5%	2.06 ± 2.00	22.9%
C2	57.1 ± 27.8	ES = 0.44** (0.25, 0.64)	3.08 ± 3.48	ES = 0.49* (0.02, 0.96)	11.6 ± 10.6	ES = 0.69* (0.16, 1.21)	15.3 ± 9.9	ES = 0.39 (-0.04, 0.74)	13.2 ± 8.10	ES = 0.23 (-0.35, 0.80)	8.32 ± 7.44	ES = 0.36 (-0.24, 0.96)	**5.92 ± 4.55**	ES = -0.18 (-0.47, 0.12)	**2.67 ± 2.39**	ES = -0.10 (-0.69, 0.50)
C4	42.6 ± 21.4	25.4%	1.22 ± 0.98	60.4%	4.57 ± 4.98	60.6%	11.2 ± 9.24	26.8%	11.4 ± 6.86	13.6%	5.90 ± 3.83	29.1%	**7.66 ± 8.37**	-29.4%	**2.96 ± 3.15**	-10.9%
C3	50.3 ± 22.6	ES = 0.32** (0.15, 0.49)	2.07 ± 1.98	ES = 0.38* (0.03, 0.73)	6.40 ± 7.15	ES = 0.23 (-0.03, 0.49)	13.3 ± 9.11	ES = 0.21 (-0.07, 0.50)	13.1 ± 6.60	ES = 0.24 (-0.01, 0.47)	11.6 ± 10.2	ES = 0.66 (-0.07, 1.39)	**5.36 ± 4.15**	ES = -0.21 (-0.47, 0.06)	**2.06 ± 2.00**	ES = -0.29 (-0.73, 0.15)
C4	42.6 ± 21.4	15.3%	1.22 ± 0.98	41.1%	4.57 ± 4.98	28.6%	11.2 ± 9.24	15.8%	11.4 ± 6.86	13.0%	5.90 ± 3.83	49.1%	**7.66 ± 8.37**	-42.9%	**2.96 ± 3.15**	-43.7%

Δ = decrease. C1 = contraction 1. C2 = contraction 2. C3 = contraction 3. C4 = contraction 4. SD = standard deviation. ES = paired Hedges' g effect size. Brackets show 95% compatibility limits of the ES. **Bold** = increase between sets. *$p < 0.05$. **$p < 0.01$. (p-values are Bonferroni corrected).

Appendix 17. Comparison of velocity (degrees per second) between contractions

Comparison	Mean velocity		30-40º		40-50º		50-60º		60-70º		70-80º		80-90º		90-100º	
	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ	Mean ± SD	Δ
C1	1.08 ± 2.2	ES = 0.16 (-0.08, 0.40)	**3.53 ± 3.1**	ES = -0.09 (-0.63, 0.45)	0.62 ± 0.73	ES = 0.29 (-0.07, 0.72)	0.57 ± 0.80	ES = 0.12 (-0.31, 0.55)	0.74 ± 0.93	ES = 0.04 (-0.72, 0.77)	0.93 ± 1.1	ES = 0.24 (-0.33, 0.81)	1.56 ± 1.2	ES = 0.08 (-0.72, 0.88)	**3.91 ± 3.4**	ES = -0.04 (-0.58, 0.50)
C2	1.23 ± 2.5	13.9%	**3.25 ± 2.9**	-7.9%	0.86 ± 0.94	38.7%	0.65 ± 1.0	14.0%	0.76 ± 1.2	2.7%	1.20 ± 1.3	29.0%	1.69 ± 2.2	8.3%	**3.75 ± 4.2**	-3.8%
C1	1.08 ± 2.2	ES = 0.29 (-0.24, 0.68)	3.53 ± 3.1	ES = 0.29 (-0.27, 0.73)	0.62 ± 0.73	ES = 0.80* (0.10, 1.50)	0.57 ± 0.80	ES = 0.22 (-0.38, 0.82)	0.74 ± 0.93	ES = 0.04 (-0.72, 0.80)	**0.93 ± 1.1**	ES = -0.06 (-0.34, 0.22)	1.56 ± 1.2	ES = 0.17 (-0.61, 0.95)	3.91 ± 3.4	ES = 0.19 (-0.11, 0.49)
C3	1.39 ± 3.1	28.7%	4.83 ± 5.1	36.8%	1.56 ± 1.4	152%	0.75 ± 1.1	31.6%	0.76 ± 1.5	2.7%	**0.86 ± 0.98**	-7.53%	1.87 ± 2.4	19.9%	4.85 ± 5.0	24.0%
C1	1.08 ± 2.2	ES = 0.48** (0.18, 0.78)	3.53 ± 3.1	ES = 0.41* (0.04, 0.79)	0.62 ± 0.73	ES = 0.98*** (-0.48, 1.48)	0.57 ± 0.80	ES = 0.41 (-0.05, 0.87)	0.74 ± 0.93	ES = 0.19 (-0.57, 0.95)	0.93 ± 1.1	ES = 0.42 (-0.15, 0.99)	**1.56 ± 1.2**	ES = -0.18 (-0.97, 0.61)	**3.91 ± 3.4**	ES = -0.14 (-0.53, 0.25)
C4	1.64 ± 3.3	51.9%	8.20 ± 10.0	132%	2.19 ± 2.0	253%	0.89 ± 1.1	56.1%	0.88 ± 1.5	18.9%	1.70 ± 2.6	82.8%	**1.31 ± 1.2**	-16.0%	**3.38 ± 3.2**	-13.6%
C2	1.23 ± 2.5	ES = 0.16 (-0.07, 0.39)	3.25 ± 2.9	ES = 0.32 (-0.06 0.70)	0.86 ± 0.94	ES = 0.54* (0.12, 0.96)	0.65 ± 1.0	ES = 0.11 (-0.34, 0.56)	0.76 ± 1.2	ES = 0.00 (-0.52, 0.52)	**1.20 ± 1.3**	ES = -0.30 (-0.80, 0.20)	1.69 ± 2.2	ES = 0.09 (-0.32, 0.50)	3.75 ± 4.2	ES = 0.24 (-0.29, 0.77)
C3	1.39 ± 3.1	13.0%	4.83 ± 5.1	48.6%	1.56 ± 1.4	81.4%	0.75 ± 1.1	15.4%	0.76 ± 1.5	0.00%	**0.86 ± 0.98**	-28.3%	1.87 ± 2.4	10.7%	4.85 ± 5.0	29.3%
C2	1.23 ± 2.5	ES = 0.30* (0.02, 0.58)	3.25 ± 2.9	ES = 0.55* (0.07, 1.04)	0.86 ± 0.94	ES = 0.76* (0.04, 1.48)	0.65 ± 1.0	ES = 0.28 (-0.24, 0.80)	0.76 ± 1.2	ES = 0.15 (-0.48, 0.78)	1.20 ± 1.3	ES = 0.29 (-0.23, 0.81)	**1.69 ± 2.2**	ES = -0.20 (-0.50, 0.10)	**3.75 ± 4.2**	ES = -0.11 (-0.71, 0.49)
C4	1.64 ± 3.3	33.3%	8.20 ± 10.0	152%	2.19 ± 2.0	155%	0.89 ± 1.1	36.9%	0.88 ± 1.5	15.8%	1.70 ± 2.6	41.7%	**1.31 ± 1.2**	-22.5%	**3.38 ± 3.2**	-9.9%
C3	1.39 ± 3.1	ES = 0.25* (0.02, 0.48)	4.83 ± 5.1	ES = 0.41 (-0.01, 0.74)	1.56 ± 1.4	ES = 0.30 (-0.02, 0.62)	0.75 ± 1.1	ES = 0.15 (-0.17, 0.47)	0.76 ± 1.5	ES = 0.14 (-0.17, 0.45)	0.86 ± 0.98	ES = 0.55 (-0.18, 1.28)	**1.87 ± 2.4**	ES = -0.25 (-0.48, 0.02)	**4.85 ± 5.0**	ES = -0.31 (-0.78, 0.16)
C4	1.64 ± 3.3	18.0%	8.20 ± 10.0	69.8%	2.19 ± 2.0	40.4%	0.89 ± 1.1	18.7%	0.88 ± 1.5	15.8%	1.70 ± 2.6	97.7%	**1.31 ± 1.2**	-30.0%	**3.38 ± 3.2**	-30.3%

Δ = increase. C1 = contraction 1. C2 = contraction 2. C3 = contraction 3. C4 = contraction 4. SD = standard deviation. ES = paired Hedges' *g* effect size. Brackets show 95% compatibility limits of the ES. **Bold** = decrease between sets. **p* < 0.05. ***p* < 0.01. (*p*-values are Bonferroni corrected).

Appendix 18. Ethical approval for Chapters 4-10

Auckland University of Technology Ethics Committee (AUTEC)

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

18 September 2018

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **18/232 The effect of eccentric quasi-isometric training on muscle morphology and performance.**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 18 September 2021.

Standard Conditions of Approval

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/research/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/research/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/research/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. You are reminded that it is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

For any enquiries, please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: dustinoranchuk@gmail.com; Adam Storey

Appendix 19. Participant information sheet for Chapters 4-10

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Participant Information Sheet

Date Information Sheet Produced:

1rd July 2018

Project Title

The effect of eccentric quasi-isometric training on the muscle morphology and performance of healthy males

An invitation

My name is Dustin Oranchuk, and I am a Doctoral student at Auckland University of Technology (AUT). I would like to invite you to assist me with my research project that aims to determine the effects of a novel type of muscle contraction training on short-term shifts in performance.

What is the purpose of this research?

Muscle structure and performance are far-reaching and are important in daily activities and athletic events alike. Sports professionals search for methods that improve the training process, leading to better health and performance. While dynamic movements are the most common training contraction, isolating different contraction types is growing in popularity. Isometric or static contractions are a staple in rehabilitation as the range of motion and intensity are easily controlled. Additionally, the resulting muscle soreness minimal. However, isometric adaptations minimally transfer to dynamic performance. Conversely, eccentric (lengthening) training has been found to have a substantial impact on muscular structure and performance, but can cause excessive soreness and fatigue. Eccentric quasi-isometric (EQI) contractions involve holding a static contraction under submaximal loads until fatigue forces the muscle to undergo lengthening. Theoretically, EQIs takes advantage of the safety of isometric training, while including performance enhancing effects of eccentric training. However, confirming the above contentions require rigorous research, which this study will begin.

How was I identified and why am I being invited to participate in this research?

You have either seen an advertisement for this research project around your training facility, have been presented the research details during a team presentation, or via a face-to-face meeting with the primary researcher. Your contact details should be provided by you to the primary researcher if you are interested in participating in this research allowing communication to take place regarding this research.

You are eligible to participate in this research if you are:

a. Male
b. Aged 18-35 years
c. Participate in sport or resistance training at least two times-per-week
d. Free of any injury that may affect your ability to participate in this research
e. Not currently using, nor have ever used anabolic steroids or anything that would dramatically effect muscular recovery.

How do I agree to participate in this research?

If you are interested in volunteering in this research project, please contact the primary researcher, Dustin Oranchuk. You will be emailed an AUT consent to participate form which you will need to fill out and sign, then return to the primary researcher either by email or in person. You will then be given a copy of your signed consent form which you will need to keep for future reference.

If you decide you no longer want to participate, you can withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to be used. However, once the findings have been produced, removal of your data may not be possible, but your specific data will not be identifiable.

What will happen in this research?

Once you have agreed to participate in this research, you will be required to take part in one-two exercise sessions and four-eight evaluation/testing sessions. During the initial session participants will have their height, weight, age and basic anthropometric data, including thigh circumference and skinfolds recorded. Ultrasound will be used to determine the architectural characteristics of the quadriceps muscle. You will then complete a general warm-up consisting of five minutes of cycling. You will then be fitted to the isokinetic dynamometer (similar to a leg extension machine). You will then complete a series of baseline isometric and dynamic contractions with maximal effort before being familiarised with maximal EQI and eccentric contractions.

Exercise sessions: Both limbs will complete each exercise and evaluation sessions in each exercise session in a random order. One limb will perform two sets of 25 eccentric contractions while the second limb will perform a work matched EQI contraction exercise session. These two exercise sessions will take approximatly 90 minutes and be seperated by seven days.

Evaluation sessions: Twenty-four hours, 48 hours, 72 hours and seven days after each exercise sessions, a measure of muscle damage will be assessed. Quadriceps swelling and architecture will be assessed via ultrasound; muscular soreness will be evaluated with the use of pressure points and a pain scale. You will then be required to perform a brief series of isometric and isokinetic contractions. These evaluation sessions will take approximately 45 minutes and are unlikely to result in additional muscle soreness or damage.

What are the discomforts and risks?

The testing and training sessions will require you to perform maximal physical efforts which may cause you to experience some temporary discomfort and muscular soreness that may persist for up to one week.

How will these discomforts and risks be alleviated?

A normal recovery process of a few days should be enough time for the body to repair itself and for soreness to completely dissipate. Although you may be familiar with this type of training intensity, you are encouraged to inform the researcher if you are experiencing any discomfort at any time so that the problem can be addressed in the best possible way. If you have any questions regarding the risks or discomfort involved in this research, please feel free to bring these concerns to the attention of the researcher so that you feel comfortable throughout each stage of this process.

What are the benefits?

The participant will gain personal knowledge about their own capabilities. Additionally, the participant will be exposed to a training methodology that is unique to them which the participant may wish to employ in their normal exercise routines. The primary researcher will gain valuable practical experience working within a research setting and be awarded a Doctorate of Philosophy in Sport Science degree upon submission and grading of this research.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

Your privacy will be protected by data being de-identified (coded numbers i.e. ID 123 instead of your name to be used throughout), and the researcher will not disclose anyone's participation in this study. No names or pictures will be used in reporting (unless the participant gives explicit additional written consent for media purposes following AUT protocols and organised via the AUT university relations team). During the project, only the applicant and named investigators will have access to the data collected. The results of the study may be used for further analysis and submission to peer-reviewed journals or submitted at conferences. However, your name will remain coded and anonymous. Your privacy and anonymity will be of primary concern when handling the data.

What are the costs of participating in this research?

The only financial cost to the participant will be money spent on petrol to get to the testing and training facilities, which would normally be required to participate at the facility. Each testing session will take approximately 90 minutes and each testing session will last approximately 30 minutes, including a warm up and cool down.

What opportunity do I have to consider this invitation?

We would appreciate it if you could let us know within four weeks whether or not you are able to participate in this research. After consideration you may withdraw your participation at any time.

Will I receive feedback on the results of this research?

Yes, each participant will receive a personalised assessment of their performance, as well as theoretical explanations following the completion of the data collection.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, Dr. John B Cronin, john.cronin@aut.ac.nz, as well as the primary researcher, Dustin J Oranchuk, dustinoranchuk@gmail.com.

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, *ethics@aut.ac.nz* , 921 9999 ext 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

Dustin J Oranchuk, dustinoranchuk@gmail.com

Project Supervisor Contact Details:

Dr. John B Cronin, john.cronin@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on the *18th of September, 2018*, AUTEC Reference number *18/232*

17 April 2020 page 3 of 3 This version was edited in May 2018

Appendix 20. Consent form for Chapters 4-10

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Consent Form

Project title: ***The effect of eccentric quasi-isometric training on muscle morphology and performance in healthy males.***

Project Supervisor: ***Dr. John B Cronin***

Researcher: ***Dustin J Oranchuk***

- I have read and understood the information provided about this research project in the Information Sheet dated / /
- I have had an opportunity to ask questions and to have them answered.
- I understand that performance tests and training sessions require maximal physical efforts which may induce normal muscle soreness for up to 72 hours following training. No other embarrassment or discomfort is likely to occur that is outside the scope of the participant's normal training and physical testing.
- I am not suffering from any musculo-skeletal injuries.
- I do not have any neurological conditions.
- I understand that taking part in this study is voluntary (my choice) and that no accolades or punishments will result from my participation. I also understand I may withdraw from the study at any time without being disadvantaged in any way.
- I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.
- I agree to take part in this research.
- I wish to receive a summary of the research findings (please tick one): YesO NoO

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

Email :..

Phone : ....

Other : ....

Date:

Approved by the Auckland University of Technology Ethics Committee on the 18th of September, 2018 AUTEC Reference number 18/232

Note: The Participant should retain a copy of this form.

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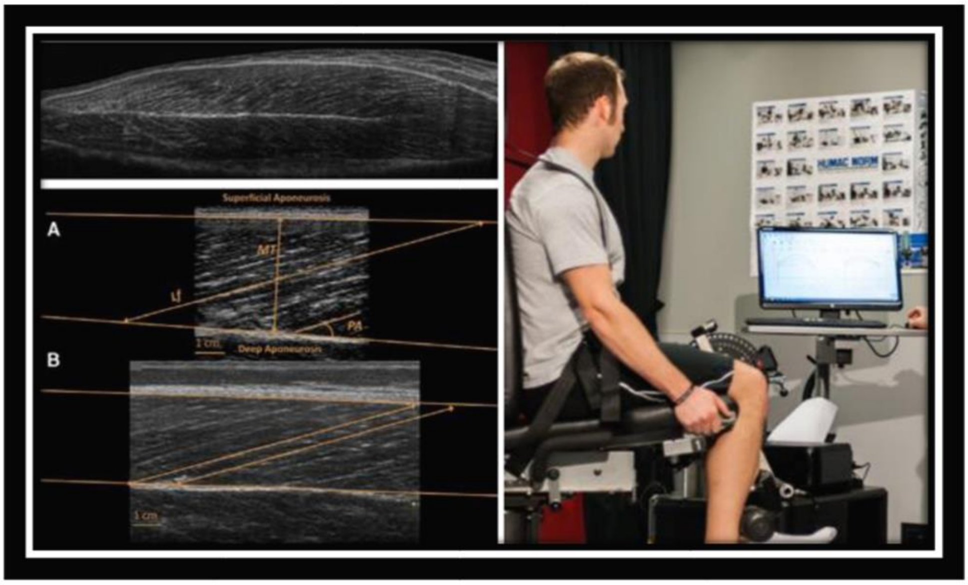
Appendix 21. Advertisement for Chapters 4-10

SPORTS PERFORMANCE RESEARCH INSTITUTE

AUT UNIVERSITY

The effect of isometric-eccentric contractions on muscle structure and performance



Are you living in the Auckland area and want to participate in a study determining the short-term (2 weeks) effects of a novel method of muscular training?

If you are:

A. Male.
B. 18-35 years of age.
C. Participate in sport or resistance training at least two times-per-week.
D. Free of any injury that may affect your ability to participate in this research.
E. Not currently using, nor have ever used anabolic steroids or anything that would dramatically effect muscular recovery.
F. Willing to participate.

Then please contact Dustin Oranchuk (PhD candidate) via email at dustinoranchuk@gmail.com

Appendix 28. Additional peer-reviewed journal outputs since starting the PhD

Watkins CM, Maunder E, van den Tillaar R, and **Oranchuk DJ**. Concurrent validity and reliability of three ultra-portable vertical jump assessment technologies. *Sensors* 20: 7240, 2020.

Mira J, Floreani M, Savoldelli A, Amery K, Koral J, **Oranchuk DJ**, Messonnier L, Rupp T, and Millet GY. Neuromuscular fatigue of cycling exercise in hypoxia. *Med Sci Sports Exerc* 52: 1888-1889, 2020.

Oranchuk DJ, Mannerberg JM, Robinson TL, and Nelson MC. Eight weeks of strength and power training improves club head speed in collegiate golfers. *J Strength Cond Res* 34: 2205-2213, 2020.

Oranchuk DJ, Koral J, da Mota GR, Wrightson J, Soares R, Twomey R, and Millet GY. Effect of blood flow occlusion on neuromuscular fatigue following sustained maximal isometric contraction. *Appl Physiol Nutr Metab* 45: 698-706, 2020.

van den Tillaar R, Roaas T, and **Oranchuk DJ**. Comparison of effect of training order of explosive strength and plyometrics training upon different physical abilities in adolescent handball players. *Biol Sport* 3: 239-246, 2020.

Koral J, **Oranchuk DJ**, Wrightson JG, Twomey R, and Millet GY. Mechanisms of neuromuscular fatigue and recovery in unilateral versus bilateral maximal voluntary contractions. *J Appl Physiol* 128: 785-794, 2020.

Stock MS, **Oranchuk DJ**, Burton AM, and Phan DC. Age-, sex-, and region-specific differences in skeletal muscle size and quality. *Appl Physiol Nutr Metab* 45: 1253-1260, 2020.

Oranchuk DJ, Ecsedy EN, and Robinson TL. Effects of a sport-specific upper-body resistance-band training program on overhead throwing velocity and glenohumeral joint range of motion. *J Strength Cond Res* Ahead of print, 2020.

da Silva BVC, Bertucci D, Branco T, Ide BN, Marocolo M, de Souza HLR, de Oliveira RAA, **Oranchuk DJ**, and da Mota GR. Comparison of high-volume and high-intensity upper body resistance exercise on acute neuromuscular outputs and perceived exertion *Int J Exerc Sci* 13: 723-733, 2020.

Oranchuk DJ, Flattery MR, and Robinson TL. Superficial heat administration and foam rolling increase hamstring flexibility acutely; with amplifying effects. *Phys Ther Sport* 40: 213-217, 2019.

Oranchuk DJ, Drinkwater EJ, Lindsay RS, Helms ER, Harbour ET, and Storey AG. Improvement of kinetic, kinematic, and qualitative performance variables of the power clean with the hook grip. *Int J Sports Physiol Perform* 14: 378-384, 2019.

Oranchuk DJ, Robinson TL, Switaj ZJ, and Drinkwater EJ. Comparison of the hang high-pull and loaded jump squat for the development of vertical jump and isometric force-time characteristics. *J Strength Cond Res* 33: 17-24, 2019.

Nichols DT, Robinson TL, and **Oranchuk DJ**. Kinesiology taping of the ankle does not improve dynamic balance in NCAA athletes. *Athl Train Sports Health Care* 11: 10-18, 2018.

da Silva BVC, Simim MAM, Reis Viegas LC, Brigido TS, **Oranchuk DJ**, and da Mota GR. The acute hypotensive effect of resistance training performed with machines vs free weights in normotensive men. *Motriz* 24: e1018173, 2018.

Koral J, **Oranchuk DJ**, Herrera R, and Millet GY. Six sessions of sprint interval training improves running performance in trained athletes. *J Strength Cond Res* 32: 617-623, 2018.

Appendix 29. Peer-reviewed conference proceedings since starting the PhD

Oranchuk DJ, Hopkins WG, Storey AG, Cronin JB and Nelson AR. The isometric length-tension relationship is not differentially affected by regional quadriceps muscle architecture. *European College of Sport Science*, Saville, Spain. (International conference, poster presentation)

Adkins SJ, Robinson TL, Martinez MM, and **Oranchuk DJ**. Effects of electrical stimulation versus exercise on abdominal muscle activity, strength, endurance, fat and muscle thicknesses. *American Council of Sports Medicine: Rocky Mountain Region*, Estes Park, Colorado. (Regional conference, poster presentation) (Cancelled due to Covid-19), 2020.

Oranchuk DJ, Storey AG, Nelson AR, Cronin JB, and Franchi MV. Accuracy and reliability of extended-field-of-view ultrasonography in the assessment of vastus lateralis pennation angle and muscle thickness: A preliminary report. *Sport Performance Research Institute New Zealand annual conference,* Denver, Colorado. (Local conference, poster presentation), 2019.

Sheppard D, **Oranchuk DJ**, Klawitter LA, and Robinson TL. Variations in Wingate load to optimize peak power output in NCAA DII collegiate athletes. *American Council of Sports Medicine: Rocky Mountain Region*, Denver, Colorado. (Regional conference, poster presentation), 2019.

Oranchuk DJ, Lindsay RS, Helms ER, Harbour ET, Storey AG, and Drinkwater EJ. Hook-grip improves power clean kinetics and kinematics. *36th International Conference on Biomechanics in Sports,* Auckland, New Zealand. (International conference, oral podium presentation), 2018.

Rupp T, Mira J, Floreani M, Savoldelli A, Amery K, Koral J, **Oranchuk DJ**, and Millet GY. Neuromuscular fatigue in hypoxia revisited. *European College of Sport Science*, Dublin, Ireland, (International conference, Oral podium presentation), 2018.

Greenfield M, Robinson TL, Klawitter LA, and **Oranchuk DJ**. Performance differences with stance variance in weightlifting. *American Council of Sports Medicine: Rocky Mountain Region*, Denver, Colorado. (Regional conference, poster presentation), 2018.

Appendix 30. Chapter 2 abstract

Isometric training is used in the rehabilitation and physical preparation of athletes, special populations, and the general public. However, little consensus exists regarding training guidelines for a variety of desired outcomes. Understanding the adaptive response to specific loading parameters would be of benefit to practitioners. The objective of this systematic review, therefore, was to detail the medium to long-term adaptations of different types of isometric training on morphological, neurological and performance variables. Exploration of the relevant subject matter was performed through MEDLINE, PubMed, SPORTDiscus and CINAHL databases. English, full-text, peer-reviewed journal articles and unpublished doctoral dissertations investigating medium to long-term (≥ 3 weeks) adaptations to isometric training in humans were identified. These studies were evaluated further for methodological quality. Twenty-six research outputs were reviewed. Isometric training at longer muscle lengths (0.86-1.69%$\cdot$week^{-1}, ES = 0.03-0.09$\cdot$week^{-1}) produced greater muscular hypertrophy when compared to equal volumes of shorter muscle length training (0.08-0.83%$\cdot$week^{-1}, ES = -0.003-0.07$\cdot$week^{-1}). Ballistic intent resulted in greater neuromuscular activation (1.04-10.5%$\cdot$week^{-1}, ES = 0.02-0.31$\cdot$week^{-1} vs 1.64-5.53%$\cdot$week^{-1}, ES = 0.03-0.20$\cdot$week^{-1}) and rapid force production (1.2-13.4%$\cdot$week^{-1}, ES = 0.05-0.61$\cdot$week^{-1} vs 1.01-8.13%$\cdot$week^{-1}, ES = 0.06-0.22$\cdot$week^{-1}). Substantial improvements in muscular hypertrophy and maximal force production were reported regardless of training intensity. High-intensity (≥ 70%) contractions are required for improving tendon structure and function. Additionally, long muscle length training results in greater transference to dynamic performance. Despite relatively few studies meeting the inclusion criteria, this review provides practitioners with insight into which isometric training variables (e.g., joint angle, intensity, intent) to manipulate to achieve desired morphological and neuromuscular adaptations.

Appendix 31. Chapter 3 abstract

Eccentric quasi-isometric (EQI) resistance training involves holding a submaximal, yielding isometric contraction until fatigue causes muscle lengthening, then maximally resisting through a range of motion. Practitioners contend that EQI contractions are a powerful tool for the development of several physical qualities important to health and sports performance. Additionally, several sports involve regular quasi-isometric contractions for optimal performance. Therefore, the primary objective of this review was to synthesize and critically analyze relevant biological, physiological, and biomechanical research and develop a rationale for the value of EQI training. Additionally, this review offers potential practical applications and highlights future areas of research. While there is a paucity of research investigating EQIs, the literature on responses to traditional contraction types is vast. Based on relevant literature, EQIs may provide a practical means of increasing total volume, metabolite build-up and hormonal signalling factors while safely enduring large quantities of mechanical tension with low levels of peak torque. Conversely, EQI contractions likely hold little neuromuscular specificity to high velocity or power movements. Therefore, EQI training appears to be effective for improving musculotendonous morphological and performance variables with low injury risk. Although speculative due to the limited specific literature, available evidence suggests a case for future experimentation.

Appendix 32. Chapter 4 abstract

Purpose: Regional muscle architecture measures are reported widely; however, little is known about the variability of these measurements in the rectus femoris, vastus lateralis and anterior and lateral vastus intermedius. Quantifying this variability provides the purpose of this paper.
Methods: Regional muscle thickness (MT), pennation angle (PA) and calculated and extended field of view (EFOV) fascicle length (FL) were quantified using ultrasonography in 26 participants across 51 limbs, on three occasions. To quantify variability, the typical error of measurement (TEM) was multiplied by two, and thresholds of 0.2-0.6 (small), 0.6-1.2 (moderate), 1.2-2.0 (large), 2.0-4.0 (very large) and > 4.0 (extremely large) applied. Additionally, variability was deemed large when the intraclass correlation coefficient (ICC) was < 0.67 and coefficient of variation (CV) > 10%; moderate when ICC > 0.67 or CV < 10% (but not both); and small when both ICC > 0.67 and CV < 10%.
Results: MT of all muscles and regions had low to moderate variability (ICC = 0.88-0.98, CV = 2.4-9.3%, TEM = 0.15-0.47). PA of the proximal and distal vastus lateralis (ICC = 0.85-0.96, CV = 3.8-8%) had low variability and moderate to large TEM (TEM = 0.42-0.83). PA of the rectus femoris was found to have moderate to very large variability (ICC = 0.38-0.74, CV = 11.4-18.5, TEM = 0.61-1.29) regardless of region. Extended-field-of-view derived FL (ICC = 0.57-0.94, CV = 4.1-11.5%, TEM = 0.26-0.88) was superior to calculated FL (ICC = 0.37-0.84, CV = 7.4-17.9%, TEM = 0.44-1.33).
Conclusions: Variability of MT was low in all quadriceps muscles and regions. Only rectus femoris PA and FL measurements were highly variable. The EFOV technique should be utilized to assess FL where possible. Inferences based on rectus femoris architecture should be interpreted with caution.

Appendix 33. Chapter 5 abstract

Quantifying echo intensity (EI), a proposed measure of muscle quality, is becoming increasingly popular. Additionally, much attention has been paid to regional differences in other ultrasonically evaluated measures of muscle morphology and architecture. However, the variability of regional (proximal, middle, distal) EI of the vastus lateralis, rectus femoris, and lateral and anterior vastus intermedius has yet to be determined. Twenty participants (40 limbs), were evaluated on three occasions, separated by seven days. Intersession variability of EI with and without subcutaneous fat correction was quantified. Furthermore, the interchangeability of corrected EI across regions was evaluated. Variability of regional quadriceps EI was substantially lower with subcutaneous fat correction (ICC = 0.81-0.98, CV = 4.5-16.8%, TEM = 0.13-0.49) versus raw values (ICC = 0.69-0.98, CV = 7.7-42.7%, TEM = 0.14-0.68), especially when examining the vastus intermedius (ICC = 0.81-0.95, CV = 7.1-16.8%, TEM = 0.23-0.49 vs ICC = 0.69-0.92, CV = 22.9-42.7%, TEM = 0.31-0.68). With the exception of the rectus femoris and vastus intermedius ($p \geq 0.143$, ES ≤ 0.18), corrected EI was greater for proximal and distal regions when compared to the mid-point ($p \leq 0.038$, ES = 0.38-0.82). Researchers and practitioners should utilize subcutaneous fat thickness correction to confidently evaluate EI at all regions of the quadriceps. Regional EI cannot be used interchangeably for the vastus muscles, likely due to an increase in fibrous content towards the myotendinous junctions.

Novelty bullets:

- Regional quadriceps echo intensity was reliable with and without correction for subcutaneous fat thickness.
- Intersession variability of regional quadriceps echo intensity was substantially improved following subcutaneous fat correction.
- Quadriceps echo intensity increased towards myotendinous junctions in the vastus muscles.

Appendix 34. Chapter 6 abstract

Objective: Length-tension relationships are widely reported in research, rehabilitation and performance settings; however, several isometric contractions at numerous angles are needed to understand these muscular outputs. Perhaps a more efficient way to determine torque-angle characteristics is via isokinetic dynamometry; however, little is known about the variability of isokinetic measurements besides peak torque and optimal-angle. This paper examines the variability of angle-specific isokinetic torque and impulse measures.

Approach: Three sessions of concentric ($60^{o}\cdot s^{-1}$) knee extensions were performed by both limbs of 32 participants. Assessments were repeated on three occasions, separated by 5-8 days. To quantify variability, the standardized typical error of measurement (TEM) was doubled and thresholds of 0.2-0.6 (small), 0.6-1.2 (moderate), 1.2-2.0 (large), 2.0-4.0 (very large) and > 4.0 (extremely large) were applied. Additionally, variability was deemed large when the intraclass correlation coefficient (ICC) was < 0.67 and coefficient of variation (CV) > 10%; moderate when ICC > 0.67 or CV < 10% (but not both); and small when both ICC > 0.67 and CV < 10%.

Main Results: Isokinetic torque and angular impulse show small to medium variability (ICC = 0.75-0.96, CV = 6.4-15.3%, TEM = 0.25-0.53) across all but the longest (100°) and shortest (10°) muscle lengths evaluated. However, moderate to large variability was found for the optimal-angle (ICC = 0.58-0.64, CV = 7.3-8%, TEM = 0.76-0.86), and torque and impulse at the beginning and end of the range of motion (ICC = 0.57-0.85, CV = 11-42.9%, TEM = 0.40-0.89). Intersession variability of isokinetic torque and impulse were small to moderate at medium (90-20°) joint angles.

Significance: Researchers and practitioners can examine the muscle torque-angle relationship and activity-specific torque outputs within these ranges, without resorting to more strenuous and time-consuming isometric evaluations.

Appendix 35. Chapter 7 abstract

Measurements of isometric force, rate of force development (RFD) and impulse are widely reported. However, little is known about the variability and reliability of these measurements at multiple angles, over repeated testing occasions in a homogenous, resistance-trained population. Thus, understanding the intersession variability of multi-angle isometric force-time characteristics provides the purpose of this paper. Three sessions of isometric knee extensions at 40º, 70º and 100º of flexion were performed by 26 subjects across 51 limbs. All assessments were repeated on three occasions separated by 5-8 days. Variability was qualified by doubling the typical error of measurement (TEM), with thresholds of 0.2-0.6 (small), 0.6-1.2 (moderate), 1.2-2.0 (large), 2.0-4.0 (very large) and > 4.0 (extremely large). Additionally, variability was deemed large when the intraclass correlation coefficient (ICC) was < 0.67 and coefficient of variation (CV) > 10%; moderate when ICC > 0.67 or CV < 10% (but not both); and small when both ICC > 0.67 and CV < 10%. Small to moderate between-session variability (ICC = 0.68-0.95, CV = 5.2-18.7%, TEM = 0.24-0.49) was associated with isometric peak force, regardless of angle. Moderate to large variability was seen in early-stage (0-50 ms) RFD and impulse (ICC = 0.60-0.80, CV = 22.4-63.1%, TEM = 0.62-0.74). Impulse and RFD at 0-100 ms, 0-200 ms and 100-200 ms were moderately variable (ICC = 0.71-0.89, CV = 11.8-42.1%, TEM = 0.38-0.60) at all joint angles. Isometric peak force and late-stage isometric RFD and impulse measurements were found to have low intersession variability regardless of joint angle. However, practitioners need to exercise caution when making inferences about early-stage RFD and impulse measures due to moderate-large variability.

Appendix 36. Chapter 8 abstract

The length-tension relationship affects knee extension performance; however, whether anatomical variations in different quadriceps regions affect this relationship is unknown. Regional (proximal, middle, distal) quadriceps thickness (MT), pennation angle (PA), and fascicle length (FL) of 24 males (48 limbs) were assessed via ultrasonography. Participants also performed maximal voluntary isometric torque (MVIT) assessments at 40º, 70º, and 100º of knee flexion. Measures were recorded on three separate occasions. Linear regression models predicting angle-specific torque from regional anatomy provided adjusted simple and multiple correlations ($\sqrt{adjR^2}$) with bootstrapped compatibility limits to assess magnitude. Middle vastus lateralis MT and MVIT at 100° ($\sqrt{adjR^2}$ = 0.64) was the largest single correlation, with distal vastus lateralis MT having the greatest mean correlations regardless of angle ($\sqrt{adjR^2}$ = 0.61 ± 0.05, mean ± SD). Lateral distal MT and architecture had larger ($\Delta\sqrt{adjR^2}$ = 0.01-0.43) single and multiple correlations with MVIT than the lateral proximal ($\sqrt{adjR^2}$ = 0.15-0.69 vs -0.08-0.65). Conversely, middle anterior MT had greater ($\Delta\sqrt{adjR^2}$ = 0.08-0.38) single and multiple correlations than proximal MT ($\sqrt{adjR^2}$ = 0.09-0.49 vs -0.21-0.14). The length-tension relationship was trivially affected by regional quadriceps architecture. The middle and distal quadriceps were the strongest predictors of MVIT at all joint angles. Therefore, researchers may wish to focus on middle and distal lateral quadriceps anatomy when performing ultrasonographic evaluations.

Novelty bullets:

- The length-tension relationship is minimally affected by regional quadriceps anatomical parameters.
- Middle and distal vastus lateralis and lateral vastus intermedius anatomy were consistently the best predictors of torque.
- Practitioners may focus their assessments on the middle and distal regions of the lateral quadriceps' musculature.

Appendix 37. Chapter 9 abstract

Purpose: Eccentric quasi-isometric (EQI) contractions have been proposed as a novel training method for safely exposing the musculotendinous system to a large mechanical load/impulse, with few repetitions. However, understanding of this contraction type is rudimentary. We aimed to compare the acute effects of a single session of isotonic EQIs with isokinetic eccentric (ECC) contractions.

Methods: Fifteen well-trained men performed a session of impulse-equated EQI and ECC knee extensions, with each limb randomly allocated to one contraction type. Immediately PRE, POST, 24/48/72 h, and 7 days post-exercise, regional quadriceps soreness, swelling, architecture, and echo intensity were evaluated. Peak concentric and isometric torque, rate of torque development (RTD), and angle-specific impulse were evaluated at each time point.

Results: There were substantial differences in number of contractions (ECC: 100.8 ± 54; EQI: 3.85 ± 1.1) and peak torque (mean: ECC: 215 ± 54 Nm; EQI: 179 ± 28.5 Nm). Both conditions elicited similar responses in 21/53 evaluated variables. EQIs resulted in greater vastus intermedius swelling (7.1-8.8%, ES = 0.20-0.29), whereas ECC resulted in greater soreness at the distal and middle vastus lateralis and distal rectus femoris (16.5-30.4%, ES = 0.32-0.54) and larger echogenicity increases at the distal rectus femoris and lateral vastus intermedius (11.9-15.1%, ES = 0.26-0.54). Furthermore, ECC led to larger reductions in concentric (8.3-19.7%, ES = 0.45-0.62) and isometric (6.3-32.3%, ES = 0.18-0.70) torque and RTD at medium-long muscle lengths.

Conclusion: A single session of EQIs resulted in less soreness and smaller reductions in peak torque and RTD versus impulse-equated ECC contractions, yet morphological shifts were largely similar. Long-term morphological, architectural, and neuromuscular adaptations to EQI training requires investigation.

Appendix 38. Chapter 10 abstract

Eccentric quasi-isometric (EQI) contractions (maintaining a yielding contraction for as long as possible, beyond task failure) have gained interest in research and applied settings. However, little is known regarding the biomechanical profile of EQIs. Fourteen well-trained males performed four maximal effort knee-extensor EQIs, separated by 180 seconds. Angular impulse, velocity, and time-under-tension through the 30-100º range of motion (ROM), and in eight ROM brackets were quantified. Statistical parametric mapping, analyses of variance, and standardized effects (Hedges' *g* (ES), %Δ) detected between-contraction joint-angle-specific differences in time-normalized and absolute variables. Mean velocity was 1.34º$\cdot$s^{-1} with most (62.5 ± 4.9%) of the angular impulse imparted between 40–70º. Most between-contraction changes occurred between 30-50º ($p \leq 0.067$, ES = 0.53 ± 0.31, 60 ± 52%), while measures remained constant between 50-100º (p = 0.069-0.83, ES = 0.10 ± 0.26, 14.3 ± 24.6%). EQIs are a time-efficient means to impart high cumulative mechanical tension, especially at short to medium muscle lengths. However, angular impulse distribution shifts towards medium to long muscle lengths with repeat contractions. Practitioners may utilize EQIs to emphasize the initial portion of the ROM, and limit ROM, or apply EQIs in a fatigued state to emphasis longer muscle lengths.

The end