Acute and Chronic Isotonic Resistance Exercise vs. Eccentric Quasi-Isometric Resistance Exercise: Exploring Sex-Differences in Physiological, Biomechanical, and Performance-Based Measures

By

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Abstract

Context: The combination of extended isometric and eccentric muscle actions (i.e., eccentric quasi-isometric resistance exercise (EQI-RE)) is postulated to have advantages over traditional isotonic resistance exercise (TRD-RE), and researchers and practitioners have suggested potential applications in both training and rehabilitation contexts. Studies investigating EQI-RE have yet to evaluate many purported benefits directly, such as greater time under tension, motor unit recruitment, muscle co-contraction/activation, improvements in strength and hypertrophy, and have not compared sex-differences. As females are generally more resistant to fatigue than males, and exercise volume during EQI-RE will be a function of fatiguability, females may exhibit differing neuromuscular responses to EQI-RE, while accruing more exercise volume, potentially leading to sex-differences in musculotendinous adaptations to EQI-RE.

Objective: In trained and untrained males and females, the thesis investigated overall and/or sex-related differences in the acute fatigue response, as well as strength and hypertrophy adaptations to unilateral TRD-RE and EQI-RE of the elbow flexors.

Methods: Using isokinetic dynamometry and surface electromyography (sEMG), study one examined sex-differences in the acute kinematic, kinetic, and muscle excitation response during successive unilateral EQI-RE elbow flexion sets. Using a unilateral dumbbell protocol, study two compared acute sex-differences in time under tension, muscle excitation, and co-activation between TRD-RE and EQI-RE. With this protocol, study three used b-mode ultrasonography and estimated 1-repetition maximum testing to evaluate elbow flexor hypertrophy and strength after 8-weeks of TRD-RE or EQI-RE, and between males and females.

Results: Females were generally less fatigable than males for both TRD-RE and EQI-RE. Greater and faster muscle excitation was produced by TRD-RE, although there were no appreciable differences in agonist-antagonist co-activation. Females accrued more exercise volume from both TRD-RE and EQI-RE, but there were no sex-differences in muscle hypertrophy and strength. TRD-RE produced significantly greater relative increases in muscle hypertrophy and strength than EQI-RE.

Conclusion: The thesis does not equivocally support the proposed benefits of EQI-RE. Females were less fatigable than males during EQI-RE and TRD-RE, but this did not lead to sex-differences in muscle hypertrophy or strength. Overall, TRD-RE was more effective for improving strength and hypertrophy, although EQI-RE still produced significant increases in untrained individuals.

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Dedication

For my future self.

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Author Contributions to Chapters and Publications

Zachariah J. Henderson was the sole and/or primary and majority contributor to all chapters in the thesis. Specific contributions and publication references are listed below and at the beginning of each chapter.

Chapter 2: Conceptualised, designed, piloted methods, collected data, analysed data, interpreted data and drafted the manuscript for the study.

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Chapter 3: Conceptualised, designed, piloted methods, collected data, analysed data, interpreted data, and drafted the chapter.

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Preamble

Over the last 20 years, many “cutting edge” modalities, such as K-tape, cupping, foam rolling, and blood flow restriction training have made their way into athletic and rehabilitation environments. While many of these modalities have become popular with mainstream practice, their initial popularity preceded the existence of convincing scientific evidence and/or subsequent recommendation in best-practice guidelines (Csapo & Alegre, 2015; Park, 2016; Williams et al., 2012). For example, modalities such as K-tape and cupping were popularised by athletes at the Olympics in the 2000s, despite still having unremarkable evidence to support their efficacy (Csapo & Alegre, 2015; Park, 2016). For a 2016 interview (ESPN, 2016), Dwight Howard discussed the role of blood flow restriction training in his rehabilitation, despite the first guidelines regarding the use of blood flow restriction in a clinical setting not appearing until 2017 (Hughes et al., 2017). Early adopters of these modalities based their decision on anecdotal evidence and/or interpretation of preliminary studies that may be subject to substantial bias and limitations to external validity. As a result, exercise and rehabilitation professionals are sometimes criticized for their over reliance on pseudoscience and non-evidence-based practices (Tiller et al., 2022; Zadro et al., 2019), and a recent study found that many continuing education courses for exercise and rehabilitation professionals have questionable bases in outcome-based scientific evidence, despite claims to the contrary (Peterson et al., 2022).

While evidence-based practice allows room for lower quality evidence in decision making, such as clinical experience or mechanistic studies in animal models, the use of unsubstantiated methods and modalities risks replacing those that do have objective efficacy (Burns et al., 2011; Djulbegovic & Guyatt, 2017; Evidence-Based Medicine Working Group,

1992; Meira, 2020). Combined with the massive influence that exercise and rehabilitation practitioners can have on social media when it comes to disseminating, interpreting, and communicating scientific evidence (Marocolo et al., 2021; Tiller et al., 2022), it is important for the scientific community to provide mechanistic, as well as relevant outcome-based data for novel clinical and exercise modalities.

Chapter 1: Introduction and Literature Review

As the name implies, resistance exercise (i.e., “weight training,” “resistance training”) involves actively contracting a muscle against resistance (e.g., gravity, elasticity; McBride, 2016). Chronic resistance exercise is associated with a variety of health and physical performance benefits, including the control of chronic disease (i.e., heart disease, diabetes, depression; Bennie et al., 2020; Ciccolo & Nosrat, 2016; Ratamess et al., 2009), improved muscular fitness (Garber et al., 2011; Ratamess et al., 2009), improved athletic performance (Suchomel et al., 2016), and a reduced risk of all-cause mortality (Shailendra et al., 2022). Although there are metabolic and biochemical effects to resistance exercise that are beneficial to health (Abou Sawan et al., 2023), resistance exercise’s ability to substantially increase muscle mass and strength, which lower total mortality (López-Bueno et al., 2022; Srikanthan et al., 2016), distinguishes it from general physical activity or aerobic exercise (Grgic et al., 2019).

Muscle Actions

There are three types of muscle contractions (or “actions”; Cavanagh, 1988) that comprise the basis of human movement and are used in resistance exercise: concentric, eccentric, and isometric. When performed together, concentric and eccentric muscle actions are defined as “isotonic” or “dynamic” exercise, whereas isometric muscle actions are referred to as “static” exercise (Ratamess et al., 2009). In concentric muscle actions, the contractile force produced by the muscle(s) are greater than the resistance applied, resulting in visible shortening of the muscle (McBride, 2016). Conversely, eccentric muscle actions involve lengthening of the muscle, and occurs when resistance or applied force overcomes the contractile force being produced by the muscle (Lindstedt et al., 2001; McBride, 2016). During isometric muscle actions, muscle length

remains constant as tension is developed; the applied resistive and contractive forces are equal (McBride, 2016). Outwardly, the muscle has no apparent shortening velocity and joint position is maintained (Cavanagh, 1988).

The musculotendinous, neuromuscular, and metabolic characteristics and/or adaptations to each type of muscle action vary considerably. Isometric resistance exercise can provide training stimulus in a specific range of motion (ROM), as muscle length remains constant for the duration of the muscle action (Houglum, 2010). Compared to concentric and eccentric muscle actions, isometric muscle actions allow for greater force development than concentric muscle actions (McBride, 2016), although strength improvements may be more specific to the joint angle trained (Lum & Barbosa, 2019; Oranchuk et al., 2019a). Comparatively, concentric muscle actions are more metabolically demanding and require greater motor unit recruitment, but produces less force than eccentric muscle actions (Douglas et al., 2017). When concentric and eccentric muscle actions are performed successively, however, they are able to harness the passive force produced by the elasticity of the muscle and tendon, adding to the actively produced force, which improves metabolic efficiency and increases power (Lindstedt et al., 2001).

Isotonic and Isometric Resistance Exercise

Traditionally, *isotonic* movements form the basis of resistance exercise programs (Ratamess et al., 2009). *Isotonic* resistance exercise involves repeatedly and consecutively alternating between concentric and eccentric muscle actions through a joint(s)'s ROM, with a single work cycle commonly referred to as a "repetition" or "rep."(McBride, 2016; Powers & Howley, 2012). Depending on the desired adaptations or outcomes, several repetitions will be

performed using a resistance (load) that is > 65% of one's "one-repetition maximum" (1RM), or rather the maximum resistance they can perform the exercise against for one-repetition (Ratamess et al., 2009). A block of consecutive repetitions constitutes a set, and the number of repetitions and sets will again vary depending on the desired adaptations (Bompa & Haff, 2009). Contemporary and conventional resistance exercise principles suggest a large range of loading, repetitions, and sets can induce muscular hypertrophy and improvements in strength, although high-loads may be more beneficial for strength adaptations (Currier et al., 2023; Ratamess et al., 2009; Schoenfeld, Grgic, et al., 2017; Schoenfeld, Ogborn, et al., 2017).

Although *isotonic* resistance exercise is typically implemented in training programs (Ratamess et al., 2009), *isometric* resistance exercise can also substantially improve muscle strength and hypertrophy (Oranchuk et al., 2019a). *Isometric* resistance exercise can be performed by exerting force against an immovable object (i.e., "pushing"), or maintaining joint position with an external load (i.e., "holding"; Schaefer & Bittmann, 2017), and, as a "static" muscle action, can be used to train specific joint angles or muscle lengths (Houglum, 2010). As such, *isometric* resistance exercise may be used in the early stages of rehabilitation and/or when a specific ROM is not tolerated (Houglum, 2010). As with *isotonic* resistance exercise, a wide range of loading, repetition, and set schemes can increase muscle strength and hypertrophy; however, *isometric* resistance exercise may need to be performed at long muscle lengths (i.e., extended joint position) to have meaningful transference to *isotonic* or dynamic tasks (Oranchuk et al., 2019a).

Eccentric Quasi-Isometric Resistance Exercise

Practically speaking, an "eccentric quasi-isometric," or "EQI" is completed by performing a holding isometric muscle action (Schaefer & Bittmann, 2017) for as long as possible. Eventually, the accumulation of fatigue results in isometric failure and the inability to maintain joint position. A low-velocity eccentric muscle action then ensues, which is voluntarily resisted through the full ROM (Oranchuk et al., 2019b, 2020, 2021).

Purported Benefits of Eccentric Quasi-Isometric Resistance Exercise

The combination of isometric and eccentric muscle actions within EQIs are purported by practitioners to increase motor unit recruitment, muscle co-contraction, post-activation potentiation, time under tension, and decrease fatigue relative to traditional resistance exercise methods, in addition to altering force-angle relationships and improving tendon health, strength, power, stability, proprioception, and hypertrophy outcomes (Morrison, 2016; Seedman, n.d.-a, n.d.-b; Sinicki, 2019). While these adaptations would give EQI resistance exercise (EQI-RE) meaningful utility in rehabilitation and training settings, especially in contexts where high-velocity muscle actions would not be well tolerated or appropriate (Oranchuk et al., 2019b) these same adaptations can also be produced with traditional, well-studied resistance training methods, such as isotonic, isometric, or eccentric only resistance exercise (Bohm et al., 2015; Carvalho et al., 2022; Currier et al., 2023; Mcleod et al., 2023; Morrison & Cook, 2022; Oranchuk et al., 2019a; Ratamess et al., 2009).

Literature Review

Currently, the study of EQI-RE lacks long-term outcome or interventional-based data, as well as direct mechanistic data to build a theoretical framework. Although a few studies to date

have examined kinematic, kinetic, and morphological responses to EQI-RE (Ličen et al., 2024; Oranchuk et al., 2020, 2021), these studies have been restricted to acute EQI-RE of the lower extremity, and have not examined sex-differences, motor unit recruitment and muscle excitation, hypertrophy, or strength adaptations to EQI-RE. Indeed, Oranchuk et al. (2019b) present a theoretical rationale for how EQI-RE could elicit some of the purported adaptations; however, the rationale is based on indirect evidence (e.g., animal models or studies of static stretching and isometric resistance exercise), given that studies directly examining EQI-RE were limited. While Oranchuk et al. (2019b) present several avenues for the application of EQI-RE in practice, they postulated that EQI-RE would be most useful as an adjunct training method to increase resistance exercise volume in a time efficient manner, which could contribute to changes in musculotendinous morphology (i.e., increased muscle thickness, fascicle length, tendon stiffness/elasticity), thereby improving muscle strength and power. Furthermore, they theorised that EQI-RE may elicit unique neuromuscular responses compared to traditional resistance exercise methods, such as increased agonist-antagonist co-activation and increased type II motor unit recruitment. An overview of key assumptions and rationale of EQI-RE are presented below.

Assumptions of Eccentric Quasi-Isometric Resistance Exercise

Time Under Tension. Specific to adaptations in muscle strength and hypertrophy, much of the justification for EQI-RE lies in the assumption that it produces substantial time under tension (TUT) relative to traditional resistance exercise methods, specifically at long (i.e., extended) muscle lengths (Oranchuk et al., 2019b). Sometimes referred to as “time to task failure,” or “endurance time” (e.g., Hunter et al., 2002, 2004b), time under tension represents the duration of a given exercise or set and is assumed to be the time with which a muscle is mechanically loaded or exerting force (Gentil et al., 2006). As such, time under tension has a

significant impact on resistance exercise volume-load, as the longer a given load is resisted, the greater the mechanical work performed (McBride, 2016). Generally speaking, resistance exercise volume is positively related to muscle hypertrophy (Mcleod et al., 2023; Schoenfeld, Ogborn, et al., 2017), therefore the ability to generate greater time under tension with a given load should theoretically benefit skeletal muscle hypertrophy.

"Metabolic Stress." Broadly, "metabolic stress" refers to the peripheral accumulation of metabolites (i.e., H+, inorganic phosphate, lactate) in response to exercise (Schoenfeld, 2020). During fatiguing contractions, muscle perfusion is decreased due to mechanical compression of circulatory structures within a muscle, which can lead to a pooling of metabolites in the muscle (Hunter, 2014; Oranchuk et al., 2019; Pearson & Hussein, 2015). As an EQI is performed as a discrete task with the goal of maintaining movement velocity at zero, muscle perfusion characteristics during EQI-RE would presumably resemble those of isometric rather than isotonic muscle actions. The intramuscular pressure produced during moderate intensity sustained isometric muscle actions can have an occlusive effect on the muscle, leading to reductions in blood flow and metabolite clearance (Hunter, 2014). Concurrently, electromyography amplitude will start out stable, but gradually increase as fatigue develops, reflecting additional motor unit recruitment and/or changing motor unit characteristics to maintain force output (Kamen & Gabriel, 2012).

Motor Unit Recruitment. Based on the size principle, motor units are recruited from small, low threshold (type I) to large, high threshold (type II) as force requirements increase or motor units fatigue (Henneman, 1957; Henneman & Olsen, 1965). While passive, static stretching may be sufficient at very high volumes to induce skeletal muscle hypertrophy and

remodelling (Panidi et al., 2023), it is generally accepted that high levels of motor unit recruitment are needed to impart mechanical tension to the active muscle fibres (Refalo et al., 2023; Schoenfeld, 2010). In other words, muscle fibres must be actively recruited to generate sufficient tension to induce skeletal muscle hypertrophy. As such, to recruit the majority of the motoneuron pool over the course of a set, while also generating high levels of mechanical tension, conventional resistance exercise prescription principles dictate loads > 60% (i.e. "high-load") of one-repetition maximum (1-RM) are necessary (Lopez et al., 2021; Ratamess et al., 2009; Schoenfeld, Grgic, et al., 2017). Contemporary research, however, suggest that if effort, or "proximity to failure" (i.e., volitional fatigue) is high, the accumulation of volume with low-load resistance exercise produces similar hypertrophy (Lopez et al., 2021; Schoenfeld, Grgic, et al., 2017). Indeed, this is thought to be due, impart, to the progressive recruitment of type II motor units to maintain muscle force with fatigue. It is therefore assumed that along with extended time under tension, EQI-RE elicits the high level of motor unit recruitment and firing rate required to induce skeletal muscle hypertrophy (Oranchuk et al., 2019b).

Co-activation. While a relatively new concept, Schaefer and Bittmann (2017) hypothesised that "pushing" and "holding" isometric muscle actions have distinct neuromuscular and metabolic properties. Specific to neuromuscular responses, they postulated that holding isometrics display greater similarities to eccentric muscle actions, whereas pushing isometric muscle actions are more analogous to concentric muscle actions. Indeed, agonist musculature is excited (i.e., "activated") to a greater degree when performing pushing isometric muscle actions; however, co-activation of antagonist and synergist musculature appears to be greater when performing holding isometric muscle actions (Hunter et al., 2002; Rudroff et al., 2007; Schaefer & Bittmann, 2017). Given the similarities of EQI-RE and holding isometric muscle actions, EQI-

RE is postulated to generate greater agonist-coactivation than isotonic and pushing isometric resistance exercise, which would theoretically improve joint stability and muscle stiffness, thereby enhancing force transference through musculotendinous structures (Oranchuk et al., 2019b; Seedman, n.d.-a).

Exercise Induced Muscle Damage. Traditionally, high-velocity eccentric muscle actions are associated with greater acute inflammation and exercise induced muscle damage than concentric or isometric resistance exercise and can reduce force output for up to one-week post exercise (Douglas et al., 2017). Oranchuk et al. (2019b) suggested that, despite performing an eccentric muscle action, the low-velocity nature of EQI-RE would make it unlikely to produce substantial exercise induced muscle damage. More specifically, based on the "popping sarcomere" theory of exercise induced muscle damage (Douglas et al., 2017; Morgan & Proske, 2004), the fewer number of sets or repetitions required to equate EQI-RE volume (i.e., time under tension) to higher-velocity resistance exercise would reduce the number of sarcomere bonds and subsequent "popping" with cyclic repetitions of eccentric resistance exercise. As such, other long-term benefits of eccentric resistance exercise could be realised without the detrimental effects of extensive delayed onset muscle soreness or exercise induced muscle damage, such as acute reductions in muscle force.

Muscle Fatigue. Muscle fatigue, or "fatigability" is defined as a reduction in force and power production in response to exercise and can be quantified by measuring the decline in force or change in electromyographic variables during or after a sustained motor task (Bigland-Ritchie & Woods, 1984). While muscle fatigue does not inherently describe task failure, "momentary failure" will occur once a repetition cannot be completed without deviating from the exercise

parameters (i.e., full ROM; Steele, Fisher, et al., 2017), ergo the musculotendinous structures can no longer produce sufficient force. Muscle fatigue can be distinguished by central factors, which occur proximal to the neuromuscular junction (Bigland-Ritchie et al., 1995; Gandevia, 2001; Taylor et al., 2016), and peripheral factors, or those that are distal to the neuromuscular junction (Taylor et al., 2016). Central nervous system (CNS) fatigue will present as a reduction in motor unit recruitment or altered motor unit firing (Bigland-Ritchie et al., 1995), whereas peripheral fatigue results from changes in blood flow, oxygen delivery, and metabolism (Bigland-Ritchie et al., 1995; Gandevia, 2001; Hunter, 2016b; Kent-Braun et al., 2002; Taylor et al., 2016; Wan et al., 2017).

Oranchuk et al. (2019b) acknowledges that EQI-RE likely produces substantial peripheral fatigue. Secondary to time under tension, Oranchuk et al. (2019b) proposed that EQI-RE may also create a hypoxic environment in the muscle, where blood flow, muscle oxygenation, and metabolite clearance are reduced. While unknown in the context of EQI-RE, the intramuscular pressure produced during moderate intensity sustained isometric muscle actions can have an occlusive effect on the muscle, leading to reductions in blood flow and metabolite clearance (Hunter, 2014). In addition to contributing to muscle hypertrophy by affecting anabolic hormones and downstream protein signalling and satellite cell satellite cell proliferation (Pearson & Hussain, 2015; Schoenfeld, 2010), the resulting build-up of metabolites may stimulate type III and IV afferents, leading to autonomic responses, such as increased oxygen delivery and blood flow to the working muscles (Amann et al., 2015). Conversely, increased activation of these afferents may excite and/or inhibit the motoneuron pool of the agonist and antagonist muscle (Jessee et al., 2018; Martin et al., 2006, 2008; Pearson & Hussain, 2015). In cases where the motoneuron pool is excited, it has been argued that this results from preferential activation of

type II motor units by group III and IV afferents (Martin et al., 2008). From a strength and hypertrophy standpoint, type II muscle fibers *may* have a slightly greater potential for hypertrophy than type I muscle fibres in men and women (McCall et al., 1996; Staron et al., 1989; Straight et al., 2020). Thus, it is plausible that preferential excitation of type II motor units may meaningfully impact muscle hypertrophy and strength outcomes from EQI-RE.

Proposed Long-Term Adaptations

Based on the assumptions of EQI-RE producing substantial and/or greater time under tension, motor unit recruitment, and co-activation/contraction than traditional resistance exercise methods, it has been proposed that EQI-RE should lead to comparable, if not greater skeletal muscle hypertrophy and strength outcomes than traditional resistance exercise (Oranchuk et al., 2019b; Seedman, n.d.-b, n.d.-a).

Skeletal Muscle Hypertrophy. At the macroscopic level, human skeletal muscle hypertrophy refers to an increase in muscle mass and/or axial-cross sectional area of individual muscle fibres and/or whole muscles (Haun et al., 2019; Lim et al., 2022; Russell et al., 2000). Although resistance exercise is widely considered the most effective extraneous means of increasing skeletal muscle mass, the mechanisms that underly skeletal muscle hypertrophy are numerus, complex, and not well-understood (Goldspink, 1999; Haun et al., 2019; Schoenfeld, 2010). While not an exhaustive list, current models suggest that mechanotransduction and related activation of anabolic pathways (e.g., mammalian target of rapamycin), systemic changes in anabolic hormone concentration (e.g., testosterone), exercise induced muscle damage, and metabolic stress increase muscle protein synthesis, and subsequently lead to skeletal muscle hypertrophy (Lim et al., 2022).

Despite the complexity of processes involved in the accrual of skeletal muscle mass, mechanotransduction is generally considered the main driver of muscle hypertrophy and occurs when (muscle) cells produce a chemical response to a mechanical stress (Lim et al., 2022). In the context of resistance exercise, this occurs when muscles are stretched and/or loaded, which produces tension in the contractile (e.g., actin & myosin), series (e.g., tendons) and parallel elastic (e.g., myofibrils) components of the muscle (Hinks et al., 2022; Ratamess et al., 2009; Schoenfeld, 2010).

The ability for chronic and intermittent mechanical and loaded stretch to produce muscle hypertrophy is well documented in avian, feline, rat, and rabbit models (Alway et al., 2005; Cholewa et al., 2014; Lowe & Alway, 2002; Strickland & Smith, 2016). Although traditional stretching practices (i.e., 3 sets of 30 seconds) in humans are unlikely to meaningfully impact muscle strength or hypertrophy, high-volume/intensity static stretching has recently been demonstrated to improve muscle thickness and strength in humans (Panidi et al., 2023; Simpson et al., 2017; Wohlann et al., 2024). It is thought that when a muscle is in a lengthened or stretched position (i.e., beyond neutral), excessive passive tension is imparted to the muscle, and, over the course of days or weeks, remodeling of muscle architecture (i.e., sarcomere number/length) occurs to reduce this passive tension and retain ideal myosin-actin overlap (Hinks et al., 2022). Indeed, performing isotonic and isometric resistance exercise in a lengthen position can produce comparable hypertrophy adaptations to performing isotonic and isometric resistance exercise through a full ROM or shorter muscle lengths (Kassiano et al., 2023; Oranchuk et al., 2019a; Pedrosa et al., 2022). With respect to EQI-RE, because the agonist muscle is slowly lengthened under load Oranchuk et al. (2019b) assumes that an extended period is spent with the muscle in a lengthened state, which will lead to the suggested muscle

remodelling and hypertrophy. Whether or not hypertrophy and remodelling occur because of EQI-RE, or is due to the aforementioned mechanisms, however, has yet to be evaluated.

Alternatively, assuming EQI-RE results in similar sustained intramuscular pressure as isometric resistance exercise, the accumulation of metabolites and acute hypoxia within the muscle could drive EQI-RE induced muscle hypertrophy. In addition to stimulating myogenesis and anabolic signalling factors (Schoenfeld, 2020), intense exercise that activates anaerobic and aerobic metabolic systems decreases intramuscular pH, limiting calcium binding and impairing myosin-actin attachment, negatively impacting the force producing capacity of type II muscle fibres. As such, it theorised that type I muscle fibres may play a greater role in maintaining force production during short but intense exercise, ergo stimulating their hypertrophic development (Schoenfeld, 2020). Conversely, the reduction in oxygen delivery during acute hypoxia, as well as the accumulation of H+ may impair contractility in aerobic type I muscle fibres; high threshold (type II) motor units and related muscle fibres are then recruited to maintain force output (Takarada et al., 2000). Assuming type II muscle fibres are more likely to experience measurable hypertrophy than type I muscle fibres, increased recruitment of anaerobic type II motor units and associated muscle fibres is thought to be one of the drivers of muscle hypertrophy from acute hypoxia or blood flow restricted exercise (Pearson & Hussain, 2015). Regardless of the specific effects, it is likely that the accumulation of metabolites increases recruitment of motor units across the spectrum of the motoneuron pool. Again, assuming the EQI-RE results in sustained intramuscular pressure, it is plausible that a pooling of metabolites would occur within the muscle during EQI-RE, leading to increased motor unit recruitment and related morphological adaptations (Oranchuk et al., 2019b).

Strength. In suggesting that EQI-RE would produce advantageous morphological adaptations (i.e. increased fascicle length, hypertrophy) for strength because they are performed at long muscle lengths, Oranchuk et al., (2019b) also discusses the potential for EQI-RE to have transference to dynamic tasks requiring large ROM (i.e., 1-repetition maximum; 1-RM) when compared to short muscle length isotonic and isometric resistance exercise. Indeed, isotonic and isometric resistance exercise at long muscle lengths produces greater strength and hypertrophic adaptations than resistance exercise at short muscle lengths, and may have some level of transference to full ROM, or in the case of isometric resistance exercise, dynamic tasks (Kassiano et al., 2023; Oranchuk et al., 2019a; Pallarés et al., 2021; Schoenfeld & Grgic, 2020). Furthermore, while relatively few studies have compared partial ROM isotonic or isometric resistance exercise at short and long muscle lengths to full ROM, systematic reviews (Kassiano et al., 2023; Pallarés et al., 2021; Schoenfeld & Grgic, 2020) conclude that full and/or larger ROM is superior to partial ROM resistance exercise at increasing muscle mass and strength, although strength improvements are generally realised within the ROM and muscle length trained. Naturally, the larger strength improvements within the muscle lengths and ROM trained highlight the principle of specificity, in that the more closely exercise resembles the test or task, the more likely it is to improve said test or task (Bompa & Haff, 2009; Ratamess et al., 2009).

When considering the aforementioned reviews (Kassiano et al., 2023; Pallarés et al., 2021; Schoenfeld & Grgic, 2020) and that EQI-RE is performed with low contraction velocities, Oranchuk et al. (2019b) highlight that any long-term improvements in strength or power production (i.e., 1-RM, rate of force development) from EQI-RE are likely indirect and due to morphological and/or architectural adaptation, such as increased fascicle length and altered force-angle relationships. Indeed, as EQI-RE is performed with low contraction velocities, it

would seem unlikely that any neuromuscular adaptations that occur would benefit higher velocity tasks (i.e., 1-RM, vertical jump height). That being said, and despite a lack of evidence, practitioners have claimed that EQI style resistance exercise improves strength by increasing motor unit recruitment and post-activation potentiation, as well as improving movement efficiency and coordination (Morrison, 2016; Seedman, n.d.-a, n.d.-b; Sinicki, 2019).

Challenging Initial Assumptions

Although Oranchuk et al. (2019b) discusses several related areas of muscle physiology and biomechanics research, and applies relevant theories and principles to EQI-RE, there is somewhat limited discussion of the role muscle fatigue could play in potential strength and hypertrophy adaptations to EQI-RE. Given that a single EQI is performed to task failure, it is likely that mechanisms underlying muscle fatigability and physiological responses to muscle fatigue are relevant to the acute response to an EQI and chronic adaptations to EQI-RE. As previously discussed, it is assumed that the ability to generate substantial time under tension and motor unit recruitment compared to other resistance exercise methods underly the purported hypertrophy and strength benefits of EQI-RE. If likening an EQI to a holding isometric muscle action, however, a pushing isometric muscle action would produce substantially greater sEMG amplitude at task failure(Hunter et al., 2002; Schaefer & Bittmann, 2017). Additionally, while antagonist co-contraction/activation may be greater when performing holding isometric muscle actions, it is suggested that greater neuromuscular, and potentially metabolic demand of utilising additional musculature results in quicker time to task failure. As such, this could actually suggest that EQI-RE would produce less motor unit recruitment and time under tension than traditional pushing isometric muscle action, which are commonly used in practice, and would contravene practitioner claims to the contrary.

Primary EQI Research

Despite preliminary rationale and justification, many of the assumptions of EQI-RE have yet to be evaluated, and no studies have examined the long-term effects of EQI-RE on muscle hypertrophy and strength. Only three-studies (Ličen et al., 2024; Oranchuk et al., 2020, 2021) to date have investigated and/or compared EQI-RE to others forms of resistance exercise, and evaluated the acute kinematic, kinetic, neuromuscular, and morphological response to EQI-RE. Specific to the aforementioned assumptions, these studies addressed the effects of EQI-RE on exercise induced muscle damage (delayed onset muscle soreness, muscle swelling), time under tension and mechanical tension at long-muscle lengths (angular impulse), and neuromuscular fatigue (isometric torque). An overview of these studies is presented below.

Current Research Model. While an EQI can theoretically be performed for any isotonic movement, for research purposes, EQI-RE has only been examined using a unilateral leg extension and flexion protocol developed by Oranchuk et al., (2020) and adapted by Ličen et al. (2024). Participants were set-up in an isokinetic dynamometer to perform unilateral leg extension/flexion from 30° (full extension) to 100° (Oranchuk et al., 2021) or 110° (Oranchuk et al., 2020; full flexion). From full extension, an eccentric (isotonic) load is gradually applied over a two-second period until equivalent to 70% of participants maximum voluntary isometric torque (MVIT). Participants are then directed to maximally "brace and maintain joint position throughout the ROM," without causing a concentric contraction (Oranchuk et al., 2020, 2021). Once isometric failure occurs at the starting position, these instructions result in low-velocity changes in joint angle, interspersed with brief periods of no visual changes in joint angle until full knee flexion. Participants then rest for 3-minutes, after which an unloaded concentric muscle

action is performed to bring the knee to full extension and initiate the next repetition, for a total of 4 “sets” (Oranchuk et al., 2020, 2021).

Studies to Date. In the first study (Oranchuk et al., 2020) to systematically investigate EQI-RE, 15 resistance trained males (26.4 ± 5.2 years), had each leg randomized to either the EQI-RE protocol, or an angular impulse matched (integral of the torque-time curved) eccentric resistance exercise (ECC-RE) protocol at $60°·s^{-1}$. Before and after the EQI-RE and ECC-RE protocol, participants maximal concentric torque at $60°·s^{-1}$ and maximal voluntary isometric torque at 40°, 70°, and 100° of knee flexion were evaluated to assess neuromuscular fatigue, while muscle architecture and morphology (fascicle length, pennation angle, muscle thickness), and pressure-pain thresholds were used to assess exercise induced muscle damage, swelling, and delayed onset muscle soreness. Based on Bayesian inferences and compared to the ECC-RE, maximal voluntary isometric torque and isometric rate of torque development was maintained to a greater extent immediately after the EQI-RE protocol, with small-moderate, and likely-very likely between-limb differences observed at 70° and 100°. However, meaningful between-limb differences in torque characteristics were not observed at 40°. A similar between-limb effect was observed for concentric dynamometry, with greater reductions in peak torque and total angular impulse observed in the ECC-RE limb compared to the EQI-RE limb. Furthermore, the ECC-RE protocol resulted in greater, yet varying reductions in angular impulse from 100° -50° of knee flexion.

Combined with maximal voluntary isometric torque and maximal voluntary isometric torque results, the preceding data would suggest a muscle length dependency of EQI-RE induced neuromuscular fatigue, while supporting the notion that EQI-RE will produce less muscular

fatigue and exercise induced muscle damage than ECC-RE, at least acutely. Differences in muscle thickness and peak torque were less apparent at 24h, 48h, 72h, and 7 days post-protocol; although differences were small, maximal voluntary isometric torque and rate of torque development at 70° recovered more quickly following EQI-RE, while maximal voluntary isometric torque and rate of torque development at 100° recovered more quickly following ECC-RE. Furthermore, there were no meaningful between-limb differences in concentric peak torque at 24h, 48h, 72h, and 7 days post-protocol, with additional trivial differences from 10°-30° at the 48h and 7-day timepoints. Additionally, EQI-RE produced greater muscle swelling for up to 72h, although delayed onset muscle soreness was trivially greater in the 72h following the ECC-RE. When considering these variables over the time course of the study (immediately pre to 7 days), the immediate, but not sustained difference in torque production following EQI-RE and ECC-RE protocols appears to be due to neuromuscular, rather than physical characteristics (Oranchuk et al., 2020).

In addition to assessing pre-post variables, Oranchuk et al., (2020) descriptively quantified the impulse and time under tension distribution of each EQI. Noting large between-participant variability, most angular impulse and time under tension occurs at short-medium muscle lengths during EQIs, but at medium muscle lengths during ECCs. In a follow-up study using the same EQI protocol, (Oranchuk et al., 2021) compared the kinematics and kinetics of successive EQI sets in a sample of fourteen resistance trained males (27.9 ± 5.1 years). Using statistical parametric mapping, no significant differences in the angle-time relationship were detected across sets. However, changes in joint angle appeared to occur more quickly from 30°-50° (i.e., short muscle lengths) with successive sets, although a similar pattern was present across sets from 50°-100° (medium-long muscle lengths). Indeed, traditional frequentist statistics

indicated a significant decrease in relative angular impulse (% set) at 40°-50° (-73.5 ± 58.1%, Hedges' g = 0.63 ± 0.27) between sets 1 and 3 ($p < .05$) , 1 and 4 ($p < .01$), 2 and 3 ($p < .05$), and 2 and 4 ($p < .05$), with concurrent increases at 60°-70° of knee flexion from set 2, to 3, to 4, and smaller and decreases in angular impulse from 30°-50°. Furthermore, total angular impulse for each set significantly decreased across and between sets ($p < .05$ to .001, omega squared = 0.11), with set 1-4 displaying an average decrease of 33.8% (, $p < .001$, Hedges g = 0.72). Unsurprisingly, similar results were observed for time under tension and angular velocity, as both were derived from the same data.

Very recently, Ličen et al. (2024) quantified and compared time under tension and angular velocity between EQI knee extension and EQI knee flexion in a sample of moderately active individuals (9 males, 7 females; 23.5 ± 2.6 years), albeit with a smaller ROM (30-80°) than Oranchuk et al. (2020) and Oranchuk et al. (2021). For both the knee extensors and knee flexors, participants performed 2 sets of maximal concentric contractions in blocks of 5 repetitions, followed by 4 EQI, and two more sets of maximal concentric contractions. All maximal concentric contractions and EQI "sets" were performed on the right leg, and order of completion (knee extension or knee flexion) were randomised. As with Oranchuk et al. (2020), torque output significantly decreased after 4 sets of EQIs, while time under tension decreased in a linear fashion with successive EQIs. Although there was a greater overall decrease in peak torque in the knee extensors ($p < .001$) following the EQI protocol, there were no significant differences in time under tension across repetitions between the knee extensors and knee flexors ($p = .259$), and similar to Oranchuk, the majority of time under tension was spent at shorter muscle lengths. Additionally, they did observe a small increase in the angle of peak torque following EQI-RE for the knee extensors ($p = .001$, Cohen's $d = 1.00$), but not knee flexors ($p =$

.811), suggesting that knee extensors are more fatigable than the knee flexors when it comes to EQI-RE.

Implications of Current Studies

Based on EQI-RE studies to date (Oranchuk et al., 2020; Oranchuk et al, 2021; Ličen et al., 2024) successive EQI sets alter the muscle length at which mechanical tension is imparted to the quadriceps, at least when performed through a full ROM. Specifically, performing EQI-RE in a state of fatigue appears to bias exercise volume and mechanical tension at longer muscle length and increase the angle of peak torque production. In keeping with Oranchuk et al.'s (2019b) suggestion the EQI-RE performed at long muscle lengths would lead to beneficial morphological adaptations for strength (i.e., muscle hypertrophy, increased fascicle length), EQI-RE increased the relative time spent at longer muscle lengths for each set as fatigue accumulated, even when performed through a full ROM. However, the relative shift in angular impulse to longer muscle lengths appears to be due to a significant decrease in angular impulse at short muscle lengths, rather than an inherent increase in volume at longer muscle lengths. Indeed, across 4 sets of EQI-RE, most training volume would still be performed at short and/or medium muscle lengths (Ličen et al., 2024; Oranchuk et al., 2020, 2021). As the relative proportion of angular impulse tends to shift towards long muscle lengths with successive EQI sets, muscular fatigue would appear to accrue in an angle and/or muscle length specific manner during EQI-RE of the lower-body (Oranchuk et al., 2021). How contextual factors such as sex and muscle influence this fatigue patter, however, remains unknown.

Considerations for EQI-RE study

While Oranchuk et al. (2020) and Oranchuk et al. (2021) provide a preliminary examination of physiological and biomechanical responses to EQI-RE in the lower-body and resistance trained males, many of the proposed responses and adaptations to EQI-RE were not investigated (Oranchuk et al., 2019b). For example, neither study examined the effect EQI-RE training on muscle hypertrophy or strength. Furthermore, while neuromuscular fatigue was quantified using maximal voluntary isometric torque (Oranchuk et al., 2020) and maximal voluntary concentric contractions (Ličen et al., 2024), muscle excitation or motor unit recruitment were not measured despite the proposed and purported effects of EQI-RE increasing motor unit recruitment. Based on the mechanisms of EQI-RE induced muscle hypertrophy and strength proposed by (Oranchuk et al., 2019b), such as increased time under tension, the potential exists for sex-differences in acute and chronic responses to EQI-RE, especially when considering that sex-differences may be specific to the musculature involved.

Sex-Differences in Hypertrophy and Strength Adaptations. On average, males have greater absolute muscle mass and strength than females (Lundberg et al., 2024; Nuzzo, 2022; Roberts et al., 2020). Differences in absolute strength are attributed to morphological and not neuromuscular factors; females having a greater proportion of type I muscle fibres, whereas males have a greater proportion of type II muscle fibres, the latter of which are better able to generate force (Lundberg et al., 2024; Nuzzo, 2022; Roberts et al., 2020). Furthermore, the degree to which males and females differ in absolute strength is dependent on the muscle and muscle action, with greater sex-differences seen for upper-body strength vs. lower body-strength, and concentric vs. eccentric muscle actions (Nuzzo, 2022). Further, strength differences are larger at long muscle lengths vs. short muscle lengths when performing isometric muscle actions.

Although males have discernably greater absolute strength, muscle mass, and participation in resistance exercise, females have similar, if not greater potential for relative improvements in strength and muscle mass from resistance exercise, especially in the upper body (Nuzzo, 2022; Roberts et al., 2020) . Several reasons for this small difference have been discussed in the literature, such as the influence of the menstrual cycle and associated sex-hormones, anthropometric distribution of muscle mass, vocation, neuromuscular and baseline strength differences (Nuzzo, 2022; Roberts et al., 2020). While data does not support the existence of sex-differences in voluntary muscle activation on measures of strength (Nuzzo, 2022), males and females display significantly different levels of voluntary excitation with fatigue (Hunter, 2014, 2016b, 2016a).

Sex-Differences in Muscle Fatigue. In resistance exercise, volitional fatigue, or "momentary failure" refers to the set endpoint point at which an individual is no longer able to voluntarily complete the concentric muscle action of a repetition (Steele, Fisher, et al., 2017), or in the case of EQI-RE, resist the eccentric muscle action.

As EQI-RE is inherently performed to volitional fatigue, the total volume and training stimulus will likely be limited by the fatiguability of an individual and/or sex. Sex-differences in muscle fatigue are highly specific to the task, muscle, and intensity involved (Hunter, 2014, 2016b). Although females are generally considered to be more resistant to muscular fatigue than males, the magnitude and/or existence of these differences is dependent on the aforementioned factors. For example, females display longer time to task failure than males when performing isometric muscle actions; however, the magnitude of this difference decreases with increasing contraction intensity (Hunter, 2014). Comparatively, females may be less fatigable than males

when performing concentric muscle actions for the elbow flexors at slow velocities, but not when performed with high velocities(Senefeld et al., 2013). Furthermore, for eccentric muscle actions, females may be more susceptible to fatigue than males (Jodoin et al., 2023a). Indeed, the mechanisms that contribute to these sex-differences are also dependent on these factors, and the reason for females' greater relative fatigue resistance is often attributed to differences in muscle fibre type distribution, size, and strength (Hunter, 2014, 2016b; Nuzzo, 2022, 2024), metabolism, blood flow, and muscle perfusion (Hunter, 2014), and voluntary muscle excitation and motor unit behaviour (Hunter, 2014; Lulic-Kuryllo & Inglis, 2022; Nuzzo, 2022), to name a few.

Surface Electromyography. During sustained submaximal isometric muscle actions to volitional fatigue, sEMG amplitude—a measure of muscle "activation" (i.e., excitation; Kamen & Gabriel, 2010a; Vigotsky et al., 2018) will gradually increase (e.g., Bazzucchi et al., 2004a; Staudenmann et al., 2014a), while spectral frequencies decrease, potentially due to recruitment of higher threshold (i.e., type II) and/or increased firing of motor units. In the context of muscle fatigue and resistance exercise volume,Voskuil et al. (2024) recently demonstrated that females were able to perform more repetitions and maintain elbow flexor excitability to a greater degree than males when performing isotonic resistance exercise, allowing them to accrue more resistance exercise volume within a single training session. Whether or not a similar sex-dependent response would be present during EQI-RE, however, is difficult to predict. As described previously, sex-differences in muscle fatigue can be dependent on the type of muscle action performed, and differ between isometric and eccentric muscle actions (Hunter, 2014, 2016b) . Thus, with no direct studies for comparison, extrapolating either isometric or eccentric muscle fatigue studies to EQI-RE provides limited insight.

Rational And Relevance of Conducted Studies

As discussed in the literature review, the ability to progress and add volume to an EQI-RE protocol is inherently related to the fatigability of an individual. Given potential sex-differences in muscle fatiguability (Hunter, 2014; Hunter, 2016) and the role that exercise volume has on muscle hypertrophy and strength outcomes (Schoenfeld et al., 2017), it is plausible that sex-differences in muscle fatigability during acute EQI-RE would manifest in differing long-term strength, neuromuscular, and morphological adaptations. Furthermore, based on Oranchuk et al. (2020) and Oranchuk et al. (2021) observing shifts in the distribution of mechanical tension to longer-muscle lengths with increasing sets, it remains plausible that any sex-differences may be muscle length dependent.

With the aforementioned context in mind, the overarching goal of the thesis was to generate preliminary mechanistic and outcome-based data for elbow flexion EQI-RE in males and females and compare these data with traditional isotonic resistance exercise. Three studies were conducted to accomplish this; one study examined the acute muscle fatigue responses to EQI-RE in resistance trained individuals, one study compared the acute muscle fatigue response to traditional isotonic resistance exercise (TRD-RE) and EQI-RE in non-resistance trained individuals, and one study compared the chronic effects of 8-weeks of EQI-RE and TRD-RE on muscle hypertrophy and strength in non-resistance trained individuals. Underlying these comparisons was the effect of sex and the relationship of resistance exercise volume and sex with muscle hypertrophy and strength adaptations to TRD-RE and EQI-RE.

Study One. To support the hypothesis that acute sex-differences in time under tension and motor unit recruitment/excitation during EQI-RE would manifest in long-term strength and

hypertrophy adaptations, it was first necessary to establish whether or not sex-differences exist in the muscle fatigue response during an acute bout of EQI-RE. As such, the primary goal of study one (Chapter 2) was to examine acute muscle fatigue responses to EQI-RE in resistance trained individuals. Specifically, the following objectives were established for study one:

1) Determine if there are sex-differences in time under tension and mechanical tension during an acute bout of EQI-RE elbow flexions.
    a. Evaluate whether any differences are specific to muscle length/ROM and/or set.
2) Determine if there are sex-differences in agonist muscle excitation during an acute bout of EQI-RE elbow flexions.
    a. Evaluate whether any differences exist are specific to muscle length/ROM and/or set.

As the first scientific investigation of EQI-RE in the upper limb, as well as the first to measure sEMG variables and quantify potential sex-differences in response to EQI-RE, study one employed an observational approach. Similar to Oranchuk et al. (2020) and Oranchuk et al (2021), unilateral EQI-RE was performed using an isokinetic dynamometer and statistical parametric mapping was utilised to address the muscle length objectives (2a). Unlike Oranchuk et al., however, EQI-RE was performed with the elbow flexors and sEMG data of agonist musculature was collected alongside kinetic and kinematic data.

Study Two. From study one, the need to evaluate EQI-RE using a more ecologically valid resistance exercise model, and to compare it to TRD-RE was identified. As such, a quasi-experimental, unilateral approach where untrained participants performed TRD-RE for the elbow

flexors with one limb, and EQI-RE for the other limb. Similar to study one, the main objectives were to evaluate the purported and theorized time under tension and motor unit recruitment characteristics of EQI-RE; however, as we compared EQI-RE to TRD-RE, the objectives of study two (Chapter 3) were to:

1) Determine if there are sex-differences in resistance exercise volume during an acute bout of unilateral TRD-RE vs. EQI-RE of the elbow flexors.
2) Determine if there are sex-differences in agonist muscle excitation during an acute bout of unilateral TRD-RE vs. EQI-RE of the elbow flexors.

In addition to evaluating time under tension and agonist muscle excitation between males and females during TRD-RE and EQI-RE, we also evaluated the purported co-activation characteristics of EQI-RE. As such, a tertiary objective of study two was to evaluate sex-differences in biceps-triceps co-activation between males and females during TRD-RE and EQI-RE.

Study Three. Based on the results from study two, we hypothesised that there may be sex-dependent differences in muscle hypertrophy and strength adaptations to TRD-RE and EQI-RE. Using a quasi-experimental approach and the same resistance exercise model as study two, the main objectives of study three (Chapter 4) were to:

1) Determine if there are sex-differences in relative muscle hypertrophy following 8-weeks of unilateral TRD-RE or EQI-RE.
2) Determine if there are sex-differences in relative strength following 8-weeks of unilateral TRD-RE or EQI-RE.

Given that the majority of our rational for sex-differences in relative muscle hypertrophy and strength adaptations to TRD-RE and EQI-RE was based on differences in resistance exercise volume between males and females, we also explored:

3) Whether any relationship between resistance exercise volume and hypertrophy was moderated by sex.
4) Whether any relationship between resistance exercise volume and strength was moderated by sex.

Chapter 2: Exploring the Acute Muscle Fatigue Response in Resistance Trained Individuals During Eccentric Quasi-Isometric Elbow Flexions—a Cross-Sectional Comparison of "Set" and Sex

Author Note and Contributions

Data and text from the following chapter appears in:

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Zachariah J. Henderson conceptualised, designed, piloted methods, collected data, analysed data, interpreted data, and drafted the published manuscript.

Abstract

Eccentric quasi-isometrics (EQIs) are a novel, low-velocity resistance exercise technique that incorporates a holding isometric contraction to positional fatigue, followed by voluntary resistance of the resulting eccentric muscle action. As females are typically more fatigue resistant than males during isometric and low-velocity dynamic muscle actions, this study explored sex-differences in the muscle fatigue response to an EQI protocol. Twenty-five (n = 12 female) participants completed 4 unilateral EQI elbow flexions. Absolute and relative surface electromyography (sEMG) amplitude (iEMG, LE peak), mean power frequency (MPF), angular impulse (aIMP), and elbow angle were compared across sets and between sexes using discrete values and statistical parametric/non-parametric mapping. There were significant and substantial sex and set differences in absolute iEMG, MPF, and aIMP, however, aIMP in males and females was not statistically different by set 4. When expressed relatively, there were no significant sex-differences. Additionally, there were significant between set changes in sEMG amplitude and elbow angle with an increasing number of sets, largely in the first-two thirds of set time. The current study suggests that there are absolute, but not relative sex-differences in EQI induced muscle fatigue, and the effects across sets occur predominately in the first two- thirds of set time.

Key words: Statistical parametric mapping, SPM, time under tension, surface electromyography, kinematics

Introduction

Eccentric quasi-isometrics (EQIs), or EQI-resistance exercise (EQI-RE) is a novel form of resistance exercise, incorporating both isometric and eccentric muscle actions (Oranchuk et al., 2019b, 2020, 2021). To perform an EQI, a holding isometric muscle action (Schaefer & Bittmann, 2017) is initiated and sustained for as long as possible; eventually, the accumulation of fatigue results in isometric failure and the inability to maintain joint position (Oranchuk et al., 2020, 2021). A low-velocity, involuntary eccentric muscle action then ensues, which is voluntarily resisted through the full and/or desired range of motion (ROM; Oranchuk et al., 2019; Verkhoshansky & Siff, 2009). In a theoretical review, Oranchuk et al., (2019) suggested that large amounts of mechanical tension, and time under tension would be produced during EQI-RE relative to traditional resistance exercise practices, thus increasing training volume and promoting morphological musculotendinous adaptations (e.g., greater muscle thickness, fascicle length, tendon stiffness) through mechanotransduction. As such, it has been theorised (Oranchuk et al., 2019b) that EQI-RE may be useful for stimulating muscle morphological changes when stress to the joint or high velocity muscle actions are not tolerated (i.e., injury), desirable (e.g., low load/volume macrocycles), and where EQI-RE may simulate sport specific requirements (i.e., grappling, speed skating, sailing).

The potential for greater time under tension relative to traditional isotonic resistance exercise underlies many of the proposed adaptations to EQI-RE, although practitioners have also suggested the EQI concept results in substantial motor unit recruitment relevant to other resistance exercise modalities (N. Morrison, 2016; Seedman, n.d.-a; Sinicki, 2019). Indeed, greater exercise volume, associated time under tension, and motor unit recruitment are suggested factors in the muscle hypertrophic response (Schoenfeld, 2010, 2013; Schoenfeld, Ogborn, et al.,

2017). Both of these factors, however, will be influenced by the development and time-course of muscle fatigue. During traditional isotonic resistance exercise, time under tension and therefore training volume will significantly decrease with subsequent sets (Paz et al., 2017), while electromyography amplitude—long considered a broad representation of motor unit recruitment—will generally increase across repetitions and time (Bazzucchi et al., 2004b; Kamen & Gabriel, 2010b; Paz et al., 2017; Staudenmann et al., 2014b). Relevant to these factors, females are generally more fatigue resistant than males, although differences are task, muscle, and intensity specific (Hunter, 2014, 2016b, 2016a), and may be influenced by modifiable factors extrinsic to sex (e.g., strength; Hunter, 2016b; Hunter et al., 2004b, 2004a; Hunter & Enoka, 2001; Nimphius, 2019). While theoretically promising, studies of EQI-RE to date (Oranchuk et al., 2020, 2021) have been limited to male participants, an acute knee extension model, and have yet to use electromyography to explore the myoelectrical manifestation of muscle fatigue during EQI-RE.

Given the potential role that exercise volume, mechanical tension, and motor unit behaviour have on muscle hypertrophy and strength outcomes (Lim et al., 2022; Schoenfeld, Ogborn, et al., 2017), it seems plausible that potential sex-differences could result in differing long-term strength, neurological and morphological adaptations to EQI-RE. To support this hypothesis, however, it is first necessary to establish whether sex-differences exist in the muscle fatigue response during an acute bout of EQI-RE, and whether potential differences may be related to factors intrinsic or extrinsic of sex. Therefore, the purpose of the current study was to define the absolute and relative fatigue response of the biceps brachii during 4 sets of EQI-RE elbow flexion and compare this response between resistance trained males and females. Surface electromyography (sEMG) and isokinetic dynamometry were used to quantify changes in muscle

excitation (e.g., peak and integrated sEMG amplitude), kinematics (e.g., elbow angle), and kinetics (e.g. torque/angular impulse) across sets, and between males and females. Specifically, absolute values were used to compare innate sex-differences, while relative values (i.e., normalised) were compared to reduce the influence of modifiable factors extrinsic of sex (e.g., strength, body composition). Further, exploratory analysis using statistical parametric (SPM) and non-parametric (SnPM) mapping was performed to see if the time-course of sEMG amplitude and elbow angle changes differ between sexes within each EQI-RE set, and across sets regardless of sex.

For the primary analysis, the null hypothesis (H0) was that there would be no differences between set, sex, or interaction of set and sex on any of the dependent variables. Based on consistent observations of lower mean power frequency, sEMG, and torque amplitude in females (Farina et al., 2004; Freilich et al., 1995; Kotte et al., 2018) the primary alternative hypothesis (H1) was that females would have lower absolute sEMG values and angular impulse (aIMP) than males for all EQI sets. It was expected, however, that females would have larger relative integrated sEMG (iEMG) and aIMP values than males due to greater fatigue resistance (Avin et al., 2010), while absolute and relative iEMG and aIMP would decrease across all sets regardless of sex.

Methods

Experimental Overview

Participants reported to a temperature-controlled lab (20 °C) at the same time of day (± 2-hours) for one familiarisation (~1.5-hours), and one experimental session (~3-hours), with at least 1-week between sessions. As is typically recommended to reduce learning effects (Biodex

Medical Systems, 2014), the familiarisation session was used to let participants practice the protocol and allow the researchers to provide detailed instruction and feedback. For the experimental session, a cross-sectional, between-subjects design was used to compare the onset of muscle fatigue between males and females, and across 4 sets of unilateral EQI-RE elbow flexion at 50% of maximum voluntary isometric torque (MVIT; Figure 1). sEMG of the biceps brachii and isokinetic dynamometry data were collected for all sets during the experimental session (Figure 2). Data were collected from August 2021 until December 2022 and represent part of a larger project.

Participants

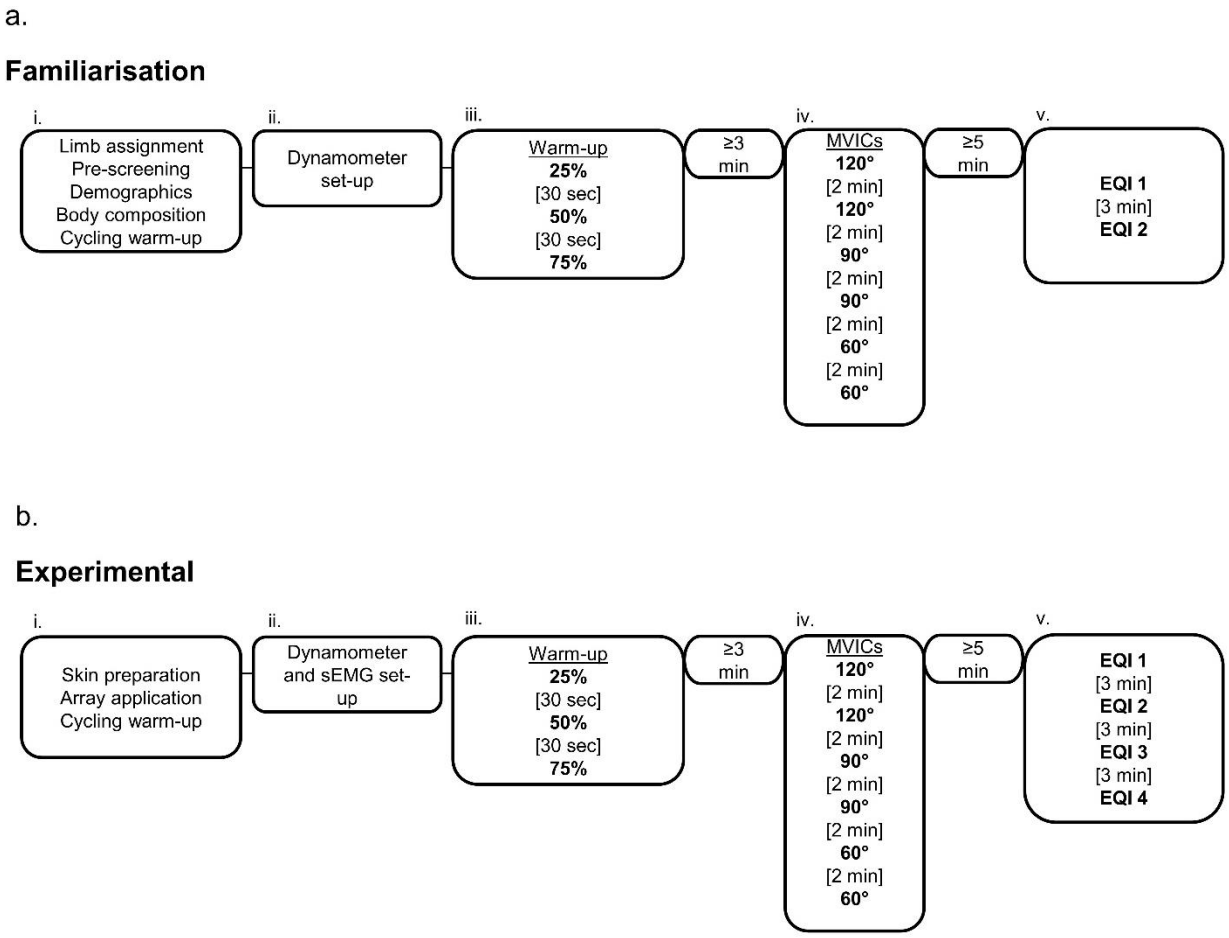
As an exploratory study, and to our knowledge the first study to investigate EQI-RE between males and females and in the upper extremity, a-priori sample size was informed by previous research, power calculations, and feasibility. Using a similar research design for a sample of 14 resistance trained males, Oranchuk et al. (2021) observed a medium-large effect size ($\omega 2 = 0.11$) for total angular impulse across 4 sets of EQI knee extension. However, given large (> 20%) sex-differences in fatiguability during isometric tasks using similar contraction intensities of the proposed study (Hunter, 2014) we elected to calculate power for a large effect size. Our a-priori power calculations (G*Power V. 3.1.9.2) for a 2(between factor; sex)*4(within factor; set) mixed factorial ANOVA indicated a sample of 30 participants were required to detect a significant ($p < .05$) sex*set interaction and large effect size ($\eta_p^2 = .14$) for aIMP, with an achieved power of 0.80 (1-β error probability) and non-sphericity correction of 0.80.

All participants were recruited from the University community via convenience sampling and the study protocol (HS24806) was approved by the University of Manitoba Research Ethics

Board (REB 1). Written and verbal informed consent was obtained from all participants before participating in the study. Potential participants were eligible if they were: 1) 18–35 years of age, and 2) considered themselves resistance trained, which was defined as a minimum of 6 exercises (regardless of muscle group), 2x per week, for 6 months. Potential participants were excluded if they answered ‘yes’ to any questions on the Get-Active Questionnaire (Canadian Society for Exercise Physiology, 2017), or experienced an acute musculoskeletal injury in the last 6-months that affected their ability to perform upper-body resistance exercise. Before each session, participants were asked to refrain from upper-body resistance exercise, alcohol and cannabis, general exercise, caffeine and a large meal for 48-hours, 24-hours, 12-hours, and 3-hours, respectively.

Figure 1

Protocol Timeline



Note. Participants completed one familiarisation session (a) and one experimental session (b). Participants were introduced to all contraction types during the familiarisation session. (a. i.) Pre-screening of participants, collection of demographic and anthropometric information, general warm-up. (a. ii.) Determination of dynamometer positioning. (a. iii.) introduction to 90° warm-up contractions. (a. iv.) Introduction to maximum voluntary isometric contractions (MVICs). (a.v.) Exposure to at least two eccentric quasi-isometrics (EQI). (b. i.) Preparation of electrode array site and general warm-up. (b. ii.) Isokinetic dynamometer and sEMG set-up. (b. iii.) 90° warm-up contractions. (b. iv.) MVICs at 120°, 90°, and 60°. (b. v.) 4 EQI elbow flexion sets to volitional fatigue.

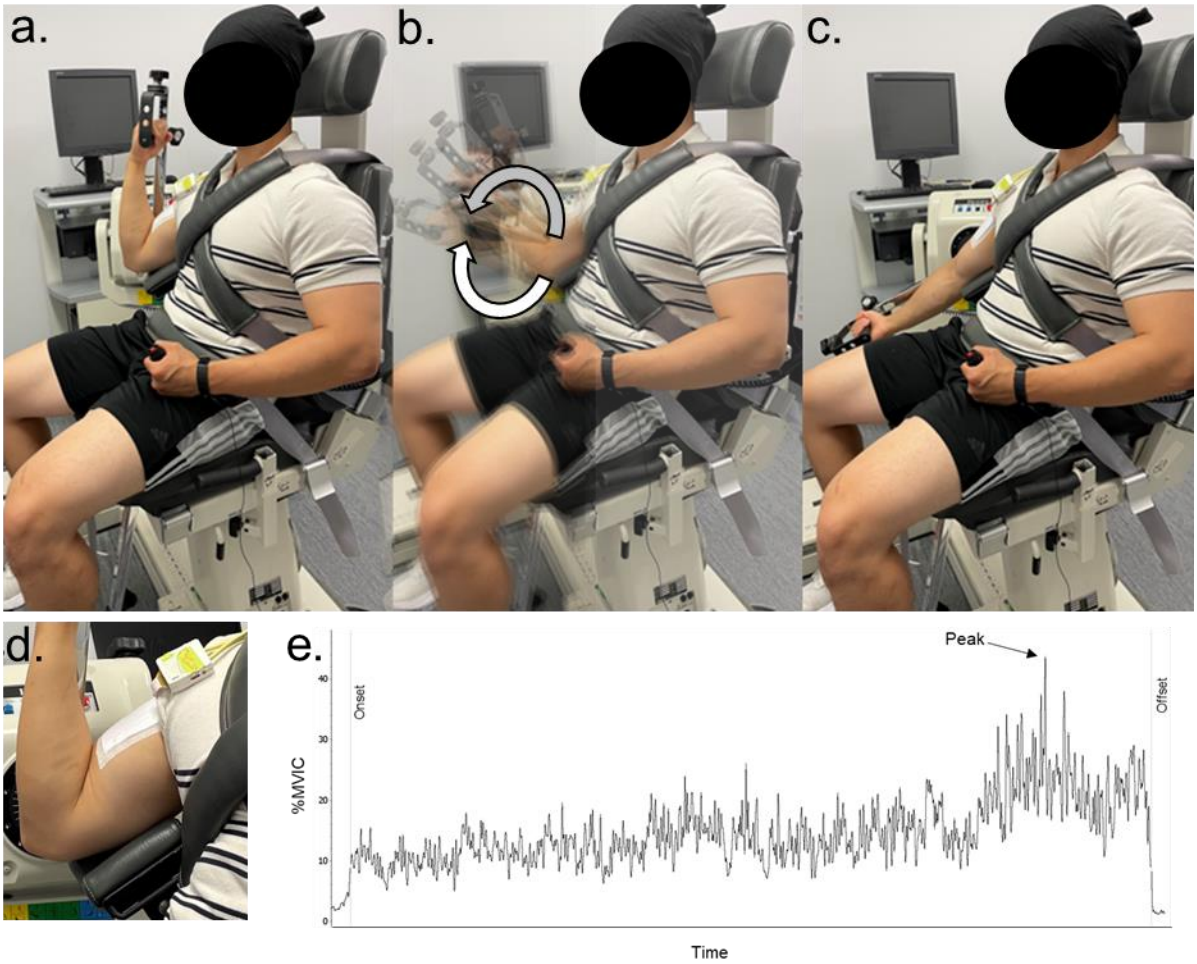
Familiarisation Session

Prior to participating in any physical components of the study, participants had their blood pressure measured with an automatic blood pressure monitor and cuff (BP761CAN and HEM RML31, OMRON Healthcare Co., Ltd, Lake Forest, IL, USA), and body composition assessed via bio-electrical impedance (InBody270; InBody Co. Seoul, South Korea) according to manufacturer recommendations. To increase core body temperature, participants then performed a 5-minute general warm-up on a stationary bike (UBK 835, Precor, Woodinville, WA, USA), at a self-selected "moderate" intensity (Oranchuk et al., 2020).

Isokinetic Dynamometry. Participants were pseudo-randomised to complete the protocol with either the dominant or non-dominant limb, based on the Edinburgh Handedness Inventory (Oldfield, 1971). In cases where participants were classified as ambidextrous, the side that they skewed towards was considered the dominant limb. One participant scored '0', and thus a coin was flipped to assign limb dominance. Participants were then set-up in an isokinetic dynamometer (Biodex Multi-Joint System Pro; Biodex Medical Systems, Inc., Shirley, New York, USA) for unilateral elbow flexion/extension of the assigned limb. Participants were seated up-right with the backrest at 85°, dynamometer arm rotated laterally 30°, and the arm supported at ~45° to the shoulder. The handle of the dynamometer was positioned horizontally such that the forearm was supinated. In this position, participants were tightly secured to the dynamometer with 2 straps across the torso, and 1 strap across the lap. Flexion/extension ROM was set anatomically at 130° (0° = full extension, 130° =full flexion). Due to attachment limitations, some participant's arm position was > 45° relative to the shoulder, although anatomical and elbow ROM remained fixed. Positions for all adjustable dynamometer components and attachments were recorded for the subsequent session.

Figure 2

Dynamometer and sEMG Set-up



Note. Participants were positioned in the isokinetic dynamometer for unilateral elbow flexion/extension, and tightly secured with straps across the lap and torso. A rectangular electrode array was affixed over the skin of the biceps brachii, while ground straps were placed on the contralateral wrist and ankle (not pictured). (a) EQI start position (130°). (b) Participants voluntarily resisted the applied torque (50% MVIT) through the full range of motion and positional failure. (c) EQI end position (0°). (d) Positioning of electrode array over biceps brachii. (e) Example linear envelope trace from EQI 1. Grey circular arrow represents direction of dynamometer torque, white circular arrow represents direction of participant resistance.

Maximum Voluntary Isometric Contractions. Once set-up in the dynamometer, participants completed a subjective warm-up involving single 5-second isometric muscle actions at 25%, 50% and 75% of their perceived maximum voluntary isometric torque (MVIT; Oranchuk et al., 2020, 2021). These warm-up sets were spaced 30-seconds apart and performed at 90° of

elbow flexion. After 3-minutes of rest, participants completed two, 5-second maximum voluntary isometric "contractions" (MVICs) at 120°, followed by two MVICs at 90° and 60° of elbow flexion, respectively. Each MVIC was followed by 2-minutes of rest, and the 120° and 60° MVICs were included as part of another study. During all MVICs, participants were given real time visual feedback of their torque output, and participants were given strong verbal encouragement to push the visual feedback bar 'as high as you can.' For MVICs, participants were also instructed to a) contract as 'hard and fast' as possible (Maffiuletti et al., 2016) without pushing into the footrest, b) to keep the non-involved hand in their lap, and c) be as relaxed as possible prior to each MVIC. Participants were presented with a countdown timer for rest and each MVIC.

Eccentric Quasi-Isometric Contractions. Following completion of all MVICs, participants were given 5-minutes rest. Using their estimated 50% MVIT at 90° of elbow flexion, participants completed 2 EQI elbow flexion sets to familiarise themselves with the EQI protocol. For EQI sets, the dynamometer was set to isotonic mode (Oranchuk et al., 2020, 2021) with the lever arm ROM anatomically set at 130°. Applied torque was set at 50% of participant's MVIT, according to the highest torque value obtained during the 90° MVICs. Based on pilot testing, 50% MVIT was selected so that participants would have an extended period of 0 movement velocity (i.e., isometric muscle action), interspaced with periods of higher velocities (i.e., eccentric muscle action; (Oranchuk et al., 2020)). As the applied torque of the dynamometer was limited to intervals of 2–5 Nm, applied torque values were rounded up to the closest interval available in the dynamometer software (Biodex Advantage Software V.4; Biodex Medical Systems, Inc., Shirley, New York, USA). Actual torque values during each EQI as a percentage of the MVIT (%MVIT) at 90° are presented in Table 1.

Table 1

Experimental Session MVIC and EQI Protocol Characteristics

	Mean ± SD		**Range**		**Mean Difference**
Sex (13 M, 12 F)	M	F	M	F	M - F
MVIT (Nm)	81.3 (17.2)	38.3 (8.3)	58.7-107.0	22.8-50.5	43*
Load (Nm)	42.2 (8.2)	20.5 (4.3)	31.7-55.3	13.4-26.5	21.6*
Velocity (°/s)	3.81 (3.1)	2.79 (2.0)	1.02-13.5	0.9-6.7	1.0
TUT EQI 1 (sec)	54.7 (23.7)	64.6 (34.6)	13.5-93.1	16.9-128.3	-9.9
TUT EQI 2 (sec)	40.8 (14.1)	51.4 (28.5)	8.8-57.66	19.1-98.7	-10.6
TUT EQI 3 (sec)	33.6 (11.8)	44.3 (19.8)	7.4-47.5	20.2-76.5	-10.7
TUT EQI 4 (sec)	29.3 (11.9)	40.4 (21.5)	8.2-47.9	10.2-82.9	-11.1

Note. MVIT = maximum voluntary isometric torque during the 90° MVICs. Load = absolute eccentric load during EQI sets. TUT = time under tension. Load and velocity data are the average of all 4 EQI sets. * Significant ($p <$ .001) difference between males and females (independent t-tests).

To start the protocol, participants slowly brought the dynamometer arm to full elbow flexion. In this position (Figure 2a), participants were given a countdown of '3-2-1-go!'. On 'go', participants were instructed to slowly apply force to the handle, which resulted in the dynamometer applying eccentric torque. Rather than allowing a controlled eccentric muscle action, participants were instructed to brace and to resist the applied torque, with the goal of maintaining joint position, but not causing a concentric muscle action (Oranchuk et al., 2020, 2021). Visual feedback of the real-time torque was provided to assist participants (OT Biolab V. 1.2, OT Bioelettronica, Torino, Italy). As participants fatigued and reached isometric/positional failure, they resisted the resulting eccentric muscle action (Figure 2b) until the dynamometer arm reached full extension (Figure 2c; (Oranchuk et al., 2020, 2021). Participants were then given 3-minutes rest, before completing one or two more sets, depending on their subjective comfort with

the protocol and their ability to perform the protocol correctly. Following completion of the EQI sets and as part of another study, participants then completed MVICs and eccentric muscle actions with the contralateral limb.

Experimental Session

The experimental session mirrored the familiarisation session, however, participants performed 4 EQI-RE elbow flexion sets (Oranchuk et al., 2020, 2021) while sEMG data were collected over the skin of the biceps brachii of the involved limb. Prior to performing the general warm-up, participant's skin was prepared for sEMG by shaving (if necessary), lightly abrading (Nuprep, Weaver and Company, Aurora, Colorado, USA), and wiping clean with water (Lulic-Kuryllo, Negro, et al., 2021; Piervirgili et al., 2014). A 2-dimensional, rectangular array of 32-electrodes (8-rows x 4-columns; GR10MM0804; 10 mm interelectrode distance, gold coated; OT Bioelettronica, Torino, Italy) and foam pad (KIT10MM0804; OT Bioelettronica, Torino, Italy) filled with conductive paste (AC Cream, Spes Medica, Genova, Italy) was applied and affixed with tape (Hypafix; BSN Medical, Hamburg, Germany) to the muscle belly of the biceps brachii, such that the 4 electrode columns were parallel to the muscle fibre orientation (Figure 2(d)). Specific placement was just proximal of 62% (measured proximal to distal) on an imaginary line from the acromion process to the distal biceps brachii tendon insertion (Barbero et al., 2012). Additionally, the electrode array was oriented so that the distal biceps tendon (palpated and marked) formed a line bisecting the array vertically. A damp ground strap was placed on the contralateral arm, and, to further reduce common-mode interference, a driven right leg circuit was implemented using straps attached to participants' contralateral ankle (OT Bioelettronica, 2021).

Data Collection and Processing

All electronics were turned on 1-hour prior to calibration. Dynamometer position and torque were calibrated daily with a level and torque verification fixture (67.8 Nm ± 0.68 Nm) as per manufacturer instructions (Biodex Medical Systems, Inc, 2014). A 400-channel bioelectrical signal amplifier (Quattrocento; OT Bioelettronica, Torino, Italy; ± 5 V total input range, common-mode rejection ratio >95 dB, 150 V/V fixed-gain, 16-bit analogue to digital converter) was used to collect analogue data (V; volts) at 2048 Hz. Raw sEMG data were acquired in differential configuration (within columns, proximal to distal) via an AD32 electrode adapter (OT Bioelettronica, Torino, Italy), using a hardware bandpass filter of 10-500 Hz (II order Butterworth, -3 dB bandwidth). Full-scale analogue dynamometer data (kinematic and kinetic) were synchronously fed to the Quattrocento auxiliary input interface (fixed gain 0.5 V/V) without filtering (rated noise 15-35 mV). All analogue data were collected, visualised, and recorded using OT BioLab+ (V 1.2) software, and saved to a secure personal computer (Latitude 5500, Dell, Inc., Round Rock, Texas, U.S.).

Preliminary data processing and visualisation were performed in OT BioLab+ (V.1.5). sEMG data were first visually inspected for any movement artefact, excessive signal noise, saturation, and poor electrode-skin contact. After visual inspection, and to mimic a traditional bipolar approach, the differential waveform from the most distal electrodes in the centre-lateral column, along with raw kinematic and kinetic data were exported as a .csv file and imported into Labchart 8 (ADInstruments Inc., Colorado Springs, USA) for further analysis. Similarly, the corresponding differential signal from a 10-second sEMG baseline (quiet sitting) was exported for the purposes of calculating the signal-to-noise ratio (SNR).

In LabChart 8, custom macros were used to perform additional bandpass filtering of the sEMG waveform (20–500 Hz, zero-phase-lag Finite Impulse Response [FIR]). MPF was calculated based on a 1024-point Fast Fourier Transform (cosine-bell) and 50% overlap. For all sEMG amplitude measures, the sEMG waveform was full-wave rectified and lowpass filtered at 8 Hz (zero-phase-lag FIR) to create a linear envelope, with the lowpass cut-off based on recommendations by Winter (2005). Initial raw values recorded during calibration and two-point conversion were then used to remove baseline noise and convert unfiltered analogue kinematic data to their respective units. For torque data, each 0.0072 V was equivalent to 1 Nm (Biodex Medical Systems, 2011). For velocity data, each 0.0098 V was equivalent to 1 deg/s (Biodex Medical Systems, 2011). For position, the minimum raw data value was equal to anatomical 0° (full elbow extension), and each 0.0287 V was equivalent to 1° of elbow flexion thereafter (Biodex Medical Systems, 2011). To express variables relatively, the filtered sEMG linear envelope and torque-time trace were normalised to the linear envelope peak (%MVIC) and MVIT (%MVIT) from the 90° MVICs, respectively.

Data Extraction and Normalisation. The start of each EQI set was determined using the peak linear envelope value obtained during EQI set 1 (EQI 1). With no direct studies for reference, a 20% sEMG amplitude threshold, confirmed with visual inspection (Figure 2(e); (Kamen & Gabriel, 2010b), was used to define the start and end of each set. The absolute sEMG linear envelope peak (LE PeakABS), relative sEMG linear envelope peak (LE Peak%MVIC), absolute integrated sEMG linear envelope (iEMGabs; V/s), relative integrated sEMG linear envelope (iEMG%MVIC; %MVIC/s), bandpass filtered sEMG mean power frequency (MPF; Hz), absolute angular impulse (aIMPabs; V/s), relative angular impulse (aIMP%MVIT; MVIT/s), time under tension (s), and angular velocity (°/s) were then extracted for all EQI sets.

Both iEMG and aIMP variables were integrated using the rectangular rule. For the purposes of SPM, the normalised LE and absolute elbow angle traces were linearly interpolated in Labchart 8 to 100 data points (0–100% set time) using node-based sampling, and iteratively smoothed with a 5-sample width Gaussian filter (Matlab R2021a; The MathWorks Inc., Natick, MA, USA) to produce LE-time and elbow angle-time continua.

General Statistical Procedures

All traditional frequentist statistical analysis were conducted in open-source Jamovi software (v 2.3.21), while all one-dimensional statistical parametric mapping (SPM; Penny et al., 2007) and subsequent statistical procedures were completed within the open-source package (SPM1D v. 0.4; http://www.spm1d.org) for Matlab (R2021a; Matlab R2021a; The MathWorks Inc., Natick, MA, USA)

Primary Analysis (Discrete Fatigue Response). To determine if there were sex-differences in absolute and relative sEMG and angular impulse variables, multiple 2(sex)*4(set) mixed-factorial ANOVAs with repeated measures on set were conducted. Additionally, two-sample t-tests were used to compare sex-differences in descriptive variables (Table 1). For all ANOVAs, normality, homogeneity of variances, and sphericity were assessed with Shapiro-Wilk's, Levene's and Mauchly's tests, using an alpha of $p < .05$ (Field, 2009; Levene, 1960), respectively. In cases where sphericity was violated, Greenhouse-Geisser corrected values were interpreted (Greenhouse & Geisser, 1959). Outliers were defined as data points outside 1.5× the interquartile range.

Due to participant drop-out, a compromise power analysis (G*Power V. 3.1.9.2), which computes α and power based on effect size, sample size, and β/α error probability ratio (Faul et

al., 2007) was calculated. Assuming a $\beta/\alpha = 1$ and a non-sphericity correction of 0.8, a power of 86.7% (1- β error probability) was achieved for a large effect size ($\eta_p^2 = 0.14$) when $\alpha = .132$ for a 2(sex)*4(set) interaction. As such, ANOVAs were considered significant at $p \leq .132$, with small, medium, and large effect sizes (η_p^2) considered to be .01, .06, and .14, respectively. Significant ANOVAs were followed up with post-hoc pairwise comparisons using conventional Bonferroni corrected p-values (.132/6 tests = .022; (Field, 2009)). For post-hoc pairwise comparisons, confidence intervals (CI) for the mean differences and the effect sizes (Cohen's d; d) are reported in text for independent and paired-sample t-tests. Due to the exploratory nature of the work and lack of comparable studies, 99% CIs are presented. Cohen's d values of 0.2, 0.5, and 0.8, were used to define small, medium, and large effect sizes, respectively (Cohen, 1988) Variability was expressed as ± standard deviation, unless otherwise indicated.

Secondary Analysis (Timing of Fatigue Response). One-dimensional SPM (Pataky, 2012) and SnPM (Nichols & Holmes, 2001; Trama et al., 2021) were used to quantify regional specific effects between males and females within LE-time and angle-time continua (i.e., data plotted over time). One-dimensional SPM is a methodology that allows for statistical inferences to be made regarding the spatiotemporal characteristics of data, while minimising the post-hoc regional focus bias and increased family wise error rate otherwise associated with conducting repeated statistical tests (Pataky, 2012; Pataky et al., 2013). Briefly, one-dimensional SPM calculates a test-statistic (e.g., *t*) at each data point (i.e., time), which forms a test-statistic continuum SPM{t}. For parametric statistical inference, a random field theory (RFT; Adler & Taylor, 2007) based t-distribution is used to calculate the critical threshold (t*) for the continua at a given α (Pataky, 2012; Pataky et al., 2015; Robinson et al., 2015). Traditional parametric statistical inference is then used to determine the probability (p) that the SPM{t} would cross t*

and produce a supra threshold region as wide as that which might be observed in an equally smoothed residual (random) continua (Pataky, 2012). For non-parametric statistical inference, permutations, rather than RFT, are used to create a test statistic distribution (Holmes et al., 1996; Nichols & Holmes, 2001; Trama et al., 2021). Both parametric and non-parametric inferences from SPM have been validated for 1D kinematic and EMG data (Pataky, 2012; Pataky et al., 2019; Penny et al., 2007; Robinson et al., 2015). Due to separate smoothness assessments, however, current post-hoc procedures in SPM1D are not considered to be valid, although potential error is likely to be small (http://www.spm1d.org).

As post-hoc procedures in SPM1D have not been shown to be valid, multiple t-tests (between-subjects, two-tailed) were conducted within each EQI set to compare LE-time and angle-time continua between males and females. The critical threshold for all tests was determined for a Bonferroni corrected *p*-value of .008 (.05/6 tests). The null hypothesis was rejected if the SPM{t} value crossed the critical threshold at any point, and *p*-values for supra-threshold clusters were calculated and interpreted as described above. Furthermore, as SPM uses frequentist statistics, the traditional assumptions of parametric statistical inference applied. The assumption of normality was tested within SPM1D using the D'agostino-Pearson K2 test (D'agostino & Belanger, 1990). Given the unequal group sizes, lack of explicit equality of variance test within SPM1D, and exploratory nature of the work, non-parametric inference (two-tailed, 1000 iterations) was also conducted using procedures based on Nichols and Holmes (2001), and compared with parametric results. As such, any non-normally distributed data was left in the analysis. As a follow-up analysis, data were then collapsed between sexes and compared set-by-set (paired-samples; two-tailed) as per Oranchuk et al. (2021).

Results

Descriptive Characteristics

In total, 32 participants were recruited to the study; one participant was screened out of the study based on their Get-Active Questionnaire responses, while 5 did not complete the protocol due to reasons unrelated to the study. As such, 26 participants completed the study. Due to technical difficulties, one male participant's data was completely excluded, and for two participants (once for aIMP, once for sEMG), data from a single EQI set was replaced with the average of the two sets performed immediately before and immediately after the replaced set. For set-by-set SPM and SnPM analysis, these participants were removed from all comparisons. Subsequently, 13 males (sex assigned at birth; age: 25.1 ± 4.2 years, height 178.2 ± 6.6 cm, weight 83 ± 12.5 kg, skeletal muscle mass: 39.5 ± 5.1 kg, %body fat 16.8 ± 6%) and 12 females (sex assigned at birth; age: 24.7 ± 3.6 years, height 165.3 ± 6.2 cm, weight 66.4 ± 8.9 kg, skeletal muscle mass: 27.5 ± 2.9 kg, %body fat 25.1 ± 4.9%) were included in the statistical analysis. Absolute kinetic and kinematic characteristics of the EQI protocol, and between sex differences are presented in Table 1. sEMG SNR (20log; Delsys, 2020) for each participant ranged from 1.25–2.17.

As expected, male participants displayed greater absolute strength (MVIT) than female participants (81.3 vs. 38.3 Nm), $t(23) = 7.87$, $p < .001$, d = 3.15, 99% CI : 27.67 to 58.33. As a result, males performed the EQI-RE with a greater (42.2 vs. 20.5 Nm) absolute load. On average, EQIs were performed with a relative load of 52.1 ± 1.88 %MVIT for males, and 53.8 ± 2.12 %MVIT for females, which represents a small, but statistically significant difference between groups, $t(23) = -2.15$, $p = .042$, d = -0.86, 99% CI: -3.96 to 0.53 at $\alpha = .05$.

ANOVAS

There was a significant main effect of sex ($p < .001$ to $p = .015$) for all absolute variables (LE Peakabs, MPF, iEMGabs, aIMPabs) with large effect sizes ($\eta_p^2 = .23$ to.41). However, there was no main effect of sex for any relative variables (LE Peak%MVIC, iEMG%MVIC, and aIMP%MVIT). There was also a significant ($p < .132$) main effect of set ($p < .001$) for MPF, iEMGabs, aIMPabs, iEMG%MVIC, and aIMP%MVIT with large effect sizes (η_p^2 .32 to .58). Furthermore, there was a significant ($p < .132$) set*sex interaction effect ($p = .015$) for aIMPabs with a large effect size ($\eta_p^2 = 0.15$). Two-way ANOVA results are presented in Table 3.

Table 2

Two-way Mixed ANOVA Results for Absolute and Relative EMG and Kinetic Variables

Dependent Variable	Comparison	df	*F*	*p*	η_p^2
LE PeakABS[#]	Set	2.28, 52.34	0.58	.586	.02
	Sex	**1, 23**	**15.82**	**< .001**	**.41**
	Set ✻ Sex	2.28, 52.34	0.29	.775	.01
MPF	**Set**	**3, 69**	**11.71**	**< .001**	**.34**
	Sex	**1, 23**	**11.73**	**.002**	**.34**
	Set ✻ Sex	3, 69	0.93	.429	.04
iEMGabs[#]	**Set**	**1.82, 41.93**	**10.86**	**< .001**	**.32**
	Sex	**1, 23**	**6.86**	**.015**	**.23**
	Set ✻ Sex	1.82, 41.93	1.57	.221	.06
aIMPabs[#]	**Set**	**1.42, 32.74**	**28.34**	**< .001**	**.55**
	Sex	**1, 23**	**8.21**	**.009**	**.26**
	Set ✻ Sex	**1.42, 32.74**	**4.16**	**.037**	**.15**
LE Peak%MVIC	Set	3, 69	0.38	.7695	.02
	Sex	1, 23	0	.9612	0
	Set ✻ Sex	3, 69	0.15	.9281	.01
iEMG%MVIC[#]	**Set**	**1.84, 42.28**	**10.92**	**< .001**	**.32**
	Sex	1, 23	0.11	.738	0
	Set ✻ Sex	1.84, 42.28	0.12	.8673	.01
aIMP%MVIT[#]	**Set**	**1.51, 34.66**	**31.38**	**< .001**	**.58**
	Sex	1, 23	2.1	.161	.08
	Set ✻ Sex	1.51, 34.66	0.01	.9734	0

Note. LE PeakABS = absolute linear envelope peak. MPF = mean power frequency. iEMGabs = absolute integrated surface EMG., aIMPabs = absolute angular impulse. LE Peak%MVIC = relative linear envelope peak. iEMG%MVIC = relative integrated surface EMG., aIMP%MVIT = relative angular impulse. df = degrees of freedom. η_p^2 = partial eta squared. Significant *p*-values ($p < .132$) are bolded. [#] = assumption of sphericity not met, and Greenhouse-Geisser degrees of freedom reported.

Post-Hoc Comparisons.

Absolute Variables. Mean differences, effect sizes, and 99% confidence intervals are presented in Table 3. Mean group differences ± standard error (SE) of the differences are reported in text where appropriate.

Table 3

Significant Pairwise Comparisons of Set Main Effect

Dependent Variable	Comparison	Mean Difference (± SE)	Mean Difference 99% CI	*p*	Cohen's d	Effect Size 99% CI
MPF	EQI 1 vs. EQI 2	-4.96 (1.27)	-8.51 to -1.41	< .001	-0.78	-1.37 to -0.19
	EQI 1 vs. EQI 3	-6.75 (1.79)	-11.77 to -1.73	.001	-0.75	-1.33 to -0.16
	EQI 1 vs. EQI 4	-8.13 (1.74)	-13 to -3.26	< .001	-0.93	-1.55 to -0.31
	EQI 2 vs. EQI 4	-3.17 (1.19)	-6.49 to 0.15	.013	-0.53	-1.08 to 0.02
iEMGabs	EQI 1 vs. EQI 2	2.26 (0.83)	-0.06 to 4.58	.012	0.55	-0.01 to 1.09
	EQI 1 vs. EQI 3	3.6 (0.96)	0.9 to 6.291	.001	0.75	0.16 to 1.33
	EQI 1 vs. EQI 4	4.2 (1.1)	1.13 to 7.26	< .001	0.77	0.17 to 1.35
	EQI 2 vs. EQI 4	1.94 (0.63)	0.16 to 3.71	.006	0.61	0.04 to 1.17
iEMG%MVIC	EQI 1 vs. EQI 2	298.66 (98.34)	23.6 to 573.71	.006	0.61	0.04 to 1.17
	EQI 1 vs. EQI 3	480.75 (118.24)	150.03 to 811.46	< .001	0.81	0.21 to 1.41
	EQI 1 vs. EQI 4	590.29 (151.59)	166.3 to 1014.28	< .001	0.78	0.18 to 1.36
	EQI 2 vs. EQI 4	291.64 (107.09)	-7.9 to 591.17	.012	0.54	-0.01 to 1.09
aIMP%MVIT	EQI 1 vs. EQI 2	736.97 (136.61)	354.87 to 1119.06	< .001	1.08	0.42 to 1.73
	EQI 1 vs. EQI 3	1120.1 (186.17)	599.38 to 1640.81	< .001	1.2	0.52 to 1.88
	EQI 1 vs. EQI 4	1353.16 (203.55)	783.84 to 1922.48	< .001	1.33	0.62 to 2.04
	EQI 2 vs. EQI 3	383.13 (117.26)	55.16 to 711.11	.003	0.65	0.08 to 1.22
	EQI 2 vs. EQI 4	616.19 (132.00)	246.98 to 985.4	< .001	0.93	0.31 to 1.55
	EQI 3 vs. EQI 4	233.06 (51.06)	90.25 to 375.87	< .001	0.91	0.29 to 1.52

Note. MPF = mean power frequency. iEMGabs = Absolute integrated surface EMG. iEMG%MVIC = Absolute integrated surface EMG. aIMP%MVIT = Relative angular impulse. Significance based on Bonferroni corrected α of .018.

Across sets, LE PeakABS was 0.43 ± 0.11 V (99% CI: 0.13 to 0.73; ES = 1.59, 99% CI: 0.26 to 2.91) higher in males compared to females; however, there was no main effect of set or interaction effect ($p > .132$; Figure 3(a)).

With medium-large effect sizes, MPF during EQI 1 was significantly less than MPF during EQI 2 ($p < .001$, d = -0.78), EQI 3 ($p = .001$, d = -0.75), and EQI 4 ($p < .001$, d = -1.55). Additionally, during EQI 2, MPF was significantly less than EQI 4 ($p = .013$, d = -0.53). Across all sets, MPF for males was 26.78 ± 7.82 Hz (99% CI: 4.83 to 48.73, $p = .002$; d = 1.37, 99% CI: 0.11 to 2.61) higher than females (Figure 3(b)).

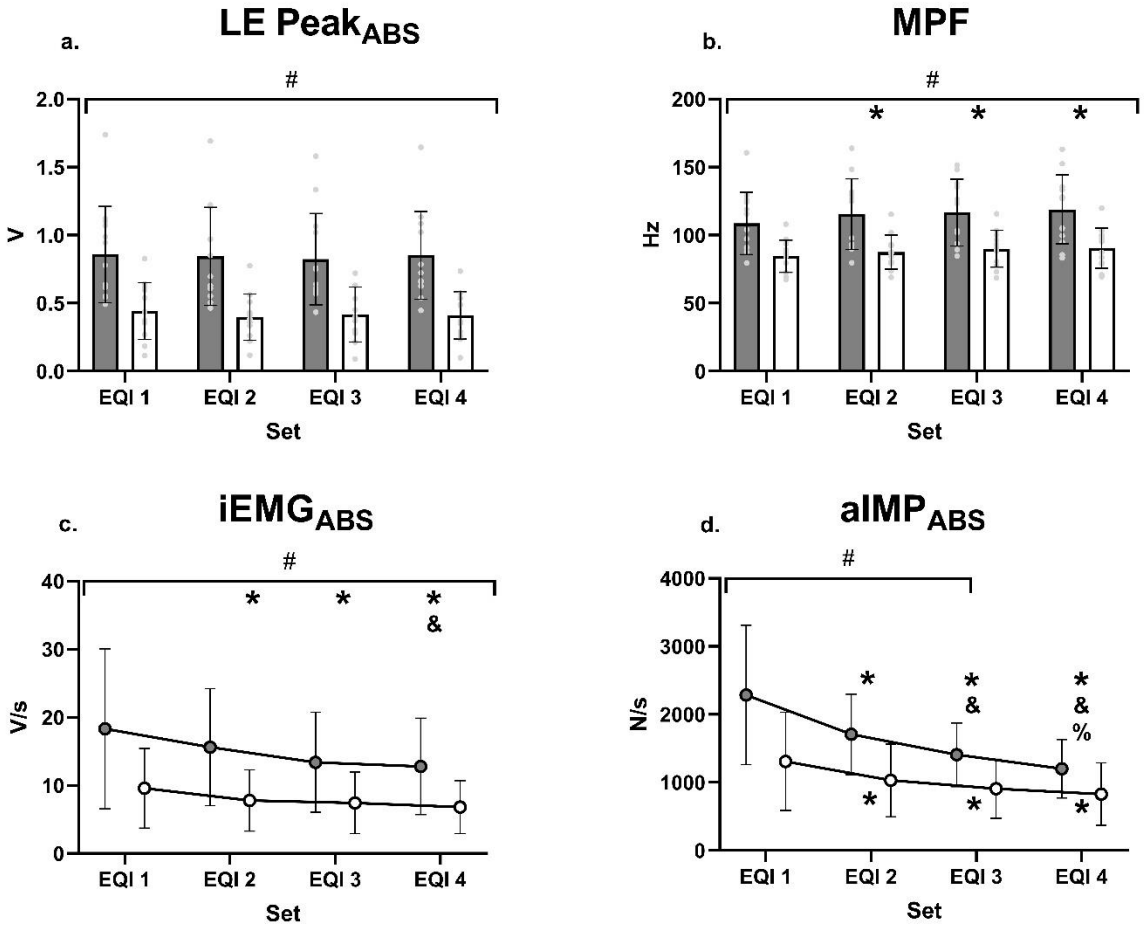
iEMGabs during EQI 1 was significantly, and with a medium-large effect sizes greater than EQI 2 ($p = .012$, d = 0.55), EQI 3 ($p = .001$, d = 0.75) and EQI 4 ($p < .001$, d = 0.77). iEMGabs for EQI 2 was also significantly greater than EQI 4 ($p = .005$; d = 0.61). There was also a main effect of sex, with males displaying greater iEMGabs across sets (7.13 ± 2.72 V/s, 99% CI: -0.51 to 14.78, $p = .015$; d = 1.05, 99% CI: -0.13 to 2.20) (Figure 3(c)).

For the aIMPabs set*sex interaction, simple main effects analysis indicated that males and females were significantly ($p < .138$) different from each other during EQI 1 (p = .012), EQI 2 ($p = .007$), and EQI 3 ($p = .011$), but not EQI 4 ($p = .480$), with males having larger aIMPabs values during EQI 1 (975.7 ± 357.3, 99% CI: -27.2 to 1978.7; d = 1.09, 99% CI: -0.01 to 2.26), EQI 2 (676.8 ± 226.4, 99% CI: 41.2 to 1312.5; d = 1.20, 99% CI: -0.02 to 2.39), and EQI 3 (501.5 ± 181.33, 99% CI: -7.6 to 1010.5; d = 1.11, 99% CI: -0.09 to 2.28). For males, all pairwise comparisons between sets were significantly ($p < .022$) different from each other ($p = .006$ to $p < .001$). For females, however, significant ($p < .022$) and large differences were only present relative to EQI 1, which produced greater aIMPabs than EQI 2 (279.6 ± 77.4, 99% CI:

39.2 to 519.9, p = .004; d = 1.04, 99% CI: 0.01 to 1.97), EQI 3 (403.2 ± 123.8, 99% CI: 18.9 to 787.6, p = .008; d = 0.94, 99% CI: 0.03 to 1.83), and EQI 4 (480.3 ± 132.8, 99% CI: 67.8 to 892.9, p = .004; d = 1.04, 99% CI: 0.01 to 1.97) (Figure 3(d)).

Figure 3

Group and Set Means for Absolute sEMG and Kinetic Variables



Note. Grey = males, white = females. Error bars denote standard deviation. Grey dots indicate individual data points. a.) absolute linear envelope peak (LE PeakABS), b.) Mean power frequency (MPF), c.) absolute integrated surface EMG (iEMGabs), d.) absolute angular impulse (aIMPabs). # = significant (p < .132) main effect of sex. * = significantly (p < .022) different from EQI 1. & = significantly (p = .022) different from EQI 2. % = significantly (p < .022) different from EQI 3. V = volts, Hz = hertz, V/s = volt-seconds, N/s = newton-seconds.

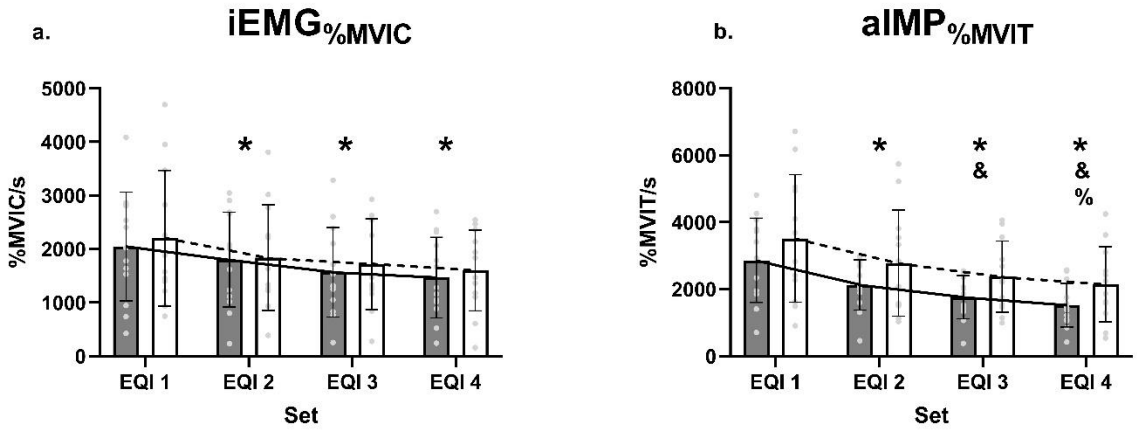
Relative Variables. Mean differences, effect sizes, and 99% confidence intervals are presented in Table 3. Mean group differences ± standard error (SE) of the difference are reported in text where appropriate.

For LE Peak%MVIC, there was no main effect for EQI set or sex, and there was no set*sex interaction ($p > .132$). With medium-large effect sizes, iEMG%MVIC during EQI 1 was significantly greater than iEMG%MVIC for EQI 2 ($p = .006$, d = 0.61), EQI 3 ($p < .001$; d = 0.81), and EQI 4 ($p < .001$, d = 0.78). Between set comparisons are presented in Figure 4(a).

With large effect sizes, aIMP%MVIT during EQI 1 was significantly greater than EQI 2 ($p < .001$, d = 1.08), EQI 3 ($p < .001$, d = 1.20), and EQI 4 ($p < .001$, d = 1.33). With medium-large effect sizes, aIMP%MVIT was also significantly greater during EQI 2 than EQI 3 ($p = .003$, d = 0.65), and EQI 4 ($p < .001$, d = 0.93), while aIMP for EQI 3 was significantly and with a large effect size greater than EQI 4 ($p < .001$, d = 0.91). Between set comparisons are presented in Figure 4(b).

Figure 4

Group and Set Means for Relative sEMG and Kinetic Variables



Note. Grey = males, white = females. Error bars denote standard deviation. Grey dots indicate individual data points. a.) relative integrated surface EMG (iEMG%MVIC), b.) relative angular impulse (aIMP%MVIT). * = significantly ($p < .022$) different from EQI 1. & = significantly ($p = .022$) different from EQI 2. % = significantly ($p < .022$) different from EQI 3. %MVIC/s = percent of maximum voluntary isometric contraction-seconds. %MVIT = percent of maximum voluntary isometric torque-seconds.

Statistical Parametric and Non-Parametric Mapping

Sex-Differences. Data for LE-time were normally distributed for all sets. Angle-time data (df = 1, 2) for EQI 2 was not normally distributed, forming one suprathreshold clusters that exceeded the critical threshold ($X^2 = 10.013$) from 48%–62% ($p =. 023$), as was angle-time data for EQI 3, forming 2 suprathreshold clusters that exceeded the critical threshold ($X^2 = 10.107$) from 4%-12% ($p =. 037$), and 44%–79% ($p < .001$) of set time.

When male and female LE-time and angle-time data were compared within sets, the critical threshold was not exceeded at any point for EQI 1, EQI 2, EQI 3, or EQI 4, and both parametric and non-parametric inference were in agreement. Therefore, at any time-point, there were no significant differences between males and females for each EQI set.

Set Differences. When male and female data were collapsed for set-by-set comparisons, angle-time data were not normally distributed, except for EQI 2 vs. EQI 4. For LE-time data, EQI 2 vs EQI 3, EQI 2 vs. EQI 4, and EQI 3 vs. EQI 4 were normally distributed.

Angle-time SPM and SnPM results are presented in Table 4. In multiple cases, parametric and non-parametric were not in agreement for angle-time data. Specifically, parametric inference revealed one suprathreshold cluster from 8%-11% of set time for EQI 1 vs. EQI 4. However, nonparametric inference resulted in 3 instances where the critical threshold was exceeded, creating suprathreshold clusters from 6%–31%, 61–72%, and 79%–84% of set time (Figure 5(c,d)). Example SnPM comparisons are presented in Figure 5.

Table 4

Set-by-Set Statistical Parametric vs. Statistical Non Parametric Results

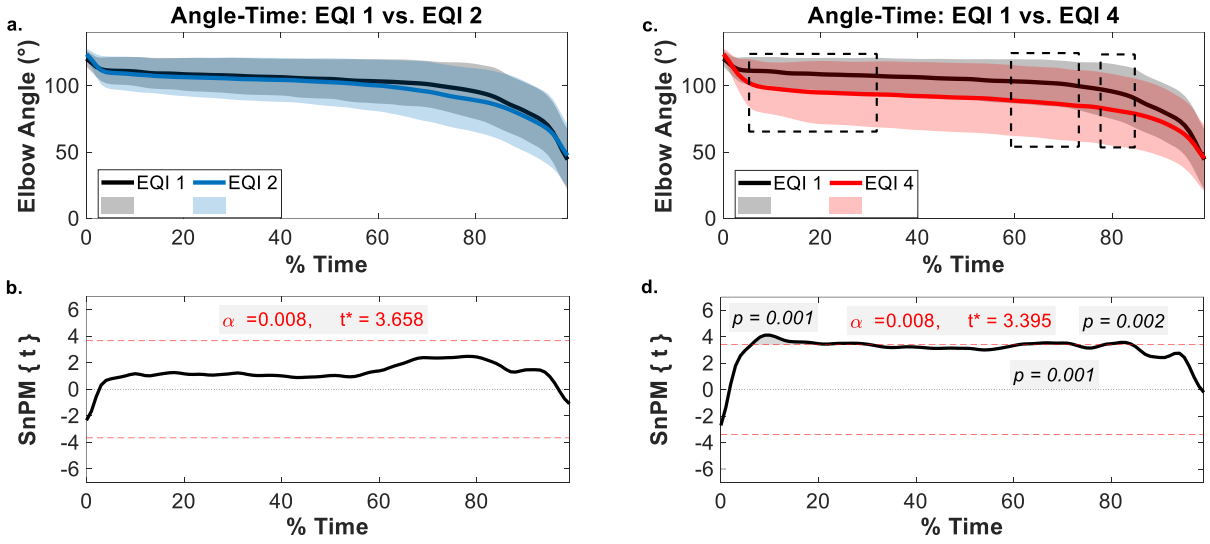
ANGLE-TIME		Parametric		Non-Parametric	
Comparison	df	t*	Suprathreshold Clusters	t*	Suprathreshold Clusters
EQI 1 vs. EQI 2	1, 23	4.039	*n/a*	3.658	*n/a*
EQI 1 vs. EQI 3	1, 23	4.012	*n/a*	3.697	*n/a*
EQI 1 vs. EQI 4	**1, 23**	**3.997**	**8-11% (*p* = .007)**	**3.395**	**6%-31% (*p* < .001) 61%-72% (*p* < .001) 79%-84% (*p* = .002)**
EQI 2 vs. EQI 3	1, 23	4.014	*n/a*	3.598	*n/a*
EQI 2 vs. EQI 4	**1, 23**	**4.017**	***n/a***	**3.625**	**12%-14% (*p* = .004)**
EQI 3 vs. EQI 4	1, 23	4.075	*n/a*	3.728	*n/a*

LE-TIME		Parametric		Non-Parametric	
Comparison	df	t*	Suprathreshold Clusters	t*	Suprathreshold Clusters
EQI 1 vs. EQI 2	**1, 22**	**4.701**	***n/a***	**4.119**	**60%-61% (*p* < .001)**
EQI 1 vs. EQI 3	**1, 22**	**4.611**	***n/a***	**4.02**	**79% (*p* = .004)**
EQI 1 vs. EQI 4	**1, 22**	**4.607**	**51%-52% (*p* = .005) 59%-62% (*p* < .001)**	**4.193**	**8% (*p* = .003) 33% (*p* = .004) 47%-52% (*p* < .001) 59%-63% (*p* < .001)**
EQI 2 vs. EQI 3	1, 22	4.661	*n/a*	4.345	*n/a*
EQI 2 vs. EQI 4	**1, 22**	**4.662**	**6%-9% (*p* < .001)**	**4.364**	**6%-9% (*p* < .001) 29% (*p* = .003)**
EQI 3 vs. EQI 4	1, 22	4.699	*n/a*	4.331	*n/a*

Note. Discrepancies between parametric and non-parametric inference are bolded. df = degrees of freedom, t* = critical threshold, n/a = no suprathreshold clusters. Discrepancies between parametric and non-parametric inference are bolded. Significance based on a Bonferroni corrected α of .008.

Figure 5

Time Normalised Elbow Angle Means, Standard Deviations, and Statistical Non-Parametric Maps (SnPM) for EQI 1 vs. EQI 2 (a, b), and EQI 1 vs. EQI 4 (c, d).



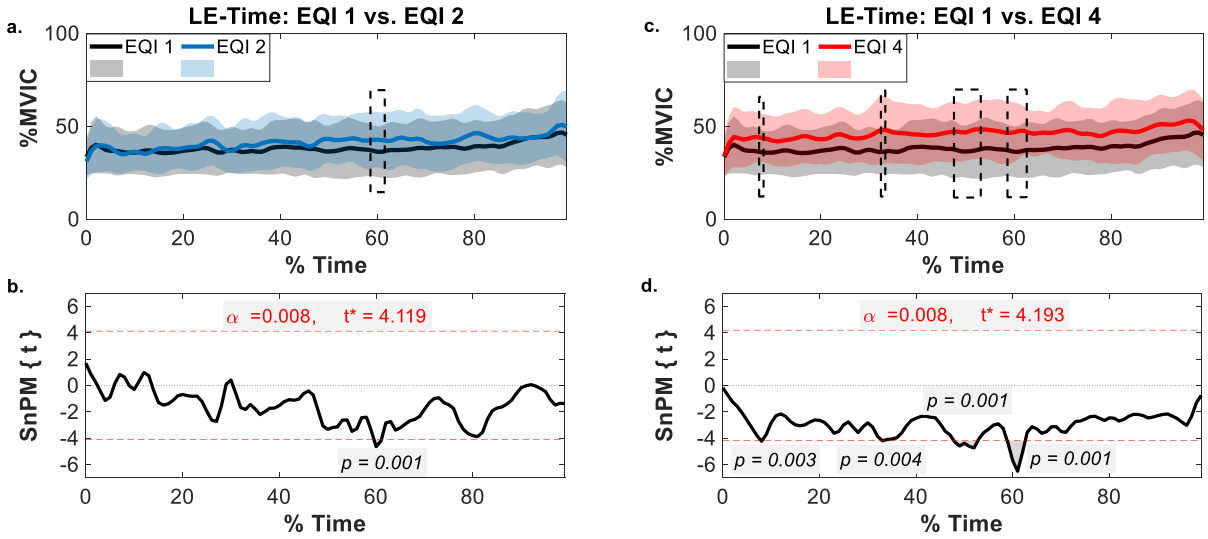
Note. Top graphs display mean values (solid lines) and standard deviations (shaded areas) at a given time point. Perforated boxes represent suprathreshold clusters imposed on observed data. Bottom graphs display the test statistic (*t*) continuum ("map"). Perforated red line represents critical threshold (t*).

For LE-time data, EQI 1 vs. EQI 2, and EQI 1 vs. EQI 3 were significantly different using non-parametric inference only. Non-parametric inference resulted in a suprathreshold cluster from 60-61% for EQI 1 vs EQI 2 (Figure 6(a,b)) and a suprathreshold cluster at 79% for EQI 1 vs. EQI 3. EQI 1 vs. EQI 4, and EQI 2 vs. EQI 4 were significantly different based on parametric and non-parametric inference. For EQI 1 vs. EQI 4, parametric inference resulted in a suprathreshold cluster from 51%-52% and 59%-62%, while non-parametric inference resulted in suprathreshold clusters at 8%, 33%, 47%-52%, and 59%–63% of set time (Figure 6(c,d)). Parametric results for EQI 2 vs. EQI 4 indicated a suprathreshold cluster from 6%-9% and non-

parametric inference produced suprathreshold clusters from 6%-9% and at 29% of set time (Table 4). All suprathreshold clusters were the result of later sets having a greater amplitude than earlier sets. Example LE-time SnPM comparison are presented in Figure 6.

Figure 6

Time Normalised Linear Envelope Means, Standard Deviation, and Statistical Non-Parametric Maps (SnPM) for EQI 1 vs. EQI 2 (a, b), and EQI 1 vs. EQI 4 (c, d)



Note. Top graphs display mean values (solid lines) and standard deviations (shaded areas) at a given time point. Perforated boxes represent suprathreshold clusters imposed on observed data. Bottom graphs display the test statistic (*t*) continuum ("map"). Perforated red line represents critical threshold (t*).

Discussion and Implications

The primary purpose of the current study was to determine if sex-differences existed in the muscle fatigue response during a 4 set EQI-RE elbow flexion protocol. Specifically, whether differences existed in absolute (LE PeakABS, iEMGabs, MPF, aIMPabs) and relative (LE Peak%MVIC, iEMG%MVIC, and aIMP%MVIT) measures of biceps brachii sEMG and angular impulse between the sexes and across sets. There were significant differences with medium-large

effects sizes between males and females for all absolute variables, with males having higher LE PeakABS, iEMGabs, MPF, and aIMPabs than females. When expressed relatively, there were no significant sex differences, although females tended to have higher values for iEMG%MVIC and aIMP%MVIT.

Irrespective of sex, the accrued muscle activity (iEMGabs, iEMG%MVIC), mechanical impulse (aIMPabs, aIMP%MVIT), and MPF significantly decreased across sets with a large effect size. There was an interaction between set and sex for aIMPabs; males experienced a larger relative drop-off in aIMPabs across sets, to the point where there were no sex-differences in aIMPabs for the last EQI. When relative data was collapsed between males and females, SPM analysis indicated that both elbow angle-time kinematics and LE-time amplitude characteristics differed from the beginning to the end of the protocol, with EQI 4 generally having larger elbow angles and greater sEMG amplitude at a given time than earlier sets. Conversely, within-set SPM analysis of angle-time kinematics and LE-time amplitude did not elucidate any sex-differences.

As integrated variables are a product of time and amplitude, the linear decrease in iEMG and aIMP across sets is not unexpected, given the concurrent reduction in time under tension across the protocol (see Table 1) and typical decreases in volume with isotonic resistance exercise as the number of sets increases (Paz et al., 2017). Similar to our findings, Oranchuk et al. (2021) observed a relatively linear and significant decrease in relative aIMP from EQI 1 to EQI 4 for an EQI resisted knee extension protocol, although the study only included resistance trained males. As was the case in the current study, males typically have greater absolute strength, muscle mass, and less adipose tissue compared to females (Janssen et al., 2000) and therefore have greater absolute EMG and torque amplitudes (Farina et al., 2004; Freilich et al.,

1995; Kotte et al., 2018). As such, this likely explains the larger iEMGabs and aIMPabs values for males. Conversely, females are generally more fatigue resistant than males (Hunter, 2014, 2016b, 2016a), and thus would theoretically be able to accrue more time under tension. In studies of isometric elbow flexion, women typically exhibit significantly greater absolute times to task failure than men during low-moderate sustained submaximal contractions (Hunter, 2009, 2014, 2016b, 2016a). For example, using the same relative intensity of the current study (50% MVIT), Avin et al. (2010) observed that females had a significantly greater time to task failure compared to men (112.3 vs 80.3 s), and generally produced greater relative EMG amplitude values in the elbow flexors and extensors for the entire task. Therefore, it was assumed for the current study that females would have greater time under tension and relative EMG amplitude, which would result in larger integrated absolute and relative values for iEMG and aIMP. Indeed, the lack of significant sex-differences for iEMG%MVIC and aIMP%MVIT is surprising, given that time under tension for females was between 18% (EQI 1) and 38% (EQI 4) longer than males. That being said, there was substantial variability in the female data relative to male participants for both iEMGabs and aIMPabs, with the 99% CI of the difference crossing 0, which can be reflected in the lack of statistical significance.

Despite a lack of statistical significance, the potential sex-differences in relative aIMP when performing EQI-RE is difficult to ignore. Cumulatively, total aIMP%MVIT across the protocol was 31% less in male participants, which represents a meaningful difference in volume when considering that even small (< 10%) relative increases in weekly set volume are associated with significant increases in muscle size (Schoenfeld et al., 2017). Thus, given the importance of mechanical tension and exercise volume for stimulating muscle hypertrophy, it seems reasonable to suggest that if potential volume and time under tension differences were compounded over the

course of a training program, that detectable sex-differences in muscle hypertrophy may be elucidated. Even at higher relative intensities than the current study, females still maintain a performance advantage in time to task failure when examining the elbow flexors using sustained isometric muscle actions (Hunter, 2014) and therefore would still theoretically accrue more time under tension. That being said, proximity to volitional fatigue or task failure appears to be more relevant than intensity for stimulating muscle hypertrophy, while intensity is relevant for strength adaptations (Lixandrão et al., 2018; Schoenfeld, Ogborn, et al., 2017). Given the proposed use of EQI-RE when high-velocity muscle actions are not tolerated (Oranchuk et al., 2019b), further research may want to compare different relative intensities of EQI-RE with respect to muscle hypertrophy and strength adaptations.

The interaction effect for aIMPabs poses some intriguing questions regarding the development of fatigue across multiple EQIs. For males, aIMPabs was significantly less than the preceding set across the entire protocol, whereas in females, EQI 2, EQI 3, and EQI 4 were only significantly less than EQI 1. Coupled with the lack of significant sex-differences during EQI 4, this suggests that females better maintain performance across EQI-RE elbow flexion sets, while males experience a substantial decline in performance with successive sets, to the point where aIMPabs is equal to females during EQI 4.

When examining the LE PeakABS and MPF data, however, males and females experienced similar effects across sets, which may suggest that mechanical or metabolic factors play a larger role than neuromuscular factors in the development of muscle fatigue during an EQI elbow flexion protocol. Indeed, other researchers have attributed sex-differences in isometric and dynamic tasks to be more likely the result of metabolic and contractile differences

between males and females (Hunter et al., 2006; Wüst et al., 2008). Given the lack of sex-differences in relative voluntary muscle excitation, iEMG, and aIMP, the present study seems to support this assertation, and could also suggest that factors intrinsic to sex (e.g., metabolic and contractile differences), rather than factors extrinsic to sex (e.g., strength) are more relevant to muscle fatigue during EQI-RE.

As there were no sex-differences for angle-time kinematics, and LE-time amplitude characteristics within each EQI set, data were collapsed across sexes for exploratory SPM and SnPM analysis and compared set-by-set as per Oranchuk et al. (2021). Although Oranchuk et al. (2021) did not observe significant differences from EQI 1 to EQI 4, initial changes in knee angle tended to occur more quickly after successive sets, with EQI 4 generally exhibiting greater displacement (i.e., larger joint angles) at the beginning of the set than EQI 1. Using an almost identical protocol, Oranchuk et al. (2020) observed that the majority of eccentric angular impulse was accumulated in the first half of the EQI ROM across all 4 sets. When considering the angle-time kinematic data of the current study, the results suggest a similar pattern and accumulation of fatigue. While there were discrepancies between parametric and non-parametric results, both indicated that EQI 4 had significantly smaller elbow angles within the first one-third of set time. As with Oranchuk et al. (2021), this suggests that initial changes in muscle length and joint angle during EQI-RE elbow flexion also occur more quickly as fatigue accumulates. Visually, however, these differences appear to remain stable through the majority of the ROM. That being said, performing repeated statistical tests in this manner is generally not recommended, due to separate smoothness assessments associated with each test (http://www.spm1d.org). Thus, the results of the set-by-set comparisons of Oranchuk et al. (2021) and the current study should be interpreted with caution.

With respect to the discrepancy between parametric and non-parametric inference, future works may consider using a time threshold when examining suprathreshold clusters. For LE-time data, there were several instances where the difference between parametric and non-parametric inference amounted to suprathreshold clusters of ~1% of set time (Table 4), which are unlikely to be clinically relevant, nor did we interpret them to be meaningful. Indeed, if these small suprathreshold clusters were removed a-priori, agreement between parametric and non-parametric inference would likely be improved. Similar threshold approaches involving time have previously been used in EMG research (Kamen & Gabriel, 2010b; Pruszynski et al., 2008).

In line with the aforementioned kinematic and kinetic data, the LE-time data from the current study supports a greater fatigue response in the first two-thirds of the EQI ROM as the number of EQI sets increases. Significant increases in sEMG amplitude from EQI 1 to EQI 4 were only observed in the first two-thirds of set time and ROM. During sustained isometric muscle actions, sEMG amplitude is known to increase, presumably due to increases in motor unit recruitment (Kamen & Gabriel, 2010b). While the current methods are unable to elucidate specific motor unit behaviours or recruitment strategies, this observation suggests that motor unit recruitment is more relevant than mechanical factors for maintaining force output during EQIs at short-medium muscle lengths (i.e., greater elbow flexion). When considering the traditional isometric length-tension relationship, the passive structures of an elongated muscle will contribute more substantially than the active structures to muscular tension (Abbott & Wilkie, 1953; Hamill et al., 2015). Thus, at longer-muscle lengths (i.e., last third of the ROM), it is logical that EQIs would be less reliant on motor unit recruitment and resulting active tension to maintain force output, even in a non-fatigued state. Although the current study was not designed to compare EQI-RE motor unit recruitment patterns relative to traditional resistance exercise,

sEMG analysis would not seem to point to an inherent advantage of EQIs for increasing motor unit recruitment when considering studies of sustained isometric elbow flexion (Avin et al., 2010; Bazzucchi et al., 2004b; Hunter et al., 2004b; Rudroff et al., 2011), although this assumption needs to be tested with future experimental or quasi-experimental research.

Given recent reviews (Pallarés et al., 2021; Schoenfeld & Grgic, 2020) that suggest emphasising longer muscle lengths during resistance exercise may have equivalent hypertrophic outcomes as resistance exercise using a full ROM, Oranchuk et al. (2021) proposed that EQI-RE could be performed with a smaller ROM, which would increase time under tension at longer muscle lengths. Based on (Oranchuk et al., 2021) and the current study, this would also be a logical suggestion, as results from both studies suggest muscle fatigue increases the relative time spent at longer muscle lengths due to fatigue at short muscle lengths, but decreases overall time under tension. Despite females having discernably greater time under tension and relative aIMP, the current study suggests that males and females have similar relative fatigue response to moderate intensity EQI-RE elbow flexions. That being said, when designing or implementing training programs, practitioners and trainees should also consider the possibility that males may have substantial drop-off in performance following a single EQI-RE set, whereas females may be able to maintain performance with subsequent sets. Furthermore, although significant, changes in sEMG amplitude across sets and during sets appear to be unremarkable, suggesting that EQI-RE may require several sets to meaningfully increase motor unit recruitment. As such, practitioners and trainees should also strongly consider the specificity and relevance of EQIs to training goals, and whether these goals can be accomplished with more traditional resistance exercise methods.

Limitations of the current study that are relevant to its interpretation, and the direction of future studies must be considered. Namely, the use of the isokinetic dynamometer to perform the EQI-RE protocol does not resemble real world applications, as the torque generated during an elbow flexion exercise will vary through the movement with the use of dumbbells, cables, or resistance bands, whereas constant torque is provided by the isokinetic dynamometer. Additionally, the initial decrease in elbow angle may have been due to participants not producing enough 'pre-activation' prior to the dynamometer applying torque, resulting in a larger and immediate change in elbow angle before participants were able to meet the applied torque, which would not be relevant in applied contexts. Participants were also aware that they would be performing 4 EQI-RE sets, which may have resulted in participants pacing themselves and not performing all sets to volitional fatigue. With respect to sEMG, the innervation zone was not identified prior to placement of the electrode array. As such, when the biceps brachii lengthened, it is possible that the innervation zone would have moved underneath the electrode, which would have altered the sEMG amplitude characteristics independent of physiological effects. As a result, we elected to take a more traditional bi- polar approach to sEMG, in line with SENIAM guidelines (www.seniam.org), which reduced the representative surface area of the sEMG data.

Conclusion

In general, absolute and relative iEMG and aIMP decreased across EQI-RE sets, regardless of sex, and exploratory analysis suggests that the accumulation of muscle fatigue predominately manifests in the first two-thirds of set time. Additionally, there were acute absolute sex-differences in sEMG and aIMP across 3 EQI-RE elbow flexion sets, but no sex-difference in absolute aIMP during set 4. When expressed relatively, there were no statistical differences between males and females in sEMG or aIMP values across 4 EQI-RE elbow flexion

sets, although there were discernable differences in time under tension and relative aIMP between males and females. As such, it is unclear if acute sex-differences in sEMG and aIMP during EQI elbow flexions can be attributed to factors intrinsic or extrinsic of sex. It remains unknown if EQI resistant exercise results in unique neuromuscular responses relative to traditional resistance exercise, and whether or not differing intensities, ROM, or tasks would contribute to any observed sex-differences.

Chapter 3: Isotonic vs. Eccentric Quasi-Isometric Resistance Exercise of the Elbow Flexors: A Cross-Sectional Comparison of sEMG, Time Under Tension, and Sex-Differences Using a Unilateral Model

Author Note and Contributions

Although an isokinetic dynamometer is valuable for investigating time under tension and muscle excitation at specific muscle lengths, all EQI-RE studies to date (including Chapter 2; Henderson et al., 2023; Oranchuk et al., 2020, 2021) have used an isokinetic dynamometer to perform and evaluate EQI-RE, which is not applicable to real-world resistance exercise practices. As a study that investigates the effects of EQI-RE on muscle hypertrophy and strength represents the end goal of the thesis, it was pertinent to examine EQI-RE using a more ecologically valid resistance exercise model, and compare EQI-RE to a traditional form of resistance exercise. As such, the following chapter represents the first EQI-RE study to utilise a common external load (dumbbell) to perform EQI-RE and reflects the model that will be used to examine long-term muscle hypertrophy and strength adaptations. While there is some overlap in dependent variables that were examined (time under tension, iEMG), the following chapter adds to Chapter 2 by examining agonist-antagonist co-activation, and comparing traditional isotonic resistance exercise (TRD-RE) to EQI-RE.

Zachariah J. Henderson conceptualised, designed, piloted methods, collected data, analysed data, interpreted data, and drafted the chapter.

Abstract

Traditional isotonic resistance exercise (TRD-RE) improves muscle mass, strength, and overall health. However, TRD-RE may be impractical or unfeasible in injury or sport specific situations. Compared to TRD-RE, eccentric quasi-isometric resistance exercise (EQI-RE) is a low-velocity resistance exercise modality suggested to acutely produce similar and/or greater time under tension, motor unit recruitment, and antagonist co-activation. With limited investigations or comparisons to other forms of resistance exercise, however, evidence is lacking. As differences between males and females exist in time under tension and motor unit behaviour in other resistance exercise contexts, the current study explored sex-differences in time under tension and surface electromyography (sEMG) across 2 sets of TRD-RE and EQI-RE. Twenty-seven (n = 13 females) participants performed unilateral TRD-RE and EQI-RE of the elbow flexors while sEMG was collected from the biceps and triceps brachii. Several main and interaction effects of resistance exercise type, set, and sex were present for time under tension, linear envelope peak (LEpeak), absolute (iEMGabs) and relative (iEMG%) integrated sEMG, with set 1 typically having higher sEMG values than set 2, and EQI-RE having greater time under tension than TRD-RE. Notably, females produced significantly more time under tension, iEMGabs, iEMG%, and co-activation than males during EQI-RE, while males experienced a more significant set-to-set reduction in time under tension and LEpeak during TRD-RE. Overall, TRD-RE may result in quicker voluntary excitation and subsequent fatigue of motor units compared to EQI-RE, while females may accrue more resistance exercise volume than males when performing EQI-RE. Theoretically, these effects could lead to long-term sex-differences in strength and hypertrophy outcomes between males and females, TRD-RE and EQI-RE.

Key words: Sex-differences, resistance training, weight training, bicep curls

Introduction

Resistance exercise alters muscle physiology and morphology acutely and chronically (McKendry et al., 2021). Acutely, isotonic resistance exercise increases electromyography (EMG) amplitude (e.g., Dankel et al., 2017; Paz et al., 2017), muscle thickness (e.g., Csapo et al., 2011; Yitzchaki et al., 2020) and muscle protein synthesis (Lim et al., 2022). Thus, repeated acute resistance exercise bouts over a period of weeks may lead to muscle morphological adaptations and improvements in performance and health outcomes, such as increased muscle mass, strength, endurance, and control and/or reduction of chronic diseases and musculoskeletal injury (Bennie et al., 2020; Ratamess et al., 2009; Schoenfeld, 2010, 2020; Suchomel et al., 2016). While chronic resistance exercise is considered a potent means of stimulating muscle hypertrophy and/or preventing muscle atrophy (Lim et al., 2022), traditional isotonic resistance exercise involves alternating concentric and eccentric muscle actions at high-velocities with loads > 65% 1-RM (Ratamess et al., 2009). As such, it may be difficult and/or not tolerable to perform with musculoskeletal injury and may not train or reflect the demands of sports that utilise low-velocity movements (Oranchuk et al., 2019b). Thus, alternative resistance exercise strategies, such as “eccentric quasi-isometrics”, or “EQIs” (Oranchuk et al., 2019), which avoid high-loads and high-velocities have been proposed.

Briefly, an EQI involves initiating and maintaining a holding isometric muscle action (Schaefer & Bittmann, 2017) to positional failure. Rather than ending the exercise at positional failure, the resulting eccentric muscle action is voluntarily resisted through the desired range of motion (ROM; Oranchuk et al., 2019b, 2020). As a novel, low-velocity resistance exercise modality, variations of EQI resistance exercise (EQI-RE) are proposed to acutely increase motor unit recruitment, muscle co-contraction/activation, and time under tension, potentially to a

greater degree than traditional isotonic resistance exercise (Morrison, 2016; Oranchuk et al., 2019b; Seedman, n.d.-a, n.d.-b; Sinicki, 2019). Since time under tension and motor unit recruitment are implicated in strength and hypertrophy processes (Lim et al., 2022; Moritani & DeVries, 1979; Nuzzo, 2022; Pearson & Hussain, 2015; Schoenfeld, 2010; Zabaleta-Korta et al., 2020), it has been suggested that the EQI concept could lead to unique musculotendinous morphological and strength adaptations with chronic training (Morrison, 2016; Oranchuk et al., 2019b; Seedman, n.d.-a, n.d.-b; Sinicki, 2019). Despite these suggestions, few studies have investigated EQI-RE acutely or chronically, or compared it to other forms of resistance exercise.

Although it is likely that EQI-RE produces substantial time under tension (Oranchuk et al. 2020), assertations that EQI-RE increases motor unit recruitment or muscle co-activation remain unsubstantiated. Our previous work (Chapter 2) suggests no unique or substantial increase in surface electromyography (sEMG) amplitude across 4 sets of EQI-RE elbow flexions to volitional fatigue, although females were generally better able to maintain performance and subsequent time under tension across multiple sets compared to males. While females displaying greater muscle fatigue resistance during low-velocity or isometric muscle actions of the elbow flexors is not a surprising outcome (Hunter, 2014, 2016b), previous studies suggest that females could lose this performance advantage when performing higher velocity muscle actions (Gomes et al., 2021; Senefeld et al., 2013; Yoon et al., 2015), such as those performed with traditional isotonic resistance exercise (TRD-RE).

Potential sex-differences in the temporal manifestation of muscle fatigue with different resistance exercise types are relevant when considering that time under tension is suggested to be the main driver of EQI-RE induced muscle hypertrophy (Oranchuk et al., 2019b). If EQI-RE

does produce greater time under tension than traditional isotonic resistance exercise (TRD-RE), theoretically this would lead to greater cumulative resistance exercise volume, and thus greater muscle hypertrophy with EQI-RE than TRD-RE. Furthermore, if females are less fatigable to EQI-RE than males, but not TRD-RE, this could result in sex-dependent differences in muscle strength and hypertrophy adaptations to EQI-RE and TRD-RE. As muscle fatigue during EQI-RE and TRD-RE, and between males and females has yet to compared, however, this remains speculative.

Given the purported advantages of EQI-RE to increase time under tension, motor unit recruitment, and agonist-antagonist co-activation relative to more traditional resistance exercise types (Morrison, 2016; Oranchuk et al., 2019b; Seedman, n.d.-a, n.d.-b; Sinicki, 2019), the current study compared the acute muscle fatigue response between EQI-RE and TRD-RE of the elbow flexors. Using a unilateral resistance exercise model (Macinnis et al., 2017), time under tension was quantified during 2 sets of TRD-RE and EQI-RE supinated bicep curls to volitional fatigue, while sEMG of the biceps brachii and triceps brachii were collected to evaluate voluntary peak muscle excitation (linear envelope peak [LEpeak], absolute integrated sEMG [iEMGabs] and relative sEMG [iEMG%] “muscle activity”, and normalised triceps brachii-biceps brachii co-activation ratio [CoA]). While LEpeak was expected to be higher during TRD-RE, based on ours (Henderson et al., 2023), and other’s (Ličen et al., 2024; Oranchuk et al., 2020, 2021) studies reporting substantial time under tension during EQI-RE, it was hypothesised that EQI-RE would produce greater time under tension, iEMGabs, iEMG%, and CoA than TRD-RE, regardless of sex. Additionally, it was expected that iEMGabs and iEMG% would decrease from set 1 to set 2 with TRD-RE and EQI-RE, as time under tension decreases with fatigue (Henderson et al., 2023; Oranchuk et al., 2021; Ratamess et al., 2012). Due to greater fatigue

resistance (Hunter, 2016b), it was also hypothesised that females would accrue greater time under tension and iEMG% than males during EQI-RE but not TRD-RE. Males, however, were expected to produce higher LEpeak and iEMGabs due to having greater muscle mass and less adipose tissue than females (Janssen et al., 2000).

Methods

Experimental Overview

The investigation was imbedded within a longitudinal training project (Chapter 4). A unilateral (resistance exercise type), cross-sectional (set), and between-group (sex) design was used to compare time under tension, voluntary biceps brachii excitation, and triceps brachii co-activation between males and females during 2 sets of TRD-RE and EQI-RE of the elbow flexors to volitional fatigue. As a unilateral design, participant's dominant and non-dominant arm (assessed using the Edinburgh Handedness Inventory), as well as order of completion, were assigned to either TRD-RE or EQI-RE types using a Latin square (Portney et al., 2015). Participants completed both sets with the first limb and assigned resistance exercise type (TRD-RE or EQI-RE), before completing the other resistance exercise type for the second limb. All sets were performed using 70% of participant's estimated 1-repetition maximum (E-1RM), while bipolar surface sEMG data were collected over the biceps and triceps brachii. The study was approved by the University of Manitoba Research Ethics Board (REB 1; HE2023-0066), and all participants provided verbal and written consent prior to participation.

Participants

Thirty participants 18-35 years old (15 females, 15 males; sex assigned at birth) were recruited via convenience sampling from the University community. All participants did not

regularly partake in structured resistance exercise (defined as ≥ 2x week, ≤ 12-repetitions per exercise), and were cleared for exercise by the Get-Active Questionnaire (Canadian Society for Exercise Physiology, 2017). Furthermore, participants had no history of neurological disorders or recent (<3 months) injury (e.g., sprain, strain) that would impact their ability to perform unilateral resistance exercise of the upper limb. Participants were instructed to avoid structured and/or strenuous upper-body exercise or physical activity for 72-hours, caffeine for 3-hrs, and alcohol and cannabis for 24-hrs before the session. All participant's body composition was as assessed by bioelectrical impedance (InBody 270; InBody Co, Seoul, South Korea) prior to the session, and as per manufacturer recommendations.

Estimated 1-RM and Protocol Familiarisation

Participants were familiarised with and completed (at least 3-days apart) 10-RM testing for a unilateral supinated bicep curl as per CSEP (Canadian Society for Exercise Physiology, 2013) to determine their estimated 1-repetition maximum (E-1RM). 10-RM testing was performed for each limb, and E-1RM was calculated as the averaged between limbs to prescribe relative load (% E-1RM) for both resistance exercise types. Additionally, participants were familiarised with the EQI-RE procedures on two occasions at least 3-days apart, and at least 3-days prior to data collection (Figure 1a.).

Protocol

Data were collected during one, 1.5-hr session in an exercise laboratory set at 20 °C (Figure 1b.). To quantify the typical error of ultrasound measures for the larger project, participants began the session by lying in a supine position for ~45 minutes. The skin over the biceps and triceps brachii were then prepped for sEMG using standard procedures, including

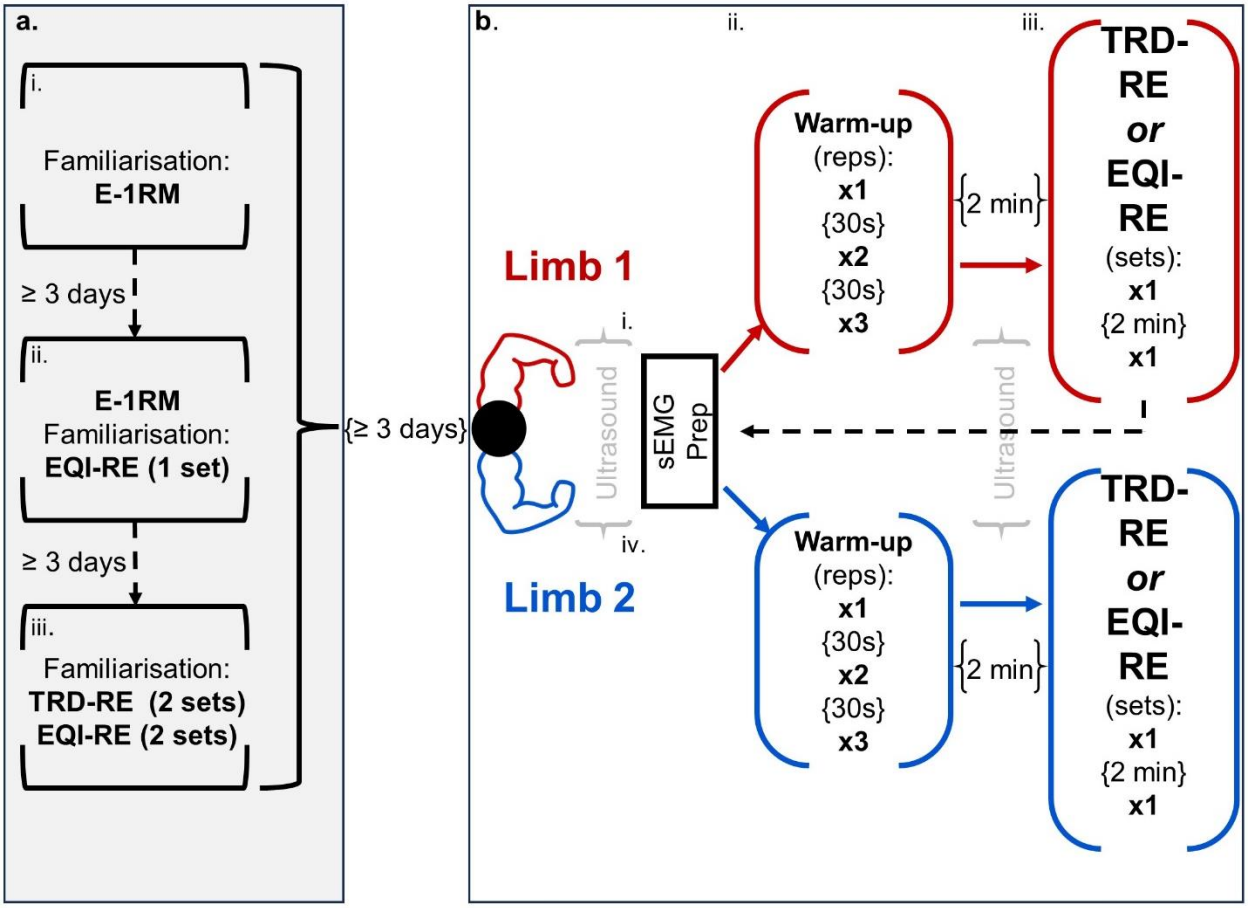
abrading the skins surface and wiping with water (Henderson et al., 2023; Lulic-Kuryllo, Thompson, et al., 2021; Piervirgili et al., 2014). Disposable dual sEMG electrodes (Ag/AgCl, 20mm interelectrode distance; Noraxon U.S.A. Inc, Scottsdale, AZ) were then positioned approximately parallel with the muscle fibres, based on procedures and recommendations by Barbero et al. (2012) and SENIAM (www.seniam.org). For the biceps brachii, the distal portion of the electrode bordered a line at 62% of the distance from the acromion to the cubital crease, while the electrode for the lateral head of the triceps brachii was positioned just lateral to 40% of the distance from the acromion to the lateral epicondyle. Electrodes were connected to an Ultium™ EMG system (24-bit sampling resolution, >100 dB common mode rejection ratio, baseline noise < 1 μV; Noraxon U.S.A. Inc.) via wireless Ultium™ EMG/inertial measurement unit (IMU) sensors (10-500 Hz bandpass filter, ± 16 g tri-axial accelerometer, 2048 LSB/g sensitivity, 16-bit sampling resolution), which were affixed to participants' skin using double sided EMG sensor tape (Noraxon U.S.A. Inc.). For the purposes of identifying repetition start and end-time via acceleration, an additional EMG/IMU sensor was placed at the radial styloid process (Figure 2).

Baseline data was then recorded with participants standing in a relaxed, upright position, with arms and hands held naturally at their sides. For both the TRD-RE and EQI-RE limbs, participants began with a 3-set warm-up consisting of 1, 2, and 3 repetitions of unilateral supinated bicep curls using 70% of their E-1RM, with 30-seconds of rest between sets. During the warm-up, the researchers monitored sEMG for signal quality; in cases of excessive baseline noise or impedance, the electrode area was re-prepped, and a new electrode was applied before continuing. After 2-minutes of rest, participants performed their first set of TRD-RE or EQI-RE followed by 2-minutes of rest and a second set. Participants then spent ~10-minutes lying in

supine rest, after which all sEMG preparation and warm-up procedures were repeated for the remaining limb, and followed 2 sets of the remaining resistance exercise type (Figure 1).

Figure 1

Study Overview and Resistance Exercise Protocol



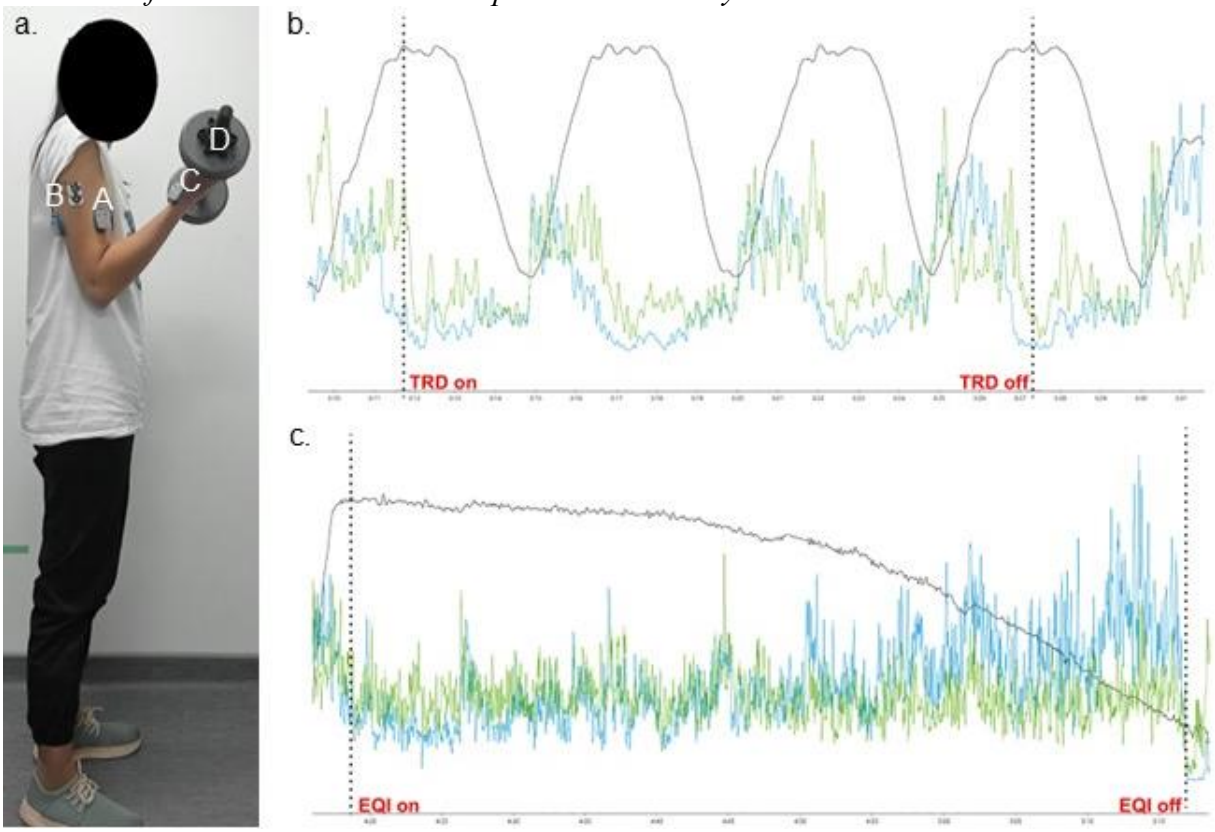
Note. Prior to the data collection session, participants completed 3 sessions in the lab (a.), where they were familiarised with the unilateral supinated bicep curl estimated 1-repetition maximum test (E-1RM; Canadian Society for Exercise Physiology) on both limbs (i), performed true baseline E-1RM tests, were familiarised with EQI resistance exercise (ii.), and practiced the TRD-RE and EQI-RE protocol (iii.). A minimum of 3 days later, participants completed the full resistance exercise protocol (b.). The first limb was prepped for surface electromyography (sEMG), then participants performed a standardised warm-up of 1, 2, and 3 unilateral bicep curl repetitions, followed by 2 sets of TRD-RE or EQI-RE to volitional fatigue. After 10-minutes of lying rest, the remaining limb was prepped for sEMG and then performed the standardised warm-up, followed by 2 sets of the remaining resistance exercise type (iv.). Shaded areas represent parts of additional investigations.

TRD-RE and EQI-RE. For both the TRD-RE and EQI-RE, participants were positioned 1-2 feet from a wall, with their feet shoulder width apart and parallel to the wall. The involved limb was positioned away from the wall, while the uninvolved limb was allowed to be abducted against the wall for support (Figure 2a.). After picking the dumbbell up off the floor, participants held the dumbbell at their side in a supinated grip, before initiating either resistance exercise type.

For the TRD-RE limb, participants performed continuous supinated dumbbell bicep curls using a metronome guided 1-second concentric and 2-second eccentric muscle action. Participants were instructed to perform repetitions from full elbow extension through at least ~130° of elbow flexion and were immediately and verbally corrected if they did not complete a repetition to full ROM. For each set, participants performed as many continuous repetitions as possible until they could no longer complete a single repetition, regardless of repetition velocity, and the set was ended if participants required excessive momentum to perform repetitions. For EQI-RE, participants were instructed to flex their elbow to ~130°, and then brace and maintain joint position for as long as possible without causing concentric or eccentric muscle actions (Oranchuk et al., 2020, 2021). Participants were told to then voluntarily resist the eccentric (lengthening) muscle action that would occur as they fatigued, for as long as possible, until the dumbbell returned to the starting position at their sides and/or contacted their thigh. If participants under or overshot the initial 130° position, their elbow angle was immediately and verbally corrected. Verbal encouragement was provided during the TRD-RE and EQI-RE.

Figure 2

Overview of Resistance Exercise Set-up and sEMG Analysis



Note. Set-up at starting position (a.) and example data trace overlay for TRD-RE (b.) and EQI-RE (c.). A= biceps brachii electrode placement, B = triceps brachii electrode placement, C = IMU placement, D = dumbbell corresponding to 70% of E-1RM. Onset and offsets are identified by dotted lines; EQI = Eccentric quasi-isometric set, TRD = Traditional isotonic set. Black line = vertical acceleration, blue line = biceps brachii linear envelope, green line = triceps brachii linear envelope. X-axis are not to scale.

Data Processing

sEMG and IMU data were sampled at 2000 Hz and 200 Hz, respectively, and recorded in MR3 Software (v. 3.18, Noraxon U.S.A). Data were then exported as .csv files and imported into LabChart 8 (ADInstruments Inc., Colorado Springs, USA), where custom macros were used to further bandpass filter (20-500 Hz; zero-phase lag Finite Impulse Response (FIR)), full-wave rectify, and subsequently lowpass filter (8Hz; FIR) the sEMG data to create a linear envelope.

Acceleration data were smoothed using a lowpass filter (5 Hz; FIR) and vertical acceleration was used to define the start and end of each TRD-RE and EQI-RE set. For TRD-RE, peak-to-peak analysis was used to define each repetition, with the first acceleration peak (i.e., peak elbow flexion) representing the start of the first repetition/set, and the last peak representing the end of the last repetition/set (Figure 2b). The start of each EQI-RE set was manually defined as the point after the initial elbow flexion where acceleration visually stabilized, while the end of each set was considered the lowest acceleration value where sEMG excitation was visibly present (Figure 2c; Kamen & Gabriel, 2010).

For each TRD-RE and EQI-RE set, the largest sEMG linear envelope value within a set was "LEpeak." The sEMG linear envelope of the biceps and triceps brachii was then integrated using the rectangular rule (iEMG), and the resulting iEMG value considered to be absolute "muscle activity" (iEMGabs). To calculate relative iEMG (iEMG%), the linear envelope was normalised to the peak value during set 1, and again integrated using the rectangular rule. To calculate antagonist co-activation ratio (CoA), the iEMG% of the triceps brachii was divided by the iEMG% of the biceps brachii. The time to perform each EQI-RE and TRD-RE set (i.e., onset to offset) was time under tension. Custom LabChart 8 macros were used to extract the variables which were then exported to Excel (Microsoft 365; Microsoft Corporation, Redmond, USA).

Statistical Analysis

Statistical analyses were performed in open-source Jamovi software (v 2.3.21) and SPSS 28 (IBM, Inc.; Armonk, USA). To compare the effects of TRD-RE vs. EQI-RE (type) on time under tension, biceps brachii excitation (LEpeak, iEMGabs, iEMG%), and triceps brachii-biceps brachii co-activation ratio (CoA) between males and females (sex) and across 2 sets (sets), 5

three-way mixed-factorial ANOVAs (2[type]*2[set]*2[sex]) with repeated measures on set and type were conducted. For main and interaction effects, α was based on a compromise power analysis.

As the current study was part of a larger project, and therefore not specifically powered to the outcomes, a compromise power analysis based on 27 participants for a 2(type) *2(set) interaction and within-subject main effects was performed to determine significance cut-offs (G*Power V. 3.1.9.2; Faul et al., 2007). Assuming a β/α probability ratio of 1, a power (1- β error probability) of 0.91 was achieved for a large effect size ($\eta_p^2 = 0.14$) when α = .21-.22. As such, 2 (type) *2(set) interactions were considered significant at $p \leq .22$, and Bonferroni corrected for post-hoc comparisons. Due to software limitations, sex was not included in compromise power calculations, and therefore three-way interactions should be interpreted cautiously. Assumptions of normality and homogeneity of variances were assessed with Shapiro-Wilk's and Levene's tests ($p < .05$; Field, 2009; Levene, 1960), respectively. Outliers and extreme outliers were defined as data points outside 1.5x and 3x the interquartile range, respectively. Due to expected variability in the data and modest sample size, outliers were left in the analysis; however, extreme outliers were replaced with the next lowest score + 1, as per (Field, 2009). Significant main and interaction effects were followed by simple main effects and pairwise contrasts. Small, medium, and large effect sizes (η_p^2) were generalised as .01, .06, and .14. Variability for all variables is presented as ± standard deviation (SD) unless otherwise specified.

Results

Of the 30 participants recruited, two participants were loss to attrition and did not complete the protocol, while one participant's data was excluded due to missing accelerometer

data. As such, 27 participants (14 male, 13 female), or 54 limbs were included in the final analysis. Demographics and body composition for each participant and limb are presented in Table 1. Both E-1RM and lean mass for TRD-RE and EQI-RE limbs were not statistically different. The resistance exercise protocol was performed with an actual relative load of 69.1 ± 2.3% and 69.5 ± 2.1% of E-1RM in males and females, respectively.

Table 1

Demographic and Descriptive Statistics for Study Sample and Assigned Limbs

	Male (*n* = 14)		**Female (*n* = 13)**	
Descriptives	M (SD)	Range	M (SD)	Range
Age (years)	21.9 (3.9)	18-30	25.1 (3.3)	19-32
Height (cm)	179.6 (9.9)	167.7-199.5	166 (5.7)	157-176
Weight (kg)	76.7 (16.9)	52.7-111.3	70.5 (17.7)	51.0-118.3
Lean Mass (kg)	34.9 (6.8)	26.3-49.8	26 (3.8)	20.7-34.2
Body Fat%	18.9 (8.9)	8.7-34.3	31.3 (9.7)	14.0-49.2
	Male		**Female**	
E-1RM[a] (lbs)	M (SD)	Range	M (SD)	Range
TRD-RE Limb (*n* = 27)	27.4 (5.8)	17.6-40.0	17.7 (4.0)	12.5-24.1
EQI-RE Limb (*n* = 27)	26.6 (5.2)	15.1-36.7	17.6 (4.0)	12.0-27.1
	Male		**Female**	
Lean Mass[a] (kg)	M (SD)	Range	M (SD)	Range
TRD-RE Limb (*n* = 27)	3.4 (0.8)	2.3-5	2.4 (0.6)	1.6-3.8
EQI-RE Limb (*n* = 27)	3.4 (0.7)	2.4-4.8	2.4 (0.6)	1.6-3.8
	Male		**Female**	
TRD-RE Repetitions	M (SD)	Range	M (SD)	Range
Set 1 (*n* = 27)	13.6 (2.6)	10-20	13.3 (2.3)	9-18
Set 2 (*n* = 27)	6.4 (2.2)	3-11	6.9 (1.7)	4-9

Note. M = mean, SD = standard deviation.

[a]TRD-RE and EQI-RE limbs were not statistically different based on paired sample t-test ($p > .05$).

As expected, data were not normally distributed, although no more than one extreme outlier was present for any variable; a total of 7 data points were replaced across all dependent

and independent variables. Traditional transformation methods (Log10, square root) did not meet the assumption of homogeneity of variance; thus, ANOVAs and interpretation were based on observed scores. Estimated marginal means, data normality, and homogeneity of variance after replacement are presented in Table 2.

Table 2

Means for Dependent Variables Split by Type, Set, and Sex

		TRD-RE	**EQI**
DV	Sex	Mean (SD)	Mean (SD)
LEpeak Set 1 [d]	M	1430.2 (529.4)	488.4 (368.7) [b]
µV	F	646.4 (263.2)	360.7 (178.3)
LEpeak Set 2 [c, d]	M	1222.79 (434.7)	542.6 (370.7)
µV	F	586.7 (180.7)	337.4 (147.4)
iEMGabs Set 1	M	18686.3 (7853.5)	17036.6 (13454.8)
µV /s	F	9571.8 (5518.3) [b]	17207.0 (11531.3)
iEMGabs Set 2 [c]	M	9544.9 (4906.2)	12776.6 (9481.3)
µV /s	F	5070.1 (2715.2) [b]	10909.7 (5793.8)
iEMG% Set 1	M	1303.3 (288.8)	3372.3 (1257.0)
%/s	F	1441.6 (402.9)	4487.5 (1752.3)
iEMG% Set 2	M	679.8 (324.1)	2620.9 (1273)
%/s	F	823.4 (272)	3085.8 (1215.8) [b]
CoA Set 1	M	1.3 (0.2)	1.2 (0.3) [b]
iEMG%/iEMG%	F	1.1 (0.2)	1.3 (0.2)
CoA Set 2 [c]	M	1.2 (0.3)	1.1 (0.4)
iEMG%/iEMG%	F	1.1 (0.1)	1.3 (0.4)
TUT Set 1	M	55.4 (12.7)	101.6 (35.7)
seconds	F	47.9 (8.3)	149.6 (67.7)
TUT Set 2	M	28.0 (10.8)	64.7 (22.1) [b]
seconds	F	28.4 (7.6)	92.0 (28.2)

Note. M = male, F = female, SD = standard deviation, DV = dependent variable, LEpeak = peak biceps brachii excitation, iEMGabs = absolute biceps brachii integrated surface electromyography, iEMG% = relative biceps brachii integrated surface electromyography, CoA = triceps brachii-biceps brachii co-activation ratio, TUT = time under tension.

[b] Significant Shapiro-Wilks Test ($p < .05$)

[c] Significant Levene's Test, TRD-RE ($p < .05$)

[d] Significant Levene's Test, EQI-RE ($p < .05$)

Effect of Resistance Exercise Type and Set

Time Under Tension. There were significant and very large main effects of type ($p <$ .001, $\eta_p^2 = 0.77$) and set ($p < .001$, $\eta_p^2 = .76$), with TRD-RE producing significantly less time under tension than EQI-RE (39.9 ± 1.75 vs. 101.97 ± 7.19 s) and set 1 producing significantly more time under tension than set 2 (88.6 ± 5.6 vs. 53.3 ± 2.8 s). There was also a significant and very large type*set interaction ($p = .002$, $\eta_p^2 = 0.324$), with simple effects and pairwise contrasts indicating that TRD-RE produced significantly less time under tension than EQI-RE during set 1 ($p < .001$, $\eta_p^2 = 0.7$) and set 2 ($p < .001$, $\eta_p^2 = 0.82$), while set 1 produced more time under tension than set 2 when performing TRD-RE ($p < .001$, $\eta_p^2 = 0.88$) or EQI-RE ($p < .001$, $\eta_p^2 = 0.63$).

LEpeak. There were significant and large main effects for type ($p < .001$, $\eta_p^2 = 0.83$) and set ($p = .01$, $\eta_p^2 = 0.24$), with TRD-RE resulting in higher LEpeak values than EQI-RE (971.5 ± 71.0 vs. 432.3 ± 55.1 μV) and set 1 resulting in higher LEpeak values than set 2 (731.5 ± 64.3 vs. 672.4 ± 54.2 μV). There was also a significant type*set interaction, ($p = .002$, $\eta_p^2 = 0.32$); simple effects and pairwise contrasts indicated TRD-RE produced significantly greater LEpeak compared to EQI-RE during set 1 ($p <.001$, $\eta_p^2 = 0.83$) and set 2 ($p < .001$, $\eta_p^2 = 0.76$). However, set 1 only produced significantly higher LEpeak than set 2 when performing TRD-RE ($p = .002$, $\eta_p^2 = 0.317$), and there were no significant differences between sets when performing EQI-RE ($p = .398$).

iEMGabs. There were significant and medium-large main effects for type ($p = .025$, $\eta_p^2 = 0.19$) and set ($p < .001$, $\eta_p^2 = 0.67$), with TRD-RE producing significantly less iEMGabs than

EQI-RE (10718.3 ± 999.3 vs. 14482.5 ± 1921.3 μV /s), and set 1 producing significantly more iEMGabs than set 2 (15625.4 ± 1652.6 vs. 9575.3 ± 1041.5 μV /s).

CoA. There were no main or interaction effects of type and/or set for CoA.

iEMG%. There were significant and modest-very large main effects for type ($p < .001$, $\eta p^2 = 0.792$) and set ($p < .001$, $\eta_p^2 = 0.732$), with TRD-RE producing significantly less iEMG% than EQI-RE (1062 ± 57 vs. 3391.7 ± 252.3 %/s), and set 1 producing significantly more iEMG% than set 2 (2651.2 ± 163.4 vs. 1802.5 ± 130.1 %/s). There was also a significant and large type*set interaction, ($p < .008$, $\eta_p^2 = 0.25$), with simple effects and pairwise contrasts indicating that TRD-RE produced significantly less iEMG% than EQI-RE during set 1 ($p < .001$ $\eta_p^2 = 0.85$) and set 2 ($p < .001$, $\eta_p^2 = 0.6$), while set 1 produced significantly more iEMG% than set 2 when performing TRD-RE ($p < .001$, $\eta_p^2 = 0.78$) or EQI-RE ($p < .001$, $\eta_p^2 = 0.77$).

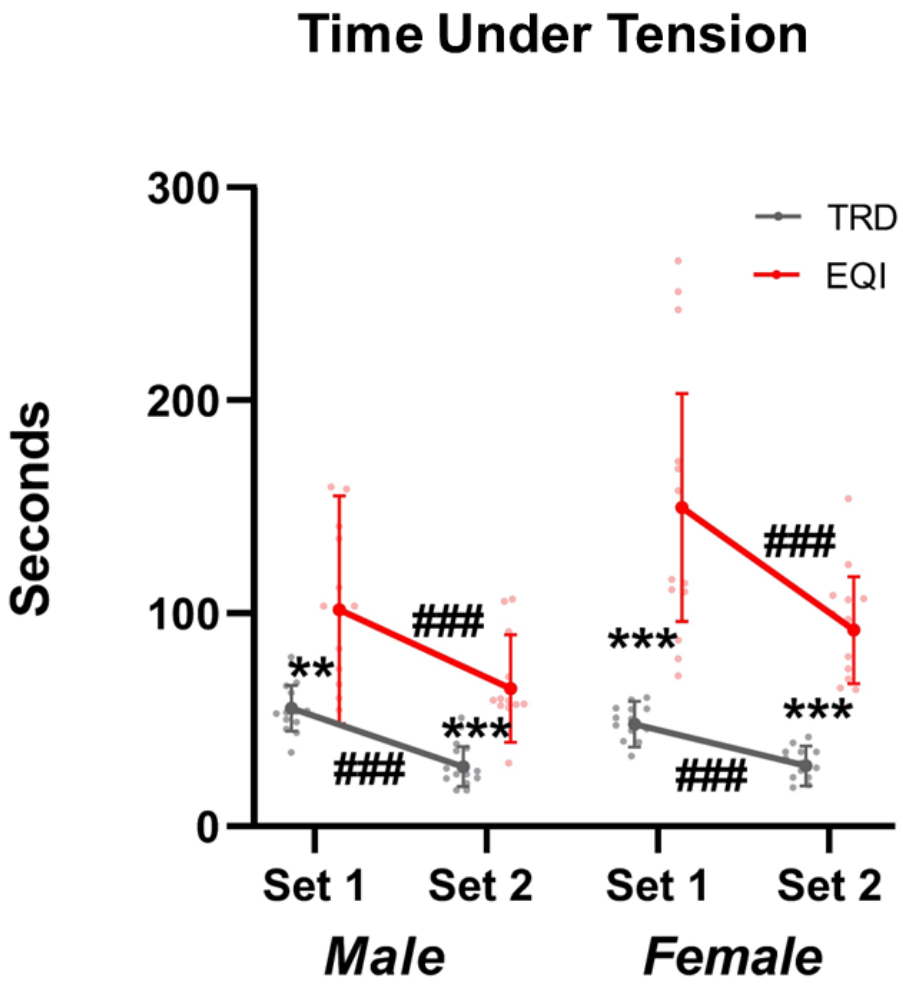
Effect of Sex

Time Under Tension. There was a significant and large main effect of sex ($p = .041$, $\eta_p^2 = .157$), with males producing significantly less time under tension than females (62.4 ± 5.5 vs. 79.5 ± 5.7 s). Furthermore, there was a large and significant type*sex ($p = .006$, $\eta_p^2 = .265$), and sex*type*set interaction ($p = .049$, $\eta_p^2 = 0.15$). Simple effects and pairwise contrasts indicated there were no sex-differences in time under tension with TRD-RE ($p = .321$). However, males produced significantly less time under tension than females when performing EQI-RE ($p = .015$, $\eta_p^2 = 0.22$). For the sex*type*set interaction, when performing TRD-RE, males produced significantly more time under tension than females during set 1 ($p = .085$, $\eta_p^2 = 0.12$), but there were no sex-differences during set 2 ($p = .915$). When performing EQI-RE, however, females

produced significantly greater time under tension than males during set 1 (p = .028, η_p^2 = 0.18), and set 2 (p = .009, η_p^2 =.24, Figure 3, Table 2).

Figure 3

Interaction of Resistance Exercise Type and Set Split by Sex for Time Under Tension

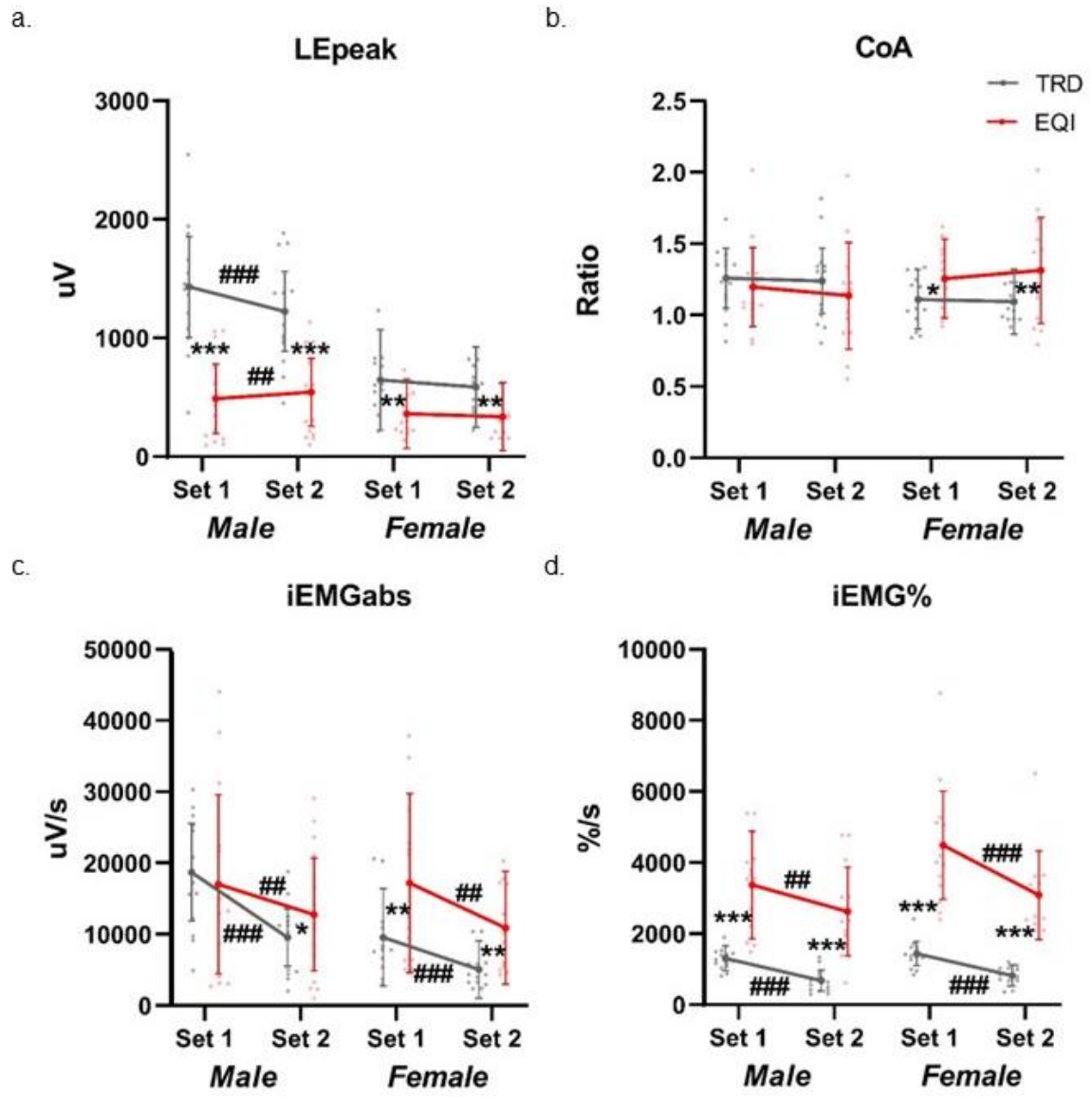


Note. ** $p \leq .05$, *** $p \leq .01$ between type. ### $p \leq .01$ between sets. Symbols represent estimated marginal means. Error bars denote standard deviation. Individual dots represent observed data points. Red = EQI-RE, grey = TRD-RE. For simplicity, significant sex-differences are not indicated on figures; *p*-values are Bonferroni corrected as in SPSS 28.

LEpeak. There was a significant and large main effect of sex ($p = .001$, $\eta_p^2 = 0.36$), with males producing higher LEpeak values than females (482.8 ± 84.3 vs. 921.0 ± 81.2 μV). Furthermore, there were significant and large type*sex ($p < .001$, $\eta_p^2 = 0.546$), and type*set*sex interactions ($p = .017$, $\eta_p^2 = 0.21$). Simple effects and pairwise contrasts indicated that males produced significantly higher LEpeak than females when performing TRD-RE ($p < .001$, $\eta_p^2 = 0.5$) or EQI-RE ($p = .143$, $\eta_p^2 = 0.08$), while TRD-RE produced higher LEpeak than EQI-RE for both males ($p < .001$, $\eta_p^2 = 0.848$) and females ($p = .001$, $\eta_p^2 = 0.360$). When this interaction was broken down by set, TRD-RE produced higher LEpeak than EQI-RE during set 1 and set 2, regardless of sex ($p = .002$ to $p < .001$, $\eta_p^2 = 0.302$ to $\eta p^2 = 0.856$). However, when performing EQI-RE, there was no significant difference in LEpeak between males and females during set 1 ($p = 0.27$), although males produced significantly greater LEpeak than females during set 2 ($p = .074$, $\eta_p^2 = .12$). Additionally, while set 1 produced higher LEpeak than set 2 when males performed TRD-RE ($p = .001$, $\eta_p^2 = .37$) or EQI-RE ($p = .039$, $\eta_p^2 = .16$), in females there was no significant difference between set 1 and set 2 when performing TRD-RE ($p = .30$) or EQI-RE ($p = .376$; Figure 4a, Table 2).

Figure 4

Interaction of Resistance Exercise Type and Set Split by Sex for Biceps Brachii



Note. LEpeak (linear envelope peak; a.), CoA (triceps brachii-biceps brachii co-activation ratio; b.) iEMGabs (absolute biceps brachii integrated surface electromyography; c.), and iEMG% (relative (normalised) biceps brachii integrated surface electromyography; d.). * $p \leq .22$, ** $p \leq .05$, *** $p \leq .01$ between type. ## $p \leq .05$, ### $p \leq .01$ between sets. Symbols represent estimated marginal means. Error bars denote standard deviation. Individual dots represent observed data points. For simplicity, significant sex-differences are not indicated on figures; *p*-values are Bonferroni corrected as in SPSS 28.

CoA. There was no main effect of sex, however, there were significant and small-large type*sex (p = .039 η_p^2 = .16) and type*set*sex interactions (p = .172, η_p^2 = .07). Simple effects and pairwise contrasts indicated that, when performing TRD-RE, males had greater CoA than females (p = .075, η_p^2 = 0.12), however, there were no sex-differences when performing EQI-RE (p = .338). In females, EQI-RE produced significantly larger CoA than TRD-RE (p = .048, η_p^2 = 0.15), while in males, CoA was not significantly different between TRD-RE and EQI-RE (p = .332). Broken down by set, when performing TRD-RE, females produced greater CoA than males during set 1 (p = .076, η_p^2 = 0.12) and set 2 (p = .114, η_p^2 = 0.10). When performing EQI-RE, however, there were no sex-differences during set 1 (p = .594) or set 2 (p = .230). Furthermore, in females, TRD-RE produced less triceps brachii CoA than EQI-RE during set 1 (p = .108 η_p^2 = 0.10) and set 2 (p = .034, η_p^2 = 0.17), however, in males, there were no significant differences between TRD-RE and EQI-RE during set 1 (p = .463) or set 2 (p = .277; Figure 4b, Table 2).

iEMGabs. There was a significant and moderate main effect of sex (p = .001, η_p^2 = 0.36), with males producing significantly more iEMGabs than females (14511.1 ± 1823.4 vs. 10689.7 ± 1892.2 μV/s). Furthermore, there was a significant and modest type*sex (p = .07, η_p^2 = .13) and type*set*sex interactions (p = .015, η_p^2 = 0.21). Simple effects and pairwise contrasts indicated that males produced significantly greater iEMGabs than females during TRD-RE (p = .002 η_p^2 = 0.67), however, there was no significant sex-difference in iEMGabs during EQI-RE (p = .827). Furthermore, TRD-RE produced significantly less iEMGabs than EQI-RE in females (p = .006, η_p^2 = 0.26), but in males there was no significant difference between TRD-RE and EQI-RE (p = .72). Broken down by set, when performing TRD-RE, males produced greater iEMGabs than females during set 1 (p =.002, η_p^2 = 0.32) and set 2 (p = .008, η_p^2 = 0.25), however, when

performing EQI-RE, there were no significant differences between males and females during set 1 (p = .972) or set 2 (p = .546). Additionally, in females, TRD-RE produced less iEMGabs than EQI-RE during set 1 (p = .017 η_p^2 = 0.2) and set 2 (p = .003, η_p^2 = 0.3). In males, iEMGabs during set 1 was not statistically different when performing TRD-RE or EQI-RE (p = .570), although TRD-RE produced significantly less iEMGabs than EQI-RE during set 2 (p = .07, η_p^2 = 0.13; Figure 4c, Table 2).

iEMG%. There was a significant and modest main effect of sex, (p = .105), with males producing significantly less iEMG% than females (1994.1 ± 192.2 vs. 2459.6 ± 199.4 %/s). Furthermore, there were small-large type*sex (p = .186, η_p^2 = .07), set*sex (p = .13, η_p^2 =.09), and type*set*sex interactions (p = .048, η_p^2 = 0.15). Simple effects and pairwise contrasts indicated there were no sex-differences in iEMG% when performing TRD-RE (p = .228), however, females produced more iEMG% than males when performing EQI-RE (p = .13, η_p^2 = 0.09). Regardless of resistance exercise type, females produced significantly greater iEMG% than males during set 1 (p = .067, η_p^2 = 0.13), but there were no sex-differences during set 2 (p = .253). When considering type, set, and sex, performing TRD-RE did not result in significant sex-differences in iEMG% during set 1 (p = .312) or set 2 (p = .226). When performing EQI-RE, however, females produced significantly greater iEMG% than males during set 1 (p = .068, η_p^2 = 0.13), although there were no sex-differences during set 2 (p = .342; Figure 4d, Table 2).

Discussion

The current study compared the acute muscle fatigue response across 2 sets of traditional isotonic (TRD-RE) and eccentric quasi-isometric resistance exercise (EQI-RE) of the elbow flexors, and between the sexes. In line with our hypothesis, EQI-RE produced significantly and

substantially more time under tension, iEMGabs, and iEMG% than TRD-RE, while TRD-RE led to higher LEpeak than EQI-RE. Furthermore, LEpeak, iEMGabs, iEMG%, and time under tension significantly decreased from set 1 to set 2, while males produced significantly higher LEpeak and iEMGabs, but significantly lower iEMG% and time under tension than females. Unlike our hypothesis, resistance exercise type, set, or sex did not individually affect CoA. Surprisingly, follow-up comparisons revealed several type*set*sex interactions that were not considered by our initial hypothesis, which will be addressed in the subsequent discussion.

The current study corroborates that when intensity is matched, EQI-RE produces more time under tension than TRD-RE. While this was assumed prior to the current study (Oranchuk et al., 2019b), only one study had directly compared EQI-RE time under tension to another form of resistance exercise (eccentric knee extension); when resistance exercise volume was equated by angular impulse, average time under tension for eccentric resistance exercise of was 135 ± 72 s, whereas average time under tension for EQI-RE was 242 ± 132 s (Oranchuk et al., 2020). Although inferential comparison was not reported, this represents a 79% and significant (paired t-test; $p < .05$) increase in time under tension when performing EQI-RE. Comparatively, there was also a significant and substantial time under tension difference between resistance exercise type in the current study, with EQI-RE producing 256% more time under tension than TRD-RE. In line with our hypothesis, when this difference was broken down by sex, females produced 45% more time under tension than males across both sets (241.6 vs. 166.3 s; Table 2). Based on our previous work (Chapter 2) and the broader muscle fatigue literature, this result is not unexpected, as females are typically more fatigue resistant than males during sustained low-velocity and/or isometric muscle actions of the elbow flexors (Hunter, 2016b, 2016a). If characterising EQI-RE as both isometric and low-velocity (Oranchuk et al., 2019b), sex-

difference in fatiguability were present in the current study, as females were able to sustain EQI-RE set 1 and set 2 longer than males.

Previous research suggests that males and females experience similar relative reductions in isometric torque (Senefeld et al., 2013), peak concentric torque (Gentil et al., 2017), time to task failure (Yoon et al., 2015), and concentric power (Senefeld et al., 2013) after and across multiple sets of concentric elbow flexions, although these studies used low training intensities well-below traditional resistance exercise practices (e.g., 20% maximal isometric torque). Conversely, when utilising a self-selected repetition velocity, and a similar intensity (75% 1-RM) and inter set rest period (2-minutes) as the current study, Ratamess et al. (2012) observed a significant reduction in repetitions performed by men, but not women, after 2 sets of bench press. Similarly, Voskuil et al. (2024) observed that resistance trained males performed significantly less repetitions and exerted less isometric strength and associated sEMG amplitudes compared to females across 4 sets of unilateral bicep curls to volitional fatigue at 50% 1RM. In comparison, the current study did not reveal sex-differences in the number of TRD-RE repetitions performed during set 1 or set 2 (Table 2), nor differences in normalised muscle activity. Indeed, while the presence of time under tension, but not repetition differences between males and females during TRD-RE in the current study could be explained by differences in repetition cadence with neuromuscular fatigue (e.g., Refalo et al., 2023), the current study also revealed no sex-differences in normalised muscle activity during TRD-RE, which may suggest that observed differences in muscle fatigue are due to sex-related contractile mechanisms (Nuzzo, 2024). However, when sEMG data were broken down by type, set and sex, a complex muscle excitation response appears to be present.

Under the broad assumption that motor unit recruitment threshold is inversely related to size, and greater sEMG amplitude indicates higher threshold motor units are being excited (Henneman, 1957; Henneman & Olsen, 1965; Kamen & Gabriel, 2010b; Lawrence et al., 1983), LEpeak data suggests that TRD-RE results in greater excitation of high threshold motor units than EQI-RE. Notably, females displayed similar LEpeak and iEMG values between sets for both TRD-RE and EQI-RE, whereas males LEpeak significantly decreased between sets when performing TRD-RE, and slightly increased between sets for EQI-RE. Coupled with a high initial LEpeak value, the large set-to-set decrease in males could suggest greater initial involvement of high threshold motor units in set 1 (Bigland-Ritche et al., 1983; Carr et al., 2021; Carr & Ye, 2020), which is followed by either a large reduction in the number, size, and/or firing rate of motor units during set 2. Furthermore, the smaller drop-off in males' iEMGabs and slight increase in males' LEpeak from set 1 to set 2 during EQI-RE could suggest EQI-RE progressively, albeit slightly, recruited additional and presumably high threshold motor units in males with multiple sets (Adam & De Luca, 2003; Carr et al., 2021). In contrast, the lack of set-to-set differences and similar behaviour of females' LEpeak for both TRD-RE and EQI-RE could suggest that females utilise similar motor unit recruitment strategies regardless of resistance exercise type. As is the case with our previous work, however, specific motor unit behaviours cannot be revealed with the current methods.

Previous works have suggested that males could experience greater decreases in muscle excitability during isotonic resistance exercise for the elbow flexors (Nuzzo et al., 2023; Voskuil et al., 2024). Although the current study suggests that EQI-RE may not excite motor units as quickly as TRD-RE, when compared to the large set-to-set decrease in LEpeak for TRD-RE, the slight increase in LEpeak for males when performing EQI-RE may suggest that males are better

able to maintain excitability (e.g., Adam & De Luca, 2003) with EQI-RE, and therefore are less fatigued relative to TRD-RE. As the ability to excite high threshold motor units would theoretically benefit muscle force output, the data of the current study would fit with the results of Oranchuk et al. (2020), who observed a smaller decrease in maximal voluntary isometric torque in resistance trained males after performing EQI-RE. Therefore, these data may loosely support claims that EQI-RE results in less fatigue than isotonic or isometric resistance exercise (Seedman, n.d.-a, n.d.-b). While muscle fatigue can limit performance, it is relevant to note that it represents an important stimulus for creating neuromuscular and muscle morphological adaptations (Hunter, 2016b). In the context of sport specific training or strength and conditioning, the principle of specificity would require high-threshold and highly fatigable motor units to be sufficiently stimulated and recruited to create progressive overload and adaptation. As discussed by Oranchuk et al. (2019), collectively these data may therefore suggest that EQI-RE have limited application for improving the neuromuscular aspects of muscle strength or power, as these motor units would experience a reduced stimulus when performing EQI-RE compared to TRD-RE.

As EQI-RE is purported to result in greater agonist-antagonist co-contraction/activation, and subsequent improvements in muscle stiffness, stabilisation, and coordination (Morrison, 2016; Oranchuk et al., 2019b; Seedman, n.d.-a, n.d.-b; Sinicki, 2019), we examined iEMG CoA of the triceps brachii and biceps brachii. The current study did not reveal a main effect of resistance exercise type on CoA. When data were examined within each sex, however, CoA was higher during EQI-RE in females only, and males in the current study had higher CoA than females when performing TRD-RE but not EQI-RE. Given studies that observed no difference in CoA and/or similar triceps brachii sEMG amplitude between sustained holding and yielding

isometrics, but differences in time to task failure (Rudroff et al., 2007, 2011; Schaefer & Bittmann, 2017), the lack of CoA differences between TRD-RE and EQI-RE are not necessarily surprising. However, the observed sex-differences in CoA when performing TRD-RE contrasts with the paucity of research suggesting that females may exert greater and/or similar triceps activation than males when performing sub-maximal isokinetic elbow flexions. For example, researchers have suggested that the increased metabolic and neuromuscular demand of recruiting additional motor units of the antagonist musculature may be detrimental to muscular endurance (Jodoin et al., 2023a; Schaefer & Bittmann, 2017; Yoon et al., 2013). As females produced substantially more time under tension than males during EQI-RE despite having greater CoA, and males produced equivalent, if not longer time under tension during TRD-RE while having greater CoA than females, the current study suggests a limited contribution of CoA to sex-differences in muscle fatigue during TRD-RE or EQI-RE.

To remove the influence of external factors that may affect results irrespective of sex, such as muscle strength, body composition, height, etc. (Halaki & Ginn, 2012) and examine relative differences, we examined relative muscle activity (iEMG%) alongside absolute muscle activity (iEMGabs). In the current study, iEMG% was not statistically different between males and females when performing TRD-RE and from these data, it would appear that sex-differences in iEMGabs during TRD-RE could therefore be attributed to differences in strength and/or anthropometry between males and females. With EQI-RE, however, females produced significant, albeit slightly greater iEMG% during set 1 even though males and females were not statistically different for iEMGabs. As differences were present when expressed relatively, this could suggest that there are sex-specific mechanisms involved in maintaining force output and motor unit recruitment during EQI-RE, but not TRD-RE. As such, sex-differences in iEMG% are

perhaps due to differences in motor unit recruitment strategies or substrate metabolism between males and females (Hunter, 2014; Nishikawa et al., 2017; Pradhan et al., 2020), which would not be revealed using the current methods. Beyond suggesting that factors intrinsic of sex may influence EQI-RE more so than TRD-RE, further speculation is beyond the scope of the current investigation.

The results of the current study lend initial support to our theory that chronic EQI-RE will lead to sex-differences in muscle hypertrophy and strength that would be different from TRD-RE. Current data suggests that untrained males and females experience similar relative increases in muscle mass from chronic TRD-RE (Roberts et al., 2020), although females may have a small advantage when it comes to improving strength (Roberts et al., 2020). Assuming mechanical tension or mechanotransduction is the primary driver of muscle hypertrophy (Haun et al., 2019; Schoenfeld, 2010) the limited sex-differences in time under tension when performing acute TRD-RE in the current study would fit with these data, as relative volume would theoretically be similar across a resistance exercise program. As females exerted substantially more time under tension and absolute muscle activity during EQI-RE compared to males and TRD-RE, however, it remains reasonable that females may experience greater relative muscle hypertrophy (Schoenfeld, Ogborn, et al., 2017) than males with EQI-RE. Furthermore, while EQI-RE produced significantly smaller LEpeak than TRD-RE for males (set 1: -293%, set 2: -225%) and females, the magnitude of difference was much smaller in females (set 1: -180%, set 2: -174%), suggesting that there may be more significant differences between TRD-RE and EQI-RE in males with respect to neuromuscular and/or strength outcomes.

There are important limitations of the current study that should be considered when interpreting our results. Although EQI-RE and TRD-RE limbs were not statistically different with respect to lean mass and strength, the left arm may be more susceptible to electrocardiogram (ECG) contamination than the right arm, while neurological effects resulting from resistance exercise by the first limb may carry over to the second limb (Aboodarda et al., 2016; Halperin et al., 2014). As limb assignment was counterbalanced, and the overall contribution of ECG to signal power is relatively small (Kamen & Gabriel, 2010b), however, it is expected that this would have minimal effect on our results. Furthermore, rapid changes in muscle length underneath bipolar sEMG electrodes can contribute to observed LEpeak and iEMG values (Kamen & Gabriel, 2010b), which could affect TRD-RE to a greater degree than EQI-RE due to repeated and higher repetition velocity. Additionally, the current study was limited to two resistance exercise sets using untrained individuals, who had only recent exposure to TRD-RE and EQI-RE. As such, these results may not reflect those of resistance trained or more experienced individuals, or those that might be expected for intensities above or below 70% 1-RM. The current study does have the advantage of being the first examination of EQI-RE using an ecologically valid model of resistance exercise, and not an isokinetic dynamometer (e.g., Henderson et al., 2023; Oranchuk et al., 2020, 2021). Most importantly, the current study does not address nor imply that EQI-RE or TRD-RE are more advantageous for muscle hypertrophy or muscle strength, as sEMG is poorly associated with muscle hypertrophy (Vigotsky et al., 2022).

Although the current study does not address long-term adaptations to TRD-RE or EQI-RE it has meaningful implications for practice. For one, it is apparent that males and females have different fatigue responses to TRD-RE and EQI-RE, and that the number of repetitions or

sets performed may be relevant depending on the sex of the individual and desired training effects. With 2-minutes of rest between sets, males accrue less time under tension than females during EQI-RE and may experience a more significant decline in TRD-RE time under tension than females when performed to volitional fatigue. Additionally, males may require multiple sets of EQI-RE to recruit the entirety of the motoneuron pool, and experience a larger drop-off in muscle excitation after 2 sets of TRD-RE. Furthermore, although the current study only had participants perform 2 sets of TRD-RE and EQI-RE, there is reason to believe that performing EQI-RE at the end of a resistance exercise session may have significantly different effects than what was observed in the current study. For example, recent work (Jodoin et al., 2023b) suggests that females may lose their fatiguability advantage over males when sustained isometric muscle actions are preceded by maximal eccentric muscle actions, which is associated with a significant increase in female antagonist activation. It should be noted that the EQI-RE data in the current study, as well as in previous studies (Henderson et al., 2023; Oranchuk et al., 2020, 2021), has been highly variable, however, this is not unexpected in resistance exercise studies of untrained individuals (Mann et al., 2014), and thus individual responses to EQI-RE may vary greatly.

Conclusion

The current study suggests there are relevant sex and set differences in the sEMG and time under tension response to TRD-RE and EQI-RE of the biceps brachii and triceps brachii that are theoretically relevant for long-term muscle hypertrophy. Overall, TRD-RE likely results in quicker recruitment and fatigue of motor units compared to EQI-RE, with similar and/or small differences in time under tension and relative muscle activation between males and females. Conversely, females appear to produce significantly more time under tension, absolute and relative muscle activity than males during EQI-RE, along with greater triceps brachii-biceps

brachii CoA, suggesting the involvement of fatigue mechanisms intrinsic of sex. More generally, males and females completed the same number of repetitions when performing unilateral isotonic dumbbell curls, although time under tension varied slightly. Based on these findings, future studies should examine whether these acute sex-differences would manifest in long-term muscle hypertrophy, strength, and/or neuromuscular adaptations between males and females, TRD-RE and EQI-RE.

Chapter 4: Exploring the Effects of Sex and Volume on Muscle Thickness and Estimated One-Repetition Maximum Following 8-weeks of Unilateral Traditional Isotonic and Eccentric Quasi-Isometric Resistance Exercise of the Elbow Flexors

Author Note and Contributions

While the previous chapters add sex comparisons to, and almost doubles the current body EQI-RE literature, the most pertinent outcomes of resistance exercise—muscle hypertrophy and strength had yet to be investigated. Based on the observed *acute* sex-differences in muscle fatigue from Chapter 2 and Chapter 3, there was mechanistic reason to believe that this may result in relative sex-differences in muscle hypertrophy and strength that were dependent on resistance exercise type (i.e., TRD-RE vs. EQI-RE). As such, the following chapter utilises the same resistance exercise model that sex-differences were observed with in Chapter 3, while also being the first study to investigate the hypertrophic and strength response to EQI-RE. Furthermore, the study explores emerging areas of discussion regarding the relationships of resistance exercise volume, muscle mass, and strength adaptations, and how sex may influence these relationships.

Zachariah J. Henderson conceptualised, designed, piloted methods, assisted with data collection and processing, analysed data, interpreted data, and drafted the chapter.

Abstract

As a novel, low-velocity resistance exercise method, eccentric quasi-isometric resistance exercise (EQI-RE) results in greater time under tension than traditional isotonic resistance exercise (TRD-RE) and is surmised to increase muscle mass and strength. However, females may be more fatigue resistant than males when performing acute EQI-RE, which could lead to long-term differences in time under tension and resistance exercise volume. At present, studies have yet to compare muscle hypertrophy or strength improvements following TRD-RE or EQI-RE training, and whether sex-differences exist in these outcomes. Twenty-two (n = 13 females) untrained individuals completed ~8-weeks of effort matched unilateral TRD-RE and EQI-RE of the elbow flexors. Muscle thickness and estimated one-repetition maximum (E-1RM) were evaluated before and after training. TRD-RE produced significantly larger relative increases in muscle thickness (2.7%, p =.004) and E-1RM (6.6%, p = .001) than EQI-RE. Although females accrued greater resistance exercise volume than males across the TRD-RE and EQI-RE training, there were no relative sex-differences in muscle thickness or E-1RM improvements (p > .25). Sex-differences in fatiguability may therefore manifest in differences in resistance exercise volume between males and females after 8-weeks of TRD-RE and EQI-RE of the elbow flexors, but this does not lead to relative differences in muscle thickness or E-1RM improvements. Although EQI-RE did produce significant increases, TRD-RE of the elbow flexors appears more effective at increasing muscle thickness and E-1RM.

Key words: Resistance training, b-mode ultrasound, bicep curls

Introduction

As fundamental components of exercise prescription, the principles of specificity and individualisation suggest that exercise selection or programing should address the desired component of fitness or outcomes, and that expected adaptations and/or needs of an individual will vary (Klavora & Locke, 2018; Prentice, 2017). With respect to resistance exercise, recent attention has been given to the potential influence of sex on strength and hypertrophy adaptations; data suggests that males and females do not substantially differ in relative hypertrophy potential to a given resistance exercise program, although females may experience slightly greater relative strength increases, especially for upper-body musculature (Nuzzo, 2022; Roberts et al., 2020). Despite this, there is continued interest and debate regarding the relevance of an individual's sex and/or gender in the context of resistance exercise prescription, especially when it comes to differences in male and female physiology (e.g., Colenso-Semple et al., 2023; Henderson & Scribbans, 2020; Nimphius, 2019; Nolan et al., 2024; Nuzzo, 2022; Parsons et al., 2021). Apart from differences in sex-hormones and menstruation, males and females typically differ in muscle fibre type distribution and size (Nuzzo, 2024), muscular endurance (Hunter, 2014, 2016b, 2016a), and absolute strength (Nuzzo, 2022). Many of these differences, however, vary and are specific to the muscle, muscle action (i.e., eccentric vs. isometric), and the intensity of the task (Hunter, 2014; Nuzzo, 2022).

Regardless of sex, improvements in overall health, muscle strength, and muscle mass can be achieved in response to a variety of resistance exercise modalities (Currier et al., 2023; Lixandrão et al., 2018; Oranchuk et al., 2019a) and "muscle strengthening" activities (World Health Organization, 2022). That being said, isotonic (alternating eccentric and concentric muscle actions) resistance exercise is typically studied, recommended, and prescribed to improve

strength and stimulate muscle growth (Currier et al., 2023; Ratamess et al., 2009). Recent work, however, suggests that the concentric component of isotonic resistance exercise may contribute little to training related improvements in muscle hypertrophy and strength relative to the eccentric component (Sato et al., 2022). As such, to optimise improvements in muscle strength and muscle mass (i.e., hypertrophy), there has been increased interest in research on resistance exercise at long muscle lengths and/or that augments the eccentric component of isotonic resistance exercise (Kassiano et al., 2023; Nuzzo et al., 2023; Oranchuk et al., 2019a, 2019b).

Eccentric quasi-isometrics (EQIs) are a low-velocity resistance exercise technique suggested to elicit the hypertrophy benefits of traditional isotonic resistance exercise (TRD-RE), while minimizing muscle fatigue and high levels of torque associated with high-velocity resistance exercise (Oranchuk et al., 2019b). By performing a “holding” isometric muscle action until positional fatigue, and then voluntarily resisting the resulting eccentric muscle action, EQI-RE produces significantly more time under tension than TRD-RE (Chapter 3). The large quantity of mechanical tension produced during EQI-RE is theorised to result in meaningful muscle hypertrophy (Oranchuk et al., 2019b), while practitioners also purport greater motor unit recruitment and strength development using the EQI concept (e.g., Morrison, 2016; Seedman, n.d.; Sinicki, 2019), despite a paucity of research supporting these claims.

The suggestion that EQI-RE would meaningfully improve isotonic strength would contravene the principle of specificity, in that the velocity of EQI-RE would have little overlap with the velocity and neuromuscular demands of expressing strength during isotonic exercise. For this reason, researchers have cast doubt on the relevance of EQI-RE for improving strength or power for during higher velocity movements (Oranchuk et al., 2019b). Furthermore, research

in our laboratory suggests no inherent neuromuscular benefit of acute EQI-RE on its own (Henderson et al., 2023; Chapter 2), or when compared to TRD-RE (Chapter 3). Males and females do, however, appear to have differing neuromuscular and fatigue responses to TRD-RE and EQI-RE (Chapter 3). Specifically, sex-differences in resistance exercise volume (total repetitions and time under tension) are much greater when performing EQI-RE compared to TRD-RE. Based on the positive relationship of resistance exercise-volume with muscle hypertrophy (Schoenfeld, Ogborn, et al., 2017), the magnitude of mechanical tension and time under tension are likely the main drivers of morphological adaptations to EQI-RE (Henderson et al., 2023; Oranchuk et al., 2019b). As such, it seems reasonable to suggest that acute sex-differences in resistance exercise volume could manifest in long-term differences in EQI-RE adaptations between males and females. At present, however, no studies have examined long-term hypertrophy or strength improvements to EQI-RE or compared them to TRD-RE.

The purpose of the current study was threefold. Primarily, the current study sought to determine if ~8-weeks of EQI-RE produced comparable changes in muscle mass (muscle thickness) and strength (estimated one-repetition maximum; E-1RM) to TRD-RE in untrained individuals, and whether sex-differences are present in these changes. For both TRD-RE and EQI-RE, the study also explored the relationship between changes in muscle thickness and E-1RM, and the relationship between resistance exercise volume (total repetitions and total time under tension), muscle thickness, and strength changes, and if these relationships were moderated by sex. For the primary objective, it was expected that TRD-RE and EQI-RE would produce significant relative increases in muscle thickness E-1RM after ~8-weeks of training (expressed as a change score relative to pre-testing; % change), with TRD-RE and EQI-RE producing comparable increases in muscle thickness, but TRD-RE resulting in a greater increases

in E-1RM. Based on our previous work indicating females produced greater time under tension during the same EQI-RE, it was hypothesised that females would experience greater muscle thickness % change and E-1RM % change than males for EQI-RE, however, we anticipated no meaningful sex-differences for TRD-RE.

Methods

Experimental Overview

A pre-post, between groups, unilateral design (Macinnis et al., 2017) was used to compare changes in elbow flexor muscle thickness and E-1RM after ~8-weeks of TRD-RE and EQI-RE between males and females. Using a Latin square (Portney et al., 2015) based on hand dominance (as assessed using the Edinburgh Handedness Inventory; Oldfield, 1971) as well as order of completion, each participant's limbs were assigned to either TRD-RE or EQI-RE. For the current study, b-mode ultrasonography and the CSEP E-1RM protocol (Canadian Society for Exercise Physiology, 2013) were used to evaluate elbow flexor muscle thickness and supinated dumbbell bicep curl E-1RM of each limb, before and after completion of the TRD-RE and EQI-RE training. All pre-post measures were collected at the same time of day (± 2 hours) when scheduling permitted. The study was approved by the University of Manitoba Research Ethics Board (REB 1; HE2023-0066), and all participants provided informed consent prior to participation.

Participants

A total of 30 male and female (sex assigned at birth) participants were recruited for the current study. Participants were eligible to participate if they 1) were between 18-35 years old, 2) were free of acute and/or chronic musculoskeletal pain or injuries that would affect their ability

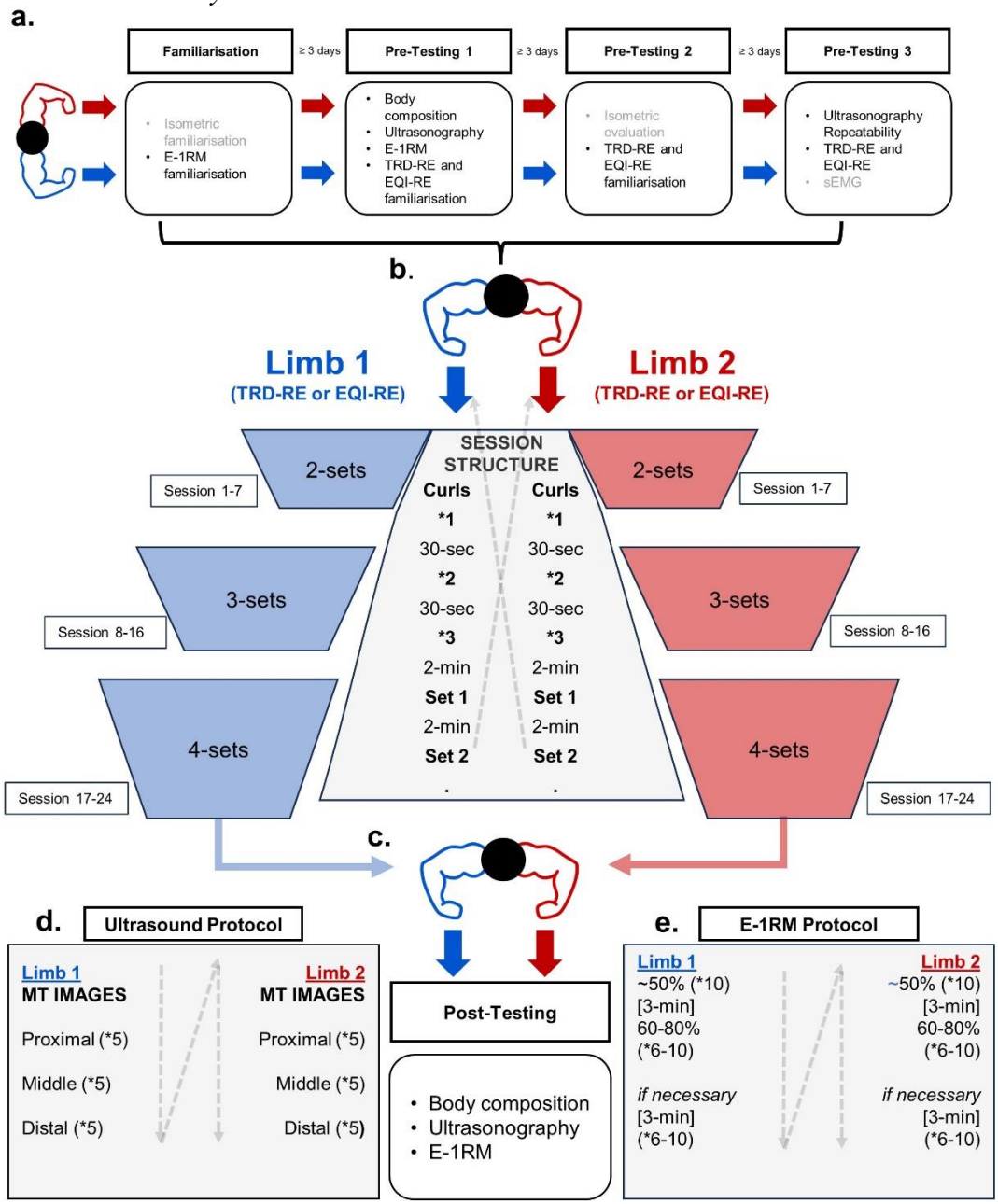
to participate in unilateral resistance exercise of the elbow flexors, 3) had no previous diagnoses of cancer or neurological disease and/or disorders, and 4) regularly use prescription anti-inflammatory medications (i.e., non-steroidal anti-inflammatory), and 5) were cleared for physical activity by the Get-Active Questionnaire (Canadian Society for Exercise Physiology, 2017). Furthermore, participants were to consider themselves untrained **(**performed structured resistance exercise <2x per week for at least 6 months) but did not have to be novel to resistance exercise. As current research suggests that the menstrual cycle and oral contraceptive use are likely to have limited and/or trivial effects on group adaptations to resistance exercise (Colenso-Semple et al., 2023; Nolan et al., 2024), and with no research examining the effects of intrauterine contraception on resistance exercise adaptations (Henderson & Scribbans, 2020), these variables were not controlled for.

Protocol Overview

As part of a larger project (see Chapter 3), participants came to the lab for 4 in-person sessions (1 familiarisation and 3 pre-testing, ≥ 3 days between sessions), followed by ~8-weeks (23 sessions, ≥ 2 days between sessions) of supervised TRD-RE and EQI-RE, and a post-testing session (≥ 3 days after last training session). The current study presents data from the first pre-testing session and the post-testing session. An overview of the study protocol is presented in Figure 1, and relevant reporting items for the resistance exercise intervention are reported in Table 1 as per Lin et al. (2023). All resistance exercise sets were performed with 70% E-1RM.

Figure 1

Protocol Summary



Note. Participants completed a familiarisation for isometric and estimated 1-repetition maximum (E-1RM) strength, followed by 3 pre-testing sessions that included body composition assessment, as well as E-1RM, b-mode ultrasound, traditional isotonic resistance exercise (TRD-RE), and eccentric quasi-isometric resistance exercise (EQI-RE) of the elbow flexors (a.). Following familiarisation and pre-testing, participants completed 23 resistance exercise sessions of 2-4 sets, with one limb performing TRD-RE only, and one limb performing EQI-RE only (b.). After completing all resistance exercise sessions, body composition, ultrasound, and E-1RM, and was repeated (c.). E-1RM protocol (d.). Ultrasound protocol (e.).

Familiarisation

To start the familiarisation session, and as part of a different project, participants were familiarised with a series of unilateral elbow flexion maximal voluntary isometric contractions (MVIC) on an isokinetic dynamometer (Biodex Multi-Joint System Pro; Biodex Medical Systems, Inc.; Shirley, NY) at short, medium, and long muscle lengths. Following MVICs, participants were familiarised with the E-1RM test for a dumbbell unilateral supinated bicep curl.

Estimated One-Repetition Maximum Familiarisation. E-1RM familiarisation was performed sequentially for both limbs. To perform the E-1RM test, participants were positioned facing parallel to a wall/table with the lateral aspect of the non-involved shoulder 1-2 feet from the wall/table. For balance only, the non-involved limb was allowed to touch the wall and/or table, while the participants held a dumbbell in the limb away from the wall. The researcher and participant first selected a weight that could easily be completed for 10 repetitions (CSEP, 2013) and corresponded to ~50% of the participants' perceived 1-RM for a strict unilateral supinated bicep curl. After visual demonstration by the researchers, participants performed 10 unilateral repetitions to full elbow flexion while maintaining an upright posture. Participants were instructed to perform as many repetitions as possible, and to try and use a "one second up, two second down" cadence; light verbal correction on cadence was provided by the researchers if necessary. After 3-minutes of rest, the weight was increased to ~60-80% of participants perceived 1-RM, to allow for volitional fatigue in 6-10 repetitions (CSEP, 2013). Participants were again instructed to perform as many repetitions as possible, and sets were only stopped if there was substantial deviation in form. If participants were able to complete 10 repetitions, the set was stopped, and participants were given another 3-minutes of rest. Weight was then increased again to allow for volitional fatigue in 6-10 repetitions (CSEP, 2013). Procedures were

then repeated for the contralateral arm. A visual reference of the set-up is presented in Chapter 3, Figure 2a.

Pre-Testing 1

Descriptive data (height, weight, age, sex) were recorded, and participants' body composition was assessed by bioelectrical impedance (InBody 270; InBody Co, Seoul, South Korea) as per manufacturer recommendations. Participants then laid supine on a treatment table for ~15 minutes, with their knees and elbows fully extended, forearms supinated, head, neck, and legs supported by a pillow. During this time, the ultrasound operator palpated and marked the acromion process and antecubital crease using a permanent marker (Perkisas et al., 2018). The distance of a line from the acromion process to the antecubital crease was then measured, and 50% (proximal), 65% (middle), and 80% (distal) of the distance from the acromion process was marked on this line. Elbow flexor muscle thickness was evaluated at these points of interest using b-mode ultrasound.

Muscle Thickness. A LOGIQ™ E10s (GE Healthcare, Chicago, U.S.) multi-purpose ultrasound and linear transducer array (ML6-15D, 50mm field of view, 80 mm depth, 4.5-15MHz bandwidth, GE Healthcare, Chicago, U.S) were used to obtain 2-dimensional b-mode ultrasound images. First, water-soluble transmission gel (Wavelength ® MP; National Therapy Products Inc, Brampton, On, Canada) was applied liberally and as needed over the marked points of interest and to the linear transducer. Starting at the most proximal point of interest, the linear transducer was oriented parallel to the biceps brachii muscle fibres. Minimal and consistent pressure was applied to the transducer to achieve maximum transducer-skin contact and limit compression of subcutaneous tissues (Chen et al., 2017; Kojić et al., 2021). With the transducer

in contact with the skin, “LOGIQView” was used visualise an initial sagittal view of the elbow flexors. With the signal frequency set at 15 MHz, gain and depth were then adjusted for each participant to obtain optimal image resolution and depth (Adkins & Murray, 2020), such that the superficial fascia and humeral surfaces were easily visible. Once image resolution and depth were optimised, a minimum of three still images were captured. Images were then obtained at the middle and distal points of interest using the same processes, and then repeated on the contralateral limb. Participants were asked to remain as still and relaxed as possible for all ultrasound measurements. Following completion of muscle thickness imaging, participants performed the E-1RM testing.

Estimated One-Repetition Maximum Testing. To increase core body temperature, participants completed a 5-minute cardiovascular warm-up on a stationary bike at a 5-6 RPE (modified BORG scale; CSEP, 2013). The estimated one-repetition maximum (E-1RM) testing was then completed as per the familiarisation session, with participants performing an initial warm-up set of 10 repetitions, followed by one or two more sets with a weight that participants could perform no more than 6-10 repetitions. After the final set for the first limb and 3-5 minutes of rest, procedures were repeated for the remaining limb. Based on the weight and number of repetitions completed, participants 1-RM was then estimated for each limb (Canadian Society for Exercise Physiology, 2013) and averaged. The average between limb E-1RM was then used to prescribe intensity for TRD-RE and EQI-RE (70% E-1RM).

Eccentric Quasi-Isometric Familiarisation. Following the E-1RM testing, participants were introduced to a dumbbell unilateral supinated EQI elbow flexion using visual and auditory instruction. Participants assumed the same position relative to the wall or table as the E-1RM

testing and were again allowed to support themselves with the opposite limb. While holding a dumbbell at their side in a supinated grip, participants flexed their elbow to approximately -130° of elbow flexion. In this position, participants were asked to maintain this position as long as possible by bracing their arm and elbow in position. When eccentric changes in joint angle occurred due to fatigue, participants were told to resist the resulting eccentric (lengthening) muscle action and attempt to maintain joint position until the dumbbell eventually reached full elbow extension, without compensating for the loss in position with a concentric (shortening) muscle action (Oranchuk et al., 2020). When participants felt comfortable with the instructions, they performed a single EQI elbow flexion repetition for the assigned limb, and any additional instructions during the repetition were given on an individual bases depending on participant's proficiency. A visual reference of the set-up is presented in Chapter 3, Figure 2a.

Pre-Testing 3 and 4

TRD-RE Familiarisation. As part of additional investigations, participants completed two more pre-testing sessions, spaced at least 3-days apart. Participants performed the unilateral elbow flexion MVICs in a similar fashion as pre-testing 1. Following completion of the MVIC protocol, participants were introduced and instructed on performing a dumbbell unilateral supinated bicep curls in a similar fashion as the E-1RM test, with the addition of a 60 beat per minute metronome to initially guide repetition tempo. Participants were told to try and perform each repetition using a 1-second up (concentric), 2-second down (eccentric) tempo, but to do as many repetitions as possible regardless of their ability to maintain tempo; sets were only stopped by the researchers if there was substantial deviation in form and/or excessive momentum. Depending on assigned order of completion, participants then performed two practice sets of the TRD-RE and EQI-RE using the corresponding limbs, with 2-minutes between sets and limbs.

Data and procedures from the final pre-testing session (pre-testing 4) are presented in Chapter 3. For the purposes of calculating muscle thickness reliability for other investigations, ultrasound procedures from pre-testing 2 were repeated. This was followed by performance of the TRD-RE and EQI-RE as they would be conducted for the duration of the training program, while surface electromyography was recorded from each limb.

Resistance Exercise Sessions

After completing the final pre-testing session, participants performed the supervised TRD-RE and EQI-RE training protocol for a total of 23 sessions. Participants were supplied with a dumbbell corresponding to their 70% E-1RM and were able to complete the training protocol in the lab or virtually over Zoom (Zoom Communications, Inc.; San Jose, USA). Alternating the starting limb every session, participants began the session with 3 warm-up sets of 1, 2, and 3 repetitions of dumbbell unilateral supinated bicep curls, with 30-seconds of rest between sets. After ~2 minutes of rest, participants performed set 1 of either TRD-RE or EQI-RE, followed by 2-minutes of rest and then set 2. After another two-minutes of rest, the warm-up procedures and sets were repeated using the remaining limb/resistance exercise type. For sessions 1-7 (phase 1), 8-15 (phase 2), and 16-23 (phase 3), participants performed 2, 3, and 4 sets of TRD-RE and EQI-RE, respectively. For all sets, the supervising researcher counted and recorded the number of repetitions for TRD-RE, and manually timed time under tension for EQI-RE using an available stopwatch.

For virtual resistance exercise sessions, participants were requested to position their device (i.e., personal computer, mobile phone, etc.) on a table or chair, such that the camera angle was perpendicular to the sagittal plane when participants were positioned parralel against a

wall or table. At minimum, the participants mid-thigh was visible in the camera frame. Participants then performed the TRD-RE and EQI-RE as described, utilising a wall or table to support the contralateral limb, and a 60 beats per-minute digital metronome (google.com) to guide repetition cadence. The supervising researcher recorded and counted the number of repetitions for TRD-RE, and time under tension for EQI-RE. In case of technical difficulties, participants were instructed to continue with the session as described. Deviations from the intended protocol are noted in Table 1.

Table 1.

Relevant Reporting Items for TRD-RE and EQI-RE

Items	TRD-RE	EQI-RE	Notes/Deviations
Exercise Description	Dumbbell unilateral supinated BC Full elbow ext. to ~full flex.	Dumbbell unilateral supinated EQI elbow flexion ~130° flex to full elbow ext.	
Frequency and Duration	23-sessions, 3-session/week, minimum 2-days between sessions	23-sessions, 3-session/week, minimum 2-days b/w	*Mean time to complete: 60.3 ± 4.3 days (8.5 weeks). 6 participants completed 22 sessions.*
Warm-up	Sets of 1, 2, and 3 BC repetitions 30-seconds b/w sets, 2-min before TRD-RE set 1	Sets of 1, 2, and 3 BC repetitions 30-seconds b/w sets, 2-min before EQI-RE set 1	
Intensity	70% E-1RM BC	70% E-1RM BC	
Repetitions and Sets	Participant determined maximum repetitions/volitional fatigue	Participant determined volitional fatigue/contact with hip, 1 EQI elbow flexion = 1 set	*For TRD-RE, participants were to complete max repetitions regardless of tempo.*
Tempo	60 BPM metronome; 2-sec ECC, 1-sec CON	N/A, variable	*Metronome for guide/assistance only, set not ended based on tempo.*
Rest Interval	2-min b/w sets	2-min b/w sets	
Focus	External + internal	External + internal	
Muscle Action	ECC + CON	Isometric + ECC	
Progression and Periodisation	Linear; + 1 set every 7-8 sessions (session 1: 2 sets)	Linear; + 1 set every 7-8 sessions (session 1: 2 sets)	
Equipment	Adjustable dumbbell, 1-inch plates, 1-1/4, 2.5, 5, 10 lbs	Adjustable dumbbell, 1-inch plates, 1-1/4 lb to 10 lbs	*70% E-1RM rounded to multiples of 2.5 lb. 0.5 lbs plates were used when participants 70% E-1RM was <10 lbs*
Location	University lab or virtually	University lab or virtually	*Virtual sessions completed through zoom.*
Supervision	In-person and/or virtually, 1:1 ratio	In-person and/or virtually, 1:1 ratio	*If necessary for scheduling and researchers were satisfied with form, participants were able to perform sessions unsupervised. Occasional 1:2 researcher to participant ratio.*
Time of Day	Variable	Variable	*Flexible based on participant schedule.*

Note. BC= Bicep curl, TRD = traditional isotonic, EQI = eccentric quasi-isometric, RE= resistance exercise, CON = concentric, ECC = eccentric, BPM = beats per minute, flex. = flexion, ext. = extension.

Post-Testing

A minimum of two-days after the last TRD-RE and EQI-RE session, participants returned to the lab, and procedures from pre-testing session 2 for muscle thickness and E-1RM were repeated.

Data Processing

Muscle thickness (cm) was defined as the distance between the superficial and deep aponeurosis (Perkisas et al., 2018). Ultrasound images were first exported as JPEG files for analysis in ImageJ open software (https://imagej.net/, V 1.54g), after which the same researcher performed all measurements. For each participant's images, pixels were converted to cm so that all distance measurements were relative to image depth. The straight-line tool was used to draw a line perpendicular to the muscle fibres at the centre of each field of view, joining the superficial and deep aponeurosis. The distance between these points was recorded for each image at the proximal, middle, and distal points of interest for both TRD-RE and EQI-RE limbs. The largest and smallest distances were removed for each region of interest, and a trimmed mean of 3 measurement was calculated for proximal, middle, and distal muscle thickness. These trimmed means were then averaged to generate a single value for each limb.

Estimated 1-RM (E-1RM) was calculated from participant's last set (2 or 3) based on the formula and values presented by the Canadian Society for Exercise Physiology (2013).

Statistical Analysis

Data analyses were performed using Excel (Microsoft 365; Microsoft Corporation, Redmond, USA), jamovi (V 2.4.11), and SPSS 28 (IBM, Inc.; Armonk, USA). To establish that the protocol increased muscle thickness and E-1RM, absolute changes in muscle thickness and

E-1RM were evaluated using paired samples t-tests within male and female groups. For the purposes of inferential statistical analysis and to examine relative effects, the difference in absolute muscle thickness and E-1RM between pre-testing and post-testing was converted to a change score (% change) relative to baseline. Two-way mixed ANOVAs were used to assess the effect of resistance exercise type (TRD-RE vs. EQI-RE) and sex (male vs. female) on muscle thickness % change and E-1RM % change. Further exploratory analysis was done to assess the influence of sex and resistance exercise volume (total repetitions and time under tension) during the TRD-RE and EQI-RE protocol with muscle thickness % change and E-1RM % change; differences between males and females were evaluated using Mann-Whitney U-tests, while Pearson correlations analyses evaluated the relationship between resistance exercise volume with muscle thickness % change and E-1RM % change. Simple moderator analysis assessed if sex affected these relationships, with total repetitions and total time under tension as predictor variables.

Assumptions of normality and homogeneity of variance were assessed via Shapiro-Wilks and Levene's tests, respectively, with significance set at $p \leq .05$ (Field, 2009; Levene, 1960). Assumptions of linearity and co-linearity were evaluated by Pearson's correlations; variables were considered highly correlated if $r \geq .8$. Outliers were defined as data points outside 1.5x the interquartile range. Small, medium, and large effect sizes (η_p^2) were generalised as .01, .06, and .14. For the moderator analysis, predictor and moderator variables were mean centred.

Based on a compromise power analysis for a large effect size ($\eta_p^2 = .14$) where β/α probability ratio was assumed to = 1, the sample size achieved a power (1-β err prob) of 0.75 when $\alpha = .25$ (G*Power V. 3.1.9.2; Faul et al., 2007). As such, $p \leq .25$ was considered significant

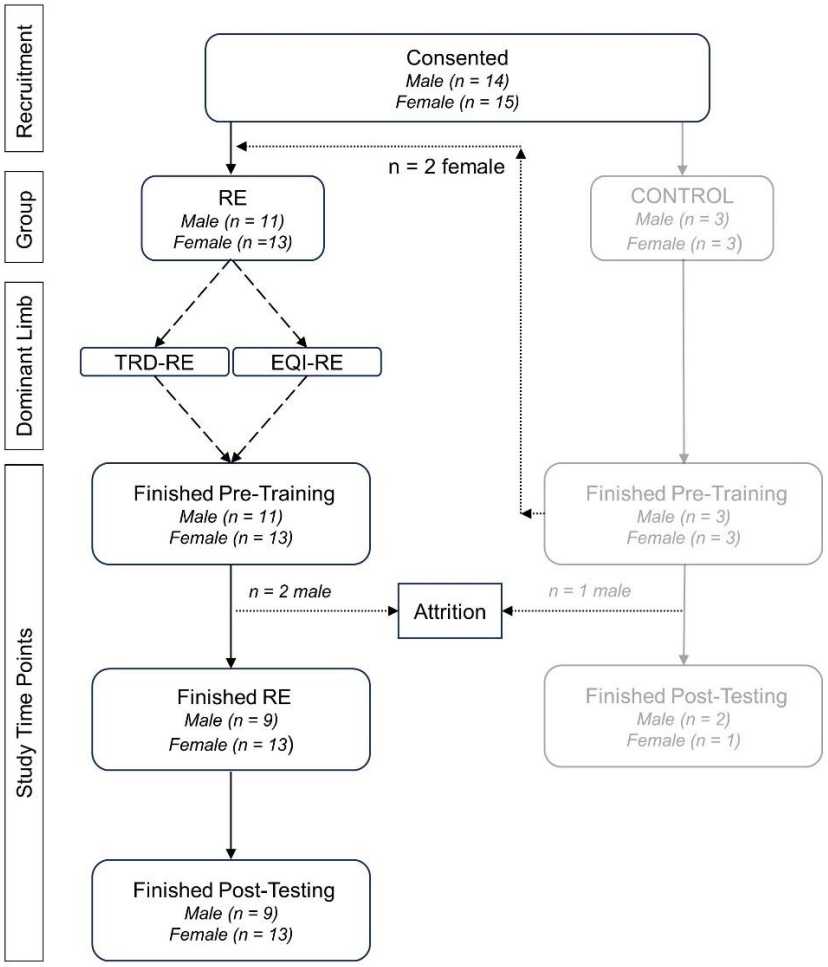
for ANOVAs. Significant main and/or interaction effects were followed up with pairwise simple contrasts. In an effort to maintain power, α was not corrected for post-hoc comparisons. For exploratory analysis, a conventional $p \leq .05$ was considered significant. Confidence intervals are presented as in SPSS, with 75% confidence intervals (CI) reported for $\alpha = .25$, and 95% CI for $\alpha = .05$. For moderator analysis, all CIs are standardised. Variability is presented as ± standard deviation (SD) unless otherwise specified.

Results

A total of 25 (12 males, 13 females) participants completed pre-testing and started the TRD-RE and EQI-RE training protocol. Further, a subset of $n = 6$ elected to serve as reference controls and did not initially perform resistance exercise between pre- and post-testing (~8-weeks); two female participants chose to complete the resistance exercise after initially serving as controls, and one male participant served as a control after initially completing two resistance exercise sessions. Three male participants were lost to attrition after completing pre-testing. As such, a total of 9 males, and 13 females were included in the final analysis ($n = 22$; Figure 2). Demographics and baseline descriptive statistics of the sample, TRD-RE, and EQI-RE limbs are presented in Table 2.

Figure 2

Study Flow Chart



Note. Twenty-nine participants were eligible and consented to the study, of which 24 participants elected to complete the resistance exercise protocol, while 6 participants elected to serve as control participants. Two participants from the control group elected to perform the resistance exercise after serving as controls. TRD-RE = traditional isotonic resistance exercise, EQI-RE = eccentric quasi-isometric resistance exercise.

Protocol Characteristics. On average, males completed the TRD-RE and EQI-RE protocol with an absolute load of 18.5 ± 4.5 lbs, resulting in an actual relative intensity of 69% E-1RM. Females completed the TRD-RE and EQI-RE protocol with an absolute load of 12.5 ± 2.6 lbs, resulting in an actual relative intensity of 70% E-1RM. Average time to complete the TRD-RE and EQI-RE was 60.3 ± 4.3 days (8.5 weeks).

Table 2

Demographic and Descriptive Statistics for Study Sample and Assigned Limbs

	Male (*n* = 9)		**Female (*n* = 13)**	
Descriptives	M (SD)	Range	M (SD)	Range
Age (years)	21.0 (2.7)	18.0-27.0	25.9 (3.4)	19.0-32.0
Height (cm)	181.1 (11)	167.7-199.5	166 (5.5)	157.0-176.0
Weight (kg)	80.4 (16.8)	64.1-111.3	69.7 (18.2)	51.0-118.3
Lean Mass (kg)	35.8 (6.1)	27.7-49.8	26.2 (3.8)	20.7-34.2
Body Fat %	20.4 (10.5)	8.8-34.3	29.8 (11.1)	12.2-49.2
	Male		**Female**	
Lean Mass[a] (kg)	M (SD)	Range	M (SD)	Range
TRD-RE Limb	3.5 (0.6)	2.3-5.0	2.4 (0.6)	1.6-3.8
EQI-RE Limb	3.5 (0.6)	2.5-4.8	2.4 (0.6)	1.6-3.8

M = mean, SD = standard deviation.

[a]TRD-RE and EQI-RE limbs were not statistically different based on paired sample t-test ($p > .05$)

Mean and standard deviation, as well as violin plots for absolute muscle thickness and E-1RM are presented for reference in Table 3 and Figure 3. Data for absolute muscle thickness and E-1RM was normally distributed ($p > .05$). Based on paired samples t-tests, TRD-RE and EQI-RE limbs were not statistically different at pre-testing for muscle thickness and E-1RM ($p > .05$). As expected, both TRD-RE and EQI-RE produced significant absolute increases in muscle thickness and E-1RM in males and females ($p = .007$ to $p < .001$) with very large effect sizes ($d > 1.195$; Table 3). A subset of reference control limbs from individuals who did not complete EQI-RE or TRD-RE between pre- and post-testing suggests that measured muscle thickness differed by 0.5 ± 1.5% ($n = 8$ limbs), while E-1RM ($n = 9$ limbs) differed by 1.0 ± 8.2% after ≥ 8-weeks.

Table 3

Absolute Muscle Thickness and Estimated One-Repetition Maximum

	Male			Female		
Muscle Thickness (cm)	*Pre*	*Post*	*Cohen's d*	*Pre*	*Post*	*Cohen's d*
TRD-RE Limb	3.18 ± 0.34	3.39 ± 0 .29[a]	2.533	2.53 ± 0.39	2.68 ± 0.36[a]	1.406
EQI-RE Limb	3.21 ± 0.37	3.35 ± 0.36[b]	1.195	2.52 ± 0.33	2.61 ± 0.33[a]	1.396
	Male			**Female**		
Estimated-1RM (lbs)	*Pre*	*Post*	*Cohen's d*	*Pre*	*Post*	*Cohen's d*
TRD-RE Limb	26.98 ± 6.42	32.73 ± 6.00[a]	2.190	18.01 ± 3.90	22.98 ± 5.25[a]	1.654
EQI-RE Limb	26.49 ± 5.79	30.11 ± 5.73[a]	2.704	17.99 ± 4.00	20.91 ± 5.32[a]	1.471

Note. Values are presented as mean ± standard deviation. TRD-RE = traditional isotonic resistance exercise, EQI-RE = eccentric quasi-isometric resistance exercise. 1-RM = one repetition maximum.

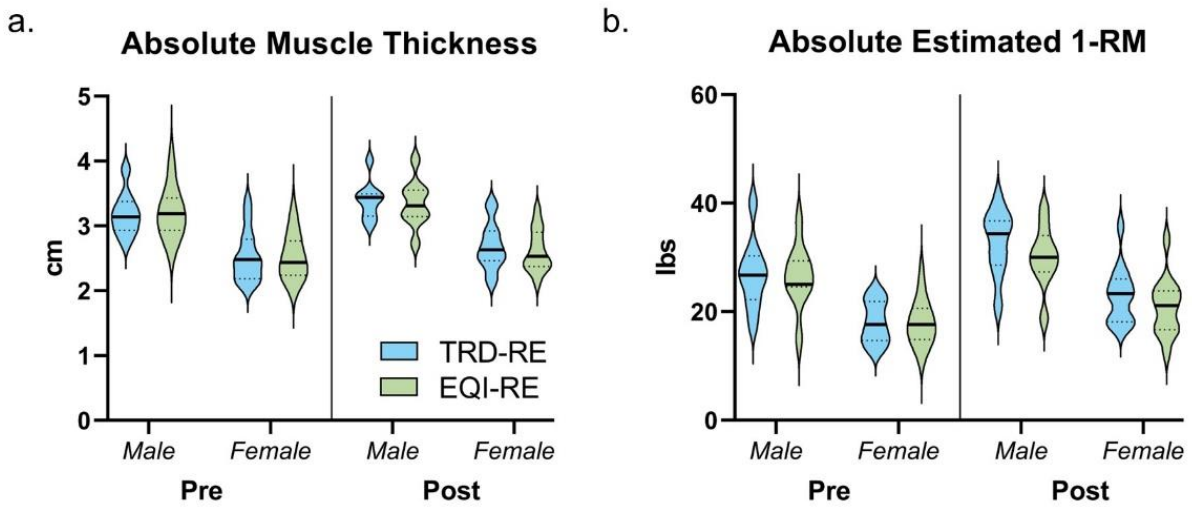
[a] Significantly greater than pre ($p < .001$)

[b] Significantly greater than pre ($p = .007$)

Muscle Thickness and E-1RM. All muscle thickness % change and E-1RM % change data were normally distributed with homogeneous error variance ($p > .05$). On average, male and female participants experienced a 6.8 ± 3.0% and 6.6 ± 4.5% increase in muscle thickness from TRD-RE, respectively. After EQI-RE, males experienced a 4.5 ± 3.9% increase in muscle thickness, while females experienced a 3.6 ± 2.9% increase in muscle thickness. Collectively, these muscle thickness % change data represent a significant main effect of RE type with a large effect size, F (1, 20) = 10.544, $p = .004$, $\eta_p^2 = .345$. Specifically, TRD-RE produced a 2.7% (standard error = 0.825, 75% CI: 1.701 to 3.655) significantly larger increase in muscle thickness % change than EQI-RE; however, there was no significant effect of sex, or type*sex interaction for muscle thickness % change ($p > .25$; Figure 4a).

Figure 3

Violin Plots of Observed Data for Traditional Isotonic Resistance Exercise (TRD-RE) and Eccentric Quasi-isometric Resistance Exercise (EQI-RE)

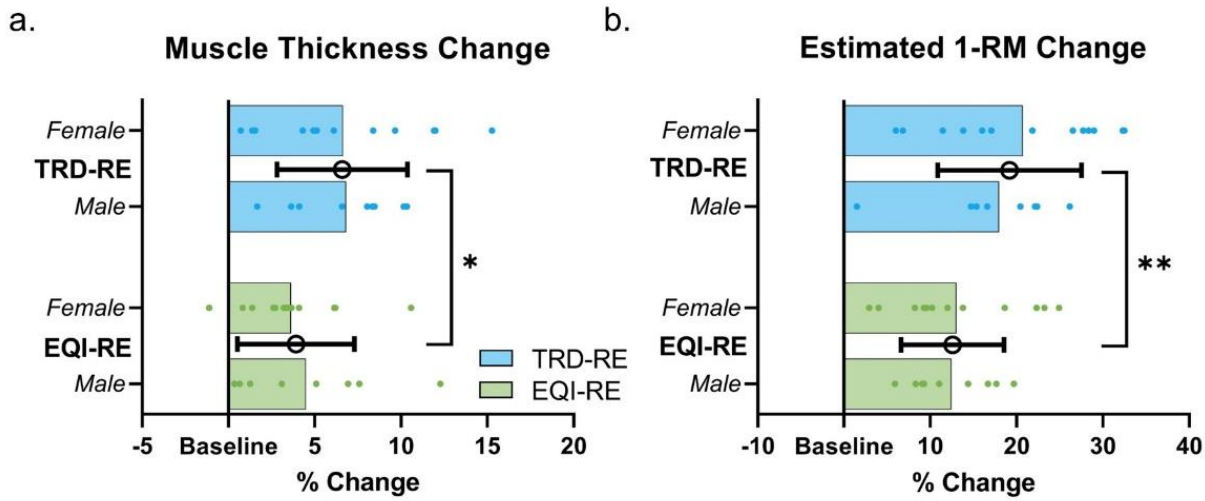


Note. Violin plot for absolute muscle thickness (a.). Violin plot for estimated 1-repetition maximum (E-1RM; b.). Solid horizontal line denotes median. Horizontal dotted lines denote 25th and 75th percentiles. Blue = TRD-RE, Green = EQI-RE.

On average, male and female participants experienced an 18.0 ± 7.3% and 20.7 ± 9.4% increase in E-1RM, respectively, after TRD-RE. After EQI-RE, males experienced a 12.4 ± 4.8% increase in E-1RM, while females experienced a 13.0 ± 7.2% increase in E-1RM. Collectively, these E-1RM % change data represent a significant main effect of RE type with a large effect size, F (1, 20) = 14.834, p = .001, η_p^2 = .426. Specifically, TRD-RE produced a 6.6% (standard error: 1.71, 75% CI: 4.57 to 8.64) significantly larger increase in E-1RM % change than EQI-RE, however, there was no significant effect of sex, or type*sex interaction for E-1RM % change (p > .25; Figure 4b).

Figure 4

Male and Female % Change for Traditional Isotonic Resistance Exercise (TRD-RE) and Eccentric Quasi-isometric Resistance Exercise (EQI-RE)



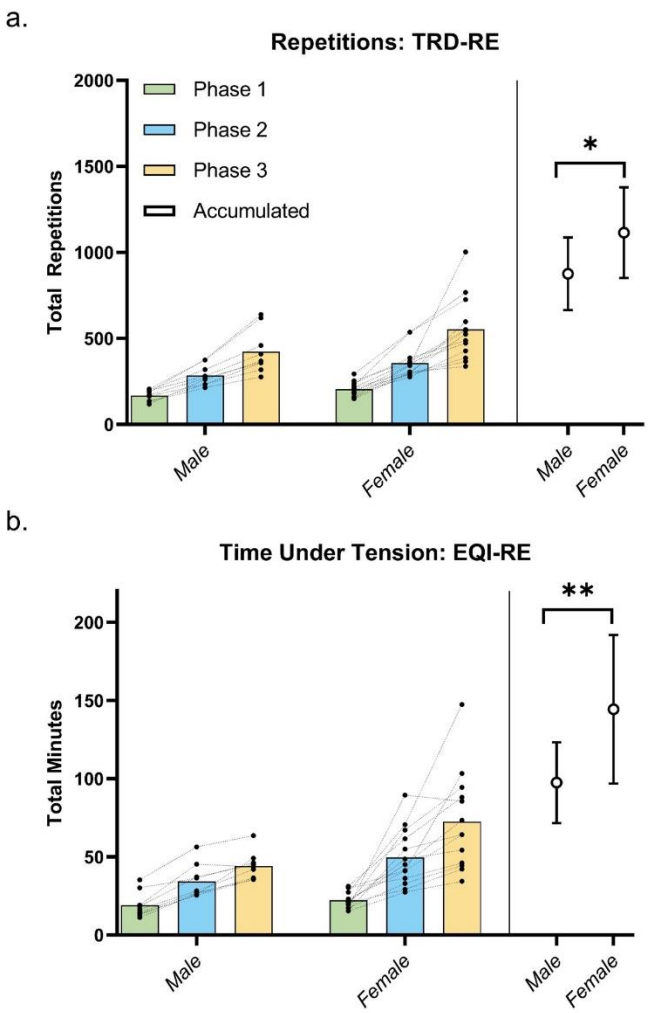
Note. Muscle thickness % change (a.). Estimated 1-repetition maximum % change (b.). Bars represent mean within sex, coloured dots represent observed data points. Symbol and error bars represent collapsed mean and standard deviation of male and female data. Blue = TRD-RE, Green = EQI-RE.

* = $p \leq .005$ between RE type, ** = $p \leq .001$ between RE type.

Repetition data for TRD-RE, and time under tension data for EQI-RE for each phase of training are presented in Figure 5. Total repetitions across the resistance exercise protocol were not normally distributed ($p = .028$). As such, given the unequal male and female group sizes, Mann-Whitney U tests were used to compare total repetitions and time under tension between males and females. Across the TRD-RE protocol, females completed significantly more repetitions than males (1115 ± 263 vs. 876 ± 212 repetitions), $U = 28.00$, $p = .043$ (Figure 5a). Females also accrued significantly more time under tension than males across the EQI-RE training (144 ± 47 min vs. 97 ± 26 min), $U = 20.00$, $p = .009$ (Figure 5b).

Figure 5

Summary Male and Female Training Data of Traditional Isotonic Resistance Exercise (TRD-RE) and Eccentric Quasi-isometric Resistance Exercise (EQI-RE)



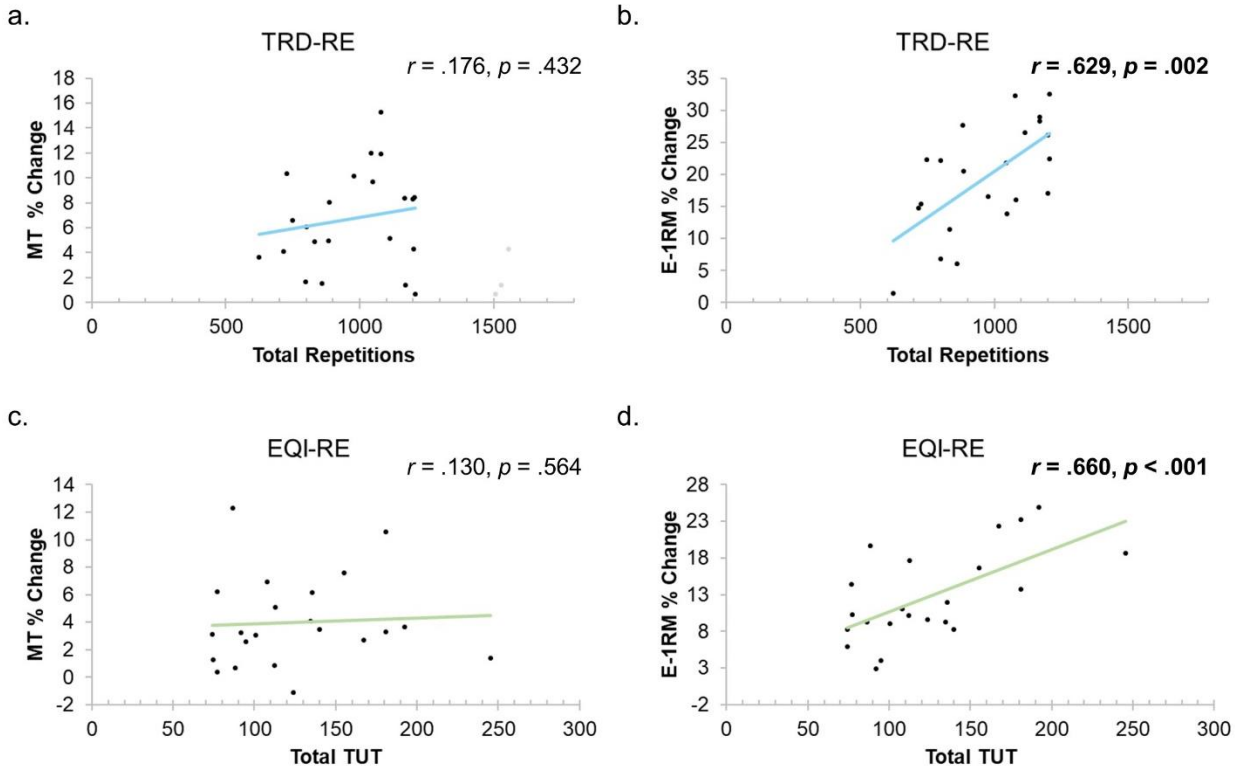
Note. Total repetitions during each phase, and accumulated repetitions across the entire protocol for TRD-RE (a.). Total time under tension (TUT) during each phase, and accumulated TUT across the entire protocol for EQI-RE (b.) Green bar = phase 1 (session 1-7), blue bar = phase 2 (session 8-15), yellow bar = phase 3 (session 16-23). Black dots represent observed data points, dotted lines link individual's data points. White symbols and error bars = mean accumulated total and standard deviation for all phases of the TRD-RE and EQI-RE protocol.

* = $p < .05$, ** = $p < .02$.

For exploratory analysis, statistical outliers and spurious outliers were removed and replaced with the next lowest score + 1(Field, 2009); total repetition data were replaced for the three highest female participants. One female participant was replaced for total time under tension, and one male participant was replaced for EQI-RE muscle thickness % change. When male and female data were collapsed (n = 22), E-1RM % change was not associated with muscle thickness % change for TRD-RE or EQI-RE ($r < .1$, $p > .05$). For TRD-RE, there was a slight positive, but non-significant association of total repetitions with muscle thickness % change, $r(20) = .176$, $p = .432$ (Figure 6a); however, there was a significant and modest positive association of total repetitions with E-1RM % change, $r(20) = .629$, 95% CI: .282 to .830, $p = .002$ (Figure 6b). Similarly, for EQI-RE, there was slight positive, but non-significant association of total time under tension with muscle thickness % change, $r(20) = .130$, $p = .564$ (Figure 6c), and a significant and modest association of total time under tension with E-1RM % change, $r(20) = .660$, 95% CI : .288 to .832, $p < .001$ (Figure 6d).

Figure 6

Relationship of Resistance Exercise Volume With Estimated One-repetition Maximum (E-1RM) and Muscle Thickness (MT)



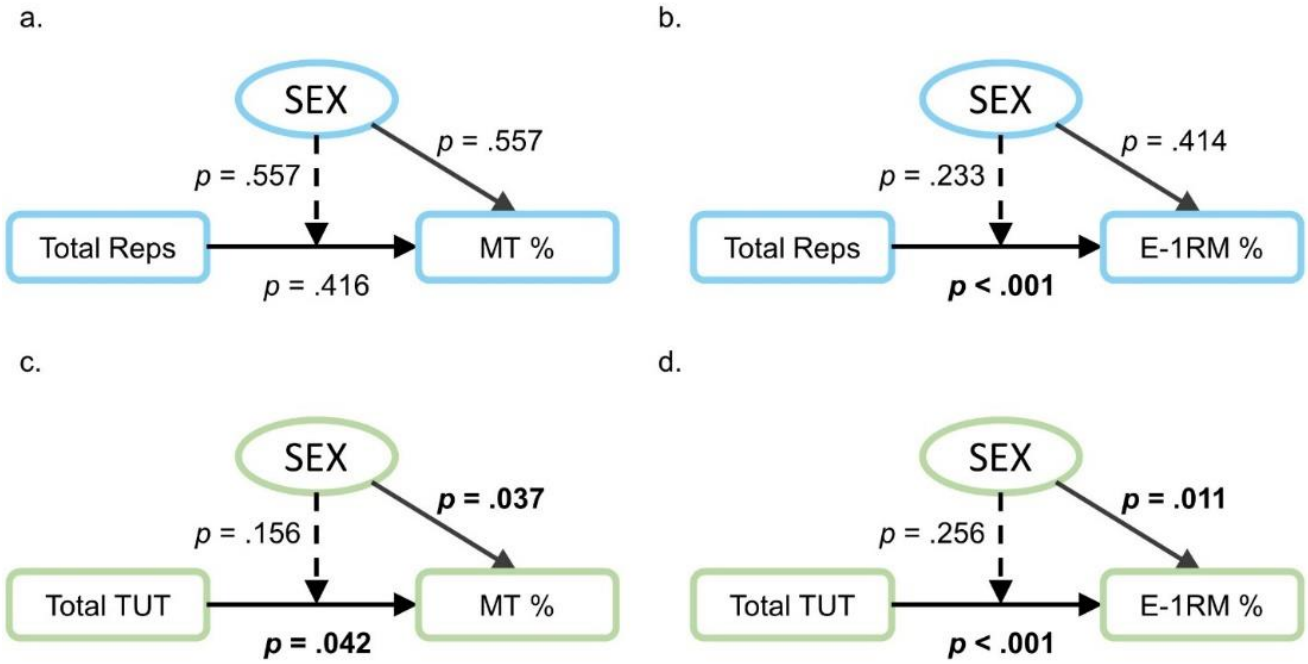
Note. Pearson's correlation of total repetitions with muscle thickness % change (MT % change) for traditional isotonic resistance exercise (TRD-RE; a.) Pearson's correlation of total repetitions with E-1RM % change for TRD-RE (b.). Pearson's correlation of total time under tension (TUT) with MT % change for eccentric quasi-isometric resistance exercise (EQI-RE; c.). Pearson's correlation of total time under tension (TUT) with E-1RM % change for EQI-RE (d.). Lines of best fit for TRD-RE are displayed by blue lines, lines of best fit for EQI-RE are displayed by green lines. For figure a.), grey dots represent spurious outliers that were removed and replaced with the next highest score +1. *r* = Pearson's r. Significant correlations ($p < .05$) are bolded.

Sex did not moderate any effect of total repetition or time under tension on muscle thickness % change or E-1RM % change ($p < .05$), although there were direct effects of total repetitions, total time under tension, and sex. For TRD-RE, there was no significant effect ($p > .05$) of total repetitions or sex on muscle thickness % change (Figure 7a). There was, however, a significant effect of total repetitions, but not sex, on E-1RM % change, $b = 0.034$ (standard error: 0.008), 95% CI: 0.019 to 0.049, $Z = 4.448$, $p < .001$ (Figure 7b), suggesting that greater total

repetitions during TRD-RE was a predictor of greater E-1RM % change. For EQI-RE, there was a significant effect of total time under tension, b = 0.033 (standard error: 0.016), 95% CI: 0.001 to 0.064, Z = 2.032, p = .042, and sex, b = -2.636 (standard error 1.216), 95% CI: -5.108 to -0.165, Z = -2.090, p = .037 on muscle thickness % change (Figure 7c). Similarly, there was a significant effect of total time under tension, b = 0.124 (standard error: 0.021), 95% CI: 0.082 to 0.166, Z = 5.806, p < .001, and sex, b = -4.277 (standard error: 1.680), 95% CI: -7.569 to -0.984, Z = -2.546, p = .011 on E-1RM % change (Figure 7d). As such, these models would suggest that greater time under tension was a significant predictor of greater muscle thickness % change and E-1RM % change, while being male was predictive of greater muscle thickness % change and E-1RM % change in response to EQI-RE.

Figure 7

Moderation Models of the Relationship of Resistance Exercise Volume With Muscle Thickness (MT) % Change, Estimated One-Repetition Maximum (E-1RM) % Change, and Sex



Note. Model of total repetitions and MT % change moderated by sex for traditional isotonic resistance exercise (TRD-RE; a.). Model of total repetitions and E-1RM % change moderated by sex for TRD-RE (b.). Model of total time under tension (TUT) and MT % change moderated by sex for eccentric quasi-isometric resistance exercise (EQI-RE, c.). Model of total time under tensions (TUT) and E-1RM % change moderated by sex for EQI-RE (d.). TUT = time under tension, MT % = muscle thickness % change, E-1RM % = estimated 1-repetition maximum % change. Solid arrows denote direct effects, dashed arrows denote moderator effect.

Significant beta estimates ($p < .05$) are bolded.

Discussion

The current study examined the effects of traditional isotonic (TRD-RE) and eccentric quasi-isometric resistance exercise (EQI-RE) between untrained males and females on relative muscle thickness change (MT % change) and E-1RM change (E-1RM % change) of the elbow flexors following ~8.5 weeks of resistance exercise training. Additionally, the current study explored the relationship of resistance exercise volume (total repetitions or total time under

tension) during the TRD-RE and EQI-RE protocol with muscle thickness % change and E-1RM % change, and whether sex influenced any relationship. When relative changes in elbow flexor muscle thickness and E-1RM were compared, TRD-RE increased muscle thickness and E-1RM significantly more than EQI-RE, however, there were no significant differences between males and females, and changes in relative muscle thickness were not related to changes in E-1RM. With respect to resistance exercise volume during TRD-RE and EQI-RE, females performed significantly more repetitions and produced significantly greater time under tension than males. Exploratory analysis revealed that, for TRD-RE, total repetitions and sex *were not* predictive of muscle thickness % change, whereas total repetitions, but not sex, *were* predictive of E-1RM% change. Conversely, for EQI-RE, total time under tension and sex were predictive of muscle thickness % change and E-1RM % change for EQI-RE. Sex did not moderate the relationship of total repetitions or total time under tension with muscle thickness % change or E-1RM % change.

There are innate differences between males and females that can contribute to differences in muscle hypertrophy and strength. From recent meta-analysis (Nuzzo, 2022, 2024; Roberts et al., 2020) it can be presumed that males have greater muscle mass, strength, and proportion of type II muscle fibres than females, while females have a greater proportion of type 1 muscle fibres than males. Unsurprisingly, this is reflected in baseline data; baseline muscle thickness for females was ~80% of males, while baseline E-1RM for females was ~68% of males. Although female's muscle thickness and E-1RM were slightly higher than what has been reported previously, it was expected that absolute values of muscle thickness and E-1RM would be higher in males regardless of resistance exercise type or time (pre to post-testing), and, given the untrained nature of participants, resistance exercise would produce significant increases in

muscle thickness and E-1RM, regardless of resistance exercise type. As such, to remove baseline differences and appropriately evaluate sex-differences we elected to examine relative changes in muscle thickness and E-1RM as our primary outcomes.

Indeed, our assumptions regarding absolute muscle thickness and E-1RM were correct, in that both TRD-RE and EQI-RE produced significant increases in muscle thickness and E-1RM, while males had greater muscle thickness and E-1RM than females at both time points. Our hypothesis for relative changes, however, were only partially correct; although TRD-RE produced significantly greater increases in muscle thickness and E-1RM than EQI-RE after ~8-weeks, there were no sex-differences in relative muscle thickness or E-1RM improvements following TRD-RE or EQI-RE. This, despite females accruing more repetitions *and* time under tension over the course of the protocol. Using an almost identical resistance exercise protocol for the elbow flexors, our previous work (Chapter 3) suggests that males and females completed a similar number of repetitions during an acute bout of unilateral TRD-RE, while females produced significantly greater time under tension than males during an acute bout of unilateral EQI-RE. Therefore, we hypothesised that this difference in time under tension would accumulate across several training sessions, and, assuming that resistance exercise volume and time under tension are predictive of muscle hypertrophy(Schoenfeld, Ogborn, et al., 2017), we hypothesised that females would experience a greater relative increase in muscle thickness than males from EQI-RE. Conversely, given the similar number of TRD-RE repetitions in the aforementioned study (Chapter 3), we hypothesised that males and females would experience similar relative increases in muscle thickness from TRD-RE. Although our exploratory analysis would seem to lend support to our hypothesis, in that total time under tension and sex were both significant and independent predictors of muscle thickness % change, it was males, and not females, who

experienced a slightly greater relative increase in muscle thickness, despite performing less time under tension.

It is regularly demonstrated that females have equivalent relative hypertrophic and strength responses to males across a variety of isotonic resistance exercise protocols, at least in the short term, and females may even have a slight advantage when it comes to improving upper-body strength (Roberts et al., 2020). As such, the current study is in line with these observations, and supports similar results for EQI-RE; males and females had similar relative improvements in elbow flexor muscle mass and strength when beginning a resistance exercise program, and females had a slightly greater, although non-significant improvement in E-1RM than males following TRD-RE. Along with the sex-differences in resistance exercise volume, the current study highlights the complexities of muscle hypertrophy and strength mechanisms, and may suggest different contributing mechanisms from males and females.

As previously discussed, measurable physiological differences between males and females exist (e.g., sex-hormones, muscle fibre type/strength), which can lead to conclusions that ascribe observed sex-differences to factors innate to males or females. Indeed, in the current study, male participants were substantially stronger and had more absolute muscle mass than females. Although our primary analysis suggests there are no sex-differences in muscle thickness % change or E-1RM % change in response to TRD-RE and EQI-RE, there is increasing discussion regarding the impact confounding and modifiable factors, such as strength, skill, or experience have on observed sex-differences (Nimphius, 2019; Parsons et al., 2021). In the context of the current study, fatiguability and/or time under tension could be considered a relevant and modifiable factor, as, despite females generally being more fatigue resistance in the

current study, it is a trainable characteristic that differs between trained and untrained individuals (Gentil et al., 2017; Hunter, 2016b). Indeed, this was our rational for exploring whether sex moderated the assumed relationship of resistance exercise volume and muscle thickness % change. As time under tension was associated with E-1RM % change for EQI-RE and given that EQI-RE volume within sets is limited by an individuals' fatiguability (Henderson et al., 2023), it is conceivable that if sex did moderate this relationship, that males and females may need to perform a differing number of EQI-RE sets to achieve similar relative resistance exercise volume. Based on the lack of sex-differences in muscle thickness % change and E-1RM % change for both TRD-RE and EQI-RE, however, it might also be inferred that males require less resistance exercise volume than females to achieve the same relative increases in muscle mass and strength.

As recent work has challenged the idea that muscle mass heavily contributes to muscle strength (Buckner et al., 2021; Spitz et al., 2023), we also examined the relationship of muscle thickness % change with E-1RM % change to determine if greater increases in muscle mass were related to changes in E-1RM. Although both TRD-RE and EQI-RE increased absolute muscle thickness and E-1RM after ~8.5 weeks, relative increases in muscle thickness and E-1RM were not associated for either resistance exercise type, suggesting that E-1RM improvements were largely due to neurological factors and not changes in muscle mass (Buckner et al., 2021; Nuzzo, 2022; Spitz et al., 2023). As alluded to by Oranchuk et al. (2019b), the fact that TRD-RE increased E-1RM significantly more than EQI-RE would indicate that EQI-RE would not be an efficient means of improving power or strength characteristics, especially at high movement velocities. While the greater efficacy of TRD-RE for increasing E-1RM strength could be easily explained by its greater specificity to the E-1RM test, the significantly greater increase in relative

muscle thickness and E-1RM from TRD-RE compared to EQI-RE challenges some of the theorised advantages of EQI-RE. For example, practitioners have espoused EQI style training as an effective, or more effective means of producing muscle hypertrophy and strength than TRD-RE (e.g., Morrison, 2016; Seedman, n.d.; Sinicki, 2019), while Oranchuk et al., (2019b) theorised that EQI-RE would be a time and energy efficient way of increasing muscle size and creating beneficial musculotendinous adaptations. Assuming 3-seconds per TRD-RE repetition, the current study suggests that EQI-RE took longer to complete, and, contrary to previous claims, produced inferior muscle thickness and E-1RM improvement compared to TRD-RE.

Limitations are present for the resistance exercise protocol, measurement techniques, and design of the current study. Specific to participant's performance of the TRD-RE and EQI-RE, participants were given the option of completing the resistance exercise protocol and being supervised virtually. As such, we elected to progress participants by adding a set (volume) rather than increasing load, removing the need for participants to return to the lab during ~8 weeks to test their strength or pick up additional weight. The downside to this, however, was that some participant's repetition and time under tension performance drastically increased, therefore relative intensity across the 8-weeks would likely have large variability across participants. Regarding ultrasound measurements, while inter rater reliability was very good for muscle thickness, there is a risk of bias in that the same researcher collected data and participated in measuring muscle thickness on ultrasound images, but was not blinded to limb assignment. Relevant to the unilateral, between limb nature of the design, systemic responses (i.e., fatigue, endocrine) to the first limb/resistance exercise type performed during a resistance exercise session or testing would have influenced the second limb/resistance exercise type. In an effort to mitigate this, participants alternated starting with TRD-RE or EQI-RE each session, while limb

assignment to resistance exercise type, as well as starting limb for pre- and post-testing were counterbalanced. With respect to confounding factors, participant's dietary, sleep, and alcohol habits were not monitored over the course of the ~8-weeks. As protein intake, sleep quality/quantity, and alcohol consumption can impact muscle hypertrophy and strength, participants' lifestyle may have been suboptimal for muscle hypertrophy and strength development. Additionally, it is important to note the study was conducted with young, healthy, untrained individuals, where training effects are more robust. As such, results cannot be extrapolated to a trained population.

With its limitations, the current study provides direction for EQI-RE and sex-differences research. It is important to note that while hypertrophy strength increases from EQI-RE were not as large as TRD-RE, they were still significant and meaningful compared to pre-testing. As suggested by Oranchuk et al. (2019), EQI-RE may therefore be useful in rehabilitation settings to stimulate strength and hypertrophy improvements where isotonic resistance exercise may not be appropriate. Although the study was not conducted in rehabilitation or injured population, resistance exercise participation among the general population is low; 20% of Americans (Kruger et al., 2006), and 13.2% of Australians (Dalbo et al., 2015) perform resistance training twice per week, with significantly less participation among certain sociodemographic, including women (Kruger et al., 2006; Dalbo et al., 2015). As such, the majority of patients in a general rehabilitation setting would be "untrained." Thus, the results of the current study may have relevance in general population musculoskeletal rehabilitation, however, future work may consider examining EQI-RE in specific populations. Relevant to intensity and progressing exercise, future work may also consider potential implications of performing EQI-RE with higher intensities (i.e., > 80% 1-RM), different ROM (short vs. long-muscle lengths), different

muscles/exercises (bench press vs. leg press) on sex-differences in muscle morphology, architecture, or tendon stiffness.

Conclusion

In untrained males and females, the current study revealed significant increases in muscle thickness and E-1RM from 8-weeks of TRD-RE or EQI-RE; however, there were no relative sex-differences in muscle thickness and E-1RM improvements. Females accrued greater relative RE volume than males for both TRD-RE and EQI-RE, but sex did not moderate the relationship of resistance exercise volume with improvements in E-1RM for TRD-RE or EQI-RE. Although the current study may broadly support that females are less fatigable than males across 8-weeks of resistance exercise, it does not support equivalent strength and hypertrophy outcomes from EQI-RE when compared to TRD-RE. Future work should consider evaluating EQI-RE in situations where TRD-RE would not be appropriate or feasible.

Chapter 5: General Discussion

The purpose of the current thesis was threefold. At its most basic level, the thesis sought to evaluate unsubstantiated theories and claims surrounding the acute response and long-term adaptations to EQI-RE. Specifically, the thesis examined the time under tension, motor unit recruitment/muscle excitation, agonist-antagonist co-activation, muscle hypertrophy, and strength characteristics of EQI-RE, whether these characteristics differed between males and females, and finally compared these characteristics with TRD-RE. As many of the reasons for promoting or utilising EQI-RE are based on indirect evidence and/or anecdote, there are many novel aspects of the included studies. Most apparently, the included studies represent the first investigations of EQI-RE in the upper-body and between males and females. The current thesis also includes the first study to evaluate strength and hypertrophy outcomes after several weeks of EQI-RE, and compare these outcomes with TRD-RE. Despite well recognised sex-differences in muscle fatigue, the thesis contains one of the few studies to date to evaluate acute set-to-set performance and accrued resistance exercise volume between males and females when resistance exercise is performed to momentary muscular failure.

Isotonic vs. Eccentric Quasi-Isometric Resistance Exercise

Overall, the assumed mechanical tension and time under tension characteristics of EQI-RE were in line with the limited previous work (Oranchuk et al., 2020, 2021). Chapter 2 indicated that muscle fatigue accrued at short muscle lengths after multiple sets of EQI-RE, resulting in a greater relative proportion of angular impulse and time under tension at long-muscle lengths by set 4. Furthermore, as theorised and assumed (Morrison, 2016; Oranchuk et al., 2019b; Seedman, n.d.-a, n.d.-b; Sinicki, 2019), EQI-RE produced substantially greater time

under tension than TRD-RE after 2 effort matches sets in Chapter 3. The assumptions of EQI-RE producing substantial and/or greater motor unit recruitment and agonist-antagonist co-activation than traditional resistance exercise practices, however, are less clear. While Chapter 2 saw significant, but small increases in sEMG excitation (LEpeak) between set 1 and set 4, visually there were minimal increases in sEMG excitation from the beginning to the end of each EQI set, and overall excitation remained modest at around 50% of MVIC. Comparatively, in Chapter 3, EQI-RE did produce greater overall excitation (iEMG), but lower peak excitation (LEpeak) than TRD-RE, which could suggest EQI-RE is slower to recruit high-threshold motor units than TRD-RE. Furthermore, when evaluating biceps-triceps co-activation, there were no significant differences between EQI-RE and TRD-RE, suggesting that co-activation is not appreciably greater in EQI-RE. Finally, while EQI-RE did produce appreciable gains in E-1RM and muscle thickness in Chapter 4, TRD-RE produced significantly greater strength and hypertrophy gains.

Sex-Dependent Differences

While there were overall differences between EQI-RE and TRD-RE for several dependent variables, a novel finding of the current thesis was that many of the observed effects were sex-dependent, and Chapter 3 revealed many instances where males and females differed based on the resistance exercise type. Indeed, previous studies of EQI-RE had only included male participants (Oranchuk et al., 2020, 2021) or had not evaluated sex-differences (Ličen et al., 2024). In the current thesis, however, females produced significantly greater time under tension and overall muscle excitation than males across 2 sets of EQI-RE, suggesting that males generally fatigued faster during EQI-RE. During TRD-RE, males had significantly greater co-activation than females, however, sex-differences in time under tension and overall excitation were appreciably smaller or non-existent compared to EQI-RE. After ~8-weeks of TRD-RE and

EQI-RE in Chapter 4, these acute sex-differences manifested in females accruing significantly greater volume than males for TRD-RE and EQI-RE, with this difference being ~10% greater for EQI-RE. That being said, there were no sex-differences in relative muscle strength or hypertrophy following TRD-RE and EQI-RE, and, while resistance exercise volume was positively associated with E-1RM, sex did not moderate this relationship.

Muscle Fatigue

While the thesis suggests there are sex-dependent differences when it comes to the manifestation of muscle fatigue during EQI-RE, it is important to highlight that this result may be specific to the elbow flexors. For example, very recent work by Ličen et al., (2024) suggests that, irrespective of sex, there are differences in how the knee flexors vs. the knee flexors fatigue in response to EQI-RE, with the knee extensors being more susceptible to EQI-RE induced fatigue. Indeed, general differences in the fatiguability of varying muscle groups, regardless of sex, are not an uncommon finding in the literature. As previously mentioned, in addition to intensity and task, the existence of sex-differences in muscle fatigue can be specific to the muscle group examined, with some muscle groups (i.e., the elbow flexors) displaying large sex-differences, and others (i.e., elbow extensors) displaying limited or no sex-differences. As such, it seems plausible that the magnitude of sex-differences in the fatigue response to EQI-RE will vary depending on the muscle group used. Beyond the EQI-RE components of the thesis, a key theme was that isotonic resistance exercise with intensities > 60% 1-RM is predominately used in practice for the purposes of improving muscle strength and/or hypertrophy (Ratamess et al., 2009). Distinct from the implications of EQI-RE, few studies have examined sex-differences in muscle fatigue using ecologically valid models of resistance exercise. Rather, a substantial portion of the literature has utilised low intensities, isokinetic dynamometers, and isometric

muscle actions to evaluate muscle fatigue(e.g., Carr et al., 2021; Carr & Ye, 2020; Gomes et al., 2021; Hunter, 2009, 2014, 2016b, 2016a; Wong et al., 2019). From a practical perspective, the accumulation of muscle fatigue during a resistance exercise protocol is most relevant to the requirements for rest between sets, as well as the maintenance of muscle strength and volume from set-to-set. Contemporary recommendations for intra set rest are 2-3 minutes, although longer rest periods may be appropriate for strength focused resistance exercise, and short rest periods may be appropriate for "assistance" exercise or building muscular endurance (Ratamess et al., 2009). Until recently, there has been little research into the potential for sex-specific intra-set rest recommendations, however, the thesis adds to recent work in this area Refalo et al. (2023) and Voskuil et al. (2024).

Relevance to Resistance Exercise Prescription

Compared to males, the current body of literature suggests that females are better able to maintain set volume, as well as muscle strength and movement velocity when performing several sets of bench press (Ratamess et al., 2012; Refalo et al., 2023) or unilateral dumbbell curls (Voskuil et al., 2024) to or approaching momentary muscular failure. This difference may present itself as early as set 2 when using rest intervals of 1-2 minutes (Ratamess et al., 2012), and, even with 4-minutes of rest between sets, significant sex- differences are present after several sets (Refalo et al., 2023). Although study two only investigated 2 sets, and repetitions were relatively equal, males produced significantly greater time under tension than females during set 1 of TRD-RE, however, experienced a significant drop-off in time under tension, to the point where there were no sex-differences in set 2. Furthermore, this was mirrored by a large reduction in absolute LEpeak in males, while LEpeak remained stable in females.

Comparatively, in Chapter 2, across 4 sets of EQI elbow flexions, we observed that females maintained angular impulse (i.e., total mechanical tension) from set 2 to set 4, while males experienced a significant and substantial decline with every subsequent set, to the point where there were no sex-differences in absolute angular impulse during set 4. This, despite males having substantially greater absolute strength. As with previous reports (Voskuil et al., 2024), Chapter 2 and Chapter 3 may indicate that females can tolerate higher resistance exercise volume than males for both TRD-RE and EQI-RE of the elbow flexors, as muscle fatigue does not manifest as quickly with subsequent sets. Conversely, males may need longer intra-set recovery time than females to minimise the accumulation of muscle fatigue and limit declines in set-to-set volume. Indeed, given expected differences between muscles (Hunter, 2009), there is ample room for future work to explore sex-differences in muscle fatigue across different intra set rest periods and upper- and lower-body movements.

Based on the results of the thesis, as well as other purported benefits and application of EQI-RE, there are still many avenues for future investigation of EQI-RE. Oranchuk et al. (2021), as well as Chapter 2 indicated that most time under tension was spent at short, and not longmuscle lengths when EQI-RE was performed through a large ROM. As such, if mechanical tension at long muscle lengths is considered an important characteristic and underlies the purported hypertrophy and strength adaptations to EQI-RE, future works should evaluate EQI-RE induced strength and muscle hypertrophy using a ROM and muscle lengths that maximize mechanical tension. Indeed, this could provide the opportunity to more accurately evaluate EQI-RE and compare to isometric resistance exercise at specific muscle lengths. Additionally, given recent works supporting non-uniform and regional differences in muscle hypertrophy at different muscle lengths and ROM (Kassiano et al., 2023; Pallarés et al., 2021; Schoenfeld & Grgic, 2020;

Zabaleta-Korta et al., 2020), secondary analysis or follow up studies could examine the region-specific effects of TRD-RE vs. EQI-RE on muscle thickness, as well as fascicle length and muscle stiffness.

Limitations

Overarching limitations of the thesis include, but are not limited to the use of both resistance trained and non-resistance trained participants between studies, differences in intensity (50% MVIT vs. 70% E-1RM) and resistance exercise models (isokinetic dynamometer vs. dumbbell) between studies, as well as the use of a unilateral model of resistance exercise. Indeed, training status may affect the response resistance exercise stimuli, and the speed at which adaptations occur (Lopez et al., 2021). Although debated in the literature, those with greater resistance exercise experience may be better able to push themselves to and/or predict true momentary muscular failure compared to less trained, or naïve individuals (Steele, Endres, et al., 2017; Zourdos et al., 2016). As such, E-1RM was likely underestimated in some participants in Chapter 2 and Chapter 3, resulting in lower-relative training intensities (load).

While statistically and logistically advantageous in that greater power is achieved with less individuals, unilateral exercise models work under the assumption that the potential response to an intervention is similar in both limbs, and the applied intervention(s) do not affect the contralateral limb (Macinnis et al., 2017). Indeed, unilateral exercise will still produce measurable systemic responses (Cornish et al., 2020; Macinnis et al., 2017; Schoenfeld, 2010; West & Phillips, 2012), which the contralateral limb would be exposed to. As such, despite being a within-subject comparison, baseline differences between limbs, and systemic responses to exercise could theoretically contribute to between-group variability and biological noise within a

unilateral exercise mode (Macinnis et al., 2017). Click or tap here to enter text.Relevant to muscle hypertrophy, local as well as systemic responses may factor into the regulation of muscle protein synthesis and muscle protein breakdown (Lim et al., 2022), and resistance exercise will increase a variety of circulating metabolites and hormones that may affect muscle hypertrophy (West & Phillips, 2012). For example, resistance exercise will lead to acute increases in circulating testosterone and growth hormone, which are classically and mechanistically associated with skeletal muscle hypertrophy (Lim et al., 2022). Local resistance exercise can also lead to increases in circulating biomarkers, such as creatine kinase and myokines, which are involved in inflammatory responses, and purported to promote and/or inhibit muscle hypertrophy away from the exercised or involved muscle (Cornish et al., 2020; Lim et al., 2022; Schoenfeld, 2010; West & Phillips, 2012). As previously discussed, however, the molecular mechanisms underlying skeletal muscle hypertrophy are complex and not well-understood (Lim et al., 2022; Schoenfeld, 2010), and it is argued that any influence of these systemic factors on muscle hypertrophy in a unilateral model are likely to be small (Macinnis et al., 2017; West & Phillips, 2012).

From a fatigue perspective, differences may exist when performing submaximal exercise in a bilateral vs. unilateral manner, such that the onset of and magnitude of peripheral and central fatigue differs depending on muscle action and exercise type(Koral et al., 2020; Rossman et al., 2014). As such, the fatigue results of the these studies may not be applicable to bilateral elbow flexion resistance exercise, or bilateral resistance exercise in general. Furthermore, when using a unilateral model to compare between limbs/resistance exercise types, it is recognized that there is a potential of a “cross-over” or “cross-education” effect, where resistance exercise with one limb influences fatigue and/or strength adaptations on contralateral or proximal limbs (Halperin et al.,

2014; Hendy et al., 2012; Manca et al., 2021; Sato et al., 2021). As such, it cannot be ruled out that results for each limb were influenced by the contralateral limb.

Implications for Practice

Broadly, the thesis highlights why practitioners should exercise extreme caution when using mechanistic studies to support clinical decision making. Although the original evidence-based practice (EBP) paradigm encourages practitioners to directly consult and evaluate the scientific literature in the absence of broader or clinical guidelines (Evidence-Based Medicine Working Group, 1992; Meira, 2020), in the case of novel practices, this may result in over-extrapolating observational studies into everyday practice (Howick et al., 2010; Zadro et al., 2019). While it would theoretically be ideal to test every clinical intervention with the "gold standard" of research design, RCTs are logistically, time, and cost-intensive ventures (Antman et al., 2001; Collier, 2009; Coutts, 2017; Hoffer, 2002; Speich et al., 2018). To justify an RCT for an intervention, it is considered prudent by many to first establish biological and clinical plausibility of an intervention using more feasible study designs (Antman et al., 2001; Hoffer, 2002; Howick et al., 2009). Based on our time under tension results from Chapter 2, it seemed mechanistically plausible that males and females would: a.) accrue differing volume across a training program; therefore, b.) would have differing strength and hypertrophic responses to EQI-RE. While the first assumption held true, as females did produce greater volume than males for EQI-RE after 8-weeks of training, this did not lead to sex-differences in the outcome of interest (E-1RM and muscle thickness). As such, this example highlights the complexities of human physiology and the limitations of observational studies, as well as the importance of having outcome-based data to inform decision making in practice.

Although EQI-RE did not produce equivalent strength or hypertrophy adaptations as TRD-RE, this does not suggest EQI-RE is without merit. The underlying epistemology of EBP suggests that clinical decision making should be based on the best available and totality of evidence (i.e., randomized controlled trial vs. expert experience; systematic review, meta-analysis, practice guidelines), within the environmental and individual contexts of the decision-maker and patient/client (Djulbegovic et al., 2009; Djulbegovic & Guyatt, 2017). Unlike broad and overarching claims, such as "neuromuscularly-efficient-induced-hypertrophy" and the elimination of muscular "dysfunction" (Seedman, n.d.-a, n.d.-b) the suggested applications of EQI-RE by Oranchuk et al. (2019b) are contextual to specific circumstances and situations. "Quasi-isometric contractions" have been used to describe sport specific demands in niche sports such as sailing (Spurway, 2007) and speed skating (Stoter et al., 2016), and thus, the environment context and principle of specificity could support the usefulness of EQI-RE. Similarly, by altering the ROM, EQI-RE could be a useful resistance exercise strategy for developing powerlifting or weightlifting movement proficiency, where isotonic strength in a specific portion of the movement is a limiting factor to progressing. With respect to rehabilitation, TRD-RE would not be appropriate for early-stage muscle strains or joint injuries due the shear forces that would be produced (Houglum, 2010), however, EQI-RE could represent a progression of isometric resistance exercise to isotonic resistance exercise in mid-late stage rehabilitation. Indeed, despite a lack of randomized controlled trials or appearing in any clinical practice guidelines, if used as an adjunct to well-supported methods, EQI-RE could still be implemented within an evidence-based framework.

Conclusion

Directly, the thesis is the first work to suggest and support the theory that males are more fatigable than females within-sets, between sets, and over several sessions of EQI-RE for the elbow flexors. Furthermore, these sex-differences in muscle fatigability when performing EQI-RE do not appear to result in relative differences in isotonic strength or hypertrophy gains over ~8-weeks of EQI-RE. While the magnitude of sex-differences in acute muscle fatigue was less for TRD-RE and after several sessions, the resulting differences in volume did not appear to result in sex-differences in isotonic strength or hypertrophy after ~8-weeks of TRD-RE. Overall, in untrained individuals, TRD-RE of the elbow flexors resulted in significantly larger improvements in isotonic strength and muscle hypertrophy compared to EQI-RE.

Resistance exercise plays an important role in overall health across the span, as well as modern sport performance (Abou Sawan et al., 2023; Suchomel et al., 2016). As such, scientific studies of resistance exercise play a key role in informing evidence-based practice (Coutts, 2017; Faulkner et al., 2006; Tiller et al., 2022); however, context and quality is key when applying or interpreting research into practice. Indeed, to remain on the cutting edge and take advantage of advances in research, there has been increasing attention to novel science in both rehabilitation and high performance sport, as well as by practitioners and social media influencers (Coutts, 2017; Marocolo et al., 2021; Tiller et al., 2022). While greater examination of sex-differences in has furthered knowledge across many aspects of exercise science and resistance exercise research, results of these studies may still be over extrapolated, over reduced, and/or misinterpreted in practice (Howick et al., 2010; Zadro et al., 2019). No doubt, there are meaningful physiological differences between males and females that likely contribute to observed sex-differences in areas such as muscle fatigue, muscle strength, and hypertrophy

(Nuzzo, 2022, 2024), and the current thesis is an example of this. The current thesis also demonstrates how easily theory or loosely related studies can be over extrapolated to expected outcomes. Combined with the massive influence that practitioners can play on social media in disseminating, interpreting, and communicating scientific evidence (Marocolo et al., 2021; Tiller et al., 2022), it is important for the scientific community to provide mechanistic, as well as relevant outcome-based data for novel clinical and training modalities, such as EQI-RE.

References

Abbott, B. C., & Wilkie, D. R. (1953). The relation between velocity of shortening and the tension-length curve of skeletal muscle. *The Journal of Physiology*, *120*(1–2), 214–223. https://doi.org/10.1113/jphysiol.1953.sp004886

Aboodarda, S. J., Šambaher, N., & Behm, D. G. (2016). Unilateral elbow flexion fatigue modulates corticospinal responsiveness in non-fatigued contralateral biceps brachii. *Scandinavian Journal of Medicine and Science in Sports*, *26*(11), 1301–1312. https://doi.org/10.1111/sms.12596

Abou Sawan, S., Nunes, E. A., Lim, C., McKendry, J., & Phillips, S. M. (2023). The health benefits of resistance exercise: Beyond hypertrophy and big weights. *Exercise, Sport and Movement*, *1*(1). https://doi.org/10.1249/esm.0000000000000001

Adam, A., & De Luca, C. J. (2003). Recruitment order of motor units in human vastus lateralis muscle is maintained during fatiguing contractions. *Journal of Neurophysiology*, *90*(5), 2919–2927. https://doi.org/10.1152/jn.00179.2003

Adkins, A. N., & Murray, W. M. (2020). Obtaining quality extended field-of-view ultrasound images of skeletal muscle to measure muscle fascicle length. *Journal of Visualized Experiments*, *2020*(166), 1–16. https://doi.org/10.3791/61765

Adler, R. J., & Taylor, J. E. (2007). *Random fields and geometry*. Springer Science + Business Media LLC.

Alway, S. E., Siu, P. M., Murlasits, Z., & Butler, D. C. (2005). Muscle hypertrophy models: Applications for research on aging. *Canadian Journal of Applied Physiology*, *30*(5), 591–624. https://doi.org/10.1139/h05-143

Amann, M., Sidhu, S. K., Weavil, J. C., Mangum, T. S., & Venturelli, M. (2015). Autonomic responses to exercise: Group III/IV muscle afferents and fatigue. *Autonomic Neuroscience: Basic and Clinical*, *188*, 19–23. https://doi.org/10.1016/j.autneu.2014.10.018

Avin, K. G., Naughton, M. R., Ford, B. W., Moore, H. E., Monitto-Webber, M. N., Stark, A. M., Gentile, A. J., & Law, L. A. F. (2010). Sex differences in fatigue resistance are muscle group dependent. *Medicine and Science in Sports and Exercise*, *42*(10), 1943–1950. https://doi.org/10.1249/MSS.0b013e3181d8f8fa

Barbero, M., Merletti, R., & Rainoldi, A. (2012). *Atlas of Muscle Innervation Zones Understanding Surface Electromyography and Its Applications*. Springer.

Bazzucchi, I., Felici, F., Macaluso, A., & De Vito, G. (2004a). Differences between young and older women in maximal force, force fluctuations, and surface EMG during isometric knee extension and elbow flexion. *Muscle and Nerve*, *30*(5), 626–635. https://doi.org/10.1002/mus.20151

Bazzucchi, I., Felici, F., Macaluso, A., & De Vito, G. (2004b). Differences between young and older women in maximal force, force fluctuations, and surface EMG during isometric knee extension and elbow flexion. *Muscle and Nerve*, *30*(5), 626–635. https://doi.org/10.1002/mus.20151

Bennie, J. A., Shakespear-Druery, J., & De Cocker, K. (2020). Muscle-strengthening exercise epidemiology: a new frontier in chronic disease prevention. *Sports Medicine - Open*, *6*(1). https://doi.org/10.1186/s40798-020-00271-w

Bigland-Ritchie, B., Rice, C. L., Garland, S. J., & Walsh, M. L. (1995). *FATIGUE Neural and Muscular Mechanisms* (S. C. Gandevia, R. M. Enoka, A. J. McComas, D. G. , Stuart, & C. K. Thomas, Eds.). Springer.

Bigland-Ritchie, B., & Woods, J. (1984). Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle & Nerve*, *7*(9), 691–699.

Biodex Medical Systems, I. (2011). *Biodex multi-joint system-pro: set-up/operation manual*.

Biodex Medical Systems, I. (2014). *Biodex advantage software (V.4X): operation manual*.

Bohm, S., Mersmann, F., & Arampatzis, A. (2015). Human tendon adaptation in response to mechanical loading: a systematic review and meta-analysis of exercise intervention studies on healthy adults. *Sports Medicine - Open*, *1*(1). https://doi.org/10.1186/s40798-015-0009-9

Bompa, T. O., & Haff, G. G. (2009). Principles of Training. In *Periodization* (5th Edition, pp. 31–56). Human Kinetics.

Buckner, S. L., Yitzchaki, N., Kataoka, R., Vasenina, E., Zhu, W. G., Kuehne, T. E., & Loenneke, J. P. (2021). Do exercise-induced increases in muscle size contribute to strength in resistance-trained individuals? *Clinical Physiology and Functional Imaging*, *41*(4), 326–333. https://doi.org/10.1111/cpf.12699

Burns, P. B., Rohrich, R. J., & Chung, K. C. (2011). The levels of evidence and their role in evidence-based medicine. *Plastic and Reconstructive Surgery*, *128*(1), 305–310. https://doi.org/10.1097/PRS.0b013e318219c171

Canadian Society for Exercise Physiology. (2013). *Physical Activity Training for Health*.

Canadian Society for Exercise Physiology. (2017). *Pre-Screening for Physical Activity: Get Active Questionnaire*. https://csep.ca/2021/01/20/pre-screening-for-physical-activity/

Carr, J. C., & Ye, X. (2020). Strength and electromyographic responses of upper and lower limbs during maximal intermittent contractions in males and females. *Journal of Strength and Conditioning Research, Ahead of Print*(March). https://doi.org/10.1519/jsc.0000000000003580

Carr, J. C., Ye, X., & Tharp, H. M. (2021). Biceps brachii muscle length affects force steadiness with and without fatigue. *Journal of Science in Sport and Exercise*. https://doi.org/10.1007/s42978-020-00102-0

Carvalho, L., Junior, R. M., Barreira, J., Schoenfeld, B. J., Orazem, J., & Barroso, R. (2022). Muscle hypertrophy and strength gains after resistance training with different volume-matched loads: a systematic review and meta-analysis. *Applied Physiology, Nutrition, and Metabolism*, *12*(January), 1–12. https://doi.org/10.1139/apnm-2021-0515

Cavanagh, P. R. (1988). On “muscle action” vs “muscle contraction.” *Journal of Biomechanics*, *21*(1), 69. https://doi.org/10.1016/0021-9290(88)90195-9

Chen, J., O'Dell, M., He, W., Du, L. J., Li, P. C., & Gao, J. (2017). Ultrasound shear wave elastography in the assessment of passive biceps brachii muscle stiffness: influences of sex and elbow position. *Clinical Imaging*, *45*, 26–29. https://doi.org/10.1016/j.clinimag.2017.05.017

Cholewa, J., Guimarães-Ferreira, L., da Silva Teixeira, T., Naimo, M. A., Zhi, X., de Sá, R. B. D. P., Lodetti, A., Cardozo, M. Q., & Zanchi, N. E. (2014). Basic models modeling resistance training: An update for basic scientists interested in study skeletal muscle hypertrophy. *Journal of Cellular Physiology*, *229*(9), 1148–1156. https://doi.org/10.1002/jcp.24542

Ciccolo, J. T., & Nosrat, S. (2016). Resistance training and chronic disease: A summary of the current evidence. *ACSM Health & Fitness Journal*, *20*(5), 44–49.

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.). Lawrence Erlbaum Associates.

Colenso-Semple, L. M., D'Souza, A. C., Elliott-Sale, K. J., & Phillips, S. M. (2023). Current evidence shows no influence of women's menstrual cycle phase on acute strength performance or adaptations to resistance exercise training. In *Frontiers in Sports and Active Living* (Vol. 5). Frontiers Media S.A. https://doi.org/10.3389/fspor.2023.1054542

Cornish, S. M., Bugera, E. M., Duhamel, T. A., Peeler, J. D., & Anderson, J. E. (2020). A focused review of myokines as a potential contributor to muscle hypertrophy from resistance-based exercise. In *European Journal of Applied Physiology* (Vol. 120, Issue 5, pp. 941–959). Springer. https://doi.org/10.1007/s00421-020-04337-1

Coutts, A. J. (2017). Challenges in developing evidence-based practice in high-performance sport. *International Journal of Sports Physiology and Performance*, *12*(6), 717–718. https://doi.org/10.1123/IJSPP.2017-0455

Csapo, R., & Alegre, L. M. (2015). Effects of Kinesio® taping on skeletal muscle strength-A meta-analysis of current evidence. *Journal of Science and Medicine in Sport*, *18*(4), 450–456. https://doi.org/10.1016/j.jsams.2014.06.014

Csapo, R., Alegre, L. M., & Baron, R. (2011). Time kinetics of acute changes in muscle architecture in response to resistance exercise. *Journal of Science and Medicine in Sport*, *14*(3), 270–274. https://doi.org/10.1016/j.jsams.2011.02.003

Currier, B. S., McLeod, J. C., Banfield, L., Beyene, J., Welton, N. J., D'Souza, A. C., Keogh, J. A. J., Lin, L., Coletta, G., Yang, A., Colenso-Semple, L., Lau, K. J., Verboom, A., & Phillips, S. M. (2023). Resistance training prescription for muscle strength and hypertrophy in healthy adults: A systematic review and Bayesian network meta-analysis. *British Journal of Sports Medicine*. https://doi.org/10.1136/bjsports-2023-106807

D'agostino, R. B., & Belanger, A. (1990). A suggestion for using powerful and informative tests of normality. *The American Statistician* , *44*(4), 316–321.

Dankel, S. J., Laurentino, G. C., Loenneke, J. P., Buckner, S. L., Mattocks, K. T., Jessee, M. B., Counts, B. R., & Mouser, J. G. (2017). Can blood flow restriction augment muscle activation during high-load training? *Clinical Physiology and Functional Imaging*, *38*(2), 291–295. https://doi.org/10.1111/cpf.12414

Delsys. (2020). *How does one verify the quality of an EMG signal?* https://delsys.com/faq-items/how-does-one-verify-the-quality-of-an-emg-signal/#:~:text=The formal signal-to-noise,SNR %3D 65dB

Djulbegovic, B., & Guyatt, G. H. (2017). Progress in evidence-based medicine: a quarter century on. *The Lancet*, *390*(10092), 415–423. https://doi.org/10.1016/S0140-6736(16)31592-6

Djulbegovic, B., Guyatt, G. H., & Ashcroft, R. E. (2009). Epistemologic inquiries in evidence-based-medicine. *Cancer Control*, *16*(2), 158–168.

Douglas, J., Pearson, S., Ross, A., & McGuigan, M. (2017). Eccentric Exercise: Physiological Characteristics and Acute Responses. *Sports Medicine*, *47*(4), 663–675. https://doi.org/10.1007/s40279-016-0624-8

ESPN. (2016). *ESPN's "Journalism Showcase" – April 8, 2016.* [Broadcast].

Evidence-Based Medicine Working Group. (1992). Evidence-based medicine. A new approach to teaching the practice of medicine. *Journal of the American Medical Association*, *268*(17), 2420–2425.

Farina, D., Merletti, R., & Enoka, R. M. (2004). The extraction of neural strategies from the surface EMG. *Journal of Applied Physiology*, *96*, 1486–1495. https://doi.org/10.1152/japplphysiol.01070.2003.-This

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191.

Faulkner, G., Taylor, A., Ferrence, R., Munro, S., & Selby, P. (2006). Exercise science and the development of evidence-based practice: A “better practices” framework. *European Journal of Sport Science*, *6*(2), 117–126. https://doi.org/10.1080/17461390500528568

Field, A. (2009). *Discovering Statistics Using SPSS* (3rd ed.).

Freilich, R. J., Kirsner, R. L. G., & Byrne, E. (1995). Isometric strength and thickness relationships in human quadriceps muscle. *Neuromuscular Disorders*, *5*(5), 415–422.

Gandevia, S. C. (2001). *Spinal and Supraspinal Factors in Human Muscle Fatigue*. www.prv.org

Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I. M., Nieman, D. C., & Swain, D. P. (2011). Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: Guidance for prescribing exercise. *Medicine and Science in Sports and Exercise*, *43*(7), 1334–1359. https://doi.org/10.1249/MSS.0b013e318213fefb

Gentil, P., Compos, M. H., Soares, S., De Conti Teixeira Costa, G., Paoli, A., Bianco, A., & Bottaro, M. (2017). Comparison of elbow flexor isokinetic peak torque and fatigue index between men and women of different training level. *European Journal of Translational Myology*, *27*(4), 246–250. https://doi.org/10.4081/ejtm.2017.7070

Gentil, P., Oliveira, E., & Bottaro, M. (2006). Time under tension and blood lactate response during four different resistance training methods. *Journal of Physiological Anthropology*, *25*(5), 339–344. https://doi.org/10.2114/jpa2.25.339

Goldspink, G. (1999). Changes in muscle mass and phenotype and the expression of autocrine and systemic growth factors by muscle in response to stretch and overload. *Journal of Anatomy, 194*(3), 323–334. https://doi.org/10.1017/S0021878298004439

Gomes, M., Santos, P., Correia, P., Pezarat-Correia, P., & Mendonca, G. V. (2021). Sex differences in muscle fatigue following isokinetic muscle contractions. *Scientific Reports*, *11*(1), 1–12. https://doi.org/10.1038/s41598-021-87443-0

Greenhouse, S. W., & Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika*, *24*, 95–112.

Grgic, J., Mcllvenna, L. C., Fyfe, J. J., Sabol, F., Bishop, D. J., Schoenfeld, B. J., & Pedisic, Z. (2019). Does aerobic training promote the same skeletal muscle hypertrophy as resistance training? A systematic review and meta-analysis. *Sports Medicine, 49*(2), 233–254. https://doi.org/10.1007/s40279-018-1008-z

Halaki, M., & Ginn, K. (2012). Normalization of EMG Signals: To Normalize or Not to Normalize and What to Normalize to? In *Computational Intelligence in Electromyographic Analysis - A Perspective on Current Applications and Future Challenges*. Intech Open. https://doi.org/10.5772/49957

Halperin, I., Aboodarda, S. J., & Behm, D. G. (2014). Knee extension fatigue attenuates repeated force production of the elbow flexors. *European Journal of Sport Science, 14*(8), 823–829. https://doi.org/10.1080/17461391.2014.911355

Hamill, J., Knutzen, K. M., & Derrick, T. R. (2015). *Biomechanical basis of human movement* (4th ed.). Wolters Kluwer.

Haun, C. T., Vann, C. G., Roberts, B. M., Vigotsky, A. D., Schoenfeld, B. J., & Roberts, M. D. (2019). A critical evaluation of the biological construct skeletal muscle hypertrophy: Size matters but so does the measurement. *Frontiers in Physiology*, *10*(MAR), 1–23. https://doi.org/10.3389/fphys.2019.00247

Henderson, Z. J., & Scribbans, T. D. (2020). Intrauterine contraception and athletic performance: Where is the data? *Health & Fitness Journal of Canada*, *13*(2), 37–45. https://doi.org/10.14288/hfjc.v13i2.308

Henderson, Z. J., Wang, S., Cornish, S. M., & Scribbans, T. D. (2023). Exploring the acute muscle fatigue response in resistance trained individuals during eccentric quasi-isometric elbow flexions—a cross-sectional comparison of repetition and sex. *Sports Biomechanics*, 1–23. https://doi.org/10.1080/14763141.2023.2269543

Hendy, A. M., Spittle, M., & Kidgell, D. J. (2012). Cross education and immobilisation: Mechanisms and implications for injury rehabilitation. *Journal of Science and Medicine in Sport*, *15*(2), 94–101. https://doi.org/10.1016/j.jsams.2011.07.007

Henneman, E. (1957). Relation between the size of neurons and their susceptibility to discharge. *Science*, *126*, 1345–1347.

Henneman, E., & Olsen, C. B. (1965). Relations between structure and function in the design of the skeletal muscles. *Journal of Neurophysiology*, *28*, 581–593.

Hinks, A., Franchi, M. V., & Power, G. A. (2022). The influence of longitudinal muscle fascicle growth on mechanical function. *Journal of Applied Physiology*, *133*(1), 87–103. https://doi.org/10.1152/japplphysiol.00114.2022

Holmes, A. P., Blair, R. C., Watson, H. D. G., & Ford, I. (1996). Nonparametric analysis of statistic images from functional mapping experiments. *Journal of Cerebral Blood Flow and Metabolism*, *16*, 7–22.

Houglum, P. A. (2010). *Therapeutic Exercise for Musculoskeletal Conditions* (D. H. Perrin, Ed.; 3rd ed.). Human Kinetics.

Howick, J., Glasziou, P., & Aronson, J. K. (2010). Evidence-based mechanistic reasoning. *Journal of the Royal Society of Medicine*, *103*(11), 433–441. https://doi.org/10.1258/jrsm.2010.100146

Hughes, L., Paton, B., Rosenblatt, B., Gissane, C., & Patterson, S. D. (2017). Blood flow restriction training in clinical musculoskeletal rehabilitation: A systematic review and meta-analysis. In *British Journal of Sports Medicine* (Vol. 51, Issue 13, pp. 1003–1011). BMJ Publishing Group. https://doi.org/10.1136/bjsports-2016-097071

Hunter, S. K. (2009). Sex differences and mechanisms of task-specific muscle fatigue. *Exercise and Sport Sciences Reviews*, *37*(3), 113–122. https://doi.org/10.1097/JES.0b013e3181aa63e2.Sex

Hunter, S. K. (2014). Sex differences in human fatigability: Mechanisms and insight to physiological responses. *Acta Physiologica*, *210*(4), 768–789. https://doi.org/10.1111/apha.12234

Hunter, S. K. (2016a). Sex differences in fatigability of dynamic contractions. *Experimental Physiology*, *101*(2), 250–255. https://doi.org/10.1113/EP085370

Hunter, S. K. (2016b). The relevance of sex differences in performance fatigability. *Medicine and Science in Sports and Exercise*, *48*(11), 2247–2256. https://doi.org/10.1249/MSS.0000000000000928

Hunter, S. K., Critchlow, A., Shin, I., & Enoka, R. M. (2004a). Men are more fatigable than strength-matched women when performing intermittent submaximal contractions. *Journal of Applied Physiology*, *96*(6), 2125–2132. https://doi.org/10.1152/japplphysiol.01342.2003

Hunter, S. K., Critchlow, A., Shin, I.-S., & Enoka, R. M. (2004b). Fatigability of the elbow flexor muscles for a sustained submaximal contraction is similar in men and women matched for strength. *Journal of Applied Physiology*, *96*(1), 195–202. https://doi.org/10.1152/japplphysiol.00893.2003

Hunter, S. K., & Enoka, R. M. (2001). Sex differences in the fatigability of arm muscles depends on absolute force during isometric contractions. *Journal of Applied Physiology*, *91*(6), 2686–2694. https://doi.org/10.1152/jappl.2001.91.6.2686

Hunter, S. K., Ryan, D. L., Ortega, J. D., & Enoka, R. M. (2002). Task differences with the same load torque alter the endurance time of submaximal fatiguing contractions in humans. *Journal of Neurophysiology*, *88*(6), 3087–3096. https://doi.org/10.1152/jn.00232.2002

Hunter, S. K., Schletty, J. M., Schlachter, K. M., Griffith, E. E., Polichnowski, A. J., & Ng, A. V. (2006). Active hyperemia and vascular conductance differ between men and womenfor an isometric fatiguing contraction. *Journal of Applied Physiology*, *101*, 140–150. https://doi.org/10.1152/japplphysiol.01567.2005.-To

Janssen, I., Heymsfield, S. B., Wang, Z., & Ross, R. (2000). Skeletal muscle mass and distribution in 468 men and women aged 18-88 yr. *Journal of Applied Physiology*, *89*, 81–88. http://www.jap.org

Jessee, M. B., Mattocks, K. T., Buckner, S. L., Dankel, S. J., Mouser, J. G., Abe, T., & Loenneke, J. P. (2018). Mechanisms of blood flow restriction: The new testament. *Techniques in Orthopaedics*, *33*(2), 72–79. https://doi.org/10.1097/BTO.0000000000000252

Jodoin, H. L., Hinks, A., Roussel, O. P., Contento, V. S., Dalton, B. H., & Power, G. A. (2023a). Eccentric exercise-induced muscle weakness abolishes sex differences in fatigability during sustained submaximal isometric contractions. *Journal of Sport and Health Science*, *12*(4), 523–533. https://doi.org/10.1016/j.jshs.2023.02.001

Jodoin, H. L., Hinks, A., Roussel, O. P., Contento, V. S., Dalton, B. H., & Power, G. A. (2023b). Eccentric exercise-induced muscle weakness abolishes sex differences in fatigability during

sustained submaximal isometric contractions. *Journal of Sport and Health Science*, *12*(4), 523–533. https://doi.org/10.1016/j.jshs.2023.02.001

Kamen, G., & Gabriel, D. A. (2010a). *Essentials of Electromyography*. Human Kinetics.

Kamen, G., & Gabriel, D. A. (2010b). *Essentials of Electromyography*. Human Kinetics.

Kassiano, W., Costa, B., Pedro Nunes, J., Ribeiro, A. S., Schoenfeld, B. J., & Cyrino, E. S. (2023). Which ROMs lead to Rome? A systematic review of the effects of range of motion on muscle hypertrophy. *Journal of Strength and Conditioning Research*, *37*(5), 1135–1144. www.nsca.com

Kent-Braun, J. A., Ng, A. V, Doyle, J. W., Towse, T. F., & Braun, K. (2002). Human skeletal muscle responses vary with age and gender during fatigue due to incremental isometric exercise. *Journal of Applied Physiology*, *93*, 1813–1823. https://doi.org/10.1152/japplphysiol.00091.2002.-The

Klavora, P., & Locke, M. (2018). *Introduction to Kinesiology* (Peter Klavora, Ed.; 3rd Edition, pp. 314–339).

Kojić, F., Mandić, D., & Ilić, V. (2021). Resistance training induces similar adaptations of upper and lower-body muscles between sexes. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-021-02867-y

Koral, J., Oranchuk, D. J., Wrightson, J. G., Twomey, R., & Millet, G. Y. (2020). Mechanisms of neuromuscular fatigue and recovery in unilateral versus bilateral maximal voluntary

contractions. *Journal of Applied Physiology*, *128*(4), 785–794. https://doi.org/10.1152/japplphysiol.00651.2019

Kotte, S. H. P., Viveen, J., Koenraadt, K. L. M., The, B., & Eygendaal, D. (2018). Normative values of isometric elbow strength in healthy adults: a systematic review. *Shoulder and Elbow*, *10*(3), 207–215. https://doi.org/10.1177/1758573217748643

Lawrence, J. H., De Luca, C. J., & De, C. J. (1983). *Myoelectric signal versus force relationship in different human muscles*.

Levene, H. (1960). Robust tests for equality of variances. In I. Olkin, S. G. Ghurye, W. Hoeffding, W. G. Madow, & H. B. Mann (Eds.), *Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling*.

Ličen, U., Oranchuk, D. J., & Kozinc, Ž. (2024). Exploring the biomechanics and fatigue patterns of eccentric quasi-isometric muscle actions in the knee extensors and flexors. *European Journal of Applied Physiology*. https://doi.org/10.1007/s00421-024-05544-w

Lim, C., Nunes, E. A., Currier, B. S., McLeod, J. C., Thomas, A. C. Q., & Phillips, S. M. (2022). An evidence-based narrative review of mechanisms of resistance exercise-induced human skeletal muscle hypertrophy. *Medicine and Science in Sports and Exercise*, *54*(9), 1546–1559. https://doi.org/10.1249/MSS.0000000000002929

Lin, T. Y., Chueh, T. Y., & Hung, T. M. (2023). Preferred reporting items for resistance exercise studies (PRIRES): A checklist developed using an umbrella review of systematic reviews. *Sports Medicine - Open*, *9*(1). https://doi.org/10.1186/s40798-023-00640-1

Lindstedt, S. L., LaStayo, P. C., & Reich, T. E. (2001). When active muscles lengthen: Properties and consequences of eccentric contractions. *News in Physiological Sciences*, *16*(6), 256–261. https://doi.org/10.1152/physiologyonline.2001.16.6.256

Lixandrão, M. E., Ugrinowitsch, C., Berton, R., Vechin, F. C., Conceição, M. S., Damas, F., Libardi, C. A., & Roschel, H. (2018). Magnitude of muscle strength and mass adaptations between high-load resistance training versus low-load resistance training associated with blood-flow restriction: A systematic review and meta-analysis. *Sports Medicine*, *48*(2), 361–378. https://doi.org/10.1007/s40279-017-0795-y

Lopez, P., Radaelli, R., Taaffe, D. R., Newton, R. U., Galvão, D. A., Trajano, G. S., Teodoro, J. L., Kraemer, W. J., Häkkinen, K., & Pinto, R. S. (2021). Resistance training load effects on muscle hypertrophy and strength gain: Systematic review and network meta-analysis. *Medicine and Science in Sports and Exercise*, *53*(6), 1206–1216. https://doi.org/10.1249/MSS.0000000000002585

López-Bueno, R., Andersen, L. L., Koyanagi, A., Núñez-Cortés, R., Calatayud, J., Casaña, J., & del Pozo Cruz, B. (2022). Thresholds of handgrip strength for all-cause, cancer, and cardiovascular mortality: A systematic review with dose-response meta-analysis. In *Ageing Research Reviews* (Vol. 82). Elsevier Ireland Ltd. https://doi.org/10.1016/j.arr.2022.101778

Lowe, D. A., & Alway, S. E. (2002). Animal models for inducing muscle hypertrophy: Are they relevant for clinical applications in humans? *Journal of Orthopaedic and Sports Physical Therapy*, *32*(2), 36–43. https://doi.org/10.2519/jospt.2002.32.2.36

Lulic-Kuryllo, T., & Inglis, J. G. (2022). Sex differences in motor unit behaviour: A review. *Journal of Electromyography and Kinesiology*, *66*. https://doi.org/10.1016/j.jelekin.2022.102689

Lulic-Kuryllo, T., Negro, F., Jiang, N., & Dickerson, C. R. (2021). Standard bipolar surface EMG estimations mischaracterize pectoralis major activity in commonly performed tasks. *Journal of Electromyography and Kinesiology*, *56*. https://doi.org/10.1016/j.jelekin.2020.102509

Lulic-Kuryllo, T., Thompson, C. K., Jiang, N., Negro, F., & Dickerson, C. R. (2021). Neural control of the healthy pectoralis major from low-to-moderate isometric contractions. *Journal of Neurophysiology*, *126*(1), 213–226. https://doi.org/10.1152/jn.00046.2021

Lum, D., & Barbosa, T. M. (2019). Brief review: effects of isometric strength training on strength and dynamic performance. *International Journal of Sports Medicine*, *40*(6), 363–375. https://doi.org/10.1055/a-0863-4539

Lundberg, T. R., Tucker, R., McGawley, K., Williams, A. G., Millet, G. P., Sandbakk, Ø., Howatson, G., Brown, G. A., Carlson, L. A., Chantler, S., Chen, M. A., Heffernan, S. M., Heron, N., Kirk, C., Murphy, M. H., Pollock, N., Pringle, J., Richardson, A., Santos-Concejero, J., … Hilton, E. N. (2024). The International Olympic Committee framework on fairness, inclusion and nondiscrimination on the basis of gender identity and sex variations does not protect fairness for female athletes. *Scandinavian Journal of Medicine & Science in Sports*, *34*(3). https://doi.org/10.1111/sms.14581

Macinnis, M. J., McGlory, C., Gibala, M. J., & Phillips, S. M. (2017). Investigating human skeletal muscle physiology with unilateral exercise models: When one limb is more powerful than two. *Applied Physiology, Nutrition and Metabolism*, *42*(6), 563–570. https://doi.org/10.1139/apnm-2016-0645

Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., & Duchateau, J. (2016). Rate of force development: physiological and methodological considerations. *European Journal of Applied Physiology*, *116*(6), 1091–1116. https://doi.org/10.1007/s00421-016-3346-6

Manca, A., Hortobágyi, T., Carroll, T. J., Enoka, R. M., Farthing, J. P., Gandevia, S. C., Kidgell, D. J., Taylor, J. L., & Deriu, F. (2021). Contralateral effects of unilateral strength and skill training: Modified delphi consensus to establish key aspects of cross-education. *Sports Medicine*, *51*(1), 11–20. https://doi.org/10.1007/s40279-020-01377-7

Mann, T. N., Lamberts, R. P., & Lambert, M. I. (2014). High responders and low responders: Factors associated with individual variation in response to standardized training. In *Sports Medicine* (Vol. 44, Issue 8, pp. 1113–1124). Springer International Publishing. https://doi.org/10.1007/s40279-014-0197-3

Marocolo, M., Meireles, A., de Souza, H. L. R., Mota, G. R., Oranchuk, D. J., Arriel, R. A., & Leite, L. H. R. (2021). Is social media spreading misinformation on exercise and health in Brazil? *International Journal of Environmental Research and Public Health*, *18*(22). https://doi.org/10.3390/ijerph182211914

Martin, P. G., Smith, J. L., Butler, J. E., Gandevia, S. C., & Taylor, J. L. (2006). Fatigue-sensitive afferents inhibit extensor but not flexor motoneurons in humans. *The Journal of Neuroscience, 26*(18), 4796–4802. https://doi.org/10.1523/JNEUROSCI.5487-05.2006

Martin, P. G., Weerakkody, N., Gandevia, S. C., & Taylor, J. L. (2008). Group III and IV muscle afferents differentially affect the motor cortex and motoneurones in humans. *Journal of Physiology, 5*, 1277–1289. https://doi.org/10.1113/jphysiol.2007.140426

McBride, J. M. (2016). *Essentials of Strength and Conditioning* (G. G. Haff & N. T. Triplett, Eds.; 4th ed.). Human Kinetics.

McCall, G. E., Byrnes, W. C., Dickinson, A., Pattany, P. M., & Fleck, S. J. (1996). Muscle fiber hypertrophy, hyperplasia, and capillary density in college men after resistance training. *Journal of Applied Physiology*, *81*(5), 2004–2012. https://doi.org/10.1152/jappl.1996.81.5.2004

McKendry, J., Stokes, T., McLeod, J. C., & Phillips, S. M. (2021). Resistance exercise, aging, disuse, and muscle protein metabolism. *Comprehensive Physiology*, *11*(3), 2249–2278. https://doi.org/10.1002/cphy.c200029

Mcleod, J. C., Currier, B. S., Lowisz, C. V., & Phillips, S. M. (2023). The influence of resistance exercise training prescription variables on skeletal muscle mass, strength, and physical function in healthy adults: An umbrella review. *Journal of Sport and Health Science*. https://doi.org/10.1016/j.jshs.2023.06.005

Meira, E. (2020). Understanding evidence-based medicine using a funnel analogy. *SportRxiv , Preprint*. https://doi.org/10.31236/osf.io/kr6aq

Morgan, D. L., & Proske, U. (2004). Popping sarcomere hypothesis explains stretch-induced muscle damage. *Clinical and Experimental Pharmacology and Physiology*, *31*(8), 541–545. https://doi.org/10.1111/j.1440-1681.2004.04029.x

Moritani, T., & DeVries, H. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. *American Journal of Physical Medicine*, *58*(3), 115–130.

Morrison, N. (2016). *The Russian Training Secret*. https://www.t-nation.com/training/qi-the-russian-training-secret/

Morrison, S., & Cook, J. (2022). Putting "heavy" into heavy slow resistance. *Sports Medicine*, *52*(6), 1219–1222. https://doi.org/10.1007/s40279-022-01641-y

Nichols, T. E., & Holmes, A. P. (2001). Nonparametric Permutation Tests For Functional Neuroimaging: A Primer with Examples. *Human Brain Mapping*, *15*, 1–25.

Nimphius, S. (2019). Exercise and sport science failing by design in understanding female athletes. *International Journal of Sports Physiology and Performance, Ahead of Print*. https://doi.org/10.3200/35-08-083

Nishikawa, Y., Watanabe, K., Takahashi, T., Hosomi, N., Orita, N., Mikami, Y., Maruyama, H., Kimura, H., & Matsumoto, M. (2017). Sex differences in variances of multi-channel surface electromyography distribution of the vastus lateralis muscle during isometric knee extension

in young adults. *European Journal of Applied Physiology*, *117*(3), 583–589. https://doi.org/10.1007/s00421-017-3559-3

Nolan, D., McNulty, K. L., Manninen, M., & Egan, B. (2024). The effect of hormonal contraceptive use on skeletal muscle hypertrophy, power and strength adaptations to resistance exercise training: A systematic review and multilevel meta-analysis. *Sports Medicine*, *54*(1), 105–125. https://doi.org/10.1007/s40279-023-01911-3

Nuzzo, J. L. (2022). Narrative review of sex differences in muscle strength, endurance, activation, size, fiber type, and strength training participation rates, preferences, motivations, injuries, and neuromuscular adaptations. *The Journal of Strength and Conditioning Research*, *37*(2), 494–536. www.nsca.com

Nuzzo, J. L. (2024). Sex differences in skeletal muscle fiber types: A meta-analysis. *Clinical Anatomy*, *37*(1), 81–91. https://doi.org/10.1002/ca.24091

Nuzzo, J. L., Pinto, M. D., & Nosaka, K. (2023). Muscle strength and activity in men and women performing maximal effort biceps curl exercise on a new machine that automates eccentric overload and drop setting. *European Journal of Applied Physiology*, *123*(6), 1381–1396. https://doi.org/10.1007/s00421-023-05157-9

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(97–113).

Oranchuk, D. J., Diewald, S. N., McGrath, J. W., Nelson, A. R., Storey, A. G., & Cronin, J. B. (2021). Kinetic and kinematic profile of eccentric quasi-isometric loading. *Sports Biomechanics*, *00*(00), 1–14. https://doi.org/10.1080/14763141.2021.1890198

Oranchuk, D. J., Nelson, A. R., Storey, A. G., Diewald, S. N., & Cronin, J. B. (2020). Short-term neuromuscular, morphological, and architectural responses to eccentric quasi-isometric muscle actions. *European Journal of Applied Physiology*, *121*, 141–158. https://doi.org/10.1007/s00421-020-04512-4

Oranchuk, D. J., Storey, A. G., Nelson, A. R., & Cronin, J. B. (2019a). Isometric training and long-term adaptations: Effects of muscle length, intensity, and intent: A systematic review. *Scandinavian Journal of Medicine and Science in Sports*, *29*(4), 484–503. https://doi.org/10.1111/sms.13375

Oranchuk, D. J., Storey, A. G., Nelson, A. R., & Cronin, J. B. (2019b). Scientific basis for eccentric quasi-isometric resistance training: A narrative review. *Journal of Strength and Conditioning Research*, *33*(10), 2846–2859. https://doi.org/10.1519/JSC.0000000000003291

Pallarés, J. G., Hernández-Belmonte, A., Martínez-Cava, A., Vetrovsky, T., Steffl, M., & Courel-Ibáñez, J. (2021). Effects of range of motion on resistance training adaptations: A systematic review and meta-analysis. *Scandinavian Journal of Medicine and Science in Sports*, *31*(10), 1866–1881. https://doi.org/10.1111/sms.14006

Panidi, I., Donti, O., Konrad, A., Dinas, P. C., Terzis, G., Mouratidis, A., Gaspari, V., Donti, A., & Bogdanis, G. C. (2023). Muscle architecture adaptations to static stretching training: A

systematic review with meta-analysis. *Sports Medicine - Open*, *9*(1). https://doi.org/10.1186/s40798-023-00591-7

Park, M. (2016). *Olympics in bright red spots: What is cupping?* .

Parsons, J. L., Coen, S. E., & Bekker, S. (2021). Anterior cruciate ligament injury: Towards a gendered environmental approach. *British Journal of Sports Medicine*, *55*(17), 984–990. https://doi.org/10.1136/bjsports-2020-103173

Pataky, T. C. (2012). One-dimensional statistical parametric mapping in Python. *Computer Methods in Biomechanics and Biomedical Engineering*, *15*(3), 295–301. https://doi.org/10.1080/10255842.2010.527837

Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics*, *46*(14), 2394–2401. https://doi.org/10.1016/j.jbiomech.2013.07.031

Pataky, T. C., Vanrenterghem, J., & Robinson, M. A. (2015). Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *Journal of Biomechanics*, *48*(7), 1277–1285. https://doi.org/10.1016/j.jbiomech.2015.02.051

Pataky, T. C., Vanrenterghem, J., Robinson, M. A., & Liebl, D. (2019). On the validity of statistical parametric mapping for nonuniformly and heterogeneously smooth one-dimensional biomechanical data. *Journal of Biomechanics*, *91*, 114–123. https://doi.org/10.1016/j.jbiomech.2019.05.018

Paz, G. A., Robbins, D. W., De Oliveira, C. G., Bottaro, M., & Miranda, H. (2017). Volume load and neuromuscular fatigue during an acute bout of agonist-antagonist paired-set vs. traditional-set training. *Journal of Strength and Conditioning Research*, *31*(10), 2777–2784. www.nsca.com

Pearson, S. J., & Hussain, S. R. (2015). A review on the mechanisms of blood-flow restriction resistance training-induced muscle hypertrophy. *Sports Medicine*, *45*(2), 187–200. https://doi.org/10.1007/s40279-014-0264-9

Pedrosa, G. F., Lima, F. V., Schoenfeld, B. J., Lacerda, L. T., Simões, M. G., Pereira, M. R., Diniz, R. C. R., & Chagas, M. H. (2022). Partial range of motion training elicits favorable improvements in muscular adaptations when carried out at long muscle lengths. *European Journal of Sport Science*, *22*(8), 1250–1260. https://doi.org/10.1080/17461391.2021.1927199

Penny, W. D., Friston, K. J., Ashburner, J. T., Kiebel, S. J., & Nichols, T. E. (2007). *Statistical parametric mapping: The analysis of functional brain images* (1st ed.). Academic Press.

Perkisas, S., Baudry, S., Bauer, J., Beckwée, D., De Cock, A. M., Hobbelen, H., Jager-Wittenaar, H., Kasiukiewicz, A., Landi, F., Marco, E., Merello, A., Piotrowicz, K., Sanchez, E., Sanchez-Rodriguez, D., Scafoglieri, A., Cruz-Jentoft, A., & Vandewoude, M. (2018). Application of ultrasound for muscle assessment in sarcopenia: towards standardized measurements. *European Geriatric Medicine*, *9*(6), 739–757. https://doi.org/10.1007/s41999-018-0104-9

Peterson, S., Weible, K., Halpert, B., & Rhon, D. I. (2022). Continuing education courses for orthopedic and sports physical therapists in the United States often lack supporting evidence: A review of available intervention courses. *Physical Therapy*, *102*(6). https://doi.org/10.1093/ptj/pzac031

Piervirgili, G., Petracca, F., & Merletti, R. (2014). A new method to assess skin treatments for lowering the impedance and noise of individual gelled Ag-AgCl electrodes. *Physiological Measurement*, *35*(10), 2101–2118. https://doi.org/10.1088/0967-3334/35/10/2101

Portney, L. G., & Watkins, M. P. (2015). *Foundations of Clinical Research Applications to Practice 3rd Edition*. www.fadavis.com

Powers, S. K., & Howley, E. T. (2012). Training for Performance. In *Exercise Physiology: Theory and Application to Fitness and Performance* (8th Edition, pp. 479–500).

Pradhan, A., Malagon, G., Lagacy, R., Chester, V., & Kuruganti, U. (2020). Effect of age and sex on strength and spatial electromyography during knee extension. *Journal of Physiological Anthropology*, *39*(1). https://doi.org/10.1186/s40101-020-00219-9

Prentice, W. E. (2017). Fitness and Conditioning Techniques. In W. E. Prentice (Ed.), *Principles of Athletic Training* (16th Edition, pp. 90–127).

Pruszynski, J. A., Kurtzer, I., & Scott, S. H. (2008). Rapid motor responses are appropriately tuned to the metrics of a visuospatial task. *Journal of Neurophysiology*, *100*(1), 224–238. https://doi.org/10.1152/jn.90262.2008

Ratamess, N. A., Alvar, B. A., Evetoch, T. K., Housh, T. J., Kibler, B., Kraemer, W. J., & Triplett, N. T. (2009). Progression models in resistance training for healthy adults. *Medicine and Science in Sports and Exercise*, *41*(3), 687–708. https://doi.org/10.1249/MSS.0b013e3181915670

Ratamess, N. A., Chiarello, C. M., Sacco, A. J., Hoffman, J. R., Faigenbaum, A. D., Ross, R. E., & Kang, J. (2012). The effects of rest interval length on acute bench press performance: The influence of gender and muscle strength. *Journal of Strength and Conditioning Research*, *26*, 1817–1826. www.nsca.com

Refalo, M. C., Helms, E. R., Hamilton, D. L., & Fyfe, J. J. (2023). Influence of resistance training proximity-to-failure, determined by repetitions-in-reserve, on neuromuscular fatigue in resistance-trained males and females. *Sports Medicine - Open*, *9*(1). https://doi.org/10.1186/s40798-023-00554-y

Roberts, B. M., Nuckols, G., & Krieger, J. W. (2020). Sex differences in resistance training: A systematic review and meta-analysis. *Journal of Strength and Conditioning Research*, *34*(5), 1448–1460. https://doi.org/10.1519/JSC.0000000000003521

Robinson, M. A., Vanrenterghem, J., & Pataky, T. C. (2015). Statistical Parametric Mapping (SPM) for alpha-based statistical analyses of multi-muscle EMG time-series. *Journal of Electromyography and Kinesiology*, *25*(1), 14–19. https://doi.org/10.1016/j.jelekin.2014.10.018

Rossman, M. J., Garten, R. S., Venturelli, M., Amann, M., & Richardson, R. S. (2014). The role of active muscle mass in determining the magnitude of peripheral fatigue during dynamic

exercise. *American Journal of Physiology- Regulatory, Integrative and Comparative Physiology*, *306*, 934–940. https://doi.org/10.1152/ajpregu.00043.2014.-Greater

Rudroff, T., Barry, B. K., Stone, A. L., Barry, C. J., & Enoka, R. M. (2007). Accessory muscle activity contributes to the variation in time to task failure for different arm postures and loads. *Journal of Applied Physiology*, *102*, 1000–1006. https://doi.org/10.1152/japplphysiol.00564.2006.-Time

Rudroff, T., Justice, J. N., Holmes, M. R., Matthews, S. D., & Enoka, R. M. (2011). Muscle activity and time to task failure differ with load compliance and target force for elbow flexor muscles. *Journal of Applied Physiology*, *110*, 125–136. https://doi.org/10.1152/japplphysiol.00605.2010.-The

Russell, B., Motlagh, D., & Ashley, W. (2000). Form follows function: How muscle shape is regulated by work. *Journal of Applied Physiology*, *88*, 1127–1132. https://doi.org/https://doi-org.uml.idm.oclc.org/10.1152/jappl.2000.88.3.1127

Sato, S., Yoshida, R., Kiyono, R., Yahata, K., Yasaka, K., Nunes, J. P., Nosaka, K., & Nakamura, M. (2021). Elbow joint angles in elbow flexor unilateral resistance exercise training determine its effects on muscle strength and thickness of trained and non-trained arms. *Frontiers in Physiology*, *12*. https://doi.org/10.3389/fphys.2021.734509

Sato, S., Yoshida, R., Murakoshi, F., Sasaki, Y., Yahata, K., Kasahara, K., Nunes, J. P., Nosaka, K., & Nakamura, M. (2022). Comparison between concentric-only, eccentric-only, and concentric–eccentric resistance training of the elbow flexors for their effects on muscle

strength and hypertrophy. *European Journal of Applied Physiology*. https://doi.org/10.1007/s00421-022-05035-w

Schaefer, L. V., & Bittmann, F. N. (2017). Are there two forms of isometric muscle action? Results of the experimental study support a distinction between a holding and a pushing isometric muscle function. *BMC Sports Science, Medicine and Rehabilitation, 9*(1). https://doi.org/10.1186/s13102-017-0075-z

Schoenfeld, B. J. (2010). The mechanisms of muscle hypertrophy and their application to resistance training. *Journal of Strength and Conditioning Research, 24*, 2857–2872. www.nsca-jscr.org

Schoenfeld, B. J. (2013). Potential mechanisms for a role of metabolic stress in hypertrophic adaptations to resistance training. *Sports Medicine, 43*(3), 179–194. https://doi.org/10.1007/s40279-013-0017-1

Schoenfeld, B. J. (2020). *Science and Development of Muscle Hypertrophy* (2nd ed.). Human Kinetics.

Schoenfeld, B. J., & Grgic, J. (2020). Effects of range of motion on muscle development during resistance training interventions: A systematic review. *SAGE Open Medicine, 8*, 205031212090155. https://doi.org/10.1177/2050312120901559

Schoenfeld, B. J., Grgic, J., Ogborn, D., & Krieger, J. W. (2017). Strength and hypertrophy adaptations between low- vs high-load resistance training: A systematic review and meta-analysis. *Journal of Strength and Conditioning Research, 31*(12), 3508–3523.

Schoenfeld, B. J., Ogborn, D., & Krieger, J. W. (2017). Dose-response relationship between weekly resistance training volume and increases in muscle mass: A systematic review and meta-analysis. *Journal of Sports Sciences*, *35*(11), 1073–1082. https://doi.org/10.1080/02640414.2016.1210197

Seedman, J. (n.d.-a). *Eccentric Isometrics: The Ultimate Way to Strength Train Part 1*. Retrieved February 14, 2021, from https://www.advancedhumanperformance.com/eccentric-isometrics-the-ultimate-way-to-strength-train-part-1

Seedman, J. (n.d.-b). *Eccentric Isometrics: The Ultimate Way to Strength Train Part 2*. Retrieved February 14, 2021, from https://www.advancedhumanperformance.com/eccentric-isometrics-the-ultimate-way-to-strength-train-part-2

Senefeld, J., Yoon, T., Bement, M. H., & Hunter, S. K. (2013). Fatigue and recovery from dynamic contractions in men and women differ for arm and leg muscles. *Muscle and Nerve*, *48*(3), 436–439. https://doi.org/10.1002/mus.23836

Shailendra, P., Baldock, K. L., Li, L. S. K., Bennie, J. A., & Boyle, T. (2022). Resistance training and mortality risk: A systematic review and meta-analysis. *American Journal of Preventive Medicine*, *63*(2), 277–285. https://doi.org/10.1016/j.amepre.2022.03.020

Simpson, C. L., Kim, B. D. H., Bourcet, M. R., Jones, G. R., & Jakobi, J. M. (2017). Stretch training induces unequal adaptation in muscle fascicles and thickness in medial and lateral gastrocnemii. *Scandinavian Journal of Medicine and Science in Sports*, *27*(12), 1597–1604. https://doi.org/10.1111/sms.12822

Sinicki, A. (2019). *Advanced Isometric Training: Ballistic and Quasi Isometrics*. https://www.thebioneer.com/advanced-isometric-training-ballistic-quasi-isometrics/

Spitz, R. W., Dankel, S. J., Jessee, M. B., Wong, V., Bell, Z. W., Abe, T., & Loenneke, J. P. (2023). Does muscle growth mediate changes in a nonspecific strength task? *Clinical Physiology and Functional Imaging*, *43*(4), 223–231. https://doi.org/10.1111/cpf.12810

Spurway, N. C. (2007). Hiking physiology and the "quasi-isometric" concept. *Journal of Sports Sciences*, *25*(10), 1081–1093. https://doi.org/10.1080/02640410601165270

Srikanthan, P., Horwich, T. B., & Tseng, C. H. (2016). Relation of muscle mass and fat mass to cardiovascular disease mortality. *American Journal of Cardiology*, *117*(8), 1355–1360. https://doi.org/10.1016/j.amjcard.2016.01.033

Staron, R. S., Malicky, E. S., Leonardi, M. J., Falkel, J. E., Hagerman, F. C., & Dudley, G. A. (1989). Muscle hypertrophy and fast fiber type conversions in heavy resistance trained women. *European Journal of Applied Physiology*, *60*, 71–79. https://doi.org/10.5005/jp/books/12678_10

Staudenmann, D., van Dieën, J. H., Stegeman, D. F., & Enoka, R. M. (2014a). Increase in heterogeneity of biceps brachii activation during isometric submaximal fatiguing contractions: A multichannel surface EMG study. *Journal of Neurophysiology*, *111*(5), 984–990. https://doi.org/10.1152/jn.00354.2013

Staudenmann, D., van Dieën, J. H., Stegeman, D. F., & Enoka, R. M. (2014b). Increase in heterogeneity of biceps brachii activation during isometric submaximal fatiguing

contractions: A multichannel surface EMG study. *Journal of Neurophysiology*, *111*(5), 984–990. https://doi.org/10.1152/jn.00354.2013

Steele, J., Endres, A., Fisher, J., Gentil, P., & Giessing, J. (2017). Ability to predict repetitions to momentary failure is not perfectly accurate, though improves with resistance training experience. *PeerJ*, *2017*(11). https://doi.org/10.7717/peerj.4105

Steele, J., Fisher, J., Giessing, J., & Gentil, P. (2017). Clarity in reporting terminology and definitions of set endpoints in resistance training. *Muscle and Nerve*, *56*(3), 368–374. https://doi.org/10.1002/mus.25557

Stoter, I. K., Macintosh, B. R., Fletcher, J. R., Pootz, S., Zijdewind, I., & Hettinga, F. J. (2016). Pacing strategy, muscle fatigue, and technique in 1500-m speed-skating and cycling time trials. *International Journal of Sports Physiology and Performance*, *11*(3), 337–343. https://doi.org/10.1123/ijspp.2014-0603

Straight, C. R., Fedewa, M. V, Toth, M. J., & Miller, M. S. (2020). Improvements in skeletal muscle fiber size with resistance training are age-dependent in older adults: a systematic review and meta-analysis. *Journal of Applied Physiology*, *129*, 392–403. https://doi.org/10.1152/japplphysiol.00170.2020.-As

Strickland, J. C., & Smith, M. A. (2016). Animal models of resistance exercise and their application to neuroscience research. *Journal of Neuroscience Methods*, *273*, 191–200. https://doi.org/10.1016/j.jneumeth.2016.08.003

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The importance of muscular strength in athletic performance. *Sports Medicine*, *46*(10), 1419–1449. https://doi.org/10.1007/s40279-016-0486-0

Takarada, Y., Takazawa, H., Sato, Y., Takebayashi, S., Tanaka, Y., & Ishii, N. (2000). Effects of resistance exercise combined with moderate vascular occlusion on muscular function in humans. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, *88*(6), 2097–2106. https://doi.org/10.1152/jappl.2000.88.6.2097

Taylor, J. L., Amann, M., Duchateau, J., Meeusen, R., & Rice, C. L. (2016). Neural contributions to muscle fatigue: From the brain to the muscle and back again. *Medicine and Science in Sports and Exercise*, *48*(11), 2294–2306. https://doi.org/10.1249/MSS.0000000000000923

Tiller, N. B., Sullivan, J. P., & Ekkekakis, P. (2022). Baseless Claims and Pseudoscience in Health and Wellness: A Call to Action for the Sports, Exercise, and Nutrition-Science Community. *Sports Medicine*. https://doi.org/10.1007/s40279-022-01702-2

Trama, R., Hautier, C., & Blache, Y. (2021). fctSnPM: Factorial ANOVA and post-hoc tests for Statistical nonParametric Mapping in MATLAB. *Journal of Open Source Software*, *6*(63), 3159. https://doi.org/10.21105/joss.03159

Verkhoshansky, Y. V, & Siff, M. C. (2009). *Supertraining* (6th ed.). Ultimate Athlete Concepts.

Vigotsky, A. D., Halperin, I., Lehman, G. J., Trajano, G. S., & Vieira, T. M. (2018). Interpreting signal amplitudes in surface electromyography studies in sport and rehabilitation sciences. *Frontiers in Physiology*, *8*(JAN). https://doi.org/10.3389/fphys.2017.00985

Vigotsky, A. D., Halperin, I., Trajano, G. S., & Vieira, T. M. (2022). Longing for a longitudinal proxy- Acutely measured surface EMG amplitude is not a validated predictor of muscle hypertrophy. *Sports Medicine, 52*(2), 193–199. https://doi.org/10.1007/s40279-021-01619-2

Voskuil, C. C., Dudar, M. D., & Carr, J. C. (2024). Sex differences in fatiguability during single-joint resistance exercise in a resistance-trained population. *European Journal of Applied Physiology*. https://doi.org/10.1007/s00421-024-05445-y

Wan, J. J., Qin, Z., Wang, P. Y., Sun, Y., & Liu, X. (2017). Muscle fatigue: General understanding and treatment. *Experimental and Molecular Medicine*, *49*(10). https://doi.org/10.1038/emm.2017.194

West, D. W. D., & Phillips, S. M. (2012). Associations of exercise-induced hormone profiles and gains in strength and hypertrophy in a large cohort after weight training. *European Journal of Applied Physiology*, *112*(7), 2693–2702. https://doi.org/10.1007/s00421-011-2246-z

Williams, S., Whatman, C., Hume, P. A., & Sheerin, K. (2012). Kinesio Taping in Treatment and Prevention of Sports Injuries A Meta-Analysis of the Evidence for its Effectiveness. *Sports Medicine*, *42*(2), 154–164.

Winter, D. A. (2005). *Biomechanics and motor control of human movement* (3rd ed.). Wiley.

Wohlann, T., Warneke, K., Kalder, V., Behm, D. G., Schmidt, T., & Schiemann, S. (2024). Influence of 8-weeks of supervised static stretching or resistance training of pectoral major muscles on maximal strength, muscle thickness and range of motion. *European Journal of Applied Physiology*. https://doi.org/10.1007/s00421-023-05413-y

Wong, V., Abe, T., Chatakondi, R. N., Bell, Z. W., Spitz, R. W., Dankel, S. J., & Loenneke, J. P. (2019). The influence of biological sex and cuff width on muscle swelling, echo intensity, and the fatigue response to blood flow restricted exercise. *Journal of Sports Sciences*, *00*(00), 1–9. https://doi.org/10.1080/02640414.2019.1599316

World Health Organization. (2022). *Physical Activity Fact Sheet*.

Wüst, R. C. I., Morse, C. I., De Haan, A., Jones, D. A., & Degens, H. (2008). Sex differences in contractile properties and fatigue resistance of human skeletal muscle. *Experimental Physiology*, *93*(7), 843–850. https://doi.org/10.1113/expphysiol.2007.041764

Yitzchaki, N., Zhu, W. G., Kuehne, T. E., Vasenina, E., Dankel, S. J., & Buckner, S. L. (2020). An examination of changes in skeletal muscle thickness, echo intensity, strength and soreness following resistance exercise. *Clinical Physiology and Functional Imaging*, *40*(4), 238–244. https://doi.org/10.1111/cpf.12630

Yoon, T., Doyel, R., Widule, C., & Hunter, S. K. (2015). Sex differences with aging in the fatigability of dynamic contractions. *Experimental Gerontology*, *70*, 1–10. https://doi.org/10.1016/j.exger.2015.07.001

Yoon, T., Schlinder-Delap, B., & Hunter, S. K. (2013). Fatigability and recovery of arm muscles with advanced age for dynamic and isometric contractions. *Experimental Gerontology*, *48*(2), 259–268. https://doi.org/10.1016/j.exger.2012.10.006

Zabaleta-Korta, A., Fernandez-Pena, E., & Santos-Concejero, J. (2020). Regional hypertrophy, the inhomogeneous muscle growth: A systematic review. *Strength and Conditioning Journal*. www.nsca-scj.com

Zadro, J., O'Keeffe, M., & Maher, C. (2019). Do physical therapists follow evidence-based guidelines when managing musculoskeletal conditions? Systematic review. *BMJ Open*, *9*(10). https://doi.org/10.1136/bmjopen-2019-032329

Zourdos, M. C., Klemp, A., Dolan, C., Quiles, J. M., Schau, K. A., Jo, E., Helms, E., Esgro, B., Duncan, S., Merino, S. G., & Blanco, R. (2016). Novel resistance training-specific ratings of perceived exertion scale measuring repetitions in reserve. *Journal of Strength and Conditioning Research*, *30*(1), 267–275. www.nsca.com

Appendix A: Get Active Questionnaire

CSEP | SCPE
THE GOLD STANDARD IN EXERCISE SCIENCE AND PERSONAL TRAINING

Get Active Questionnaire

CANADIAN SOCIETY FOR EXERCISE PHYSIOLOGY –
PHYSICAL ACTIVITY TRAINING FOR HEALTH (CSEP-PATH®)

Physical activity improves your physical and mental health. Even small amounts of physical activity are good, and more is better.

For almost everyone, the benefits of physical activity far outweigh any risks. For some individuals, specific advice from a Qualified Exercise Professional (QEP – has post-secondary education in exercise sciences and an advanced certification in the area – see csep.ca/certifications) or health care provider is advisable. This questionnaire is intended for all ages – to help move you along the path to becoming more physically active.

☐ I am completing this questionnaire for myself.
☐ I am completing this questionnaire for my child/dependent as parent/guardian.

PREPARE TO BECOME MORE ACTIVE

The following questions will help to ensure that you have a safe physical activity experience. Please answer **YES** or **NO** to each question before you become more physically active. If you are unsure about any question, answer **YES**.

YES	NO	
		1 Have you experienced **ANY** of the following (A to F) **within the past six months**?
○	○	**A** A diagnosis of/treatment for heart disease or stroke, or pain/discomfort/pressure in your chest during activities of daily living or during physical activity?
○	○	**B** A diagnosis of/treatment for high blood pressure (BP), or a resting BP of 160/90 mmHg or higher?
○	○	**C** Dizziness or lightheadedness during physical activity?
○	○	**D** Shortness of breath at rest?
○	○	**E** Loss of consciousness/fainting for any reason?
○	○	**F** Concussion?
○	○	**2** Do you currently have pain or swelling in any part of your body (such as from an injury, acute flare-up of arthritis, or back pain) that affects your ability to be physically active?
○	○	**3** Has a health care provider told you that you should avoid or modify certain types of physical activity?
○	○	**4** Do you have any other medical or physical condition (such as diabetes, cancer, osteoporosis, asthma, spinal cord injury) that may affect your ability to be physically active?

NO to all questions: go to Page 2 – ASSESS YOUR CURRENT PHYSICAL ACTIVITY

YES to any question: go to Reference Document – ADVICE ON WHAT TO DO IF YOU HAVE A YES RESPONSE

CSEP | SCPE
THE GOLD STANDARD IN EXERCISE SCIENCE AND PERSONAL TRAINING

Get Active Questionnaire

ASSESS YOUR CURRENT PHYSICAL ACTIVITY

Answer the following questions to assess how active you are now.

1 During a typical week, on how many days do you do moderate- to vigorous-intensity aerobic physical activity (such as brisk walking, cycling or jogging)? ☐ DAYS/ WEEK

2 On days that you do at least moderate-intensity aerobic physical activity (e.g., brisk walking), for how many minutes do you do this activity? ☐ MINUTES/ DAY

For adults, please multiply your average number of days/week by the average number of minutes/day: ☐ MINUTES/ WEEK

Canadian Physical Activity Guidelines recommend that adults accumulate at least 150 minutes of moderate- to vigorous-intensity physical activity per week. For children and youth, at least 60 minutes daily is recommended. Strengthening muscles and bones at least two times per week for adults, and three times per week for children and youth, is also recommended (see csep.ca/guidelines).

GENERAL ADVICE FOR BECOMING MORE ACTIVE

Increase your physical activity gradually so that you have a positive experience. Build physical activities that you enjoy into your day (e.g., take a walk with a friend, ride your bike to school or work) and reduce your sedentary behaviour (e.g., prolonged sitting).

If you want to do **vigorous-intensity physical activity** (i.e., physical activity at an intensity that makes it hard to carry on a conversation), and you do not meet minimum physical activity recommendations noted above, consult a Qualified Exercise Professional (QEP) beforehand. This can help ensure that your physical activity is safe and suitable for your circumstances.

Physical activity is also an important part of a healthy pregnancy.

Delay becoming more active if you are not feeling well because of a temporary illness.

DECLARATION

To the best of my knowledge, all of the information I have supplied on this questionnaire is correct.
If my health changes, I will complete this questionnaire again.

I answered NO to all questions on Page 1

Sign and date the Declaration below

I answered YES to any question on Page 1

Check the box below that applies to you:

☐ I have consulted a health care provider or Qualified Exercise Professional (QEP) who has recommended that I become more physically active.

☐ I am comfortable with becoming more physically active on my own without consulting a health care provider or QEP.

Name (+ Name of Parent/Guardian if applicable) [Please print] | Signature (or Signature of Parent/Guardian if applicable) | Date of Birth

Date | Email (optional) | Telephone (optional)

With planning and support you can enjoy the benefits of becoming more physically active. A QEP can help.

☐ Check this box if you would like to consult a QEP about becoming more physically active.
(This completed questionnaire will help the QEP get to know you and understand your needs.)

Appendix B: Godin Leisure-Time Questionnaire

Godin Leisure-Time Exercise *Questionnaire*

During a typical **7-Day period** (a week), how many times on the average do you do the following kinds of exercise for **more than 15 minutes** during your free time (write on each line the appropriate number).

Weekly leisure activity score = (9 × Strenuous) + (5 × Moderate) + (3 × Light)

	Times per week		Totals
a) **STRENUOUS EXERCISE (HEART BEATS RAPIDLY)** (e.g., running, jogging, hockey, football, soccer, squash, basketball, cross country skiing, judo, roller skating, vigorous swimming, vigorous long distance bicycling)		**X9**	
b) **MODERATE EXERCISE (NOT EXHAUSTING)** (e.g., fast walking, baseball, tennis, easy bicycling, volleyball, badminton, easy swimming, alpine skiing, popular and folk dancing)		**X5**	
c) **MILD/LIGHT EXERCISE (MINIMAL EFFORT)** (e.g., yoga, archery, fishing from river bank, bowling, horseshoes, golf, snow-mobiling, easy walking)		**X3**	
WEEKLY LEISURE-TIME ACTIVITY SCORE			

EXAMPLE

Strenuous = **3** times/wk
Moderate = **6** times/wk
Light = **14** times/wk
Total leisure activity score = (9 × **3**) + (5 × **6**) + (3 × **14**) = 27 + 30 + 42 = 99

Godin Scale Score	Interpretation
24 units or more	Active
14 – 23 units	Moderately Active
Less than 14 units	Insufficiently Active/Sedentary

Adapted from: Godin, G. (2011). The Godin-Shephard leisure-time physical activity questionnaire. Health & Fitness Journal of Canada, 4(1), 18-22.

ONS® Oncology Nursing Society

Appendix C: Edinburgh Handedness Inventory

Edinburgh Handedness Inventory[1]

Your Initials:_____

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓ | ✓).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)		

[1] Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsycholoigia*, *9*, 97-113.

Appendix D: Additional Female Information

Additional Female Information

Participant ID_____ DATE:_____

Menstrual Cycle
Do you experience regular menstrual bleeding every 21-35 days? YES/NO
a. Do you track your menstrual cycle? YES/NO
b. How many days is a typical cycle?_____
c. What date did your last cycle begin (give best estimate if not tracking)_____
d. When do you expect your next cycle to begin? (give best estimate if not tracking)_____

Do you experience associated side effects (e.g., cramps, headaches, mood-swings) before, during, or after the beginning of your cycle? YES/NO

If yes, describe as best you can your exact symptoms and when they start/how long they last, and any other information you wish to provide_____
_____
_____
_____
_____

Do you take any medications (e.g., advil, motrin, aleve) to relieve symptoms? YES/NO
If yes,
a. What type(s)?_____
b. How often?_____
c. For what symptoms?_____
Do you feel that your menstrual cycle affects your physical activity or exercise performance? YES/NO

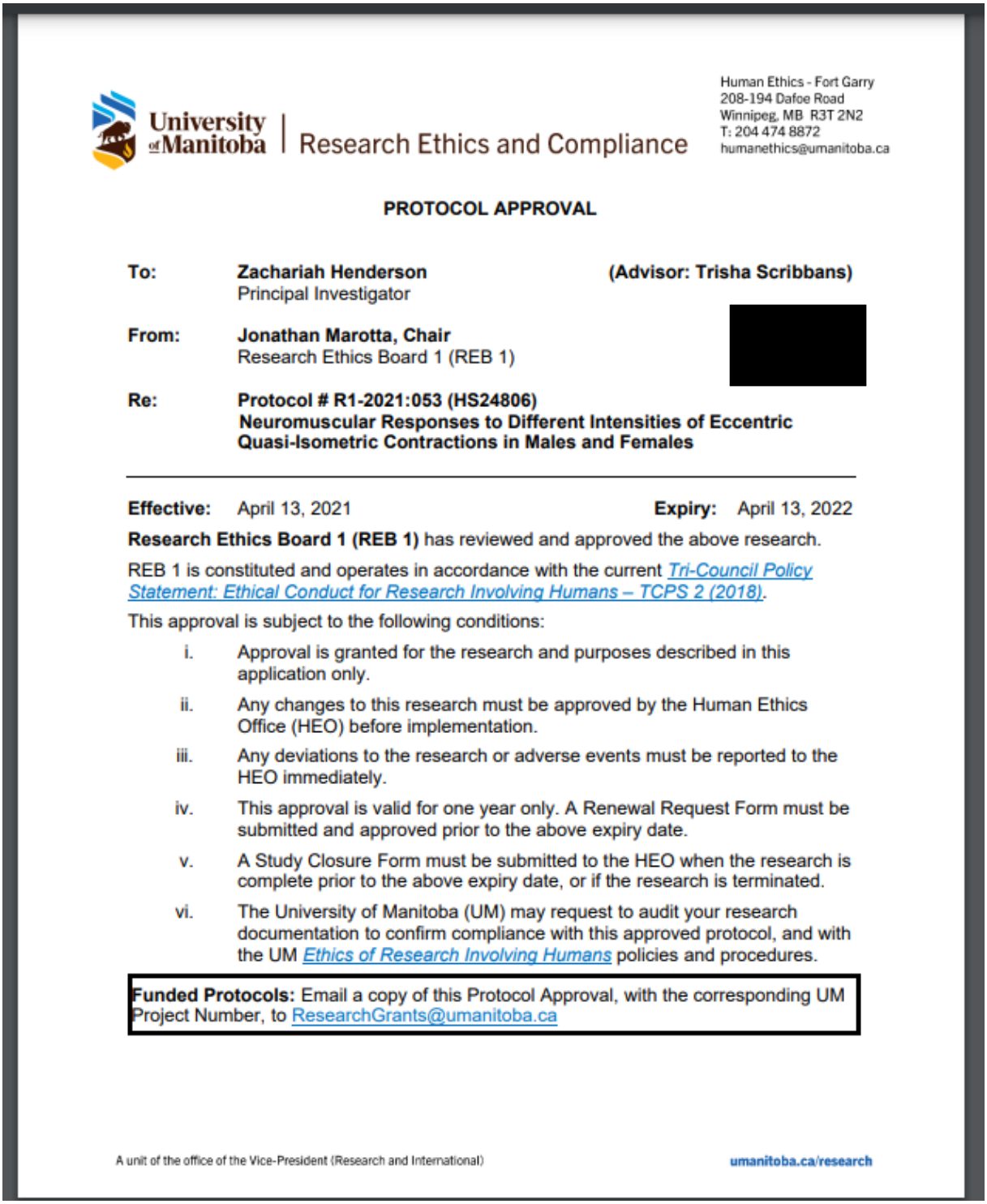
If yes,
a. Positively or negatively? (circle one)
b. How many days is this effect present?____

Birth Control
Do you currently use a female method of birth control (i.e., “the pill,” intrauterine device, patch, vaginal ring)? YES/NO

Do you currently take an oral contraceptive (i.e., “the pill”)? YES/NO
If yes, proceed to “Oral Contraceptive”

Do you currently have an intrauterine device (IUD)? YES/NO
If yes, proceed to “Intrauterine Device”
Oral Contraceptive:
What brand/type?_____

Appendix E: Project 1 Original REB Approval



University of Manitoba | Research Ethics and Compliance

Human Ethics - Fort Garry
208-194 Dafoe Road
Winnipeg, MB R3T 2N2
T: 204 474 8872
humanethics@umanitoba.ca

PROTOCOL APPROVAL

To: **Zachariah Henderson** **(Advisor: Trisha Scribbans)**
Principal Investigator

From: **Jonathan Marotta, Chair**
Research Ethics Board 1 (REB 1)

[redacted]

Re: **Protocol # R1-2021:053 (HS24806)**
Neuromuscular Responses to Different Intensities of Eccentric Quasi-Isometric Contractions in Males and Females

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Effective: April 13, 2021 **Expiry:** April 13, 2022

Research Ethics Board 1 (REB 1) has reviewed and approved the above research.

REB 1 is constituted and operates in accordance with the current *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans – TCPS 2 (2018)*.

This approval is subject to the following conditions:

i. Approval is granted for the research and purposes described in this application only.

ii. Any changes to this research must be approved by the Human Ethics Office (HEO) before implementation.

iii. Any deviations to the research or adverse events must be reported to the HEO immediately.

iv. This approval is valid for one year only. A Renewal Request Form must be submitted and approved prior to the above expiry date.

v. A Study Closure Form must be submitted to the HEO when the research is complete prior to the above expiry date, or if the research is terminated.

vi. The University of Manitoba (UM) may request to audit your research documentation to confirm compliance with this approved protocol, and with the UM *Ethics of Research Involving Humans* policies and procedures.

Funded Protocols: Email a copy of this Protocol Approval, with the corresponding UM Project Number, to ResearchGrants@umanitoba.ca

Appendix F: Project 2 Original REB Approval

University of Manitoba | Research Ethics and Compliance

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PROTOCOL APPROVAL

Effective: May 9, 2023 Expiry: May 8, 2024

Principal Investigator:	Zachariah Henderson
Advisor:	Trisha Scribbans
Protocol Number:	HE2023-0066
Protocol Title:	*Exploring Eccentric Quasi-Isometric and Traditional Isotonic Elbow Flexion/ Extension in Untrained Individuals: Effects on Muscle Morphology, Muscle Excitation, Kinetics, and Kinematics*

Jonathan Marotta, Chair, REB1

Research Ethics Board 1 has reviewed and approved the above research. The Human Ethics Office (HEO) is constituted and operates in accordance with the current *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans*- TCPS 2 (2022).

This approval is subject to the following conditions:

i. Approval is granted for the research and purposes described in the protocol only.

ii. Any changes to the protocol or research materials must be approved by the HEO before implementation.

iii. Any deviations to the research or adverse events must be reported to the HEO immediately through an REB Event.

iv. This approval is valid for one year only. A Renewal Request must be submitted and approved prior to the above expiry date.

v. A Protocol Closure must be submitted to the HEO when the research is complete or if the research is terminated.

vi. The University of Manitoba may request to audit your research documentation to confirm compliance with this approved protocol, and with the UM *Ethics of Research Involving Humans*Ethics of Research Involving Humans policies and procedures.