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THE RELATIONSHIP AMONG MUSCLE MASS, CONTRACTILE PROPERTIES, AND CRITICAL TORQUE

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THE RELATIONSHIP AMONG MUSCLE MASS, CONTRACTILE PROPERTIES, AND CRITICAL TORQUE

A THESIS APPROVED FOR THE DEPARTMENT OF
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TABLE OF CONTENTS

List of Tables

List of Figures

Abstract

Critical Torque (CT) is defined as the asymptote of the torque-duration relationship, representing the maximal force a muscle can sustain with wholly aerobic metabolism. In this way, CT serves as a determinant of pacing in individual muscles. Impulse Above Critical Torque (IACT) represents a finite amount of work produced above CT before fatigue accumulates. IACT is often linked to anaerobic energy stores, such as creatine phosphate, and represents anaerobic work capacity within the muscle. It has been suggested that both CT and IACT are determined, in part, by muscle mass and fiber type. Increased lean muscle mass has been associated with greater anaerobic work capacity, like IACT, and the whole-body analog of CT, Critical Power (CP). Muscle fiber biopsies have revealed significant relationships among fiber type, CT, %CT (CT relative to maximum voluntary contraction [MVC]), and IACT. Alternatives to muscle biopsy have been demonstrated using maximal neuromuscular stimulation (to derive contractile properties) and the Thorstensson protocol. These noninvasive measures of fiber type have yet to be examined in relation to CT and IACT. Therefore, the primary purpose of this study was to assess the relationship among lean muscle mass, contractile properties, and CT. A secondary purpose was to assess the intersession reliability of the Thorstensson protocol. ***Methods.*** Thirty-one participants (18 males, 13 females) took part in this study, with thirty participants completing all three visits across one week. One female participant dropped out of the CT protocol and was subsequently omitted from the correlations among lean thigh mass, contractile properties, and CT. Visit 1 consisted of electrically stimulating the right knee extensor (KE) muscle for contractile properties, familiarization with MVC and CT protocols, and the Thorstensson protocol. Visit 2 involved a DXA scan, followed by the MVC and CT protocols. Electrical stimulation was provided on the 1st and every 6th contraction during the CT protocol.

Visit 3 consisted of the Thorstensson protocol only. ***Results.*** Pearson correlations revealed a weak correlation between TLM and CT ($r = 0.389$, $p < 0.05$). No significant correlation was found between TLM and %CT ($r = -0.334$, $p > 0.05$). Positive correlations were found between P_t and CT ($r = 0.362$, $p < 0.05$; Table 4), as well as RTR and CT ($r = 0.434$, $p < 0.05$). No significant correlations were found among TPT and CT ($r = 0.163$, $p > 0.05$), 1/2RT and CT ($r = -0.238$, $p > 0.05$), or RTD and CT ($r = 0.299$, $p > 0.05$). No significant correlations were found among contractile properties and %CT ($p > 0.05$). Significant negative correlations were found among %Type-II fibers and CT ($r = -0.422$, $p < 0.05$) and %CT ($r = -0.57$, $p < 0.001$). ICCs for %Type-II Fiber demonstrated moderate reliability and variability (ICC = 0.616, $p < 0.05$, CV= 12.9%). ***Conclusion.*** Findings of this study are consistent with previous studies suggesting that CT is positively associated with greater lean thigh mass and negatively associated with increased distributions of type-II fibers. A novel finding of this study is the moderate intersession reliability of the Thorstensson predicted fiber type—suggesting that it is fairly consistent between trials.

Chapter 1

Introduction

The power-duration curve posits that power output (P) is inversely related to time-to-task failure (T_{lim}) (Poole et al., 2016). As the duration of an activity increases, maximal sustainable power output declines, eventually reaching the asymptote of this relationship, Critical Power (CP). Mathematically, this relationship can be represented in the following equation (Burnley, 2009):

$$T_{lim} = W' / (P-CP)$$

The curvature constant, (W'), represents the finite, total amount of work that can be performed above the CP threshold (Abdalla et al., 2018). At intensities above the CP threshold, W' is depleted more rapidly, whereas below the threshold, the amount of work performed can be sustained longer (Jones et al., 2008). In this way, the CP threshold is a major determinant of pacing during exercise. Metabolically, CP represents the greatest rate of *wholly* oxidative metabolism. Oxygen consumption (VO_2) and blood lactate levels are relatively constant at and below the CP threshold, but above the threshold, blood lactate and VO_2 increase, with the latter increasing until VO_2 Max is obtained (Poole et al., 1988). Therefore, CP indicates a threshold, above which steady-state aerobic metabolism cannot be achieved. Exercise above the CP threshold has also been linked to increasing hydrogen (H^+) ion concentrations and decreasing creatine phosphate (PCr) concentrations, whereas at CP, they are relatively constant (Jones et al., 2008). The increased depletion of PCr and production of H^+ above CP suggest that the threshold exists as the upper boundary of steady state activity, above which, peripheral fatigue metabolites begin to accumulate.

Critical Torque (CT) represents a parameter similar to CP. Over time, during intermittent maximal isometric contractions, torque falls until the asymptote (CT) is reached. When utilizing Burnley's 5-minute CT protocol, the average of the last six contractions of the protocol are deemed end-test torque (ET), which is assumed to represent the CT asymptote (Burnley, 2009). The analog of W' is Impulse Above Critical Torque (IACT), whose utilization is linked to the depletion and reconstitution of PCr above the CT threshold (Abdalla et al., 2023). In this way, CT and IACT represent similar parameters to CP and W'.

Greater total lean-mass of the thigh (TLM) has been demonstrated to positively influence W' during CP testing, suggesting that muscle mass may be a determinant of CP (Byrd et al., 2018). There is a positive correlation between contractile force and intramuscular pressure, where muscles of smaller size experience increased oxygen delivery and blood flow due to low intramuscular pressures (Abdalla et al., 2018). When CT values were compared between muscles of different sizes, the knee extensor (KE) muscles demonstrated higher absolute IACT/CT values than the plantar flexor (PF) muscles (Abdalla et al., 2018). However, when CT was relativized to each muscle's maximal voluntary contraction (MVC), the PF demonstrated greater relative CT, but not relative IACT, values than the KE (Abdalla et al., 2018), suggesting that muscle characteristics, like MVC, muscle mass, and fiber type, given the well documented differences between the PF and KE, may be a determinant of IACT/CT. Considering that CP is sensitive to oxygen delivery and blood flow (Vanhatalo et al., 2010; Kellawan et al., 2014), it is plausible that fiber type, such as oxidative Type-I fibers, could positively influence CP/CT parameters. Indeed, fiber type composition has been correlated to both CP and CT. Type-I, slow-twitch fibers have been shown to be positively correlated to the CP threshold, while Type-II fast-twitch fibers are negatively correlated to CP (Vanhatalo et al., 2016). Additionally, type-I fiber distribution

has been shown to positively correlate with CT (relative to maximal voluntary contraction), with type-II fiber distribution positively correlating with IACT (McDougall et al., 2023).

Aside from histochemical analysis, relative fiber type composition among muscles or individuals can be identified through skeletal muscle contractile properties such as peak torque (P_t), time-to-peak tension (TPT), half-relaxation time ($^1/_2$RT), Rate of Torque Development (RTD), and Rate of Relaxation (RTR). Using interpolated twitches, Harridge et al. (1996) demonstrated that Type-I fibers in the soleus muscle produced lower P_t values, possessed slower TPT, and slower RTD, than Type-II fibers in the triceps and quadriceps. Another contractile characteristic, fatiguability during repeated isokinetic muscle contractions, has been demonstrated to be predictive of Type-II fiber type in the KE muscles (Thorstensson and Karlson, 1976). To our knowledge, no study has examined the relationship between twitch contractile properties and type-II fiber distribution estimated from the Thorstensson fatigability test.

Given the limited data available on the potential influence of fiber type on critical torque the purpose of the present study will be to assess the relationships (1) between lean mass of the thigh and CT (relative to maximal voluntary contraction) (2) among twitch contractile properties and absolute and relative CT (3) and among estimated type II fiber type percentage from the Thorstensson fatigue test and absolute, and relative, CT. A fourth purpose of the study will be to assess the reliability of the Thorstensson fatigue test between days.

1.1 Research Questions/Hypotheses

0. Is there a relationship between total lean mass of the thigh and i) absolute and ii) relative critical torque?
1. Is there a relationship among muscle twitch properties (which are linked to fiber type), like iii) P_t, iv) TPT, v) $^1/_2$RT, vi) RTD, and vii) RTR and relative critical torque?
2. Is there a relationship between predicted type II fiber percentage from the Thorstensson test and viii) absolute and ix) relative critical torque?

3. Is the Thorstensson fatigue test a x) reliable measure of type-II fiber distribution across two testing sessions?

    a. Research Hypotheses:
        i. Lean mass of the thigh will positively correlate to absolute CT
        ii. Lean mass of the thigh will positively correlate to relative CT
        iii. Pt will negatively correlate to relative CT
        iv. TPT will positively correlate to relative CT
        v. 1/2RT will positively correlate to relative CT
        vi. RTD will negatively correlate to relative CT
        vii. RTR will negatively correlate to relative CT
        viii. %Type-II Fibers will negatively correlate to CT
        ix. %Type-II Fibers will negatively correlate to relative CT
        x. %Type-II fibers will be a reliable between visits
        xi. **Null hypotheses will be no relationship among contractile properties, thigh lean mass, absolute and relative CT, and estimated fiber type percentage from the Thorstensson test.

1.2 Significance

CT represents an important fatigue threshold that separates domains of intensity. Unlike CP, there is a paucity of research on the individual physiological characteristics that influence/determine differences in CT among individuals. A better understanding of the role of skeletal muscle fiber type, muscle mass, and associated muscle contractile properties in CT, if at all, can lead to more individualized training regimes to aid endurance performance.

1.3 Delimitations of the Study

1. Males and Females 18-35 years of age.
2. Healthy individuals without cardiometabolic disease.
3. Healthy individuals without neuromuscular disease or injury within the previous 12 months.
4. Individuals capable of generating repetitive maximal voluntary contractions.
5. Individuals capable of withstanding electrical stimulation of the muscle.

1.4 Limitations of the Study

1. Will not reflect dynamic/ecological conditions.
2. Non-invasive measure of fiber type.

1.5 Assumptions of the Study

1. Participants will give maximum effort during all voluntary exercises.
2. KE will have a high percentage of type-II fibers.

3. The Thorstensson fatigue test is a valid and reliable estimate of type II fiber percentage.
4. Time to peak tension is primarily influenced by myosin ATPase enzyme function.
5. Half-relaxation time is primarily influenced by calcium ATPase enzyme (SERCA) function.

1.6 Operational definitions

1. Critical Torque (CT): during isometric exercise, the threshold above which force production cannot be sustained without a reduction in force, and below which time-to-task failure becomes unpredictable. Considered the equivalent of the average of the last six contractions (end-test torque; ET) of the 5-minute, all-out protocol (Burnley 2009)
2. Half relaxation time ($^1/_2$RT): the halfway point on the downward slope of the force curve
3. Impulse Above Critical Torque (IACT): total area of impulse above CT; represents the total work that can be done above CT (Abdalla et al., 2018).
4. Knee Extensor (KE) muscles: quadriceps femoris (vastus intermedius, vastus lateralis, vastus medialis, and rectus femoris)
5. Maximal Voluntary Contraction (MVC): average of the two highest torque values produced during a single bout of effort
6. Peak Twitch Torque (P_t): greatest value of produced torque during electrically evoked muscular contraction (Harridge et al., 1996)
7. Rate of Relaxation (RTR): relaxation rate of twitch torque (Harridge et al., 1996)
8. Rate of Torque Development (RTD): slope of peak twitch torque over TPT (Harridge et al., 1996)
9. Time to peak torque (TPT): total amount of time from the initiation of force to maximal force production during electrical muscular stimulation (Harridge et al., 1996).

10. Thigh Lean Mass (TLM): local mineral-free lean mass (g) of the thigh (Byrd et al., 2018), as measured by DXA, in the determined region of interest (ischial tuberosity to middle knee joint of the leg)
11. %CT: CT relative to MVC (Abdalla et al., 2018)

Chapter 2: Literature Review

2.1 Introduction

Fatigue has long been an area of interest for exercise physiologists. Critical Torque (CT) represents an important fatigue threshold that separates domains of exercise intensity during intermittent isometric contractions. A threshold similar to CT, deemed Critical Power (CP), has demonstrated correlations to fiber type and muscle mass in contemporary research. Recently, CT has been compared between muscle groups of different sizes. However, there is still a paucity of research examining muscle mass, fiber type characteristics, and their relationship to CT parameters. Therefore, the purpose of this literature review is to consolidate current research regarding CT, fiber type characteristics, and muscle mass.

This literature review includes studies from SPORTDiscus, PubMed, CINAHL, and the Journal of Applied Physiology. The search process included several key words: "power-duration," "Critical Power," "Critical Torque," "Isometric torque," "Fiber type," "Contractile properties," "Rate of force development," "twitch," "SERCA," and "central and peripheral fatigue." Studies from these results were included in this review. Some studies included in this review were found through manually searching the references provided within articles.

2.2 Fatigue

Fatigue is a reduction in the expected or required force needed to sustain performance. It can be characterized as central fatigue, arising from the alterations in the central nervous system (CNS), or peripheral fatigue, arising from mechanical and metabolic mechanisms distal to the neuromuscular junction (Costa Filho et al., 2019). The metabolic factors contributing to peripheral fatigue include intracellular calcium (Ca2+) and byproducts of anaerobic metabolism. The accumulation of lactic acid in the blood, and therefore Hydrogen ions (H^+), are two

byproducts associated with peripheral fatigue (Burnley et al., 2012). The incerasing presence of H^+ decreases the pH of the intracellular space, creating acidic conditions. Decreased pH can inhibit the recycling of Ca2+ by calcium pumps into the sarcoplasmic reticulum (SR), increasing intracellular Ca2+ and reducing the number of cross-bridges that can form (Costa Filho et al., 2019). In this way, metabolic mechanisms limit the mechanical properties of muscles, resulting in peripheral fatigue.

Today, fatigue is understood to occur at different rates depending on the exercise intensity (Poole et al., 2016) and can be characterized by specific domain-linked mechanisms. The accumulation of metabolic byproducts, like H^+ and lactate, has been associated with peripheral fatigue, increasingly impairing neuromuscular function at higher rates of intensity (Jones et al., 2008; Burnley, 2009). Development of peripheral fatigue at high intensities is supported by muscular activation during exercise. Burnley et al. demonstrated greater prevalence of peripheral fatigue at increasing intensities than at lower intensities by comparing voluntary activation to EMG activity in the knee extensor muscles (2012). The presence of different metabolic and electrical activity at high and low intensities suggests that fatigue is domain-dependent. Where these domains of fatigue occur can be explained by the power-duration curve and the purported relationships derived from it.

2.3 Power-Duration Relationship and Critical Power

It is well established that exercise at high intensities is not sustainable for long durations, while submaximal exercise can be sustained much longer before task failure. This hyperbolic relationship is represented by the power-duration curve (Burnley and Jones, 2018), which posits that power output is inversely related to time-to-task failure. As power output (P) increases, time-to-task failure decreases, eventually approaching the asymptote of this relationship, deemed

Critical Power (CP). The curvature constant in the power-duration curve, W', represents the total amount of work that can be sustained above CP (Abdalla et al., 2018). This relationship is represented in the equation (Burnley, 2009) below:

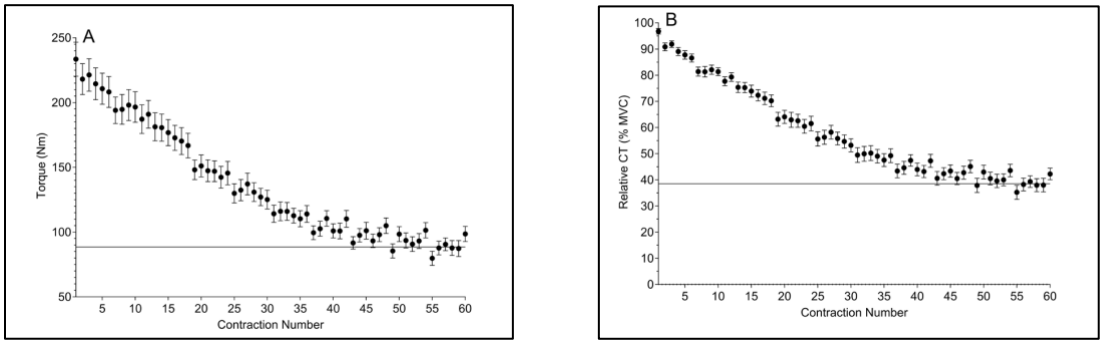
$$T_{lim} = W'/(P-CP)$$

In other words, time-to-task failure can be predicted by the relationship between CP and W'. CP represents the greatest rate of primarily oxidative metabolism (Poole et al., 2016). This is evidenced by the metabolic profile at and above CP. During cycling, pulmonary gas exchange, ventilation, and blood lactate all reach a steady state at exercise intensities at CP, while exercise above CP is characterized by the slow component rise of oxygen consumption (VO_2) until VO_2Max is reached, and increasing blood lactate levels (Poole et al., 1988). Jones et al. found that H^+ and Creatine Phosphate (PCr) levels were constant at CP, but above CP, H^+ levels and PCr depletion increased drastically (2008). In this way, CP identifies the threshold below which steady state metabolic activity is achievable, but above which it is not.

2.4 Critical Torque

When the power-duration relationship is examined in intermittent isometric contractions, it is deemed the Critical Torque (CT). The asymptote of the torque-duration relationship (Abdalla et al., 2018), CT, represents a threshold similar to CP. For example, the amount of force produced above CT before task failure, Impulse above Critical Torque (IACT), represents a parameter akin to W' (Kellawan et al., 2014; Abdalla et al., 2023). Formerly, a major limitation of CT testing was the necessity to perform multiple tests across multiple days. Five submaximal tests (intensities ranging from 35% to 60% of maximal voluntary contraction) would be performed until task failure, days apart, with CT being calculated from all five trials (Burnley, 2009). However, Burnley developed a 5-minute CT protocol involving 60 isometric MVCs; each

contraction is sustained for 3 seconds, followed by 2 seconds of rest (2009). Within this protocol, the torque produced in the final 6 contractions was considered the end-test torque (ET). The ET for the 5-minute protocol (77.8 ± 17.8 N·m) was no different than the time impulse model CT (77.8 ± 17.8 N·m vs 77.9 ± 15.1 N·m; t = 0.07, p = 0.95), and was significantly correlated to time impulse model CT (r = 0.88, p = 0.004) (Burnley, 2009). This protocol illustrates that repeated isometric contractions can estimate CT within one visit.



Studies have shown that, like W', IACT values are related to PCr utilization. Abdalla et al. demonstrated that PCr supplementation increased IACT compared to baseline measures (7878 ± 1903 N·m·s vs 5761 ± 1710 N·m·s) (Abdalla et al., 2023). In fact, creatine supplementation increased the reconstitution of IACT (669 ± 98s, p = 0.001, F = 90.364) when compared to the placebo group (792 ± 166s, p = 1.0, F = 0.072) (Abdalla et al. 2023). The link between PCr utilization and IACT suggests that the parameters of IACT/CT are similar to W'/CP. Moreover, different fatigue profiles have been demonstrated above and below CT using electromyography (EMG) to assess voluntary activation. Burnley et al. showed that peripheral and central fatigue were present below the CT threshold, yet muscles were still capable of producing more force (2012). Peripheral fatigue developed up to five times greater above the CT threshold than trials below CT (Burnley, 2012). Like CP, this implicates CT as a measure of fatigue, not just time-to-task failure.

2.5 Muscle Mass, Critical Power, and Critical Torque

Attempts to link whole muscle metabolic characteristics to CP parameters have relied on muscle mass and histochemical analysis thus far. In a body composition study, total lean mass of the thigh (TLM) explained 47.9% of the variance in W' ($r^2 = 0.479$, $p = 0.004$) (Byrd et al, 2018). As well, Byrd et al. found that TLM positively correlated to CP ($r = 0.538$, $p < 0.05$). This study posits that muscle mass potentially influences both W' and CP. While muscle mass has yet to be linked to IACT, muscles of different sizes have demonstrated distinct absolute and relative CT values.

When CT and IACT were compared between muscles possessing different masses, the plantar flexor (PF) and knee extensor (KE) muscles, the KEs demonstrated greater absolute CT (84.4 ± 24.8 vs 73.9 ± 19.5 N·m), IACT (7243.2 ± 1942.9 vs 3357.4 ± 1132.3 N·m·s), and MVCs (294.9 ± 62.5 vs 181.5 ± 37.6 N·m) than the PF muscles (Abdalla et al., 2018). However, when CT was expressed relative to MVC, the PFs demonstrated greater relative CT (CT/MVC) (0.41 ± 0.08 vs 0.29 ± 0.08, ES = 1.50) than the KE, but not relative IACT (IACT/MVC) (PF 17.7 ± 5.4 vs KE = 22.4 ± 7.9, ES = 1.25) (Abdalla et al., 2018).

Both the PF ($r= 0.62$, $p < 0.05$) and KE ($r= 0.67$, $p < 0.05$) demonstrated significant correlations between MVC and IACT (Abdalla et al., 2018), suggesting that greater absolute maximum force, due to increased muscle size, influences IACT. This study did not measure muscle mass; however, it can be readily done via dual x-ray absorptiometry (DXA) scans. DXA has been demonstrated to be a valid measure of thigh muscle mass when compared with MRI ($r= 0.89$, $p < 0.001$) (Tavoian et al., 2019) and has been demonstrated to be a reliable measure of thigh lean mass between days ($r= 0.99$, $p \leq 0.05$) (Byrd et al., 2018). By using DXA, as in Byrd et al. (2018), the relationship between CT and muscle mass can be further characterized. Still,

Abdalla et al. (2018) suggests that metabolic and contractile properties inherent to each muscle may play a part in determining their fatiguability.

2.6 Oxygen (O_2) Delivery, Critical Power, and Critical Torque

It is widely accepted that larger muscles, which produce greater force, are associated with greater intramuscular pressures that inhibit blood flow and oxygen delivery. Conversely, muscles with smaller volume to force ratios experience less intramuscular pressure, resulting in more adequate oxygen delivery during exercise (Abdalla et al., 2018). Oxygen concentration and oxygen delivery have been implicated as factors influencing both CP and CT, respectively. In a study comparing an individual's CP between hyperoxic and normoxic conditions, the hyperoxic condition exhibited greater CP values (18.0 ± 2.3 W; $p < 0.05$) than the normoxic condition (16.1 ± 2.6 W, $p < 0.05$) (Vanhatalo et al., 2010). This confirms that the CP threshold is sensitive to alterations in oxygen concentrations, suggesting that a greater ability to utilize and deliver oxygen is beneficial to performance. In fact, interindividual variation in CT has been demonstrated to be influenced by oxygen (O_2) delivery to the muscle. O_2 delivery explained 85% of the variance in CT ($r^2 = 0.85$, $p < 0.001$) when blood flow and arterial oxygen content were measured in the forearm (Kellawan et al., 2014). In conjunction, these studies suggest that fatiguability is dependent on muscles' ability to receive (based on blood flow and oxygen content) and utilize oxygen.

2.7 Fiber Type, Critical Power, and Critical Torque

A muscle's ability to utilize oxygen is innately tied to the composition of the muscle itself, or muscle fiber type. This is evidenced further by the positive correlation found between type-I fiber distribution and CP ($r = 0.67$, $p < 0.05$), and the inverse relationship between type-II fiber distribution and CP ($r = -0.76$, $p < 0.05$) (Vanhatalo et al., 2016). The same relationship is

demonstrated in CT. Type-I fibers were demonstrated to strongly correlate to relative CT (CT/MVC) ($r = 0.615$, $p < 0.05$), while type-II fibers correlated negatively to relative CT ($r = -0.495$, $p < 0.05$), but positively to IACT ($r = 0.541$, $p < 0.05$) (McDougall et al., 2023). The relationships between fiber type and CT suggest that the ability of individual muscle fibers to utilize oxygen, or lack thereof, may be a considerable determinant of exercise tolerance, like CP and CT.

2.8 Contractile Properties and Fiber Type

Type-I and type-II fibers possess different mitochondrial densities that contribute to oxidative capacity. Type-I fibers are more mitochondrially dense and can utilize more oxygen for energy and ATP resynthesis than type-II fibers (Blaauw et al., 2013). The high oxidative capacity of type-I fibers makes them more fatigue resistant and less forceful, yet may also present significant implications for muscle size. Type-II fibers with low mitochondrial density have been shown to be comparatively bigger than type-I fibers with high mitochondrial density (van Wessel et al., 2010). This is indicative of a trade-off between mitochondrial density (oxidative capacity) and force production, suggesting that metabolic properties intrinsic to the fiber may influence contractile force and similar mechanical properties.

Muscle fibers can be identified by the contractile properties that they possess, most commonly through histochemical staining or electrophoresis, which reveal the presence of different myosin isoforms (Harridge et al., 1996). Myosin isoforms display different myosin-ATPase activity, which directly influences the rate at which ATP can be hydrolyzed for force production (Blauuw et al., 2013), giving rise to the nomenclature “fast” vs “slow” twitch fibers. Slow-twitch, or type-I, fibers are defined by their low mechanical power and slow myosin-ATPase activity, while type-II, fast-twitch fibers possess greater mechanical power and myosin-

ATPase activity (Blaauw et al., 2013). The differences in myosin isoforms contribute to contraction time, shortening speed, and fatiguability between fiber types (Harridge et al., 1996). It is these contractile properties that can help identify fiber type without the use of a muscle biopsy.

2.9 Electrical Stimulation and Fiber Type

Electrical stimulation (e-stim) is a tool that can be utilized to determine contractile characteristics of muscles. In a study comparing electrically evoked contractions to muscle biopsies, it was demonstrated that the PF muscles exhibited the slowest time to peak torque (TPT) (120 ± 15 ms) when compared to the KEs (81 ± 8 ms) (Harridge et al., 1996). Incidentally, both histochemical analysis (78.1 ± 16.8% vs 47.3 ±14.6%) and electrophoresis (70.4 ± 14.0% vs 47.1 ± 8.5%) confirmed that the PF had higher distributions of Type-I fibers compared to the KE (Harridge et al., 1996). This suggests that contractile characteristics of whole muscle, like TPT, are influenced by the fiber type distributions within them.

This is further evident when correlations are run between fiber distribution, TPT, fatiguability, and the rat. Harridge demonstrated that Type-II fiber composition was highly predictive of TPT ($r = 0.990$, $p < 0.05$), RTD ($r = 0.957$, $p< 0.05$), and fatiguability ($r = 0.976$, $p < 0.05$) (1996). This study demonstrates that whole muscle contractile properties, as measured by e-stim, are associated with type-II fiber distributions in the KE muscles. While contractile properties like twitch half-relaxation time ($^1/_2$RT), and Rate of Relaxation (RTR) are associated with Ca^{2+} reuptake, Harridge et al. did not find significant differences in $^1/_2$RT, or RTR, between the three muscle groups (1996). However, this could be that single twitches are not sensitive enough to detect differences in $^1/_2$RT between fiber types. Still, e-stim poses a viable option for assessing fiber type properties in muscle.

2.10 Thorstensson Protocol

Another way fiber type can be differentiated is through Thorstensson's fatigue test. The protocol involves 50 maximal isokinetic contractions of the KE performed at 180 deg/s across a 90° range of motion (Thorstensson and Karlson, 1976). The mean peak torque of the initial three contractions is compared to the mean of the last three contractions, and a force decrement percentage is calculated. The resulting percent force decrement for 10 active males was highly correlated to the distribution of Type-II fibers ($r = 0.86$, $p < 0.01$) in the KE muscles (Thorstensson and Karlson, 1976). Using the regression equation from this protocol, the distribution of Type-II fibers in the KE muscles can be estimated. While the Thorstensson test has been utilized to estimate type-II fiber distribution since 1976, seemingly no study has tested the reliability of the protocol to date. Thus, the present study will also aim to investigate the reliability of the Thorstensson fatigue test.

2.11 Conclusion

In summary, CT represents a threshold of fatigue specific to intermittent isometric contractions, like the CP threshold. Muscle mass has been associated with both CP/W' and has been suggested to influence CT/ IACT. Type-I fiber distributions have been demonstrated to positively correlate with CP and CT, indicating that fiber type plays a role in exercise tolerance. In the absence of a muscle biopsy, a valid alternative for measuring fiber type lies in the contractile characteristics derived from electrically evoked muscular contractions. Additionally, the Thorstensson protocol provides a noninvasive measure of Type-II fiber distributions in the KE muscles that can be compared to the electrically stimulated contractile characteristics. In

conjunction, assessing muscle mass and contractile properties in the KE may further elucidate the relationship among skeletal muscle fiber type, muscle mass, and CT.

Chapter 3: Methods

3.1 Introduction

Critical Torque (CT) represents a fatigue threshold above which fatigue becomes predictable, but below which fatigue is less predictable. An individual's CT can be estimated in one visit using a 5-minute all-out protocol of the KE muscles (Burnley, 2009). CT parameters from this protocol have been suggested to be influenced by muscle mass and fiber type through comparison of different muscle groups (Abdalla et al., 2018), though no study to our knowledge has examined lean thigh mass (TLM) specifically. DXA has been shown to be a reliable and valid measure of TLM in the KE muscles (Byrd et al., 2018; Tavoian et al, 2019). Without the use of muscle biopsies, fiber type composition in the KE can be estimated using the Thorstensson protocol (Thorstensson and Karlson, 1976), while twitch interpolation can be used to infer contractile characteristics of fiber type in different muscle groups (Harridge et al., 1996). By running correlations between muscle mass, contractile characteristics, and CT parameters, the relationship between fiber type in the KE and CT can be better understood.

3.2 Sample and General Design

A power calculation was performed using the G Power program based on the results of Byrd et al. (2018). Using the correlation between thigh lean mass and CP ($r= 0.538$, $p < 0.05$), G Power determined a total sample of 18 participants would be required at an α level of 0.05 and a β level of 0.20. However, given that 30 participants are considered the suggested minimum sample size for correlational studies (Baumgartner et al., 2021), the present study aimed to recruit over 30 participants. The sample was collected from the University of Oklahoma, and Norman, Oklahoma, specifically males and females aged 18-35. Similar age groups have been

used to examine CT and fiber type composition in previous studies (Abdalla et al., 2017; Abdalla et al., 2023; Burnley, 2009; Burnley et al., 2012). Recruitment involved word-of-mouth recruitment, flyers, and emails. Convenience sampling was used, given that we cannot randomly choose participants from the University for neuromuscular testing and must rely on volunteers.

Inclusion criteria consisted of males and females 18-35 years of age. Participants were excluded if they possessed any neuromuscular or cardiometabolic conditions, as well if they experienced any significant musculoskeletal injury in the last twelve months. Participants were excluded if they could not sustain repetitive maximal voluntary contractions or neuromuscular stimulation. Overall, thirty-two total participants were recruited for this study (18 males, and 14 females). However, one female participant withdrew from the study entirely, while one female participant elected not to complete the CT protocol. In total, thirty participants (18 males and 12 females) completed the entirety of the study.

An overview of experimental procedures can be seen in Figure 1. Each subject participated in a total of three visits. *Visit 1* involved participant consent and familiarization with the study protocols. Contractile properties of the KE were assessed using single and doublet twitch responses. Electrode placement was marked for each participant to ensure consistency between Visits 1 and 2. Following stimulation, participants were familiarized with generating maximal voluntary contractions (MVC) separated by three minutes of rest and followed by five minutes of rest after the third effort. Following MVC assessment, participants were familiarized with the CT protocols for the KE muscle. Positioning on the dynamometer was recorded for each participant for consistency. After an additional ten minutes of rest, each participant completed a familiarization of the Thorstensson test, followed by completion of the full Thorstensson

protocol. The percent type-II fiber distribution was estimated and recorded using the percent force decrement expressed during the Thorstensson protocol.

Visit 2 occurred within 24-72 hours of Visit 1. First, muscle mass was assessed using dual X-ray absorptiometry (DXA) scans. Afterwards, each participant generated three MVCs separated by three minutes of rest. After five minutes of rest, participants completed the total CT protocol using the KEs. Finally, *Visit 3* consisted of a second Thorstensson test for a reliability assessment. Intraclass correlation coefficients were run for Thorstensson percent type-II fiber predictions and force decrement between Visits 1 and 3.

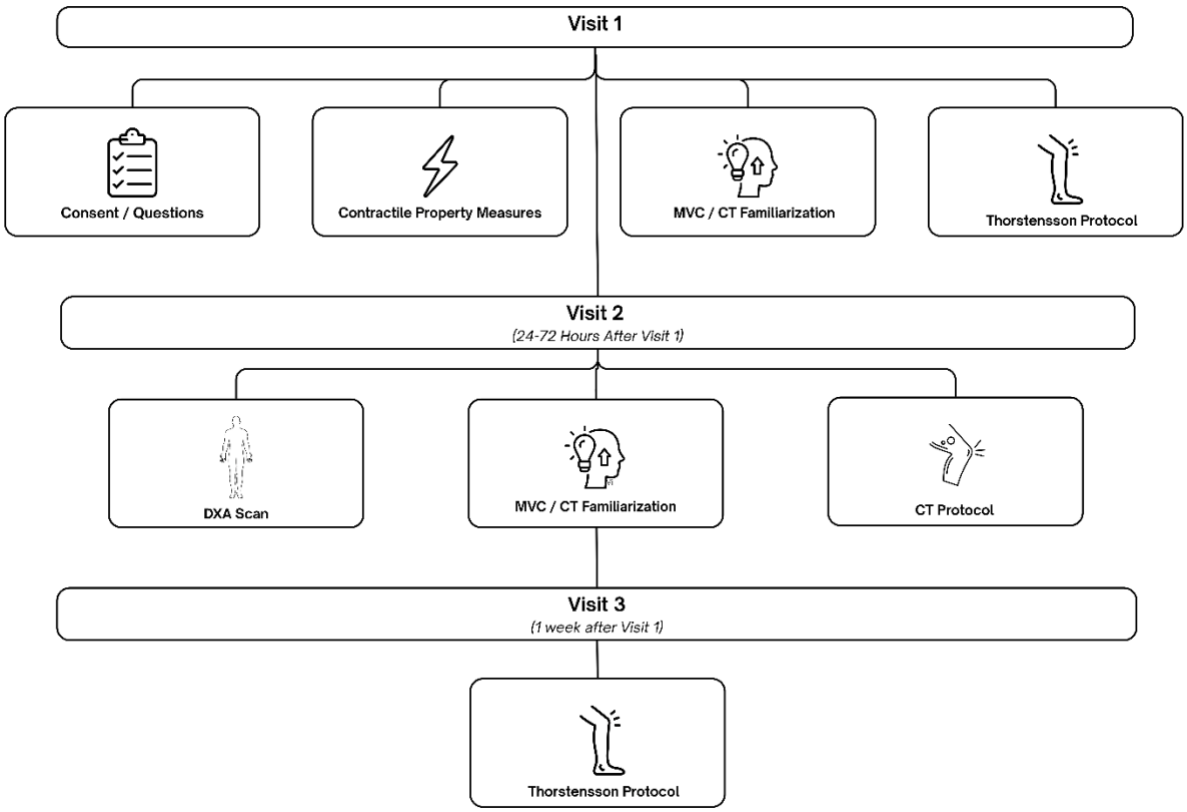


Figure 1 – Experimental overview

3.3 Instrumentation

Dynamometry—Participants were seated on a KinCom 125AP (*Chattex Corp*; Chattanooga, TN) isokinetic dynamometer for three different measures. All dynamometry testing was completed on the right leg. With the KinCom in an upright seated position, participants were secured with a strap across the waist, shoulders, and non-exercising left leg. The participant's knee joint was aligned with the KinCom's axis of rotation. The force transducer was positioned above the lateral malleolus of the right foot and secured firmly

Thorstensson Protocol. Range of motion was limited to 90° as described previously (Thorstensson and Karlson 1976). Range of motion was relativized to each participant by finding the average of three maximum knee extension trials, then subtracting by 5° to determine the stop angle. The start angle was determined by subtracting 90° from the stop angle. Torque was recorded continuously for the entirety of the Thorstensson Protocol.

Assessment of Knee Extensor MVC and Critical Torque. The KinCom was in a similar upright configuration to the Thorstensson Protocol. The participant's knee was aligned with the KinCom axis of rotation, and the force transducer secured above the lateral malleolus (Abdalla et al., 2018). Range of motion was restricted to 0°, specifically at 109° for isometric torque measures. Participants were strapped around the waist, shoulders, and non-exercising leg as described above. Torque was recorded continuously throughout the CT protocol.

Electrical Stimulation—The KE muscles were electrically stimulated via two (3"x 4") gel adhesive rectangular electrodes (*Axelgaard Manufacturing Co., LTD*; Fallbrook, CA). One electrode was placed on the proximal portion of the vastus lateralis and the distal portion of the vastus medialis. A single twitch and double twitch pulse (doublet) were delivered to the KE

muscles in stepwise increments until no more force was evoked. The force produced from the maximal doublet twitches was then used to calculate the time-to-peak tension (TPT), half relaxation time ($^1/_2$RT), rate of torque development (RTD), and rate of relaxation (RTR) (Harridge et al., 1996).

Muscle Mass— Total lean mass (TLM) of the thigh was measured using dual X-ray absorptiometry (DXA) (*GE Healthcare, Schenectady, NY*). The region of interest for the thigh was drawn from the ischial tuberosity to the middle of the knee joint of the right leg (Byrd et al., 2018). TLM was assessed as the lean mass (g) of this region of interest. Participants were asked to remove shoes and wear light clothing for the DXA scan. Female participants completed a pregnancy test before DXA procedures began.

3.4 Measures

MVC—Participants were asked to generate three maximal voluntary isometric contractions for three seconds, separated by three minutes of rest. The MVC was considered the average of the two highest contractions. Standardized verbal encouragement was provided during each MVC attempt.

CT —The CT protocol involved 60 isometric MVCs (3 sec contraction, 2 sec rest) for a total of five minutes (Burnley, 2009). Standardized verbal encouragement was provided throughout the protocol such as “Kick hard as you can,” and “Hard as you can, every time.” Each participant’s MVC was displayed visually to ensure maximal effort was achieved. An audio queue sounded for three seconds during the time participants needed to exert maximal effort, followed by two seconds of silence for rest. was CT was measured as the average of the last six contractions, and IACT was calculated as the total area under the torque-time curve minus the

torque area for CT (Burnley, 2009). CT was then relativized to MVC (%CT) for the KE muscles. Lastly, the total amount of force generated across the entirety of the CT test is considered Total Impulse and will be included in reported results.

Contractile Properties—For the assessment of contractile properties, the KE muscles were electrically stimulated until a stepwise increase in amplitude did not yield an increase in torque (Harridge et al., 1996). A single and doublet twitch were delivered to each muscle at this maximum amplitude. P_t was measured as the highest value in torque evoked from the maximal doublet twitch. TPT was calculated from the doublet twitch as the time from the onset of force generation to maximum twitch torque. The halfway point between maximum force generation and complete relaxation from a single twitch was considered $^1/_2$RT. RTD and RTR were rates of torque development, and relaxation, calculated by dividing maximal twitch torque by the time to reach peak tension (for RTD) and by dividing maximal twitch torque by 2 and then dividing by the ½ relaxation time (for RTR).

Thorstensson Fatigue Test—The relative distribution of Type-II fibers in the KE muscles were assessed via the Thorstensson protocol. Participants were familiarized beginning with three MVCs at 60 deg/s, followed by three MVCs at 180 deg/s. After rest, the participants performed 50 isokinetic contractions of the KE and hamstrings at 180 deg/s. Percent force decrement was calculated as the percent change from the average peak force of the first three contractions (PF_i) to the average peak force of the last three contractions (PF_f) and plugged into the regression equation for Type-II fiber distribution, where $y = 0.9x + 5.2$ (Thorstensson and Karlsson, 1976).

3.5 Data Collection Procedures

Data was collected over a sixteen-week period by the Sensory and Muscle Function Lab and its members. Quantitative data was collected for muscle mass, CT, impulse above critical torque (IACT), P_t, TPT, $^1/_2$RT, RTD, and RTR, in BioPac. Personalized information was deidentified and stored in a password-protected file on a password-protected device.

Statistical Analysis

SPSS v. 31 was used for data analysis. The Shapiro-Wilk test confirmed normality for each data distribution. Pearson correlations were performed to examine the relationship between TLM and CT values, among contractile properties (P_t, TPT, ½ RT, RTD, and RTR) and CT values obtained from the KE, and between type II fiber percentage and CT. Intra-class correlation coefficients were used to assess the reliability of the Thorstensson protocol. Statistical significance was set *a priori* at $P < 0.05$.

Chapter 4: Results

4.1 Sample

Mean participant characteristics are expressed in Table 1. A total of 31 (18 males and 13 females) participants took part in this study, with one female participant opting out of the Critical Torque (CT) protocol. As such, this participants data was excluded from correlations between CT, Contractile Properties, and Body Composition, but was used to assess the reliability of Thorstensson. Mean values for CT, Contractile Properties, and Body Composition are provided in Table 1 and contraction-by-contraction values for the CT test can be seen in Figure 2.

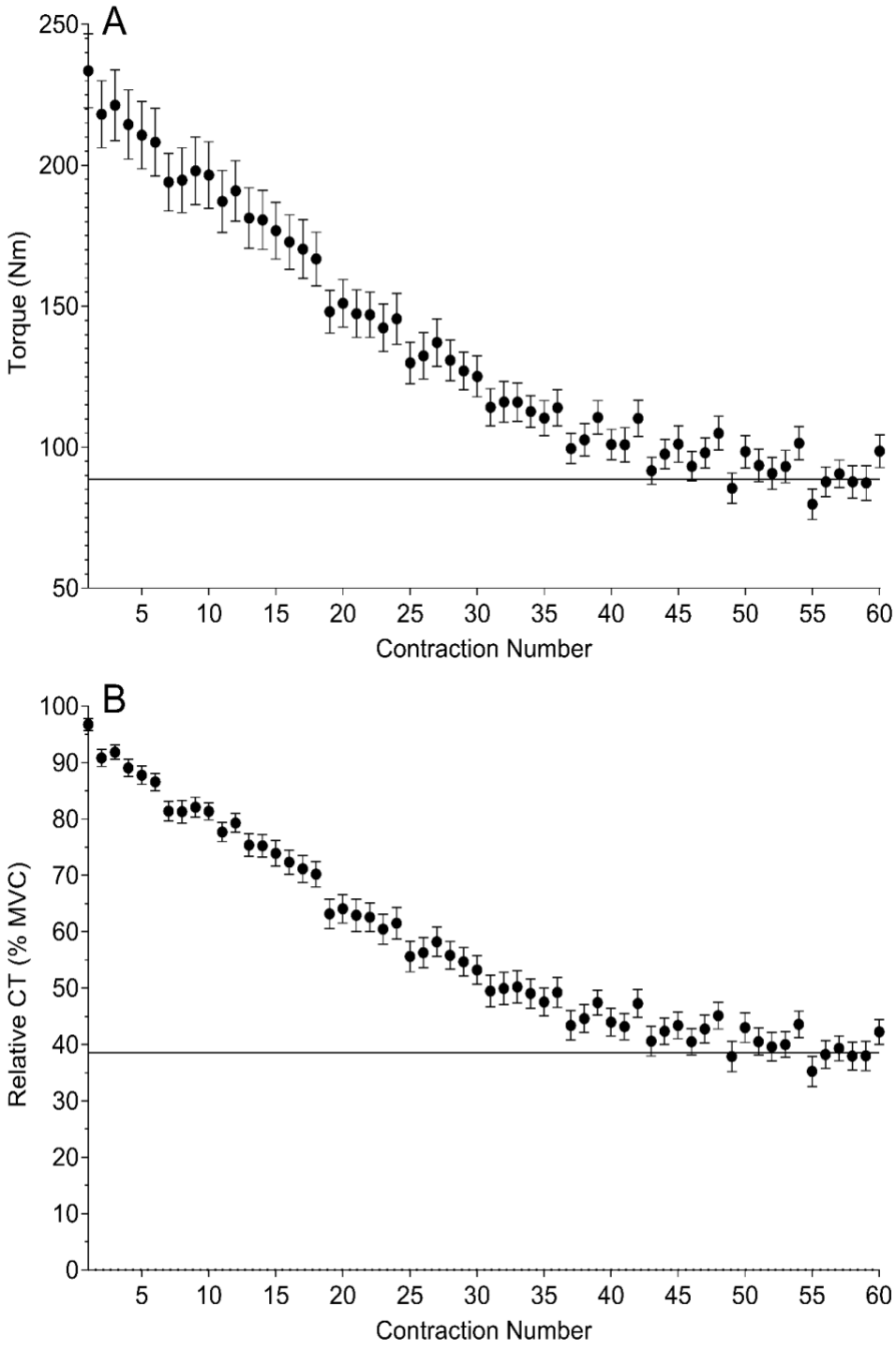


Figure 2 – Absolute (A) and relative (B) torque values across the 60 contractions of the critical torque assessment.

While not the primary focus of this research, sex differences were observed in the present study. Men were taller ($p < 0.05$), heavier ($p < 0.05$), and had greater thigh lean mass ($p < 0.05$) than women. Men had a greater MVC than women ($p < 0.01$) as well as a greater absolute CT ($p < 0.05$) and total torque impulse ($p < 0.05$). No differences were observed in relative CT ($p > 0.05$) or IACT ($p > 0.05$). In relation to twitch properties, men had a larger peak twitch torque ($p < 0.05$) and a faster rate of torque development ($p < 0.05$), but no differences were found for time to peak tension ($p > 0.05$), ½ relaxation time ($p > 0.05$), or rate of torque relaxation ($p > 0.05$).

Table 1. – Participant characteristics and neuromuscular outcomes

Measure	**Total (n = 30)**	**Male (n = 18)**	**Female (n = 12)**
Age (yr)	23.4 ± 3.0	23.3 ± 2.4	23.5 ± 3.8
Height (cm)	173.9 ± 9.8	177.5 ± 8.5	168.8 ± 9.5*
Weight (kg)	76.3 ± 15.9	81.1 ± 15.1	69.5 ± 15.0*
Thigh Lean Mass (g)	6895.6 ± 1747.3	7537.4 ± 1706.2	5932.8 ± 1365.8*
Voluntary Measures			
MVC (Nm)	250.5 ± 81.6	293.3 ± 73.3	186.3 ± 42.0*
Critical Torque (Nm)	88.6 ± 27.3	98.0 ± 27.0	74.5 ± 21.6*
Relative Critical Torque (%MVC)	37.4 ± 12.9	34.9 ± 12.3	41.3 ± 13.4
IACT (Nm·s)	7745.0 ± 3517.1	8533.0 ± 3630.5	6563.1 ± 3114.8
Total Torque Impulse (Nm·s)	20707.4 ± 5422.3	22700.2 ± 5221.2	17718.2 ± 4374.5*
Twitch Properties			
P_t (Nm)	64.1 ± 22.4	72.2 ± 22.8	51.9 ± 15.8*
Time to peak tension (sec)	0.134 ± 0.009	0.132 ± 0.010	0.137 ± 0.009
1/2 Relaxation time (sec)	0.067 ± 0.013	0.070 ± 0.015	0.064 ± 0.007
Rt Torque Development ($Nm \cdot s^{-1}$)	484.2 ± 186.5	550.9 ± 191.3	384.0 ± 130.1*
Rt Torque Relaxation ($Nm \cdot s^{-1}$)	485.8 ± 176.8	535.1 ± 193.9	411.7 ± 119.8

Values expressed as mean ± SD; **MVC** = maximum voluntary contraction; **IACT** = impulse above critical torque; $\mathbf{P_t}$ = peak twitch torque. *indicates a significant difference (t-test) between values for men and women ($p < 0.05$).

4.2 Thorstensson Measures

Mean values for the Thorstensson trials are represented in Table 2 and Figure 3. Mean values for initial force (PF_i) were lower ($p < 0.05$) during Visit 2 compared to Visit 1. Mean values for final force (PF_f) were higher ($p < 0.05$) during Visit 2 compared to Visit 1. This resulted in less force decrement ($p < 0.01$) during Visit 2 compared to Visit 1 and therefore a lower predicted type II fiber type percentage ($p < 0.01$) in Visit 2 compared to Visit 1. Women had significantly lower PF_i and PF_f compared to men across both Visit 1 and Visit 2 ($p < 0.05$) for all), as expected. Additionally, percent force decrement and estimated type II fiber percentage were lower in Visit 2 compared to Visit 1 for both men and women ($p < 0.05$ for all). Initial force did not differ between Visit 1 and Visit 2 for both men and women. Final force did not differ between visits for men but was higher in Visit 2 for women ($p < 0.05$).

Table 2. – Values from Thorstensson Tests Between Visits

Measure	**Visit 1**	**Visit 3**
$PF_{i\,(N)}$	439.0 ± 121.1	414.6 ± 121.5*,#
$PF_{f\,(N)}$	144.3 ± 49.8	155.2 ± 49.9*,#
Percent Force Decrement	67.1 ± 8.4	61.6 ± 11.1*,#
Estimated Type II%	65.6 ± 7.6	60.7 ± 9.9*,#
Men		
PF_i	497.4 ± 121.7	473.1 ± 121.9*
PF_f	165.3 ± 46.1	172.0 ± 48.5*
Percent Force Decrement	66.1 ± 8.8	62.5 ± 11.5*
Estimated Type II%	64.7 ± 7.9	61.4 ± 10.3*
Women		
PF_i	358.2 ± 59.5	333.6 ± 59.9*,#
PF_f	115.2 ± 40.1	132.1 ± 43.5*,#
Percent Force Decrement	68.3 ± 8.1	60.5 ± 10.9*
Estimated Type II%	66.7 ± 7.3	59.6 ± 9.8*

Values expressed as mean ± SD; $\mathbf{PF}_i$ = mean peak force of initial three contractions, $\mathbf{PF}_f$ = mean peak force of final three contractions. *indicates a significant main effect for time between visit 1 and visit 3 ($p < 0.05$). # indicates a significant main effect for sex with values differing between men and women ($p < 0.05$).

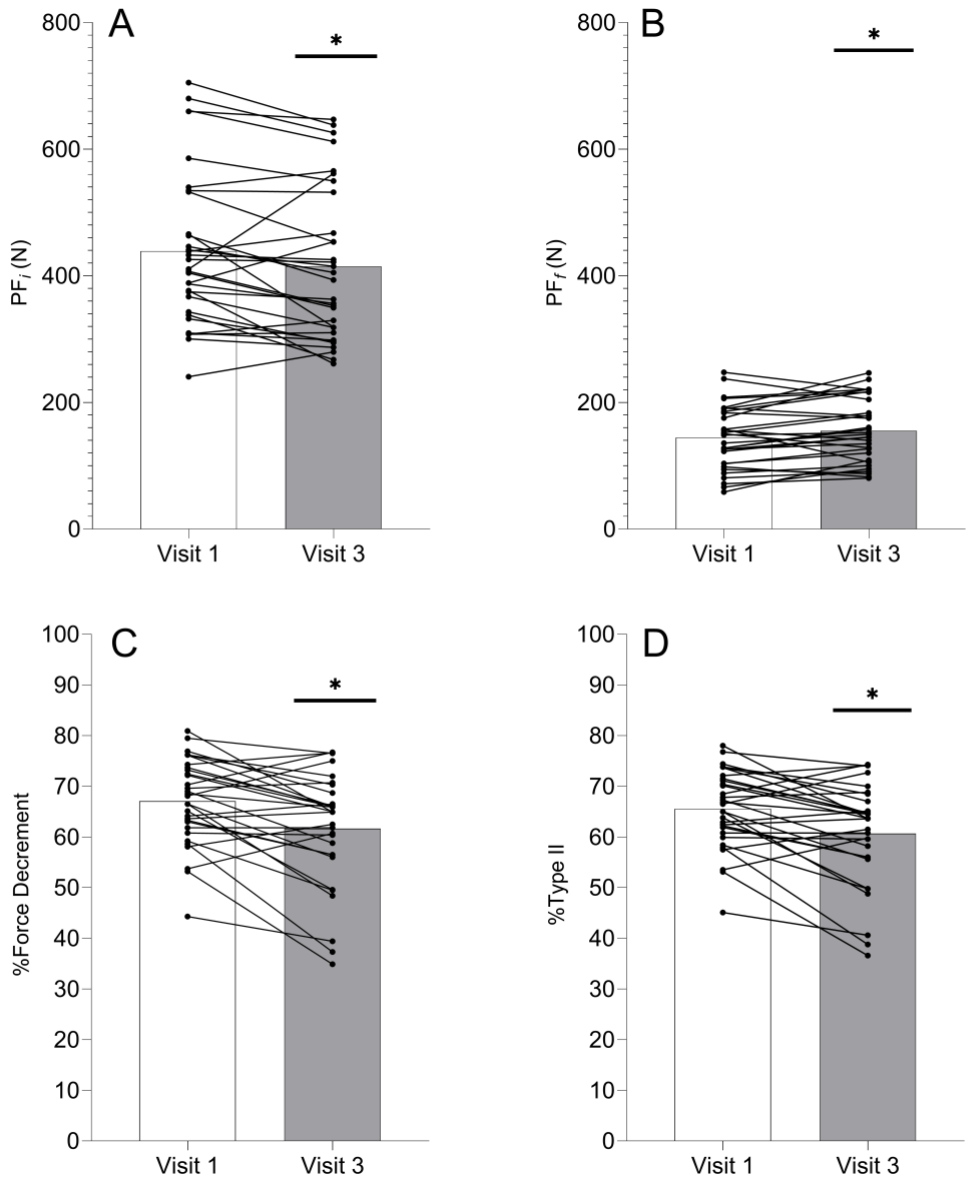


Figure 3 – Values from Thorstensson tests for Visit 1 and Visit 2. PF$_i$ = mean peak force of the initial three contractions in the Thorstensson test; **PF$_f$** = mean peak force of the final three contractions in the Thorstensson test; **%Force Decrement** = percentage of decline in force from the initial to final three contractions; **%Type-II** = mean value of type-II fiber distribution predicted by Thorstensson test on Visit 1 and Visit 3.* indicates a significant difference between Visit 1 and 2 ($p < 0.05$). Values are means with individual participants shown.

The intra-class correlation coefficients for Thorstensson are shown in Table 5. %Type-II Fiber was found to have moderate intersession reliability and variability (ICC = 0.616, $p < 0.05$, CV = 12.9%).

Table 3. Intra-class Correlation Coefficients for Thorstensson Values *(N=31)*

	ICC	*CV*	*CI*	*Reliability*	*Variability*
PF_i	0.883*	27.7	0.749-0.945	Good	High
PF_f	0.848*	32.1	0.690-0.926	Good	High
%FD	0.616*	14.1	0.202-0.819	Moderate	Moderate
%Type-II Fiber	0.616*	12.9	0.202-0.819	Moderate	Moderate

PF_i = mean peak force of initial three contractions; **PF_f** = mean peak force of final three contractions; **%FD** = percent force decrement; **%Type-II Fiber =** Thorstensson percent type-II fiber prediction. * indicates significance at ($p < 0.05$).

4.3 Relationships to Critical Torque

Thigh Lean Mass - A weak positive correlation was found between TLM and CT ($r = 0.389$, $p < 0.05$; Table 4). No significant correlation was found between TLM and %CT ($r = -0.334$, $p > 0.05$; Table 4).

Contractile Properties - Positive correlations were found between P_t and CT ($r = 0.362$, $p < 0.05$; Table 4), as well as RTR and CT ($r = 0.434$, $p < 0.05$). No significant correlations were found among TPT and CT ($r = 0.163$, $p > 0.05$), 1/2RT and CT ($r = -0.238$, $p > 0.05$), or RTD and CT ($r = 0.299$, $p > 0.05$). No significant correlations were found among contractile properties and %CT ($p > 0.05$).

IACT - Positive correlations were found among IACT and TLM ($r = 0.727$, $p < 0.01$). Significant positive correlations were also found among contractile properties and IACT, such as P_t ($r = 0.692$, $p < 0.01$), RTD ($r = 0.669$, $p < 0.01$), and RTR ($p = 0.534$, $p < 0.01$). Total Impulse

performed in the CT protocol was found to positively correlate to LTM ($r= 0.720$, $p < 0.01$), P_t ($r = 0.643$, $p < 0.01$), RTD ($r = 0.578$, $p < 0.01$), and RTR ($r = 0.606$, $p < 0.01$).

Predicted Fiber Type - %Type-II Fiber was found to significantly correlate to CT ($r = -0.422$, $p < 0.01$). As well, a moderate negative correlation was found between %Type-II Fibers and %CT ($r = -0.57$, $p < 0.01$), displayed in Figure 4.

Table 4. Correlations Among Muscle Mass, Contractile Properties and Critical Torque Parameters (N=30)

	MVC	**CT**	**%CT**	**IACT**	**Total Impulse**
TLM	0.731*	0.389*	-0.334	0.727*	0.720**
P_t	0.677*	0.362*	-0.302	0.692*	0.643*
TPT	-0.044	0.163	0.188	-0.144	0.063
1/2RT	-0.001	-0.238	-0.258	0.206	-0.052
RTD	0.630**	0.299	-0.314	0.669**	0.578**
RTR	0.634**	0.434*	-0.182	0.534**	0.606**
%Type-II	0.162	-0.421*	-0.570**	0.130	-0.312

TLM = lean thigh mass; **P_t** = peak twitch torque; **TPT** = time to peak torque; **1/2RT** = half-twitch relaxation time; **RTD** = rate of force development; **RTR** = relaxation rate; **MVC** = maximum voluntary contraction; **CT =** Critical Torque; **%CT =** critical torque relative to MVC; **IACT** = impulse above critical torque; **%Type-II**, mean Thorstensson predicted Type-II fiber distribution between Visits 1 and 3. *Significant at 0.05 **Significant at 0.01

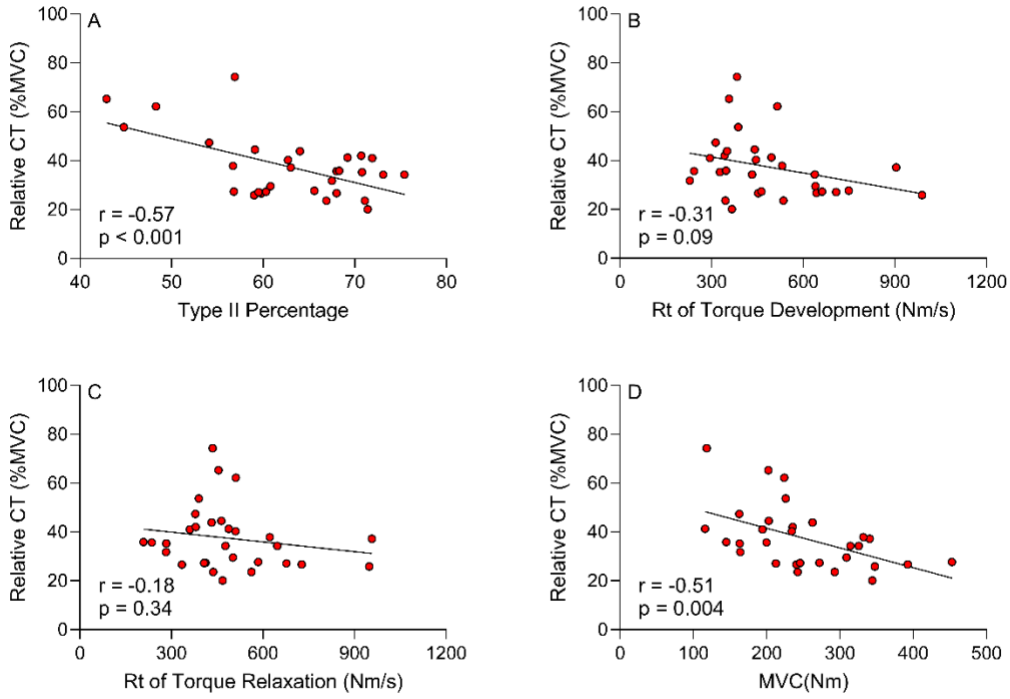


Figure 4 – Correlations among relative CT and a) %Type-II Fiber, b) RTD, c) RTR, and d) MVC. Relative CT (%MVC) = Critical Torque (CT) relative to maximum voluntary contraction and expressed as a percentage; **%Type-II Fiber** = mean Thorstensson predicted Type-II fiber distribution between Visits 1 and 3; RTD = rate of torque development; and RTR = rate of relaxation.

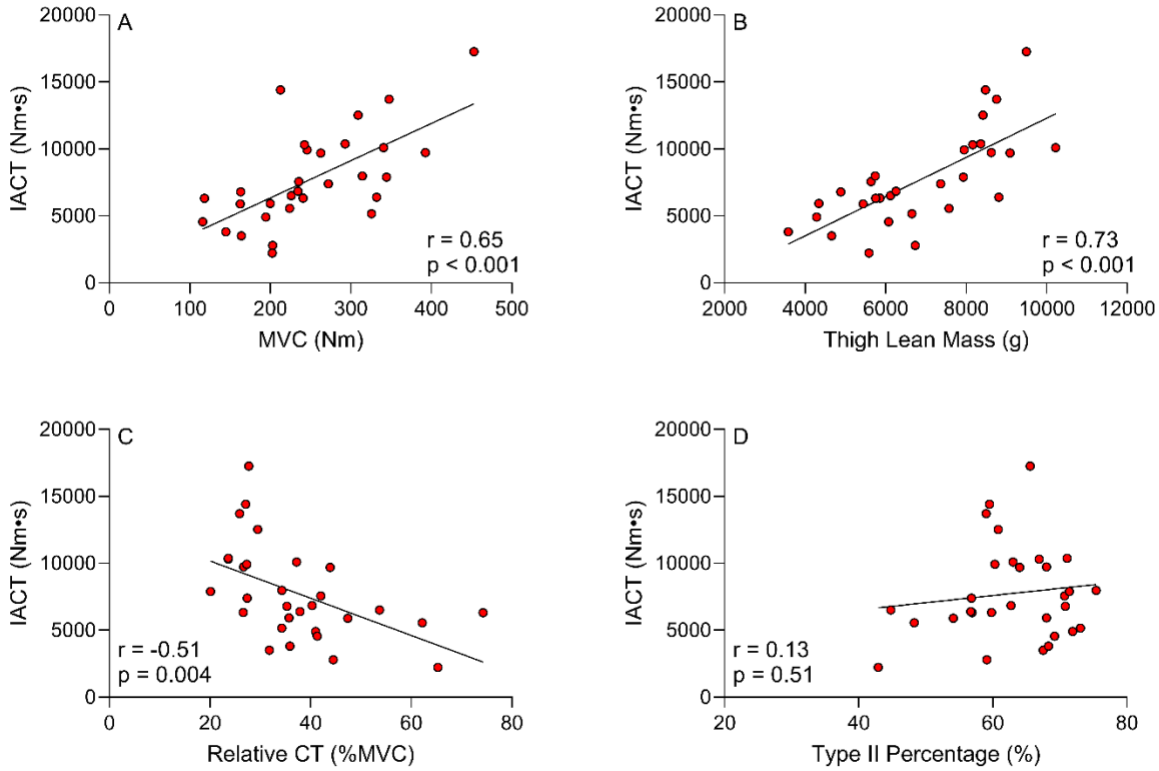


Figure 5—Correlations among IACT and a) MVC, b) TLM, c) Relative CT, and d) %Type-II Fibers. IACT = impulse above Critical Torque; **MVC** = maximum voluntary contraction; **TLM** = thigh lean mass; **%CT**= Critical Torque (CT) relative to maximum voluntary contraction and expressed as a percentage; **%Type-II fibers** = mean Thorstensson predicted Type-II fiber distribution between Visits 1 and 3.

Chapter 5: Discussion

The present study sought to examine the relationship among muscle mass, contractile properties, and parameters of the Critical Torque (CT) threshold, as well as assess the reliability of the Thorstensson test, commonly used in fiber-type prediction. Results from the present study found TLM to positively correlate to CT ($r = 0.389$). These results are consistent with research examining the relationship between TLM and CP. However, Byrd et al. found a stronger correlation between TLM and CP ($r = 0.538$). This difference could be attributed to the smaller average muscle mass in the present study (6895.6 ± 1747.3 g) compared to Byrd et al. (14,330 ± 2,560 g) (2018), or the greater homogeneity of the sample (resistance trained males) in the former study. Still, the results of the present study uphold the notion that lean thigh mass is associated with localized and whole-body aerobic capacity.

Whole muscle contractile properties have been shown to differ between muscles of different fiber types, with muscles possessing more Type-II fibers demonstrating greater P_t and RTD, and lower TPT (Harridge et al., 1996). Weak, positive correlations among P_t, RTR, and CT were found in the present study. These results conflict with research examining fiber type biopsies and CT, that suggest higher proportions of type-II fibers should negatively correlate with CT (McDougall et al., 2023). Whole muscle contractile characteristics (TPT and RTD) have been previously demonstrated to correlate to %Type-II fiber distribution (Harridge et al. 1996). Results of the present study did not find any significant correlations among %Type-II Fibers and contractile characteristics. However, a negative correlation was found between %Type-II Fibers and %CT, suggesting that a higher percentage of type-II fibers are associated with a lower CT value. This relationship is visible in Figure 1.

To our knowledge, this is the first study to assess intersession reliability of the Thorstensson test. In the present study, ICCs for %FD and %Type-II Fibers demonstrated moderate reliability between Visits 1 and 3. The relative error in %FD and %Type-II Fibers could be explained by the high variability in the dynamic force measures between visits. In the present study, PF_i between visits was reliable (ICC = 0.883), meaning measurements of participant's peak force remained consistent in relation to one another, but demonstrated significant error (CV = 27.7%). The PF_f measures shared similar consistency and slightly higher variability. These results slightly conflict with the findings of studies examining the intersession reliability of knee extensor peak torque. Mau-Moeller et al. found knee extensor peak torque, performed at 180 deg/s, to be reliable between visits separated by a week (ICC = 0.98, CV = 4.9%) (2017).

Therefore, it is possible that the error and relative inconsistency expressed in %FD and %Type-II Fiber is due to the notable error in PF_i and PF_f. PF_i values were found to significantly decrease between Visit 1 and Visit 3 (439.0 ± 121.1 vs 414.6 ± 121.5 N; $t = 2.467$, $p < 0.05$). However, PF_f values significantly increased between Visit 1 and 3 (144.3 ± 49.8 vs 155.2 ± 49.9 N; $t = -2.355$, $p < 0.05$). While PF_i decreased between visits, the %FD exhibited on Visit 3 was lower than Visit 1 (61.6 ± 11.1% vs 67.1 ± 8.4%; $t = 3.986$, $p < 0.01$), suggesting less fatigue occurred during the second trial. No intrasession, or intersession, learning effect has been found for maximal peak torque of the KEs (Lund et al., 2005), leaving the reason for this uncertain. However, it could suggest that participants engaged in some level of pacing given that they better understood the demands of the Thorstensson protocol by their second trial.

When PF_i and PF_f are converted from Newtons (N) to kilograms (kg), the apparent differences between visits appear trivial. While PF_i exhibited a 24.4 N difference between visits 1 and 3 (439.0 vs 414.6 N), it is only a 2.5 kg difference (44.8 vs 42.3 kg) when converted.

Similarly, when expressed as kg, PF_f values exhibit an increase of 1.1 kg (14.7 vs 15.8 kg) as opposed to an increase of 10.9 N (144.3 vs 155.2) between visits. These results suggest that the differences in force measures between visits 1 and 3 may not be as large as originally observed, and therefore, may not be as meaningful in interpretation. Still, a decrease in %Type-II fibers and %FD was observed between visits, suggesting that less fatigue may have occurred. Given the Thorstensson test's reliance on fatigability correlating to type-II fibers, it is possible that the first attempt at the Thorstensson trial may yield the most accurate results. Future studies should examine the Thorstensson test's fiber prediction across several visits in order to confirm this notion.

It is worth mentioning that, due to the Thorstensson's type-II fiber prediction being calculated out of 100%, that Type-I fiber distribution can be inferred through simple subtraction. Each participant's %Type-II fiber values were subtracted from 100 and averaged across Visits 1 and 3. Mean Type-I fiber distribution was found to be 36.9 ± 8.2 %, compared to the mean Type-II fiber distribution of 63.1 ± 8.2%. Given the moderate reliability of the Thorstensson test, and this indirect measure of Type-I fiber distribution, the present study refrained from calculating correlations among Type-I fibers, CT, contractile properties, and LTM.

Lastly, results from this study indicate a strong, positive correlation among TLM and IACT. While IACT and W' are not synonymous, they both represent anaerobic work capacity above CT/CP, respectively. Therefore, these results are consistent with previous findings regarding TLM and W' (Byrd et al., 2018). However, the present study found a stronger correlation between TLM and IACT (r = 0.727), compared to Byrd et al. (r = 0.692) (2018). Since CP represents the greatest rate of wholly oxidative metabolism, it is possible a single muscle group measure does not correlate as strongly to whole-body CP parameters such as W'.

Whereas, the present study examines this rate of wholly oxidative metabolism within the thigh itself, potentially lending to a stronger correlation between LTM and IACT. However, consistent with McDougall et al. (2018), the present study found positive relationships among P_t, RTD, RTR, and IACT, suggesting contractile characteristics frequently associated with type-II fibers are fairly correlated to IACT.

Conclusion

In conclusion, the results of our study suggest that lean thigh muscle mass is associated with an increased ability to perform work above the CT threshold, while mildly contributing to CT in the thigh. Contractile characteristics associated with type-II fibers were found to positively correlate to IACT, and to a weak degree, CT. Still, this study is limited by its use of a single muscle group. Future research should examine these non-invasive measures of contractile characteristics between muscle groups with known fiber type differences. Examining a wider distribution of contractile characteristics could help further characterize the relationship among fiber type and fatigability without the use of fiber biopsy. Lastly, this study sought to test the reliability of the Thorstensson test, finding weak consistency and considerable variability between days. Therefore, future studies should exercise caution when utilizing the Thorstensson test for measures of fiber type.

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APPENDIX A: IRB APPROVAL

The UNIVERSITY of OKLAHOMA

Institutional Review Board for the Protection of Human Subjects

Initial Submission – Board Approval

Date:	January 13, 2026	**IRB #**:	19245
To:	Christopher D Black, PhD	**Meeting Date**:	01/12/2026
		Approval Date:	01/12/2026
		Expiration Date:	12/31/2026

Study Title: Relationship Among Muscle Mass, Contractile Properties, and Critical Torque
Study Status: Active - Open | CR Req

The University of Oklahoma Health Sciences Center's Institutional Review Board (IRB) reviewed and approved the above-referenced research study at its regularly scheduled meeting. It is the IRB's judgement that the proposed research, including the process of obtaining informed consent, will be conducted in a manner consistent with the requirements of 45 CFR 46 or 21 CFR 50 & 56.

Approval for this research is limited to the activities described in the approved protocol and application. In accordance with this approval, specific conditions for the conduct of this research are listed below, and informed consent from participants must be obtained as indicated.

Risk/Benefit Assessment: Research not involving greater than minimal risk.

Informed Consent Determination:
Informed consent and research privacy authorization must be obtained using the currently approved, stamped forms. You must retain all original, signed forms.

Continuing Review Determination:
As part of this approval, annual continuing review is required. You must promptly submit a Continuing Review/Final Closure Report Form and appropriate supporting documents to the IRB upon notification; approximately 60 days prior to the expiration date indicated above.

NOTE: The Board recommends that participants are asked to not sign the PARQ form, as this may help to protect their PHI.

Principal Investigator Responsibilities:

- Conduct the research study in a manner consistent with the requirements of the IRB and federal regulations at 45 CFR 46 and/or 21 CFR 50 and 56.
- Request approval from the IRB prior to implementing any/all modifications.
- Promptly report to the IRB any harm experienced by a participant that is both unanticipated and related per IRB Policy.
- Maintain accurate and complete study records for evaluation by the HRPP quality improvement program and if applicable, inspection by regulatory agencies and/or the study sponsor.

The following are also required if applicable to this research study:

- You may *not begin your study* until the contract through Office of Research Administration (ORA) is finalized and signed as per OUHSC Institutional policy.
- If this study involves external sites requiring a reliance agreement for OUHSC to serve as IRB of record, submit a modification to add each non-OU site and non-OU collaborator to the application after a reliance agreement has been finalized.

1122 NE 13th Street, Suite CB202, Oklahoma City, OK 73117 (FWA00007961)

APPENDIX B: CONSENT FORM

Consent Form to Participate in a Research Study
University of Oklahoma Health Sciences Center (OUHSC)

Study Title: Relationship Among Muscle Mass, Contractile Properties, and Critical Torque

Sponsor: University of Oklahoma Health and Exercise Science

Principal Investigator: Dr. Christopher Black

Phone Number: 706-255-3750

KEY INFORMATION ABOUT THE RESEARCH STUDY

You are being asked to participate in a research study. Research studies are voluntary and include only people who choose to take part. This consent form begins with a 'Key Information' section to provide important information to help you decide whether or not to participate in this study. More detailed information is provided after the key information. Please take your time, discuss this with family and friends, and ask the investigator and study team any questions you may have.

WHY HAVE I BEEN ASKED TO PARTICIPATE IN THIS STUDY?

You are being asked to participate in this research study because you are a male or female between the ages 18-35.

WHY IS THIS STUDY BEING DONE AND HOW LONG WILL IT LAST?

This research aims to assess the relationship between characteristics of your skeletal muscles such as how big they are and how fast they can contract, and with property called Critical Torque which is highest amount of force your muscles can produce when asked to contract over and over again without rest for 5 minutes.

We think that you will be in the study for a full time commitment of 1.5-2.5 hours between three visits.

WHAT WILL I BE ASKED TO DO IN THIS STUDY?

If you decide to participate in this study, you will be asked to contract your dominant leg as forcefully as you can over and over again following two different exercise protocols. In the first, you will contract your leg over and over again while your knee and lower leg move at a very fast speed . In the second, you will contract over and over again against a strap that prevents your knee and lower leg from moving. You will also be asked to complete a whole body X-ray called a DXA scan . You will lie on a table for a few minutes while the x-ray scans your entire body. Finally, we will place electrode pads on your leg muscles and run an electrical current into the muscle to make it contract without you "asking" it to so. The current will be applied for less than a second and while you will feel it, it should not be painful..

WHY MIGHT I WANT TO PARTICIPATE IN THIS STUDY?

If you agree to take part in this study, there may not be direct medical benefit to you. You will gain a better understanding of your fatiguability and individual skeletal muscle characteristics.

WHY MIGHT I NOT WANT TO PARTICIPATE IN THIS STUDY?

You may not want to participate in this study if you suffer from cardiometabolic or neuromuscular conditions that make exercise difficult. You may not want to participate in this study if you have suffered a physical injury within the last year, or if you cannot handle electrical stimulation to the muscle.

The researchers do not know all of the side effects that could happen. For a complete description of known risks, refer to the Detailed Information section of the consent form.

WHAT OTHER OPTIONS ARE THERE?
You may choose not to participate in this study.

Please talk to your regular doctor about these and other options.

HOW WILL PARTICIPATING IN THE STUDY AFFECT ME FINANCIALLY?
There is no additional cost to you if you participate in this study.

DETAILED INFORMATION ABOUT THE RESEARCH STUDY

The following pages of the consent form will provide you with more information about this study. Please take your time in reviewing this information and ask the investigator and study team any questions you may have.

HOW MANY PEOPLE WILL TAKE PART IN THE STUDY?
About *40* people will take part in this study

WHAT IS INVOLVED IN THE STUDY?

Visit 1
At Visit 1, we will go over the consent form and answer any questions you have. You will fill out a a short PAR-Q form about your health and your usual physical activity. After you agree to participate, we will measure how your right thigh muscles work. We will measure: (1) how strong you can kick, (2) how fast you can reach your strongest kick, (3) how quickly your muscles relax after a kick, and (4) how your muscles respond to quick electrical pulses. To do this, we will place small sticky pads (electrodes) on your right leg. One sticky pad will be placed above your kneecap and one near the top of the thigh. If leg hair makes it hard for the pads to stick, we may need to shave a small area.

Next, you will do an exercise task with 50 very hard kicks using your thigh muscles. The speed of the movement will stay the same each time. After that, we will teach you how to do the strength and fatigue tests. Fatigue means your muscles cannot make the same force they could earlier. By having you push as hard as you can several times, we can see how your muscles tire. This visit will take about 30-45 minutes.

Visit 2

Visit 2 includes a DXA scan and fatigue test. A DXA scan is a special, low-dose X-ray that takes a picture of your whole body. You will wear light clothing and take off your shoes for the scan. If you are female, you will take a pregnancy test first to make sure you are not pregnant.

After the DXA scan, you will do three maximum kicks using your right thigh. Then you will do 60 kicks where you press against a lever as hard as you can, but the lever will not move. During this test, we will again use quick electrical pulses to help us understand how your muscles are working. This visit will take about 30-45 minutes.

Visit 3

Visit 3 repeats the same exercise from Visit 1: 50 very hard kicks with the same movement speed each time. This visit will take about 15-20 minutes.

If you take part in this study, you will have the following tests and procedures:

Procedures that are being tested in this study will be:

- Muscle Properties using electrical signals will be measured once on Visit 1
- Constant-speed Fatigue Task on Visit(s) 1 and 3
- DXA scan on Visit 2
- Maximal Strength test on Visit 2
- Constant-lever Fatigue Task on Visit 2
- Electrical Signals delivered throughout the Constant-length Fatigue Task in Visit 2

All procedures will take place at the Department of Health and Exercise Science at the University of Oklahoma

WHAT ARE THE RISKS OF THE STUDY?

As with any physical activity, there is a small risk of physical injury by participating in this study.
If you participate in this research, you will be exposed to radiation from a DXA scan (a type of x-ray). The amount of radiation you will receive from one DXA scan is approximately less than 1% of the amount of radiation that we are exposed to each year from natural background sources of radiation. The risk of radiation exposure is cumulative over your lifetime. Due to this exposure to radiation women who are pregnant (as determined by a urine pregnancy test) will be excluded from the study.

In addition to the risks described in the Key Information section, you may also be at risk for these side effects:

- Discomfort, or soreness, during or in the days following participation in the study

For more information about risks and side effects, ask the researcher

TO WHAT EXTENT WILL MY INFORMATION BE KEPT CONFIDENTIAL?

Efforts will be made to keep your personal information confidential. You will not be identifiable by name or description in any reports or publications about this study. We cannot guarantee absolute confidentiality. Your personal information may be disclosed if required by law. You will be asked to sign a separate authorization form for use or sharing of your protected health information.

There are organizations outside the OUHSC that may inspect and/or copy your research records for quality assurance and data analysis. These organizations may include the US Food & Drug Administration and other regulatory agencies. The OUHSC Human Research Participant Program office, the OUHSC Institutional Review Board, OUHSC Office of Compliance, and other University administrative offices may also inspect and/or copy your research records for these purposes.

Storing and Sharing Your Information:
Your data/measurements may be used for future studies without your additional consent. We will remove direct identifiers from your data/measurements and assign a code. The key to this code will be kept separately and only the researcher for this study will have access to the code. If your data/measurements is shared with another investigator for research purposes, they will not have access to the key code and will not be able to re-identify you.

CAN I WITHDRAW FROM THE STUDY?
You can stop participating in this study at any time. However, if you decide to stop participating in the study, we encourage you to talk to the researcher first.

There may be circumstances under which your participation may be terminated by the investigator without your consent.

Examples:
- [He/She] feels that it is in your medical best interest.
- Your condition worsens.
- New information becomes available.
- You fail to follow study requirements.

WHAT IF I AM INJURED OR BECOME ILL WHILE PARTICIPATING IN THIS STUDY?
In the case of injury or illness results from this study, emergency medical treatment is available. If symptoms are not resolved in what the research team deems a reasonable time period then medical advice or assistance may be sought from the Goddard Health Center (405-325-4611) or by calling 911 if the research team deems it necessary.
The sponsor will reimburse your reasonable and necessary medical costs for diagnosis and treatment for a research-related illness or injury if the illness or injury:

- is a result of device being studied;
- is not the sole result of the investigator's failure to follow the study plan;
- is not the sole result of negligence of the investigator, the University, or a University employee.

Complications arising as a result of the natural progression of an underlying or pre-existing condition may be billed to you or your insurance. Please check with the investigator or with your insurance company if you have questions.

No other funds have been set aside by the University of Oklahoma Health Sciences Center, you or your insurance may be charged to compensate you in the event of injury, illness, or for other damages related to your event of injury or illness.

Complications arising as a result of the natural progression of an underlying or pre-existing condition will be billed to you or your insurance. Please check with the investigator or with your insurance company if you have questions.

WHAT ARE MY RIGHTS AS A PARTICIPANT?
Taking part in this study is voluntary. You may choose not to participate. Refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled.

If you agree to participate and then decide against it, you can withdraw for any reason and leave the study at any time. However, at certain times during the treatment, it may be harmful for you to withdraw, so please be sure to discuss leaving the study with the principal investigator or your regular doctor. You may discontinue your participation at any time without penalty or loss of benefits to which you are otherwise entitled.

We will provide you with any significant new findings developed during the course of the research that may affect your health, welfare, or willingness to continue your participation in this study.

You have the right to access the medical information that has been collected about you as a part of this research study. However, you may not have access to this medical information until the entire research study has completely finished. You consent to this temporary restriction.

Results of research testing on your sample will be returned to you if asked.

WHOM DO I CALL IF I HAVE QUESTIONS, SUGGESTIONS, OR CONCERNS?
If you have questions, concerns, or complaints about the study or have a research-related injury, contact **Dr. Christopher Black** at 706-255-3750

If you cannot reach the Investigator or wish to speak to someone other than the investigator and for questions about your rights as a research participant, contact the OUHSC Director, Office of Human Research Participant Protection, at 405-271-2045.

SIGNATURE:

By signing this form, you are agreeing to participate in this research study under the conditions described. You have not given up any of your legal rights or released any individual or entity from liability for negligence. You have been given an opportunity to ask questions. You will be given a copy of this consent document.

I agree to participate in this study:

_____	_____	_____
PARTICIPANT SIGNATURE (age ≥18)	**Printed Name**	**Date**
_____	_____	_____
SIGNATURE OF PERSON OBTAINING CONSENT	**Printed Name**	**Date**

APPENDIX C: HIPPA FORM

AUTHORIZATION TO USE or SHARE
HEALTH INFORMATION[1] THAT IDENTIFIES YOU FOR RESEARCH
An Informed Consent Document for Research Participation may also be required.

Title of Research Project: **Relationship Among Muscle Mass, Contractile Properties, and Critical Torque**

Leader of Research Team: **Dr. Christopher Black**

Address: **[Department of Health and Exercise Science, 1401 Asp Avenue, S.J. Sarkeys Complex, Norman, OK 73019]**

Phone Number: **706-255-3750**

If you decide to sign this document, University of Oklahoma Health Sciences Center (OUHSC) researchers may use or share information that identifies you (protected health information) for their research. Protected health information will be called PHI in this document.

PHI To Be Used or Shared. Federal law requires that researchers get your permission (authorization) to use or share your PHI. If you give permission, the researchers may use or share with the people identified in this Authorization any PHI related to this research from your medical records and from any test results. Information used or shared may include all information relating to any tests, procedures, surveys, or interviews as outlined in the consent form; medical records and charts; name, address, telephone number, date of birth, race, government-issued identification numbers, and email address].

Purposes for Using or Sharing PHI. If you give permission, the researchers will use your PHI to [include in possible future research. Direct identifiers will be removed.]

Other Use and Sharing of PHI. If you give permission, the researchers may also use your PHI to develop new procedures or commercial products. They may share your PHI with other researchers, the research sponsor and its agents, the OUHSC Institutional Review Board, auditors and inspectors who check the research, and government agencies such as the Food and Drug Administration (FDA) and the Department of Health and Human Services (HHS), and when required by law. The researchers may also share your PHI with [list all such persons or groups, including collaborating researchers or teams at other institutions, as well as family members or other groups]

Confidentiality. Although the researchers may report their findings in scientific journals or meetings, they will not identify you in their reports. The researchers will try to keep your information confidential, but confidentiality is not guaranteed. The law does not require everyone receiving the information covered by this document to keep it confidential, so they could release it to others, and federal law may no longer protect it.

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[1] Protected Health Information includes all identifiable information relating to any aspect of an individual's health whether past, present or future, created or maintained by a Covered Entity.

Voluntary Choice. The choice to give OUHSC researchers permission to use or share your PHI for their research is voluntary. It is completely up to you. No one can force you to give permission. However, you must give permission for OUHSC researchers to use or share your PHI if you want to participate in the research and, if you cancel your authorization, you can no longer participate in this study.

Refusing to give permission will not affect your ability to get routine treatment or health care unrelated to this study from OUHSC.

Canceling Permission. If you give the OUHSC researchers permission to use or share your PHI, you have a right to cancel your permission whenever you want. However, canceling your permission will not apply to information that the researchers have already used, relied on, or shared, or to information necessary to maintain the reliability or integrity of this research.

End of Permission. Unless you cancel it, permission for OUHSC researchers to use or share your PHI for their research will never end.]

Contacting OUHSC: You may find out if your PHI has been shared, get a copy of your PHI, or cancel your permission at any time by writing to:

Privacy Official University of Oklahoma Health Sciences Center PO Box 26901 Oklahoma City, OK 73190	or	Privacy Board University of Oklahoma Health Sciences Center PO Box 26901 Oklahoma City, OK 73190

If you have questions, call: (405) 271-2511 or (405) 271-2045.

Access to Information. You have the right to access the medical information that has been collected about you as a part of this research study. However, you may not have access to this medical information until the entire research study is completely finished. You consent to this temporary restriction.

Giving Permission. By signing this form, you give OUHSC and OUHSC's researchers led by the Research Team Leader, permission to share your PHI for the research project listed at the top of this form.

Patient/Participant Name (Print): _____

_____ _____
Signature of Patient-Participant Date
(or Parent if participant is a minor)

Or

_____ _____
Signature of Legal Representative** Date

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Version 08/20/2024

IRB NUMBER: 19245
IRB APPROVAL DATE: 01/12/2026

**If signed by a Legal Representative of the Patient-Participant, provide a description of the relationship to the Patient-Participant and the authority to act as Legal Representative:

_____

OUHSC may ask you to produce evidence of your relationship.

A signed copy of this form must be given to the Patient-Participant or the Legal Representative at the time this signed form is provided to the researcher or his representative.

APPENDIX D: HEALTH STATUS QUESTIONNAIRE

Health Status Questionnaire

Part 1. Information about the individual

_____
Date

_____
Date of Last Physical Examination

6. Gender (circle one) Female Male

7. Age _____

8. Height _____ Weight_____

9. Do you smoke? Yes No

10. If you are a smoker, indicate number smoked per day:
Cigarettes: 40 or more 20-39 10-19 1-9
Cigars or pipes only: 5 or more or any inhaled Less than 5, none inhaled

11. Are you currently taking prescription or over-the-counter medication(s)? If so, please list the medication, daily dose, and why you are taking it.

_____
_____
_____

12. Are you currently taking any vitamins or nutritional supplements? If so, please list the vitamin/supplement, the daily dose, and why you are taking it.

_____
_____
_____

Part 2. Medical History

You have had or currently have any of the following:

History
___ A heart attack
___ Heart surgery
___ Cardiac catheterization
___ Coronary angioplasty (PTCA)
___ Pacemaker-implantable cardiac defibrillatory/ rhythm disturbance
___ Heart valve disease
___ Heart failure
___ Heart transplantation

IRB NUMBER: 19245
IRB APPROVAL DATE: 01/12/2026

___ Congenital heart disease
___ Peripheral arterial disease
___ Stoke

Signs/Symptoms
___ You experience discomfort and/or pain with exertion in the chest, neck, jaw, arms
___ You experience unreasonable breathlessness at rest or with mild exertion
___ You experience dizziness, fainting, or blackouts
___ You experience ankle edema
___ You experience heart palpitations or tachycardia (unpleasant awareness of force or rapid heart beats)
___ You have or experience intermittent claudication (muscle pain due to ischemia)
___ You have a heart murmur
___ You take medication(s) for ANY type of heart condition or high blood pressure

Other health issues
___ You have diabetes
___ You have a thyroid disorder
___ You have a renal (kidney) disorder
___ You have liver disease (e.g. cirrhosis)
___ You have COPD, asthma, cystic fibrosis or other lung disease
___ You have burning or cramping sensation in your lower legs when walking short distances
___ You have musculoskeletal problems that limit your physical activity (arthritis, etc.)
___ You are pregnant

Part III: Cardiovascular Risk Factors

Age
___ You are a man older than 45 years
___ You are a woman older than 55 years, have had a hysterectomy, or are postmenopausal

Medical/Lifestyle
___ You smoke, or quit smoking within the previous 6 months

___ A physician has ever said have high blood pressure (>140/90)?

___ A physician has said you have high cholesterol (Total >200 mg/dl or LDL cholesterol is >130 mg/dl)

___ You have a close blood relative who had a heart attack or heart surgery before age 55 (father or brother) or age 65 (mother or sister)

___ You are physically inactive (i.e., you get <30 minutes of physical activity 3 days per week)

___ You have impaired fasting glucose (> 100mg/dl) that has been confirmed by a doctor on two separate occasions

___ Your BMI is >30 **BMI**_____

I understand my signature signifies that I have read and understand all the information on the questionnaire, that I have truthfully answered all the questions, and that any questions/concerns I may have had have been addressed to my complete satisfaction.

Name (please print)_____

Signature _____Date _____

APPENDIX E: IPAQ

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE (October 2002)

LONG LAST 7 DAYS SELF-ADMINISTERED FORMAT

FOR USE WITH YOUNG AND MIDDLE-AGED ADULTS (15-69 years)

The International Physical Activity Questionnaires (IPAQ) comprises a set of 4 questionnaires. Long (5 activity domains asked independently) and short (4 generic items) versions for use by either telephone or self-administered methods are available. The purpose of the questionnaires is to provide common instruments that can be used to obtain internationally comparable data on health–related physical activity.

Background on IPAQ

The development of an international measure for physical activity commenced in Geneva in 1998 and was followed by extensive reliability and validity testing undertaken across 12 countries (14 sites) during 2000. The final results suggest that these measures have acceptable measurement properties for use in many settings and in different languages, and are suitable for national population-based prevalence studies of participation in physical activity.

Using IPAQ

Use of the IPAQ instruments for monitoring and research purposes is encouraged. It is recommended that no changes be made to the order or wording of the questions as this will affect the psychometric properties of the instruments.

Translation from English and Cultural Adaptation

Translation from English is encouraged to facilitate worldwide use of IPAQ. Information on the availability of IPAQ in different languages can be obtained at www.ipaq.ki.se. If a new translation is undertaken we highly recommend using the prescribed back translation methods available on the IPAQ website. If possible please consider making your translated version of IPAQ available to others by contributing it to the IPAQ website. Further details on translation and cultural adaptation can be downloaded from the website.

Further Developments of IPAQ

International collaboration on IPAQ is on-going and an ***International Physical Activity Prevalence Study*** is in progress. For further information see the IPAQ website.

More Information

More detailed information on the IPAQ process and the research methods used in the development of IPAQ instruments is available at www.ipaq.ki.se and Booth, M.L. (2000). *Assessment of Physical Activity: An International Perspective.* Research Quarterly for Exercise and Sport, 71 (2): s114-20. Other scientific publications and presentations on the use of IPAQ are summarized on the website.

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the **last 7 days**. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the **vigorous** and **moderate** activities that you did in the **last 7 days**. **Vigorous** physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. **Moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal.

PART 1: JOB-RELATED PHYSICAL ACTIVITY

The first section is about your work. This includes paid jobs, farming, volunteer work, course work, and any other unpaid work that you did outside your home. Do not include unpaid work you might do around your home, like housework, yard work, general maintenance, and caring for your family. These are asked in Part 3.

1. Do you currently have a job or do any unpaid work outside your home?

   ☐ Yes

   ☐ No → ***Skip to PART 2: TRANSPORTATION***

The next questions are about all the physical activity you did in the **last 7 days** as part of your paid or unpaid work. This does not include traveling to and from work.

2. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, digging, heavy construction, or climbing up stairs **as part of your work**? Think about only those physical activities that you did for at least 10 minutes at a time.

   _____ **days per week**

   ☐ No vigorous job-related physical activity → ***Skip to question 4***

3. How much time did you usually spend on one of those days doing **vigorous** physical activities as part of your work?

   _____ **hours per day**
   _____ **minutes per day**

4. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** physical activities like carrying light loads **as part of your work**? Please do not include walking.

   _____ **days per week**

   ☐ No moderate job-related physical activity → ***Skip to question 6***

5. How much time did you usually spend on one of those days doing **moderate** physical activities as part of your work?

_____ **hours per day**
_____ **minutes per day**

6. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time **as part of your work**? Please do not count any walking you did to travel to or from work.

_____ **days per week**

☐ No job-related walking → ***Skip to PART 2: TRANSPORTATION***

7. How much time did you usually spend on one of those days **walking** as part of your work?

_____ **hours per day**
_____ **minutes per day**

PART 2: TRANSPORTATION PHYSICAL ACTIVITY

These questions are about how you traveled from place to place, including to places like work, stores, movies, and so on.

8. During the **last 7 days**, on how many days did you **travel in a motor vehicle** like a train, bus, car, or tram?

_____ **days per week**

☐ No traveling in a motor vehicle → ***Skip to question 10***

9. How much time did you usually spend on one of those days **traveling** in a train, bus, car, tram, or other kind of motor vehicle?

_____ **hours per day**
_____ **minutes per day**

Now think only about the **bicycling** and **walking** you might have done to travel to and from work, to do errands, or to go from place to place.

10. During the **last 7 days**, on how many days did you **bicycle** for at least 10 minutes at a time to go **from place to place**?

_____ **days per week**

☐ No bicycling from place to place → ***Skip to question 12***

11. How much time did you usually spend on one of those days to **bicycle** from place to place?

_____ **hours per day**
_____ **minutes per day**

12. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time to go **from place to place**?

_____ **days per week**

☐ No walking from place to place → ***Skip to PART 3: HOUSEWORK, HOUSE MAINTENANCE, AND CARING FOR FAMILY***

13. How much time did you usually spend on one of those days **walking** from place to place?

_____ **hours per day**
_____ **minutes per day**

PART 3: HOUSEWORK, HOUSE MAINTENANCE, AND CARING FOR FAMILY

This section is about some of the physical activities you might have done in the **last 7 days** in and around your home, like housework, gardening, yard work, general maintenance work, and caring for your family.

14. Think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, chopping wood, shoveling snow, or digging **in the garden or yard**?

_____ **days per week**

☐ No vigorous activity in garden or yard → ***Skip to question 16***

15. How much time did you usually spend on one of those days doing **vigorous** physical activities in the garden or yard?

_____ **hours per day**
_____ **minutes per day**

16. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** activities like carrying light loads, sweeping, washing windows, and raking **in the garden or yard**?

_____ **days per week**

☐ No moderate activity in garden or yard → ***Skip to question 18***

17. How much time did you usually spend on one of those days doing **moderate** physical activities in the garden or yard?

_____ **hours per day**
_____ **minutes per day**

18. Once again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** activities like carrying light loads, washing windows, scrubbing floors and sweeping **inside your home**?

_____ **days per week**

☐ No moderate activity inside home → ***Skip to PART 4: RECREATION, SPORT AND LEISURE-TIME PHYSICAL ACTIVITY***

19. How much time did you usually spend on one of those days doing **moderate** physical activities inside your home?

_____ **hours per day**
_____ **minutes per day**

PART 4: RECREATION, SPORT, AND LEISURE-TIME PHYSICAL ACTIVITY

This section is about all the physical activities that you did in the **last 7 days** solely for recreation, sport, exercise or leisure. Please do not include any activities you have already mentioned.

20. Not counting any walking you have already mentioned, during the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time **in your leisure time**?

_____ **days per week**

☐ No walking in leisure time → ***Skip to question 22***

21. How much time did you usually spend on one of those days **walking** in your leisure time?

_____ **hours per day**
_____ **minutes per day**

22. Think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **vigorous** physical activities like aerobics, running, fast bicycling, or fast swimming **in your leisure time**?

_____ **days per week**

☐ No vigorous activity in leisure time → ***Skip to question 24***

23. How much time did you usually spend on one of those days doing **vigorous** physical activities in your leisure time?

_____ **hours per day**
_____ **minutes per day**

24. Again, think about only those physical activities that you did for at least 10 minutes at a time. During the **last 7 days**, on how many days did you do **moderate** physical activities like bicycling at a regular pace, swimming at a regular pace, and doubles tennis **in your leisure time**?

_____ **days per week**

☐ No moderate activity in leisure time → ***Skip to PART 5: TIME SPENT SITTING***

25. How much time did you usually spend on one of those days doing **moderate** physical activities in your leisure time?
_____ **hours per day**
_____ **minutes per day**

PART 5: TIME SPENT SITTING

The last questions are about the time you spend sitting while at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading or sitting or lying down to watch television. Do not include any time spent sitting in a motor vehicle that you have already told me about.

26. During the **last 7 days**, how much time did you usually spend **sitting** on a **weekday**?

_____ **hours per day**
_____ **minutes per day**

27. During the **last 7 days**, how much time did you usually spend **sitting** on a **weekend day**?

_____ **hours per day**
_____ **minutes per day**

This is the end of the questionnaire, thank you for participating.

APPENDIX F: PAR-Q

2023 PAR-Q+

The Physical Activity Readiness Questionnaire for Everyone

The health benefits of regular physical activity are clear; more people should engage in physical activity every day of the week. Participating in physical activity is very safe for MOST people. This questionnaire will tell you whether it is necessary for you to seek further advice from your doctor OR a qualified exercise professional before becoming more physically active.

GENERAL HEALTH QUESTIONS

Please read the 7 questions below carefully and answer each one honestly: check YES or NO.	YES	NO
1) Has your doctor ever said that you have a heart condition ☐ **OR** high blood pressure ☐?	☐	☐
2) Do you feel pain in your chest at rest, during your daily activities of living, **OR** when you do physical activity?	☐	☐
3) Do you lose balance because of dizziness **OR** have you lost consciousness in the last 12 months? Please answer **NO** if your dizziness was associated with over-breathing (including during vigorous exercise).	☐	☐
4) Have you ever been diagnosed with another chronic medical condition (other than heart disease or high blood pressure)? **PLEASE LIST CONDITION(S) HERE:** _____	☐	☐
5) Are you currently taking prescribed medications for a chronic medical condition? **PLEASE LIST CONDITION(S) AND MEDICATIONS HERE:** _____	☐	☐
6) Do you currently have (or have had within the past 12 months) a bone, joint, or soft tissue (muscle, ligament, or tendon) problem that could be made worse by becoming more physically active? Please answer **NO** if you had a problem in the past, but it **does not limit your current ability** to be physically active. **PLEASE LIST CONDITION(S) HERE:** _____	☐	☐
7) Has your doctor ever said that you should only do medically supervised physical activity?	☐	☐

If you answered NO to all of the questions above, you are cleared for physical activity.
Please sign the PARTICIPANT DECLARATION. You do not need to complete Pages 2 and 3.

- Start becoming much more physically active – start slowly and build up gradually.
- Follow Global Physical Activity Guidelines for your age (https://www.who.int/publications/i/item/9789240015128).
- You may take part in a health and fitness appraisal.
- If you are over the age of 45 yr and NOT accustomed to regular vigorous to maximal effort exercise, consult a qualified exercise professional before engaging in this intensity of exercise.
- If you have any further questions, contact a qualified exercise professional.

PARTICIPANT DECLARATION

If you are less than the legal age required for consent or require the assent of a care provider, your parent, guardian or care provider must also sign this form.

I, the undersigned, have read, understood to my full satisfaction and completed this questionnaire. I acknowledge that this physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if my condition changes. I also acknowledge that the community/fitness center may retain a copy of this form for its records. In these instances, it will maintain the confidentiality of the same, complying with applicable law.

NAME _____ DATE _____

SIGNATURE _____ WITNESS _____

SIGNATURE OF PARENT/GUARDIAN/CARE PROVIDER _____

If you answered YES to one or more of the questions above, COMPLETE PAGES 2 AND 3.

Delay becoming more active if:

- You have a temporary illness such as a cold or fever; it is best to wait until you feel better.
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the ePARmed-X+ at www.epafmedx.com before becoming more physically active.
- Your health changes - answer the questions on Pages 2 and 3 of this document and/or talk to your [illegible] professional before continuing with any physical activity program.

01-11-2022

2023 PAR-Q+

FOLLOW-UP QUESTIONS ABOUT YOUR MEDICAL CONDITION(S)

1. Do you have Arthritis, Osteoporosis, or Back Problems?

If the above condition(s) is/are present, answer questions 1a-1c — If **NO** ☐ go to question 2

1a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
1b.	Do you have joint problems causing pain, a recent fracture or fracture caused by osteoporosis or cancer, displaced vertebra (e.g., spondylolisthesis), and/or spondylolysis/pars defect (a crack in the bony ring on the back of the spinal column)?	YES ☐ NO ☐
1c.	Have you had steroid injections or taken steroid tablets regularly for more than 3 months?	YES ☐ NO ☐

2. Do you currently have Cancer of any kind?

If the above condition(s) is/are present, answer questions 2a-2b — If **NO** ☐ go to question 3

2a.	Does your cancer diagnosis include any of the following types: lung/bronchogenic, multiple myeloma (cancer of plasma cells), head, and/or neck?	YES ☐ NO ☐
2b.	Are you currently receiving cancer therapy (such as chemotheraphy or radiotherapy)?	YES ☐ NO ☐

3. Do you have a Heart or Cardiovascular Condition? This includes Coronary Artery Disease, Heart Failure, Diagnosed Abnormality of Heart Rhythm

If the above condition(s) is/are present, answer questions 3a-3d — If **NO** ☐ go to question 4

3a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
3b.	Do you have an irregular heart beat that requires medical management? (e.g., atrial fibrillation, premature ventricular contraction)	YES ☐ NO ☐
3c.	Do you have chronic heart failure?	YES ☐ NO ☐
3d.	Do you have diagnosed coronary artery (cardiovascular) disease and have not participated in regular physical activity in the last 2 months?	YES ☐ NO ☐

4. Do you currently have High Blood Pressure?

If the above condition(s) is/are present, answer questions 4a-4b — If **NO** ☐ go to question 5

4a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
4b.	Do you have a resting blood pressure equal to or greater than 160/90 mmHg with or without medication? (Answer **YES** if you do not know your resting blood pressure)	YES ☐ NO ☐

5. Do you have any Metabolic Conditions? This includes Type 1 Diabetes, Type 2 Diabetes, Pre-Diabetes

If the above condition(s) is/are present, answer questions 5a-5e — If **NO** ☐ go to question 6

5a.	Do you often have difficulty controlling your blood sugar levels with foods, medications, or other physician-prescribed therapies?	YES ☐ NO ☐
5b.	Do you often suffer from signs and symptoms of low blood sugar (hypoglycemia) following exercise and/or during activities of daily living? Signs of hypoglycemia may include shakiness, nervousness, unusual irritability, abnormal sweating, dizziness or light-headedness, mental confusion, difficulty speaking, weakness, or sleepiness.	YES ☐ NO ☐
5c.	Do you have any signs or symptoms of diabetes complications such as heart or vascular disease and/or complications affecting your eyes, kidneys, **OR** the sensation in your toes and feet?	YES ☐ NO ☐
5d.	Do you have other metabolic conditions (such as current pregnancy-related diabetes, chronic kidney disease, or liver problems)?	YES ☐ NO ☐
5e.	Are you planning to engage in what for you is unusually high (or vigorous) intensity exercise in the near future?	YES ☐ NO ☐

IRB NUMBER: 19245
IRB APPROVAL DATE: 01/12/2026

01-11-2022

2023 PAR-Q+

6. Do you have any Mental Health Problems or Learning Difficulties? This includes Alzheimer's, Dementia, Depression, Anxiety Disorder, Eating Disorder, Psychotic Disorder, Intellectual Disability, Down Syndrome

If the above condition(s) is/are present, answer questions 6a-6b If **NO** ☐ go to question 7

6a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
6b.	Do you have Down Syndrome **AND** back problems affecting nerves or muscles?	YES ☐ NO ☐

7. Do you have a Respiratory Disease? *This includes Chronic Obstructive Pulmonary Disease, Asthma, Pulmonary High Blood Pressure*

If the above condition(s) is/are present, answer questions 7a-7d If **NO** ☐ go to question 8

7a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
7b.	Has your doctor ever said your blood oxygen level is low at rest or during exercise and/or that you require supplemental oxygen therapy?	YES ☐ NO ☐
7c.	If asthmatic, do you currently have symptoms of chest tightness, wheezing, laboured breathing, consistent cough (more than 2 days/week), or have you used your rescue medication more than twice in the last week?	YES ☐ NO ☐
7d.	Has your doctor ever said you have high blood pressure in the blood vessels of your lungs?	YES ☐ NO ☐

8. Do you have a Spinal Cord Injury? *This includes Tetraplegia and Paraplegia*

If the above condition(s) is/are present, answer questions 8a-8c If **NO** ☐ go to question 9

8a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
8b.	Do you commonly exhibit low resting blood pressure significant enough to cause dizziness, light-headedness, and/or fainting?	YES ☐ NO ☐
8c.	Has your physician indicated that you exhibit sudden bouts of high blood pressure (known as Autonomic Dysreflexia)?	YES ☐ NO ☐

9. Have you had a Stroke? *This includes Transient Ischemic Attack (TIA) or Cerebrovascular Event*

If the above condition(s) is/are present, answer questions 9a-9c If **NO** ☐ go to question 10

9a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
9b.	Do you have any impairment in walking or mobility?	YES ☐ NO ☐
9c.	Have you experienced a stroke or impairment in nerves or muscles in the past 6 months?	YES ☐ NO ☐

10. Do you have any other medical condition not listed above or do you have two or more medical conditions?

If you have other medical conditions, answer questions 10a-10c If **NO** ☐ read the Page 4 recommendations

10a.	Have you experienced a blackout, fainted, or lost consciousness as a result of a head injury within the last 12 months **OR** have you had a diagnosed concussion within the last 12 months?	YES ☐ NO ☐
10b.	Do you have a medical condition that is not listed (such as epilepsy, neurological conditions, kidney problems)?	YES ☐ NO ☐
10c.	Do you currently live with two or more medical conditions?	YES ☐ NO ☐

PLEASE LIST YOUR MEDICAL CONDITION(S) AND ANY RELATED MEDICATIONS HERE: _____

GO to Page 4 for recommendations about your current medical condition(s) and sign the PARTICIPANT DECLARATION.

01-11-2022

2023 PAR-Q+

If you answered NO to all of the FOLLOW-UP questions (pgs. 2-3) about your medical condition, you are ready to become more physically active - sign the PARTICIPANT DECLARATION below:

- It is advised that you consult a qualified exercise professional to help you develop a safe and effective physical activity plan to meet your health needs.
- You are encouraged to start slowly and build up gradually - 20 to 60 minutes of low to moderate intensity exercise, 3-5 days per week including aerobic and muscle strengthening exercises.
- As you progress, you should aim to accumulate 150 minutes or more of moderate intensity physical activity per week.
- If you are over the age of 45 yr and **NOT** accustomed to regular vigorous to maximal effort exercise, consult a qualified exercise professional before engaging in this intensity of exercise.

If you answered **YES** to **one or more of the follow-up questions** about your medical condition:

You should seek further information before becoming more physically active or engaging in a fitness appraisal. You should complete the specially designed online screening and exercise recommendations program - the **ePARmed-X+ at www.eparmedx.com** and/or visit a qualified exercise professional to work through the ePARmed-X+ and for further information.

Delay becoming more active if:

- You have a temporary illness such as a cold or fever; it is best to wait until you feel better.
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the ePARmed-X+ **at www.eparmedx.com** before becoming more physically active.
- Your health changes - talk to your doctor or qualified exercise professional before continuing with any physical activity program.

- You are encouraged to photocopy the PAR-Q+. You must use the entire questionnaire and NO changes are permitted.
- The authors, the PAR-Q+ Collaboration, partner organizations, and their agents assume no liability for persons who undertake physical activity and/or make use of the PAR-Q+ or ePARmed-X+. If in doubt after completing the questionnaire, consult your doctor prior to physical activity.

PARTICIPANT DECLARATION

- All persons who have completed the PAR-Q+ please read and sign the declaration below.
- If you are less than the legal age required for consent or require the assent of a care provider, your parent, guardian or care provider must also sign this form.

I, the undersigned, have read, understood to my full satisfaction and completed this questionnaire. I acknowledge that this physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if my condition changes. I also acknowledge that the community/fitness center may retain a copy of this form for records. In these instances, it will maintain the confidentiality of the same, complying with applicable law.

NAME _____ DATE _____

SIGNATURE _____ WITNESS _____

SIGNATURE OF PARENT/GUARDIAN/CARE PROVIDER _____

For more information, please contact

www.eparmedx.com
Email: eparmedx@gmail.com

Citation for PAR-Q+
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The PAR-Q+ was created using the evidence-based AGREE process (1) by the PAR-Q+ Collaboration chaired by Dr. Darren E. R. Warburton with Dr. Norman Gledhill, Dr. Veronica Jamnik, and Dr. Donald C. McKenzie (2). Production of this document has been made possible through financial contributions from the Public Health Agency of Canada and the BC Ministry of Health Services. The views expressed herein do not necessarily represent the views of the Public Health Agency of Canada or the BC Ministry of Health Services.

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IRB NUMBER: 19245
IRB APPROVAL DATE: 01/12/2026

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01-11-2022

APPENDIX G: MENSTURAL HISTORY QUESTIONNAIRE

Department of Health and Exercise Science
University of Oklahoma

MENSTRUAL HISTORY QUESTIONNAIRE

Participant ID:_____Date:_____

We are asking you to give us as complete a menstrual history as possible. All information is strictly confidential.

Are you pregnant (circle your response)

YES- Do not complete the rest of this form
NO- Continue to section A.

SECTION A: CURRENT MENSTRUAL STATUS

1. Approximately how many menstrual periods have you had during the past 12 months?
   (please circle what months you have had a period. This means from this time last year to the present month)

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

2. What is the usual length of your menstrual cycle (first day of your period to the next onset of your period)?

   _____days. Today is day _____ of your present menstrual cycle.

3. When was the date of the onset of your last period?

4. When do you expect your next period?

5. What is the average length (number of days) of your menstrual flow? _____ days

   How many of these days do you consider "heavy"?_____days

6. Do you take oral contraceptives or any other medication that includes estrogen and/or progesterone?

   If yes, how long have you been taking this medication?_____

   What is the brand name and dosage of this mediation?_____

Has this medication affected your menstrual cycle (regularity, length and amount of flow)? If yes, indicate changes.