AGE-RELATED EFFECTS OF NEUROMUSCULAR FATIGUE AND RECOVERY ON VOLUNTARY MAXIMAL AND RAPID TORQUE CHARACTERISTICS OF THE LEG FLEXORS AND EXTENSORS IN YOUNG AND OLD MEN

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Abstract: The purpose of the present study was to examine the effects of acute neuromuscular fatigue and recovery on maximal and rapid torque characteristics in young and old men for the knee extensors and flexors. Twenty-one young (mean±SD:age=24.76 years) and nineteen old (age=72.05±3.60 years) men performed maximal voluntary contractions (MVCs) prior to performing a fatigue-inducing bout of sub-maximal, intermittent isometric contractions using a .6 duty cycle at 60% of MVC until volitional fatigue. MVCs were then performed again at immediately after, 7, 15, and 30min following the completion of the fatigue task. Endurance time was the elapsed time from onset until failure during the course of the fatigue protocol. Maximal (peak torque; PT) and rapid (absolute and relative rate of force development; RFD and nRFD, respectively) torque characteristics were calculated from the torque-time curves for each time period. Three-way mixed factorial ANOVAs (muscle [knee extensors vs leg flexors] × age [young vs old men] × time period [Pre vs Post vs Recovery 7 vs Recovery15, vs Recovery30) were used to analyze all maximal and rapid torque variables. The present findings revealed that older men had greater overall endurance times compared to young men. No differences were observed in the fatigue-induced reductions immediately following the fatigue task for the absolute rapid force characteristics among early and late phases of the torque-time curve, muscles, and age groups. However, differential recovery patterns were observed for PT, and early and late RTD phases between the knee extensor and flexor muscle groups such that the early rapid torque variables (RTD30 and RTD50) and the knee flexors demonstrated slower recovery compared to later rapid torque variables (>RFD100) and the knee extensors. The normalized RTD variables declined to a lesser extent following the fatigue task and differential muscle and group effects were observed where the knee flexors were reduced more at the early phase (nRTD1/6) compared to the knee extensors, however, for the later phase (nRTD2/3) the young men exhibited a significantly greater reduction compared to the old men. These findings may have important fatigue related performance, and injury risk implications for a variety of populations and settings.

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CHAPTER I

INTRODUCTION

Fatigue may be defined as the occurrence of 'any exercise-induced reduction in the maximal capacity to generate force or power output'[1]. However, our understanding of fatigue is far from complete[1-4] and despite its integral importance and universal implications pertaining to a variety of human performance activities, settings and populations, we have limited conclusive evidence, leaving much to be determined. Although many studies have examined fatigue, most have yielded disparate findings in terms of physiological responses, patterns, processes, mechanisms and applications. These contrasting findings are likely a result of the variety of fatigue protocols used, assessment methods, muscle groups, equipment and populations used by researchers as well as the physiological complexity underlying human fatigue mechanisms and performance across a nearly infinite number of movement activities, durations and settings available in the vast range of potential human movement tasks[1]. Understanding these collective attributes of fatigue is inherently difficult because of the complexity underlying fatigue, given it may occur at any number of locations along the supra-spinal to muscle contractile component pathway. Additional factors such as metabolic, thermoregulatory, hormonal, or the range of types of movement activities/patterns and durations substantially add to the complexity and difficulty of obtaining understanding, applying and revealing these processes.

Researchers primarily examine neuromuscular fatigue during and following maximal and sub-maximal muscular contractions in which the muscle or muscle groups produce force continuously or intermittently against an external load. These force related assessments are important indicators of fatigue as suggested by Vollestad[1] who stated the "reliable assessment of muscle fatigue is highly dependent upon measurement of the force generating capacity" (p. 221), which is most often and appropriately observed in the form of maximal voluntary isometric contractions (MVCs)[1].

Although the processes involved in fatigue and recovery are not completely understood, Miller et al.[5] suggested three recovery phases following fatigue, which provide insight relating to the nature of these processes and their reversal at various time periods, and suggest that multiple mechanisms contribute to fatigue induced impairments. These and other findings[5,6] demonstrate that in addition to a short term recovery period, a longer period of recovery is observed in neuromuscular fatigue, owing to excitation contraction coupling failure (EC-F), which is commonly referred to as low frequency fatigue (LFF). This form of fatigue is characterized by a preferential reduction of force output at lower (< 50 Hz) electrically stimulated frequencies relative to higher frequencies (>50 Hz). These findings suggest that both the magnitude of neuromuscular fatigue and the recovery toward pre-fatigue performance levels, may be of primary importance when evaluating the effects of fatigue on human performance. LFF may commonly occur in human muscles from a various forms of physical activities[7,8] that may typically be performed pertaining to activities of daily living (walking, gardening, etc.). Thus, intermittent sub-maximal contractions which are representative of the repetitive movements performed typically in many sport, occupational, and daily activities, may be more functionally relevant when compared to other types of fatiguing protocols (i.e., maximal sustained contractions)[2,9]. Because LFF entails a longer recovery period, this may further impact its functional significance pertaining to many typical human activities.

Maximal and rapid muscle force characteristics also have profound functional importance for human performances. These variables may be derived from an isometric torque-time curve obtained from a maximal voluntary contraction (MVC) and include peak torque (PT), which is a maximal torque characteristic, and rate of torque development (RTD) and contractile impulse (IMPULSE), which are rapid torque characteristics because they are rate dependent. These variables provide information pertaining to a muscle or muscle groups' capacity to develop both maximal and rapid torque production. Although maximal muscle force (i.e. strength) has been used extensively[10] as a measure of the capacity of muscle force production, many authors have suggested that rapid force variables may be more practically useful indicators to represent many human muscle performances[10-16]. The functional importance of rapid torque characteristics is based on the principle that many human performance activities require the attainment of high force in relatively short time periods. For example, many typical human performance activities such as running[17-20], jumping[18,19,21], throwing[19] and accelerating[19,22,23], involve movement durations lasting less than 250ms. Because of the relatively long durations that are required to attain maximal strength (>300ms)[12,24,25], rapid torque characteristics may provide a more sensitive representation of muscle function[26] pertaining to a variety of physical activities and settings.

Studies examining fatigue in elderly humans are relatively few when compared to the overall volume of fatigue literature, resulting in a lack of insight into fatigue processes across the life span. Previous studies examining fatigue in the elderly reveal mixed findings, with several studies suggesting no difference in fatigability between young and old adults while others reveal both lower and higher fatigue resistance[27]. As previously mentioned, these contrasting findings are likely a consequence of differences in fatigue inducing protocols, contraction type, muscle group differences etc. used across studies. It seems likely that age related physiological impairments would theoretically have negative consequences on neuromuscular fatigue resistance. For example, age related alterations in EC-F resulting in reductions of calcium supply to contractile proteins have been reported and would likely exacerbate LFF as a result of the relationship of this form of fatigue to EC-F[28]. However, in practice, previous authors have reported no age related deficits between young and older adults on the effects of fatigue on muscle performance[2,27] while other authors have suggested older adults may actually exhibit improved fatigue resistance capacities[29]. A paucity of studies relating to fatigue and aging makes interpretation of these findings difficult, and more studies are warranted to further elucidate the effects of fatigue across the life span.

Although a number of previous studies have examined the influence of fatigue on PT using a variety of muscle groups, few studies have investigated these effects on rapid torque characteristics. The effects of fatigue on rapid torque characteristics could have more negative functional consequences compared to maximal torque as rapid torque characteristics have been shown to decrease to a greater extent with aging compared to maximal torque[30] and are highly relevant in many functional fatigue inducing tasks (i.e. lifting, running, throwing, balance etc.). Further, no studies have evaluated the effects of neuromuscular fatigue and recovery specifically for the knee flexor muscle group (i.e. hamstrings) in a comparison of younger and older men. Fatigue characteristics of the knee flexors may have important implications and consequences for elderly individuals because of the contribution of this muscle group to functional daily activities and loco-motor related movements. Further, no studies have examined the differences between fatigue and muscle performance characteristics between opposing joint muscles, such as the primary loco-motor muscles of the leg. Given the loco-motor muscles of the anterior and posterior thigh have been suggested as having different structural[31-34], functional[31,35], and physiological[36] characteristics; these muscles may exhibit differential fatigue, recovery, and aging-related effects. Collectively, these conflicting findings and limited research on neuromuscular fatigue, aging, and maximal and rapid torque characteristics warrant further investigation to elucidate the interactions and effects of these critical human performance variables as they relate to the aging adult in the functionally important loco-motor muscle groups.

Statement of Purpose

The purpose of the present study was to examine and compare the effects of an acute fatigue-inducing bout of sub-maximal intermittent isometric contractions and the resulting neuromuscular fatigue and recovery on maximal and rapid torque characteristics of the knee extensors and flexors in young and older men.

Hypotheses

1. H_0: There will be no fatigue-induced differences between the effects of the maximal and rapid torque variables at immediately following nor during the recovery period.

   H_A: The rapid torque variables will be reduced to a greater extent than maximal torque immediately following fatigue and will also recover at a slower rate.
2. H_0: There will be no differences in the fatigue-induced effects on rapid torque variables between the young and old men at immediately after nor during the recovery period.

H_A: Older men will exhibit greater reductions in rapid torque variables compared to younger men and will also recover at a slower rate.

3. H_0: There will be no differences observed for the endurance times for the knee extensors or flexors between the young and old men due to the relative nature of the sub-maximal isometric fatigue protocol.

   H_A: The old men will exhibit greater endurance times for both the knee extensors and flexors.

4. H_0: No fatigue related differences will be observed between the knee extensors and flexors.

   H_A: Differential muscle group fatigue related effects will be observed such that the knee flexors will be affected to a greater extent than the knee extensors given their structural, functional and physiological differences.

Definitions

Isometric Muscle Contraction: A muscular contraction where no change in the length of the muscle or joint angle is observed.

Torque: The amount of force applied by the muscle multiplied by the moment arm of the muscle insertion point and axis of rotation of the joint.

Torque-Time Curve: A tracing of the magnitude of torque as a function of time during a muscular contraction.

Peak Torque: The maximal amount of torque attained during a muscle contraction, defined as the highest point on a torque-time curve.

Rapid Torque Variables: The variables derived from a torque-time curve that are time dependent. These include rate of force development, contractile impulse, and torque at specified (early) time intervals.

Endurance Time: Time elapsed from the onset of the fatigue protocol until the required force is no longer capable of being maintained at the specified level.

Delimitations

This study was delimited to convenience samples of participants between the ages of 21-29 and 66-75 years of age. Additionally, all participants were required to be male and recreationally active based on their response to a health history questionnaire. Participants were ineligible to participate in the study if they engaged in resistance training activities regularly (> 3 times per month) or had any recent (6 months) or ongoing neuromuscular or cardiovascular disorders, based on the initial health screening questionnaire. Participants will also be excluded from the study in the event that their physician has advised against muscular exertion or if they feel they are not capable of performing intermittent sub-maximal muscular exertion for ~5-15 minutes.

Assumptions

1. The samples are normally distributed and representative of their respective populations.

2. Participants' responses to the health history questionnaire were accurate and valid.

3. That all participants gave a maximal voluntary effort on all strength tests and maximal exertion on the fatigue protocol.

4. The equipment is appropriately calibrated and functioning properly.

5. That there are no data collection, data analyses, data entry or statistical processing errors.

6. The samples for the younger and older groups are similarly represented in terms of the population and their relative physical fitness levels when compared to the norms for their respective age groups.

Limitations

1. Differences in the activity levels of participants both between and within the groups may have an effect on the responses to the bout of fatigue and recovery periods.
2. A handheld goniometer was be used to measure the leg angle for all MVCs and the fatigue protocol and thus slight deviations in joint angle between subjects and trials may be present.
3. Differences in motivation levels between participants may produce varying levels of maximal exertion for MVC’s
4. Differences in motivation levels and pain tolerance between participants may produce varying levels of relative maximal effort/exertion for the fatigue protocol.

CHAPTER II

REVIEW OF LITERATURE

The purpose of this review of literature is to present, synthesize and integrate the available and pertinent research in the areas of isometric muscle torque and rapid torque characteristics pertaining to neuromuscular fatigue and the influence of aging on these parameters.

Isometric Muscle Function Testing

Isometric testing is commonly performed in laboratories, sports facilities, clinics and a variety of research settings as a means of muscle function assessment. Isometric muscle contractions are performed when participants exert a maximal or sub-maximal force against a resistance that is immovable[37], which consequently yields a muscle contraction in which no change in the length of the muscle occurs. These assessments are usually performed with devices that are equipped with a strain gauge such as a dynamometer, load cell, or force platform which allows for the measurement of the applied forces. This mode of muscular assessment is popular among researchers and clinicians due to the potential advantages of precision of measurement, high reliability and safety that isometric testing provides in a controlled laboratory or research setting[37,38]. Isometric testing has been widely utilized in the field of exercise science for the purpose of providing researchers and clinicians with a measurement of various muscle function characteristics. Through the use of isometric testing, researchers and practitioners often obtain muscle performance information that includes maximal or sub-maximal peak or average force/torque, for a wide variety of isolated and multiple joint muscle groups.

Additionally, the analysis of the isometric torque – time curve derived from isometric muscle contractions can provide several muscle performance variables other than the more commonly assessed torque/force measures. For example, the rate of force/torque development (RFD/RTD), time to peak RTD, contractile impulse, and torque values at specified early time intervals may be derived from the isometric – torque time curve[12] and may provide useful information when assessing muscle contractile and functional capacities. Collectively, the muscle function measurements that are derived from isometric assessments may provide important insight and information pertaining to the performance capabilities of a given muscle or muscle groups in a wide variety of populations and settings.

Torque and Rapid Torque Characteristics: Implications for Functional Performance

Muscular strength has been defined as 'the magnitude of torque exerted by a muscle or muscles in a single maximum isometric contraction'[39]. The assessment of muscular strength has been the most popular and widely utilized measure for testing both general and specific muscle function and performance abilities relating to human movement[10,40]. One reason for the continued popularity and use of strength as a muscle function assessment variable may be its practicality and economy as it is relatively simple to measure, cost effective, and appears to provide relatively accurate generalized estimations of muscle function abilities and potential regarding performance related movements. The external validity regarding strength measures and its predictive efficacy relating to various dynamic performances has been questioned by some authors and the literature reveals conflicting findings and theoretical viewpoints[37,41]. However, given the practicality and economy of this relatively simple muscle performance measure and its reasonable effectiveness as a predictor of global muscle performance abilities and potential, it continues to be a useful muscle performance test, especially in light of its cost to benefit advantages.

The previous definition of muscular strength being a 'single maximum isometric contraction' suggests that this measure may be effectively evaluated with the performance of an isometric contraction using peak torque as the specific measurement variable. Peak torque is most commonly assessed during an isometric maximal voluntary contraction (MVC) of a given muscle or muscle group. An isometric MVC is obtained when a participant produces their maximal amount of force for the specified muscle group against an isometric measurement device usually lasting between 3-4 s. The subsequent analysis of the torque – time curve allows a computation of peak torque, defined as the highest portion of the curve, often assessed as the highest averaged 500 ms time interval during the entire MVC.

Although muscular strength has been the most applied muscle function variable relating to muscle testing in the fields of exercise science and rehabilitation, previous authors have questioned the strength of its functional efficacy[12,37,41,42]. The basis for the lack of strong support by some authors regarding muscle strength as an effective muscle performance assessment has its foundation from the results of previous findings. Some previous studies have revealed a lack of a strong association between isometric strength measures and commonly performed dynamic movements[41,43,44]. Several authors[37,44,45] have related these findings to the lack of specific functional relevancy of maximal strength measures pertaining to many common dynamic performance related movements. Given that the nature of most common performance related movements require explosive muscle actions, several authors[12,24,42] have suggested that a more functionally appropriate measure of muscle function, often termed ‘explosive strength’, should be assessed in addition to conventional muscle strength or peak torque measures.

The rationale for explosive strength is based upon the discrepancy of the time course for the attainment of maximal muscular force, in comparison to the times required to perform many dynamic performance activities[11-13,24]. Because maximal strength requires >300ms to attain[12,25] and many dynamic performance movements last <250ms[12,13,24], explosive strength has been suggested to potentially be a more sensitive muscle function measure for a variety of human movements. For example, previous findings have demonstrated that movement durations for commonly performed dynamic movements such as sprinting (~100ms)[17,20,23,46], jumping (~150ms)[18,21], throwing (150-270ms)[19], accelerating (~160ms)[19] and cutting (~160ms)[19] are much shorter than the time required to develop maximal force. Several rapid torque variables have been investigated and reported in the literature in the attempt to quantify or evaluate the ability of a muscle or muscle group to rapidly contract and thus exhibit explosive strength qualities.

One of the most commonly reported variables used to assess explosive strength is rate of force/torque development (RFD/RTD)[10-14,24,47,48]. RTD has been assessed and reported more frequently in recent years as a muscle performance test that is based on an explosive strength and time dependent performance rationale. This variable is usually calculated from an isometric force/torque – time curve and is defined as the change in force/torque divided by the change in time. RTD may be assessed from a number of time epochs along the ascending phase (~ <

200ms) of the torque – time curve. The most commonly evaluated time epochs are 30, 50, 100 and 200 ms from the point of onset, which is usually set at ~2% of the MVC[12]. The most commonly reported RTD variable in the literature, however, is Peak RTD[10,12-14,49]. Peak RTD is the steepest portion of the entire torque – time curve (< 200ms) and is representative of the highest RTD capacity the individual muscle or muscle group is capable of producing at any point along the slope of the curve[12]. The time to Peak RTD may also be calculated and has been evaluated in previous studies. Although less evaluated than other rapid force variables, the time to Peak RTD may be an additional useful measure in relation to its representation of early muscle torque characteristics, particularly as it has been shown to effectively discriminate among athletic playing abilities. For example, Thompson et al.[50] reported that the time to achieve Peak RTD was a significant predictor of playing level in elite collegiate football players as it was more sensitive at discriminating playing level in this population than the majority of the other torque and rapid torque – time variables.

Although RTD is typically defined as the slope (Δtorque/Δtime) of the initial 200ms of the isometric torque – time curve, various alternate rapid force measures have been reported in the literature that represent similar measures and rapid muscle function characteristics. For example, some previous authors[10,51-53] have examined the time interval elapsed between 2 absolute or relative predetermined torque or percent of MVC values (i.e., time to achieve 500 N or time between 30 and 70% of MVC etc.). Along with these absolute force values, authors have commonly reported relative RTD values. Relative RTD is assessed in a similar manner as absolute RTD (i.e. slope of the line or time epochs at specified intervals), however, the main purpose for the calculation of this variable is to remove the influence of muscular strength (i.e., peak torque) from the rapid force/torque measures when evaluating and relating these variables.

Because muscular strength and RTD are related, the removal of the influence of the magnitude of strength allows for equitable comparisons between individuals of differing strength levels[10-12,14,15]. This may be advantageous in studies involving various training protocols or clinical populations as well as in studies investigating the effects of aging and rapid torque variables, where muscle size and strength are significantly different across groups, but rapid torque characteristics are of primary interest. Altogether, these variables and terms are often collectively referred to in the literature as RFD/RTD and involve the measurement of the slope of a line at various time intervals or the time elapsed from various torque/force values on the curve in absolute and relative measurement scales.

Contractile impulse is another rapid muscle performance variable that may be derived and evaluated from an isometric torque-time curve. Although this force-time variable represents similar time dependent functional attributes as the RTD variables, the mechanical and movement related characteristics that it represents are quite different from the RTD variables. Mathematically impulse is defined as the integral of force over the time course that force is applied and it may further be described graphically as the area under the force-time curve[12]. The implications of contractile impulse are particularly important because of the relation of the continued application of forces over intervals of time. The measurement of forces applied over a period of time may give further insight into muscle characteristics, which differ from RTD measures, because RTD only gives information pertaining to a particular instance in time[12]. In support of the importance of this time – integrated concept, Aagaard et al.[12] has suggested that "…impulse reflects the entire time history of contraction, including the overall influence of the various time related RFD parameters" (pg. 1320). The time history of contraction has very important dynamic movement implications because of its relationship to the applied forces across a given interval of time. This relationship is significant because the values obtained from isometric impulse correspond to the angular momentum of the limb. In other words, the change in impulse represents the resulting change in the momentum of the system. For example, the amount of impulse and its changes over the course of an isometric MVC, represent the angular velocity that the limb would have reached if it would have been able to freely move. Because of the relationship between impulse and momentum, which represents functional and dynamic implications, the measurement of this variable has been suggested by Aagaard et al.[12] as "…the single most important strength parameter because it incorporates the aspect of contraction time, which is neglected using most other strength parameters" (pg. 1322). Contractile impulse has been reported much less in the literature when compared to the other rapid force variables[12] (i.e. RFD), perhaps due to the relative level of difficulty in calculating this variable compared to the other rapid torque measures. Thus, given the strong performance implications and scientific support for contractile impulse measures obtained from isometric contractions, future research is needed in which impulse is used and evaluated as a muscle function measure in a variety of athletic and clinical populations for a range of muscles and muscle groups. Contractile impulse measurements may provide researchers and clinicians with additional and unique sensitive and discriminatory muscle function information regarding human performance capacities/potential that neither peak torque nor RFD are able to provide.

In summary, the aforementioned isometric torque and rapid torque muscle performance measures represent important muscle function characteristics and are often utilized in research, clinical and sports related settings. These measurements have demonstrated to be of value to aid researchers and clinicians in distinguishing and evaluating muscle performance capacities of various muscles and groups of muscles and may provide sensitive muscle function information.

For example, they have demonstrated efficacy and sensitivity for evaluating a wide variety of human movement performances including athletic playing ability/potential in sport related activities[15,54,55], effects of various treatments/interventions (i.e. supplements, training, etc.)[12,14,56,57], aging[30,56,58-60] and muscular fatigue[61,62]. Further, they have demonstrated to be particularly sensitive measures and useful diagnostic tools in clinical evaluations of special populations with musculoskeletal impairments[61,63,64]. Perhaps the best approach to use when assessing muscle function abilities and capacities is to use a comprehensive evaluation of a given muscle or muscle group, in which a variety of maximal strength and rapid torque measures are used and incorporated into the functional assessments and subsequent performance evaluations.

Effects of Muscle Fatigue on Torque and Rapid Torque Characteristics

Although a variety of definitions have been used to describe the phenomenon known as muscle fatigue, a collective and commonly accepted description describes it as “a condition in which there is a loss in the capacity for developing force and/or velocity of a muscle, resulting from muscle activity under load which is reversible by rest.”[4] The implications of muscular fatigue relating to human movement activities are far reaching. The etiology and mechanisms of fatigue are very complex, largely not understood and may stem from several locations and cellular processes along the entire neuromuscular chain[4,27]. Failure of physiological processes at any one of a number of locations from the supra-spinal centers of the brain to the contractile machinery within the muscle may compromise neuromuscular performance and hence lead to fatigue. To further complicate the understanding of this topic, a variety of other non muscular processes such as energy/substrate supply and utilization, thermoregulation, blood supply, and differences in fitness status and other participant characteristics have all been suggested to contribute to the onset and accumulation of fatigue. Although the specific mechanisms of fatigue are beyond the scope of this review, it is worthwhile to note that the etiology of fatigue is not described as a universally applicable construct, as previous authors have suggested that a variety of factors combine to yield a model of fatigue mechanisms that are dependent upon the task and populations studied[27,39]. This concept entails that the etiology of fatigue would differ according to a given task (i.e. dynamic vs. isometric; single joint vs. multi-joint activity; intensity, duration etc.) and population (i.e. across ages, gender, muscle fiber type expression, etc.)[27,39]. Perhaps the complexity and difficulty in assessing the factors that influence fatigue are among the reasons that have yielded disparate findings and lack of considerable research and evidence pertaining to muscle fatigue, despite the magnitude of importance of this field of study relating to human movement activities.

The measurement of fatigue is often quantified as the time that a given force or power output may be sustained (endurance time), or the magnitude in which force or power are reduced in a given time period[27]. Pertaining to the latter, the effects of fatigue are observed almost immediately following the onset of intense muscular contraction as is manifest in the immediate reduction in maximal force production capabilities of the involved muscles[39].

It is well accepted that high intensity type activities result in neuromuscular fatigue as opposed to metabolic based fatigue. These types of activities may include either maximal or sub-maximal contractions performed either as a continuous or intermittent contraction. Although the nature and processes of these may yield different patterns and involve a variety of mechanisms, the one constant that emerges as a result of moderate/high intensity muscle contractions is that subsequent performance is diminished. The resulting decrease in performance capacity due to fatigue is best observed via the assessment of the force producing capacity of the muscle[1]. This phenomenon may be observed in an MVC, in which the magnitude and rate of recovery may be obtained from the values derived from an isometric MVC torque-time tracing.

Previous studies examining the influence of fatigue on maximal and rapid torque variables have reported significant reductions in these variables, and that the nature of the recovery may be phase dependent. Many of these studies have demonstrated that the rapid torque variables were depressed to a greater extent than maximal torque. For example, Chiu et al.[65], reported a decrease of 16.9-19.9% for peak torque while RFD from 0-25% of the torque curve was reduced by 32.2-42.5% in the leg extensor muscle group. Several other studies have reported substantially greater reductions in rapid torque variables compared to maximal torque following a variety of fatigue protocols in various populations[66-70]. Hakkinen and Komi[67] also reported that RFD was slower to recover toward pre fatigue levels in comparison to maximal force. These findings provide further support that these muscle characteristics may be more sensitive and prone to alterations from physical activities compared to maximal force output as suggested by Morris et al.[26]. These reductions in maximal and rapid torque characteristics are expected to have a negative impact on human performance due to their relevant and functional importance in typical human activities that involve sprinting, kicking, throwing, accelerating etc.[71].

To further exacerbate the influence of depressed maximal and rapid torque characteristics on human performance tasks, these characteristics commonly demonstrate a slow recovery phase due to fatigue. For example, studies by Baker et al.[6] and Miller et al.[5] both reveal a multi-phase recovery process following fatigue. Their findings suggest that following a bout of fatigue, both fast and slow recovery periods are observed. The slower recovery period is likely due to impaired excitation-contraction coupling, which results in low frequency fatigue (LFF)[1,5-8,72] which is characterized by proportionally lower force output at lower (<50Hz) electrical stimulation frequencies relative to higher frequencies (>50Hz). Given LFF may last from several hours to more than a day[1,8], this type of fatigue may have substantial performance limiting implications, because LFF is more commonly observed and incurred by typical daily physical activities[7-9], and the effects of LFF are likely to be relatively unnoticeable by individuals. Thus, performance may suffer unknowingly for hours or days following a bout of fatigue. This may result in a detriment to a variety of performance settings, including athletic, recreation, occupation and important daily living activities. Support for the effects of long duration fatigue on rapid torque characteristics is limited, and further research is necessary to elucidate these effects.

Knee Flexor Fatigue and Rapid Torque Characteristics

When compared to the total body of fatigue related literature, the leg flexor muscle group has been grossly under researched in comparison to other muscles, and thus, our understanding of the effects of fatigue on muscle function characteristics in the leg flexors is very limited. For the lower body muscles, it has been suggested that fatigue related research has been primarily focused on the quadriceps femoris muscle group[73]. This seems rather peculiar given the functional significance and importance of the leg flexor muscle group for a wide range of human movements which profoundly influences human performance in all populations and in many loco-motor related tasks. For example, the leg flexors have been suggested as being a significant contributor to a variety of loco motor activities including sprinting[23,74,75], jumping[18], and accelerating[23,74,75]. Further, Thompson et al.[50] examined the ability of strength and rapid torque characteristics of either the leg extensors or leg flexors to discriminate among playing level in elite athletes, and revealed that only the rapid torque variables of the leg flexor muscle group could predict playing status, suggesting the importance of the leg flexor muscle group in athletic related tasks.

Injury rates also play an important role relating to the leg flexor muscle group as it has been demonstrated the hamstrings specifically are at high risk for injuries as evidenced by the prevalence of hamstring related injuries in sport and performance related activities[76,77]. Injuries of the hamstrings are likely exacerbated by fatigue as is often observed that hamstring injuries occur during later periods of sporting events/activities which suggest the prevalence of fatigue[78]. In addition to the performance related importance of the leg flexors, research has also shown that they may be more susceptible to fatigue when compared to the leg extensors. For example, Emery et al.[73] examined the influence of the fatigue response to an isokinetic fatigue test for both the leg extensors and leg flexors muscles and reported that the leg flexors resulted in earlier and greater fatigue. Given the prevalence and importance of the leg flexors in human performance tasks and the high relative fatigability, further investigations are warranted to objectively examine and elucidate the association between fatigue and muscle contractile characteristics so that training, injury prevention measures, and greater understanding of the consequences, relationships and processes may be obtained and applied in a variety of settings and populations.

The majority of research relating to fatigue has primarily evaluated maximal torque of the investigated muscles, and the effects a fatigue inducing bout of exercise has on the maximal force producing capacities of the involved muscle. Few studies have investigated the rapid force characteristics for any given muscle, and even fewer exist to demonstrate the effects fatigue may have on the leg flexors. The author is aware of only two studies examining rapid force variables on fatigue of the hamstrings. Thorlund et al., examined the effects of either soccer match play[71] or a handball match[70] on maximal and rapid force variables. Both studies revealed a significant decrease in the rapid force variables following either the soccer or handball match, however only the handball match rapid force variables were reduced significantly more than maximal force. The rapid force decreased (17-21%) approximately two times more than maximal force decreased (10-11%), following the handball match. These findings suggest that rapid force variables are sensitive toward common fatigue inducing activities and that the magnitude of sensitivity is task dependent. The decline of rapid force with fatigue would likely have significant consequences on performance during explosive tasks, which are often critical and decisive for success in many sport and daily activities. The authors suggest that the higher decline in rapid force for the handball match compared to the soccer match is likely a function of the higher explosive intensity of the sport. Thus, it appears that explosive tasks may lead to higher disproportionate declines in rapid force variables compared to maximal force, and functional consequences may be higher in this instance.

Further research is required to examine the influence of a moderate to large amount of neuromuscular fatigue of the leg flexor muscle group to validate previous findings. The only two studies examining fatigue of the leg flexors were both performed following a match play, and therefore little control over the magnitude of fatigue was possible. Large fatigue differences between individuals may have been present due to the nature of the un-standardized activities which may have been affected by skill level and effort given during the match play etc. Thus, our understanding of how a specified amount of fatigue affects the maximal and rapid torque variables remains unknown. In order to more objectively evaluate and quantify these effects, a more controlled fatigue protocol is needed, where all individuals reach a similar magnitude of specified fatigue. Such a fatigue protocol would be best suited for a dynamometer, in which ‘real time’ force recordings, standardized leg angles, and a specified level of fatigue may be precisely attained.

Effects of Fatigue and Aging

Although widespread research pertaining to age related functional and neuromuscular changes has been conducted, research on fatigue in older individuals (>60 years) is scarce. Our understanding of the effects of aging on physiological responses to fatigue is limited and few consistent findings have been reported in the literature, which adds to our lack of understanding on this important topic. Whereas many neuromuscular changes occur across the lifespan, one would expect to see differences in fatigue resistance responses between young and older individuals. Inconsistent findings, however, have reported a variety of fatigue responses between young and old. It is difficult to ascertain what would be the expected responses/alterations given many physiological differences between young and old. Indeed, studies have reported no differences, increased fatigue resistance and decreased fatigue resistance in the fatigability between young and old[27]. These mixed findings are likely due to the limited number of studies, and the variety of fatigue protocols, testing methods, populations and muscle groups used in the studies. It is possible that different types of muscles result in different fatigue patterns in aging adults. In a review of the literature, a variety of muscle groups appear to have been studied and assessed between young and old relating to fatigue responses. However, not one of these studies has examined the leg flexor muscle group and the fatigue response between young and old humans. Further, none of these fatigue and aging related studies appears to have investigated the influence of fatigue on rapid force characteristics of the involved muscles. An investigation of the rapid force characteristics of the leg flexors would be valuable to ascertain the effects on aging, given the aforementioned functional importance of the hamstrings for many typical physical activities, especially associated with the loss of function observed in the elderly.

Conclusions

Human performance activities are dependent upon force and rapid force characteristics of the muscles that produce these movements. The assessment of maximal torque (i.e., strength) is commonplace in the literature; however, fewer studies have examined the influence of rapid force variables pertaining to human performance tasks. Rapid force variables may be more sensitive in discriminating among athletic and functional abilities as well as changes in performance resulting from muscular fatigue. Neuromuscular fatigue will depress both maximal and rapid muscle performance with larger deficits often appearing in rapid vs. maximal force variables. Large functional implications of these consequences are likely to affect a variety of human performance paradigms, including athletics, recreation, occupation and aging populations and settings. Furthermore, limited research is available examining the influence of fatigue on rapid force characteristics particularly for the aging adult, and none have evaluated these effects on the leg flexor muscle group. Clearly, more research is warranted that examines the influence of fatigue on maximal and rapid force characteristics of the leg flexors across the human life span. Improved understanding of these functional consequences and processes may allow researchers, clinicians, coaches, trainers and practitioners alike to better prescribe and evaluate exercise models, to improve human performance, and reduce the risk of injuries, in a wide variety of populations and settings.

CHAPTER III

METHODS

Participants

Twenty-one young (mean ± SD: age = 24.76 ± 2.90 years; height = 179.05 ± 7.72 cm; mass = 87.12 ± 21.73 kg) and nineteen old (age = 72.05 ± 3.60 years; height = 177.42 ± 5.68 cm; mass = 87.34 ± 12.78 kg) recreationally active, non-resistance trained males completed the investigation, following the exclusion of 7 participants due to failure to meet physical impairment, age range, and fatigue requirements (Figure 1). This study was approved by the university Institutional Review Board for human subjects and all participants completed a health history questionnaire and signed a written informed consent document prior to any testing. None of the participants reported any current or ongoing neuromuscular diseases or musculoskeletal injuries of the knee or hip of their right leg within 1 year prior to testing.

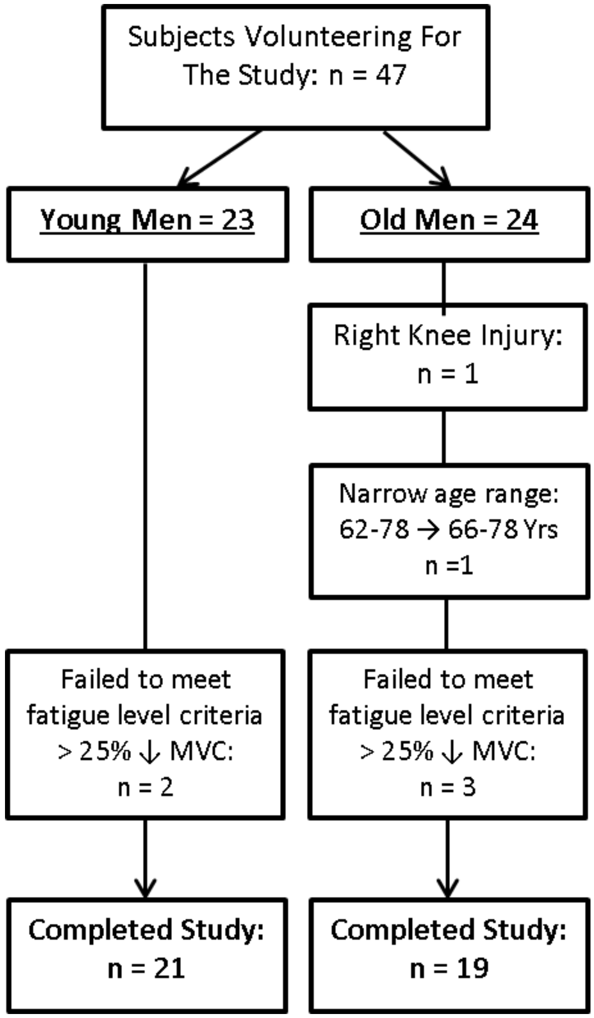

Figure 1. Schematic diagram showing the study participant sample size flow

Experimental Design

Participants visited the laboratory on three separate occasions with the first session being a familiarization trial where all participants practiced the maximal voluntary contractions and the fatigue protocol of both the leg extensors and flexors, and the next two visits were the experimental trials. Within 2-4 days following the familiarization trial, participants reported back to the laboratory for the first experimental trial (day 2) and then again 7 (± 1) days later for the second experimental trial (day 3). The two experimental trials involved testing of either the leg extensor or flexor muscle group only, on each respective day. The order of testing of the muscle groups was randomized. For both experimental trials, participants were instructed to refrain from any caffeine consumption within 12 hours of testing to avoid possible ergogenic affects of caffeine consumption on fatigue performance, and to refrain from vigorous physical activity 48 hours prior to any testing and throughout the duration of the study. The effects of neuromuscular fatigue immediately following completion of the fatigue protocol and during the recovery period were assessed to test the hypothesis that rapid torque characteristics are reduced to a greater extent than maximal torque and that these effects are more pronounced with aging in adult males.

Maximal and Rapid Isometric Strength Testing

Isometric MVCs were performed on the right leg using a calibrated Biodex System 4 isokinetic dynamometer (Biodex Medical Systems, Inc. Shirley, NY, USA). For all strength assessments, participants were seated with restraining straps placed over the trunk, pelvis, and thigh and the input axis of the dynamometer was aligned with the axis of rotation of the knee. All MVCs were performed at leg flexion angles of 60° and 30° below the horizontal plane for the knee extensors and flexors, respectively. Prior to the maximal strength testing, participants performed a five minute warm-up on a cycle ergometer (Monark Exercise828E, Vansbro, Sweden) at a self-selected low-intensity workload, followed by three sub-maximal isokinetic knee extension and flexion muscle actions at $60°\cdot s^{-1}$ at approximately 75% of their perceived maximal effort. Depending on the randomized testing order, and prior to the experimental protocol, the participant performed two-three MVCs with either the knee extensors or flexors with one minute of recovery between each contraction. Participants were verbally instructed for the knee flexion and extension MVCs to “pull” or “push”, “as hard and fast as possible” for a total of 3-4 s[79].

Fatigue Protocol

The highest torque value (PT) recorded from the baseline isometric MVCs (Pre) was used to determine the target torque level for the subsequent experimental fatigue protocol. The target torque level was set at 60% of PT, as this target level has been used effectively in previous investigations[1,2] to elicit neuromuscular fatigue during intermittent sub-maximal contractions. Five minutes following the Pre MVCs, participants performed the fatigue protocol, which consisted of cyclical intermittent contractions using a .6 duty cycle, involving a 6 s isometric contraction followed by a 4 s relaxation phase[1,9,80,81]. This protocol was selected in an attempt to elicit long duration, neuromuscular fatigue also known as low frequency fatigue (LFF), as this has been suggested to have functional implications and may be more commonly observed in typical activities of daily living. During the fatigue protocol participants were required to track their torque production by tracing a horizontal line set at the target torque level, on a computer monitor placed directly in front of them, which displayed the real time torque signal (Figure 2). When participants were no longer able to reach their target torque level, despite giving a maximal effort, the fatigue test was terminated. Upon termination of the fatigue protocol, two-three MVCs were then recorded immediately (Post), seven (Recov7), fifteen (Recov15) and thirty (Recov30)[81] minutes following the fatigue task. Strong verbal encouragement was provided throughout the duration of the fatigue protocol, and during all MVCs. The endurance time, which is defined as the elapsed time from the onset of the fatigue protocol until its termination, was recorded and used as an index of muscle fatigue in addition to the maximal and rapid torque variables.

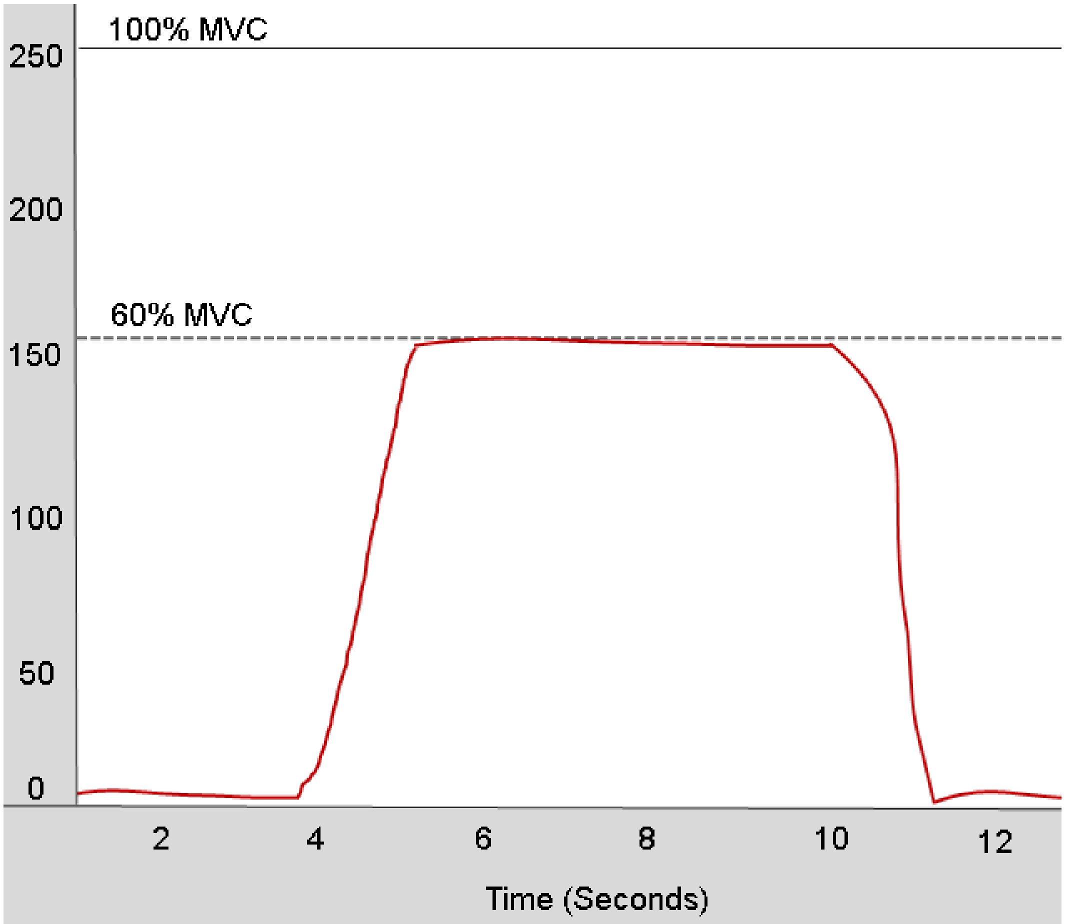

Figure 2. Illustration depicting the torque signal tracing during the fatigue protocol where participants were instructed to increase the torque level to 60% of their maximum MVC for a total of 6 s, followed by a 4 s relaxation period. Participants performed the fatiguing contractions until they were unable to achieve the required 60% torque level.

Signal Processing

The torque signal (Nm) was sampled at 2 KHz with a Biopac data acquisition system (MP150WSW, Biopac Systems, Inc.; Santa Barbara, CA, USA), stored on a personal computer and processed off-line with custom written software (Labview 8.5, National Instruments, Austin, TX, USA). The scaled torque signal was filtered using a fourth order, zero phase shift low pass Butterworth filter with a 10 Hz cutoff frequency. The passive baseline torque value was considered the limb weight and subtracted from the signal so that the new baseline value was set at 0 Nm. All subsequent analyses were performed on the scaled, filtered, and gravity-corrected torque signal. Isometric MVC PT was calculated as the highest 0.5 s epoch during the entire 3-4 s MVC (Figure 3). Absolute rate of torque development (RTD) was calculated as the slope of the torque-time curve (Δtorque/Δtime) over the time intervals of 0 – 30 (RTD30), 0 – 50 (RTD50), 0 – 100 (RTD100), 0 – 200 (RTD200) and 100 – 200 (RTD100-200) ms (Figure 3). Normalized RTD (nRTD) was calculated by taking the linear slope of the normalized torque-time curve at 1/6 (nRTD1/6), 1/2 (nRTD1/2), and 2/3 (nRTD2/3) of the percent of MVC. The onset of contraction was determined as the point when the torque signal reached a threshold of 4 Nm for the leg flexors and 7.5 Nm for the leg extensors or 2.5% on the relative curve[12,50] (Note: a higher RTD value indicates more rapid torque production). Additionally, the ratio of normalized rapid torque to maximum torque capacity was calculated from the nRTD curve at 50 ms (nRTD50/PT ratio), to assess the relative capacity of rapid torque production relative to individualized maximal strength levels.

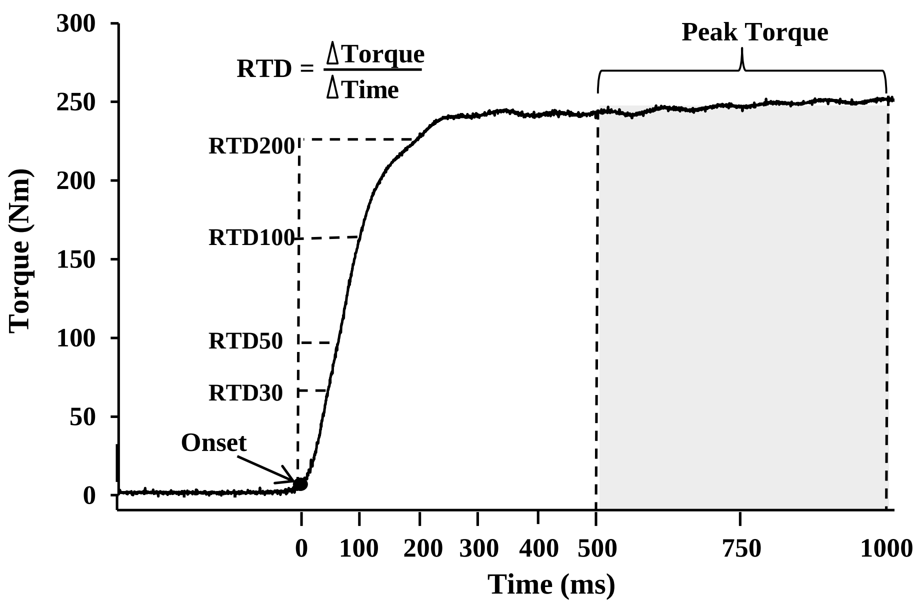

Figure 3. An example of a raw torque-time curve during a maximum voluntary contraction (MVC). Peak torque (PT) and rate of torque development (RTD) were determined from the

highest .5 s epoch and the slope of the torque-time curve, respectively. RTD was calculated at intervals of 30, 50, 100, 200 and 100-200 ms from the onset along the torque-time curve.

Statistical Analyses

A 2 way mixed factorial analysis of variance (ANOVA) (age [young vs old] × muscle [knee extensors vs flexors]) was used to analyze endurance times. Separate 3 way mixed factorial (ANOVAs) (age [young vs. old] × time [Pre vs. Post. vs. Recov7 vs. Recov15 vs. Recov30] × muscle [knee extensors vs. flexors]) were performed using the relative percentage scores (% of Pre fatigue values)[2,81] to analyze all maximal and rapid torque dependent variables. When appropriate, follow up analyses included ANOVAs and Bonferroni pairwise comparisons on either the simple main effects (when a significant interaction was present) or main effects collapsed across the opposing variable (when no significant interaction was present)[82]. PASW software version 18.0 (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses and an alpha level of $P \leq 0.05$ was used to determine statistical significance for all comparisons.

CHAPTER IV

RESULTS

Baseline Strength Characteristics and Endurance Time

All participants' demographic characteristics are presented in Table 1. All baseline absolute PT, RTD and nRTD variables are presented in Table 2 and all relative (% of Pre MVC) PT, RTD and nRTD variables across all time periods are presented in Table 3. At baseline, the young men's results were greater than the old men for PT and all absolute RTD variables for both the knee extensors and flexors ($P = <0.001 – 0.001$). There were no differences between age groups for all nRTD variables for the knee extensors ($P = 0.089 – 0.897$), however, for the knee flexors the young had greater ($P < 0.001$) nRTD1/6 than the old while the old had greater ($P = 0.030$) nRTD2/3 compared to the young men. For endurance time, there was no interaction ($P = 0.335$) and no main effect for muscle ($P = 0.087$), but there was a main effect for age group such that the old men (352.66 ± 303.67 s) had greater ($P = 0.048$) endurance time than the young men (243.24 ± 161.96 s) (Figure 4).

Peak Torque

There were no differences in MVC PT reductions following the fatigue protocol (i.e., Post), between age groups (mean ± SD: young = 62.21 ± 5.75, old = 63.79 ± 6.51 % of Pre; $P = 0.305$) or muscle groups (extensors = 62.73 ± 6.02, flexors = 63.20 ± 6.19 % of Pre; $P = 0.696$).

For PT, there was no 3 way interaction (P = 0.078) and no 2 way interactions for muscle × group (P = 0.069) or time × group (P = 0.326), but there was a 2 way interaction for muscle × time (P = 0.002). Follow up analyses revealed that for the knee extensors, the time periods of Post, Recov7 and Recov15 were lower than Pre values (P = 0.001 – 0.050) and Post was also lower compared to Recov7, Recov15, and Recov30 (P < 0.001). For the knee flexors, all time periods (P < 0.001) were significantly lower compared to Pre values and Post was lower compared to Recov7, Recov15, and Recov30 (P < 0.001) (Figure 5).

Early Rate of Torque Development Variables

For RTD30 and RTD50, there were no 3 way interactions (P = 0.610 – 0.849), and no 2 way interactions for muscle × group (P = .885 – 0.954) or time × group (P = 0.137 – 0.151), but there were 2 way interactions for muscle × time (P = 0.001). Follow-up analyses revealed that for the knee extensors for RTD30, the time periods of Post, Recov7 and Recov15 were significantly lower (P = <0.001 – 0.001) compared to Pre values and for RTD50 all time periods were lower compared to Pre values (P = < 0.001 – 0.041). For both RTD30 and RTD50, the time period of Post was also lower compared to Recov7, Recov15, and Recov30 (P < 0.001). For the knee flexors for both RTD30 and RTD50, all time periods were significantly lower (P < 0.001) compared to Pre values. However, no differences were observed for Post compared to Recov7, Recov15, (P = 0.058 – 1.000) for both RTD30 and RTD50 and Recov30 (P = 0.386) for RTD30 only, but for RTD50, Post was lower compared to Recov30 values (P = 0.016) (Figure 6).

Late Rate of Torque Development Variables

For RTD100, there was no 3 way interaction (P = 0.436), and no 2 way interaction for muscle × group (P = 0.916) or time × group (P = 0.826), but there was a 2 way interaction for muscle × time (P = 0.008). Follow-up analyses revealed that for both the knee extensors and flexors, all time periods were lower compared to Pre values (P = <0.001 – 0.001) and Post was also lower compared to Recov7, Recov15, and Recov30 (P < 0.001).

For RTD200, there was no 3 way interaction (P = 0.958), and no 2 way interaction for muscle × group (P = 0.756), time × group (P = 0.618), or muscle × time (P = 0.066). There was a main effect for time (P < 0.001). All time periods were lower compared to Pre values (P = <0.001 – 0.001) and Post was lower compared to Recov7, Recov15, and Recov30 (P <0.001).

For RTD100-200, there was no 3 way interaction (P = 0.374), and no 2 way interaction for muscle × group (P = 0.703), time × group (P = 0.783), or muscle × time (P = 0.746). There was a main effect for time (P < 0.001). Post was lower compared to Pre values (P < 0.001), however, there were no differences between Pre and Recov7, Recov15, and Recov30 (P = 0.392 – 1.000). Also, Post was lower compared to Recov7, Recov15, and Recov30 (P < 0.001) (Figure 7).

Normalized Rate of Torque Development Variables

For nRTD1/6, there was no 3 way interaction (P = 0.873), and no 2 way interaction for muscle × group (P = 0.349) or time × group (P = 0.091), but there was a 2 way interaction for muscle × time (P= 0.012). For the knee extensors, there were no differences between any of the time periods (P = 0.125 – 1.000). However, for the knee flexors, there was no difference between Pre vs. Post (P = 0.235), but Recov7, Recov15 and Recov30 were lower compared to Pre (P = 0.005 – 0.016) values (Figure 8).

For nRTD1/2, there was no 3 way interaction (P = 0.439) and no 2 way interaction for muscle × group (P = 0.101), time × group (P = 0.132) or muscle × time (P = 0.311). There was a main effect for time (P = 0.001). Post, Recov7 and Recov15 were lower compared to Pre (P = 0.009 – 0.041) but Recov30 was not different compared to Pre (P = 0.064).

For nRTD2/3, there was no 3 way interaction (P = 0.854), and no 2 way interaction for muscle × group (P = 0.283), or muscle × time (P = 0.365), but there was a 2 way interaction for time × group (P = 0.043). Follow-up analyses revealed that for the young men, the time periods of Post and Recov7 were lower compared to Pre values (P = 0.002 – 0.034), but Recov15 and Recov30 were no different than Pre values (0.114 – 0.364). Also, Post was not different compared to Recov7 or Recov30 (P = 0.200 – 0..367), but was lower compared to Recov15 (P = 0.014). For the old men, however, there were no differences between any of the time periods (P = 1.000) (Figure 9).

For the nRTD50/PT ratios, there was no 3 way interaction (P =0.717), and no 2 way interaction for muscle × time (P = 0.363), but there were 2 way interactions for group × muscle (P = 0.001) and group × time (P = 0.003). Follow-up analyses for group × muscle revealed that the knee flexors were greater than the knee extensors for the young (P < 0.001), but not for the old men (P = 0.494) (Figure 10). Follow-up analyses for group × time revealed that Post was greater in both young (P = < 0.001 to 0.006) and old (P = < 0.001 – 0.002) men compared to all other time periods and that the old men had greater values (P = < 0.001 – 0.002) at all time periods compared to the young men (Figure 11**).**

TABLE 1. Mean (SD) demographic values for age, height, and body mass for the young and old men.

Variable	Young	Old
Age (years)*	24.76 (2.90)	72.05 (3.60)
Height (cm)	179.05 (7.72)	177.42 (5.68)
Mass (kg)	87.12 (21.73)	87.34 (12.78)

* indicates signficant (*P* < 0.05) difference between young and old

TABLE 2. Mean (SD) baseline absolute torque and rapid torque characteristic values for the leg extensors and flexors for the young and old men.

	Extensors		Flexors	
Variable	Young	Old	Young	Old
PT (Nm)	249.63 (53.75)	154.20 (26.67)*	128.91 (20.39)	95.44 (14.94)*
RTD_{30} ($N{\cdot}m{\cdot}s^{-1}$)	1336.70 (309.77)	1001.28 (243.08)*	490.81 (103.49)	358.67 (116.39)*
RTD_{50} ($N{\cdot}m{\cdot}s^{-1}$)	1536.72 (386.64)	1058.83 (265.30)*	604.51 (131.17)	422.08 (122.14)*
RTD_{100} ($N{\cdot}m{\cdot}s^{-1}$)	1505.94 (377.66)	872.07 (196.55)*	707.96 (154.69)	482.33 (108.99)*
RTD_{200} ($N{\cdot}m{\cdot}s^{-1}$)	994.17 (229.19)	544.31 (142.71)*	565.64 (119.59)	384.41 (85.46)*
$RTD_{100\text{-}200}$ ($N{\cdot}m{\cdot}s^{-1}$)	568.84 (176.79)	392.31 (135.89)*	362.00 (99.83)	255.11 (96.71)*
nRTD1/6 ($\%MVC{\cdot}s^{-1}$)	499.34 (95.53)	553.19 (108.92)	553.19 (77.69)	344.91 (87.84)*
nRTD1/2 ($\%MVC{\cdot}s^{-1}$)	626.81 (148.95)	629.81 (196.16)	515.06 (126.61)	477.31 (81.23)
nRTD2/3 ($\%MVC{\cdot}s^{-1}$)	527.94 (181.75)	462.70 (183.85)	381.10 (125.90)	460.75 (93.40)*

* indicates significant (*P* < 0.05) difference between young and old

TABLE 3. Mean (SD) relative maximal torque (% of Pre MVC) values for all maximal and rapid torque variables for both the leg extensors and flexors in young and old men.

Group	Variable		Leg Extensors Pre	Post	Recov7	Recov15	Recov30	Leg Flexors Pre	Post	Recov7	Recov15	Recov30
Young Men	PT (Nm)	†	100	62.06 (5.32)*	94.57 (8.90)*[a]	97.64 (10.81)*[a]	99.35 (9.40)[a]	100	62.36 (6.18)*	85.72 (10.62)*[a]	87.91 (11.10)*[a]	90.31 (11.73)*[a]
	RTD30 ($N \cdot m \cdot s^{-1}$)	†	100	62.46 (19.55)*	89.04 (17.55)*[a]	89.16 (12.84)*[a]	93.07 (21.15)[a]	100	60.47 (28.54)*	74.54 (20.60)*	75.45 (22.29)*	81.00 (25.59)*
	RTD50 ($N \cdot m \cdot s^{-1}$)	†	100	56.82 (17.72)*	86.47 (17.05)*[a]	88.58 (14.54)*[a]	89.60 (20.65)*[a]	100	56.44 (25.50)*	74.85 (20.95)*	74.51 (23.06)*	81.91 (24.83)*[a]
	RTD100 ($N \cdot m \cdot s^{-1}$)	†	100	50.60 (13.97)*	83.32 (15.01)*[a]	88.68 (15.85)*[a]	84.54 (16.81)*[a]	100	52.93 (15.56)*	78.13 (17.69)*[a]	79.65 (20.69)*[a]	85.67 (20.52)*[a]
	RTD200 ($N \cdot m \cdot s^{-1}$)		100	52.40 (12.27)*	87.29 (13.31)*[a]	91.09 (16.02)*[a]	87.31 (16.94)*[a]	100	57.08 (12.50)*	82.08 (13.74)*[a]	86.62 (15.87)*[a]	87.17 (15.65)*[a]
	RTD100-200 ($N \cdot m \cdot s^{-1}$)		100	65.62 (28.76)*	95.23 (25.70)[a]	94.51 (19.65)[a]	95.25 (29.25)[a]	100	69.12 (29.43)*	90.44 (29.09)[a]	94.43 (32.55)[a]	93.92 (37.85)[a]
	nRTD1/6 ($\%MVC \cdot s^{-1}$)	†	100	97.14 (23.10)	95.43 (12.89)	94.25 (11.69)	96.11 (19.17)	100	83.01 (30.06)	85.59 (17.28)*	85.19 (18.19)*	89.37 (19.35)*
	nRTD1/2 ($\%MVC \cdot s^{-1}$)		100	77.41 (25.61)*	87.04 (19.23)*	87.76 (21.00)*	83.03 (27.38)	100	81.90 (23.66)*	91.29 (16.74)*	88.69 (17.21)*	94.07 (19.16)
	nRTD2/3 ($\%MVC \cdot s^{-1}$)	α	100	75.30 (33.07)*	85.28 (27.91)*	91.52 (35.31)[a]	83.33 (36.35)	100	78.30 (25.40)*	89.25 (21.55)*	91.59 (18.84)[a]	94.54 (19.41)
Old Men	PT (Nm)	†	100	63.46 (6.78)*	90.60 (12.36)*[a]	90.83 (13.61)*[a]	93.17 (15.27)[a]	100	64.12 (6.24)*	87.08 (9.32)*[a]	92.22 (8.22)*[a]	89.59 (11.19)*[a]
	RTD30 ($N \cdot m \cdot s^{-1}$)	†	100	70.34 (14.92)*	88.66 (17.12)*[a]	92.14 (14.23)*[a]	92.70 (17.81)[a]	100	74.31 (31.19)*	75.62 (20.61)*	79.75 (26.66)*	75.45 (26.61)*
	RTD50 ($N \cdot m \cdot s^{-1}$)	†	100	63.99 (15.89)*	88.07 (16.01)*[a]	90.56 (15.39)*[a]	90.87 (19.72)*[a]	100	70.38 (31.19)*	75.42 (19.59)*	79.65 (24.16)*	75.66 (24.26)*[a]
	RTD100 ($N \cdot m \cdot s^{-1}$)	†	100	52.97 (19.04)*	88.46 (13.94)*[a]	88.51 (18.38)*[a]	89.33 (22.02)*[a]	100	60.02 (19.61)*	79.68 (18.20)*[a]	83.42 (20.40)*[a]	83.02 (19.46)*[a]
	RTD200 ($N \cdot m \cdot s^{-1}$)		100	56.93 (12.74)*	91.38 (14.44)*[a]	89.80 (18.86)*[a]	90.95 (20.92)*[a]	100	62.21 (16.82)*	85.44 (19.41)*[a]	89.62 (20.13)*[a]	92.15 (22.18)*[a]
	RTD100-200 ($N \cdot m \cdot s^{-1}$)		100	73.58 (18.66)*	89.54 (22.70)[a]	95.07 (29.73)[a]	96.03 (31.52)[a]	100	65.73 (25.68)*	94.60 (37.26)[a]	108.17 (56.61)[a]	101.92 (42.95)[a]
	nRTD1/6 ($\%MVC \cdot s^{-1}$)	†	100	113.25 (20.00)	97.87 (18.16)	102.98 (17.19)	101.24 (14.66)	100	93.23 (33.62)	85.60 (19.22)*	87.13 (27.57)*	84.75 (28.42)*
	nRTD1/2 ($\%MVC \cdot s^{-1}$)		100	98.28 (38.90)*	100.65 (22.62)*	106.13 (31.91)*	98.25 (37.98)	100	92.04 (26.80)*	91.23 (17.12)*	88.54 (21.02)*	92.64 (15.16)
	nRTD2/3 ($\%MVC \cdot s^{-1}$)	α	100	108.09 (78.33)[b]	101.73 (31.30)	100.92 (35.87)	91.91 (33.83)	100	95.22 (29.73)[b]	93.38 (28.01)	89.92 (25.62)	97.45 (15.90)

† significant muscle × time interaction (collapsed across age group); α significant time × group interaction (collapsed across muscle); * signficantly different than Pre; [a] significantly different than Post (collapsed across age group); [b] significantly different than young (collapsed across muscle); shaded block indicates significant difference between muscle

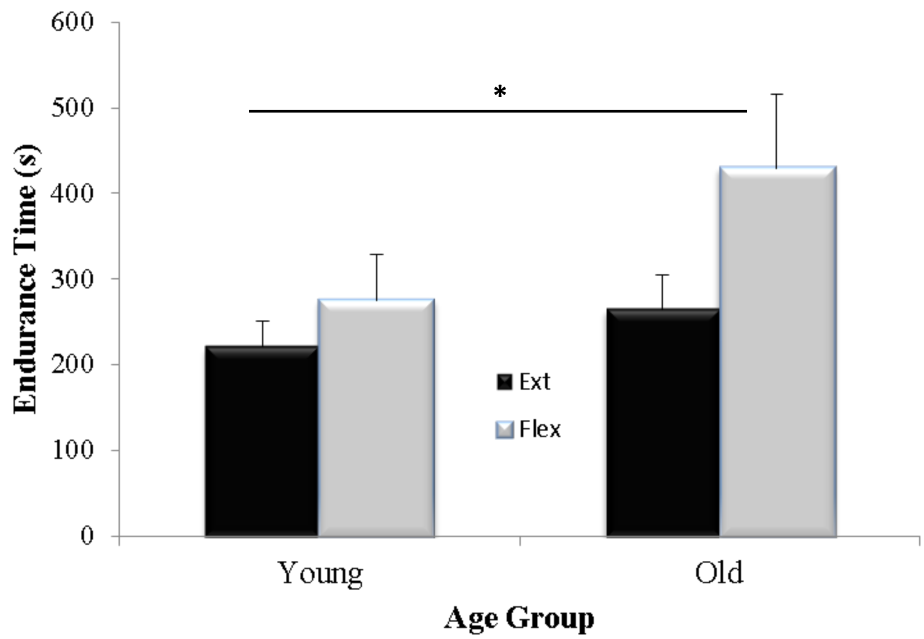

Figure 4: Endurance time values for the young and old men for the knee extensors and flexors. * indicates a main effect for group showing the old were greater than the young men. Values are mean ± SEM.

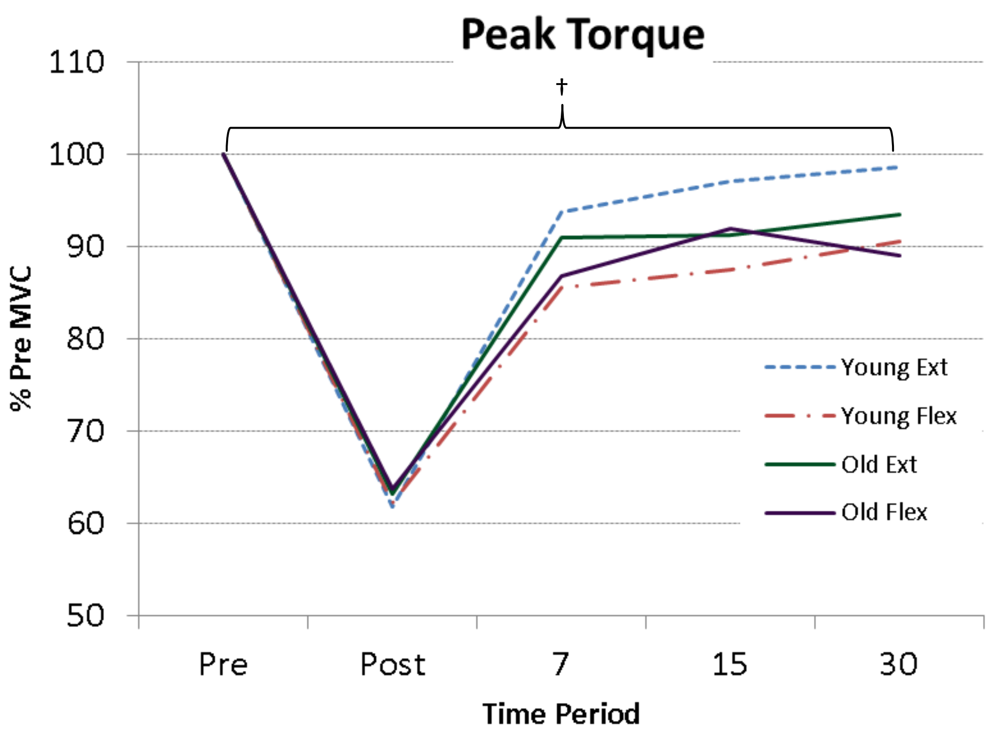

Figure 5: Mean peak torque (PT) values expressed relative to Pre MVC (%) for all time periods in the young and old men for the knee extensors and flexors. † indicates a significant muscle × time interaction where the leg extensors were significantly lower than Pre compared to Post, Recov7 and Recov15, and the leg flexors were lower than Pre compared to all time periods. Also, Post was lower compared to all other time periods for both extensors and flexors.

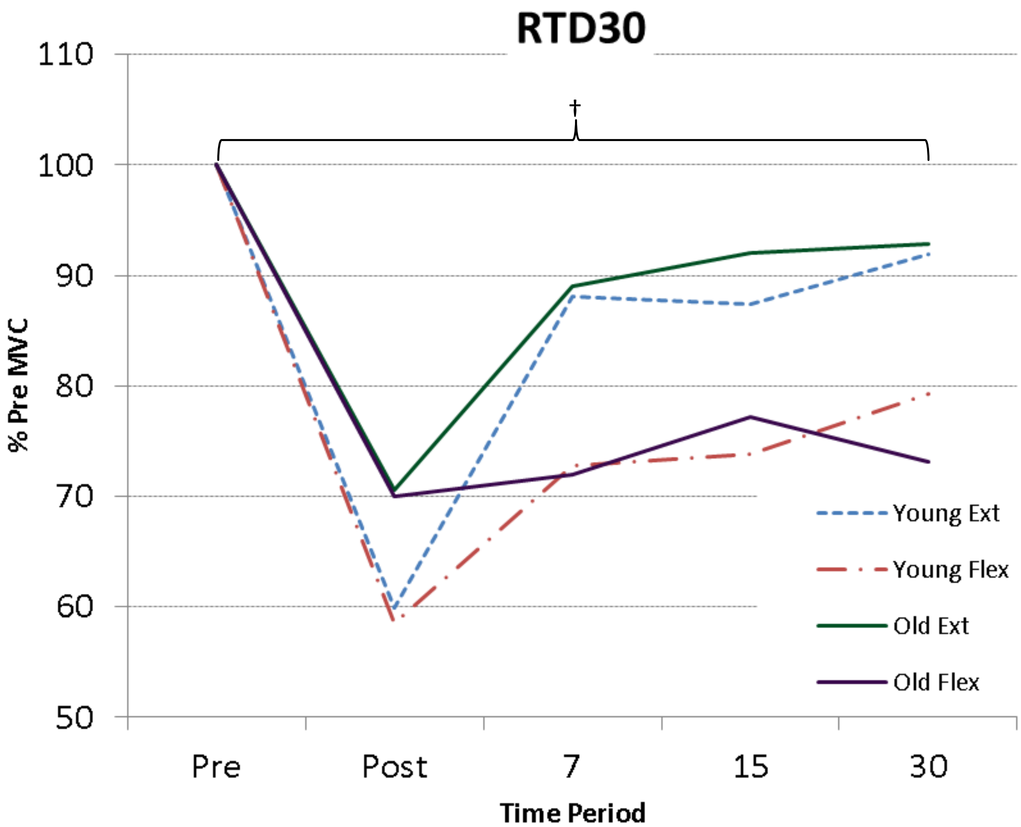

Figure 6: Mean rate of torque development at 30 ms (RTD30) values expressed relative to Pre MVC (%) for all time periods in the young and old men for the knee extensors and flexors. † indicates a significant muscle × time interaction where the knee extensors were significantly lower than Pre compared to Post, Recov7, and Recov15, and the knee flexors were lower than Pre compared to all other time periods. Also, for the extensors, Post was lower compared to Recov7, Recov15 and Recov30, but for the flexors, no differences were observed between post and all Recov time periods.

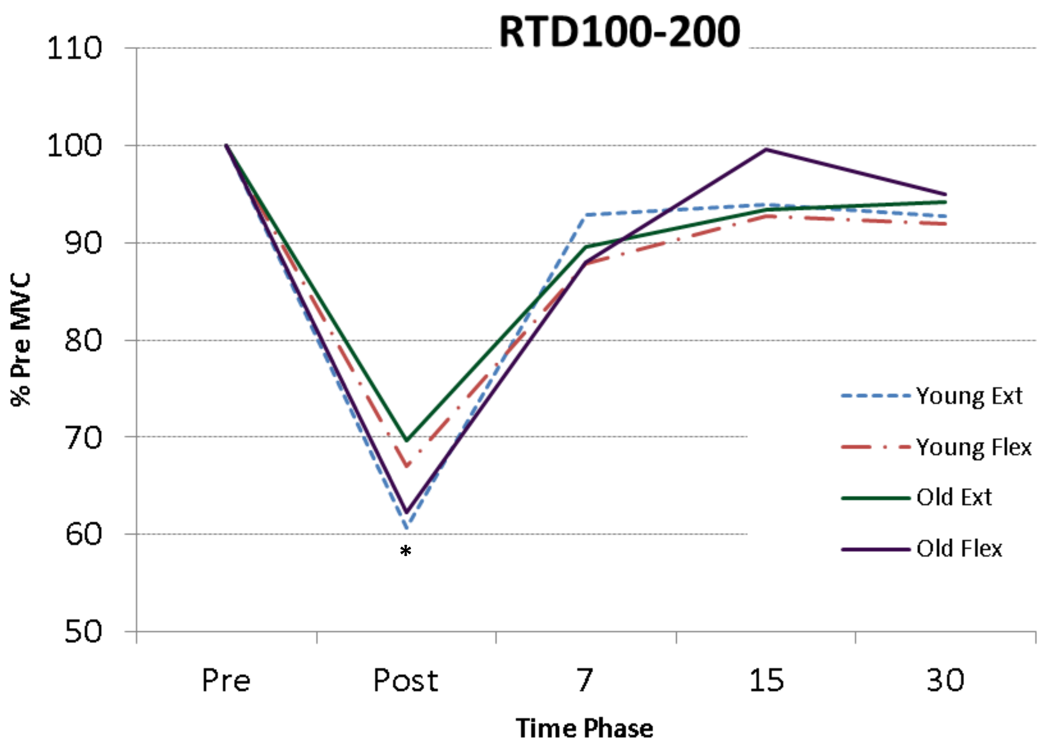

Figure 7: Mean rate of torque development at 100-200 ms (RTD100-200) values expressed relative to Pre MVC (%) for all time periods in the young and old men for the knee extensors and flexors. * indicates a significant main effect for time where post was lower compared to Pre, Recov7, Recov15 and Recov30 time periods (collapsed across age and muscle).

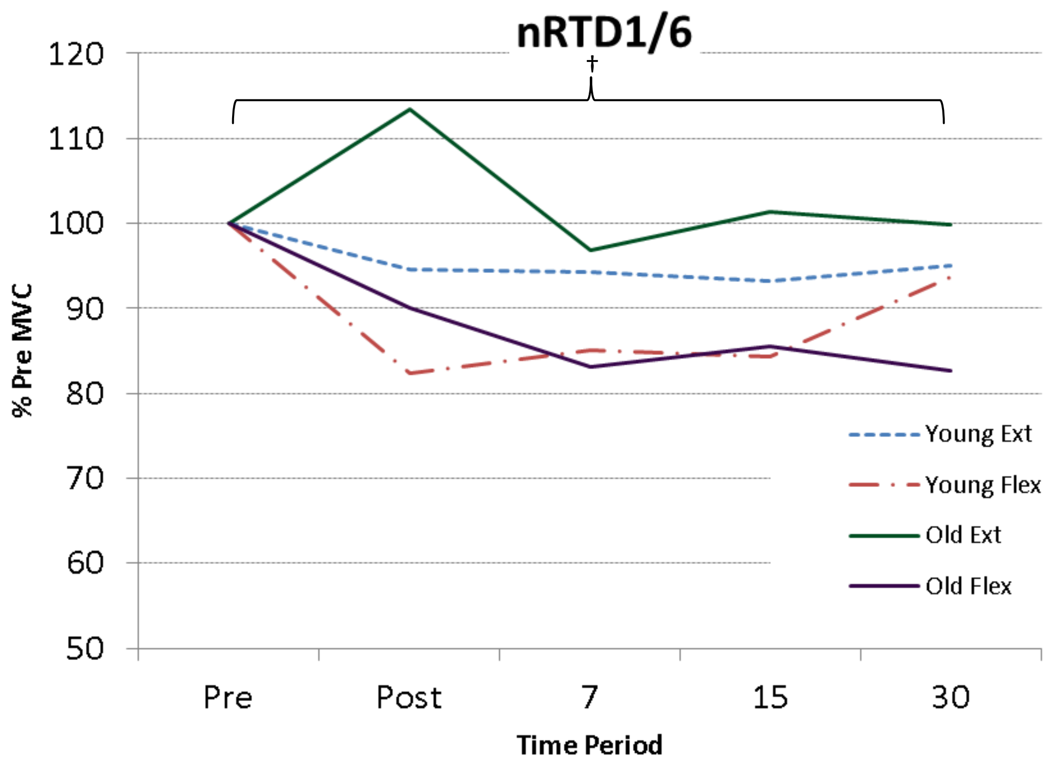

Figure 8: Mean normalized rate of torque development at 1/6 (nRTD1/6) of the normalized torque-time curve showing values expressed relative to Pre MVC (%) for all time periods in the young and old men for the knee extensors and flexors. † indicates a significant muscle × time interaction where no differences were observed between any of the time periods for the knee extensors but the knee flexors were lower for Recov7,15 and 30 compared to Pre values.

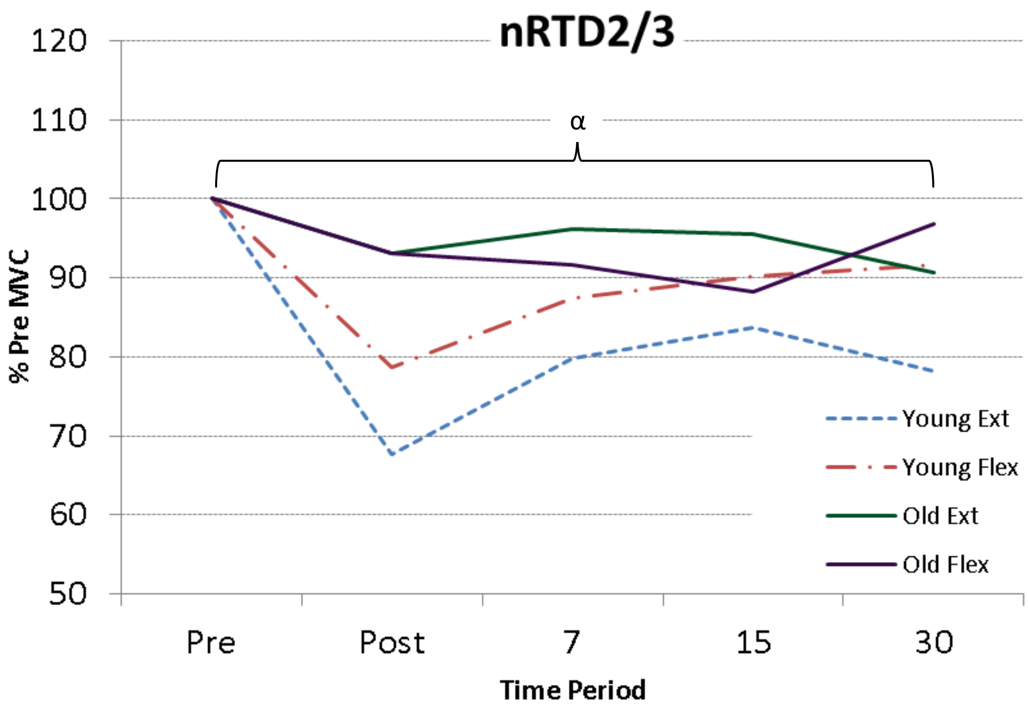

Figure 9: Mean normalized rate of torque development at 2/3 (nRTD2/3) of the normalized torque-time curve showing values expressed relative to Pre MVC (%) for all time periods in the young and old men for the knee extensors and flexors. α indicates a significant group × time interaction where significant differences were found for the young men between Pre compared to Post and Recov7 and no differences were observed between any of the time periods for the old men.

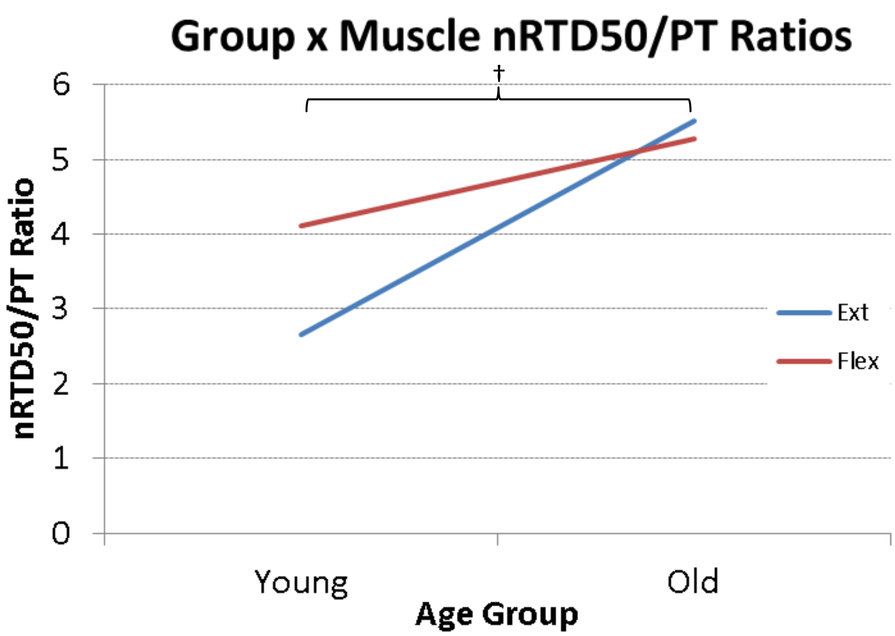

Figure 10: Mean nRTD50/PT ratios for the knee extensors and flexors in the young and old men (collapsed across all time periods). † indicates a significant group × muscle interaction where the knee flexors were greater compared to the knee extensors in the young, but not in the old men.

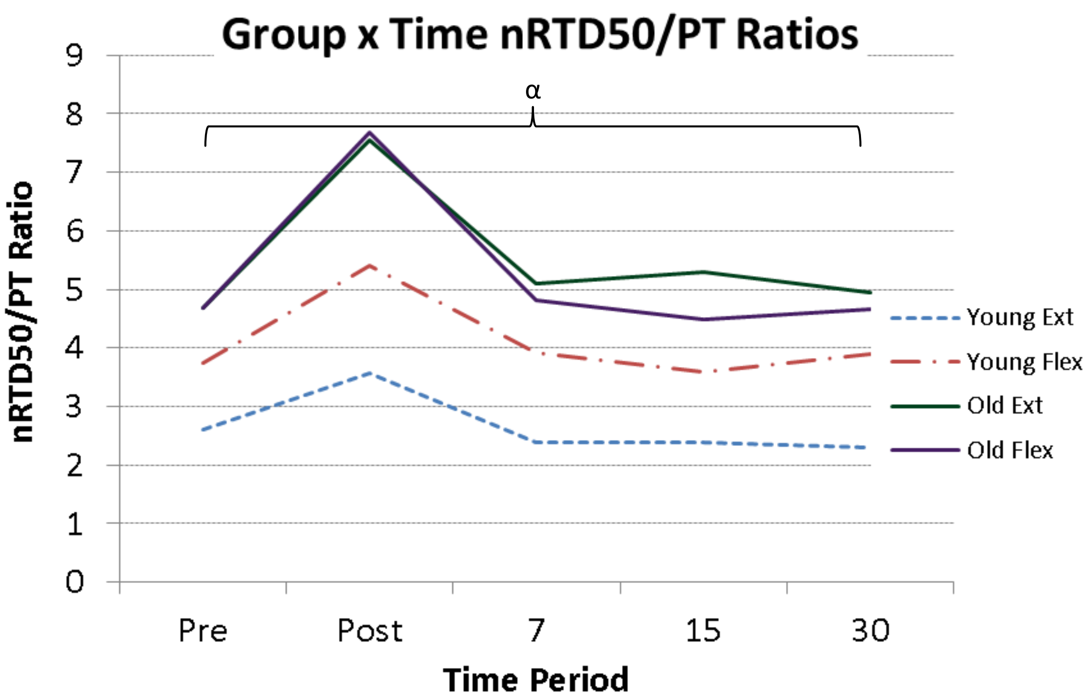

Figure 11: Mean nRTD50/PT ratios for all time periods in the young and old men for the knee extensors and flexors. α indicates a significant group × time interaction where Post was greater in both young and old men compared to all other time periods. Additionally, the old men had greater values at all time periods compared to young men.

CHAPTER V

DISCUSSION

The primary findings of the present investigation showed that older men had greater endurance on the fatigue task compared to young men. Although neuromuscular fatigue resulted in similar reductions in absolute rapid force production among early and late phases of the torque-time curve, muscles, and age groups immediately following the fatigue task; differential recovery patterns were observed for PT, and early and late RTD phases between the knee extensor and flexor muscle groups. Specifically, the early rapid torque variables (RTD30 and RTD50) and the knee flexors demonstrated slower recovery compared to later rapid torque variables (>RFD100) and the knee extensors. The normalized RTD variables declined to a lesser extent following the fatigue task and differential muscle and group effects were observed where the knee flexors were reduced more at the early phase (nRTD1/6) compared to the knee extensors, however, for the later phase (nRTD2/3) the young men exhibited a significantly greater reduction compared to the old men.

The present findings showed that the old men exhibited an overall 36.7% greater endurance time compared to the young men (collapsed across muscle groups). These findings are in agreement with previous studies that have reported greater endurance times or fatigue resistance for old compared to young men for the elbow flexors[83-87], plantar flexors[88], dorsiflexors[89-93], wrist flexors[94], shoulder abductors[95], and knee extensors[94,96,97] during isometric fatigue tasks. Although the present study revealed no significant differences in endurance times between the knee extensors and flexors, the flexors demonstrated a trend ($P = 0.087$) towards greater endurance times compared to the extensors. For example, when comparing the knee extensors and flexors endurance times between young and old men, the old men exhibited 22.0% and 47.3% greater endurance times for the knee extensors and flexors, respectively. When examining the knee extensors muscle group specifically, previous authors have shown similar age-related enhanced fatigue resistance values (i.e. 14.0 – 26.5%)[94,96,97] as the present findings while others have revealed no differences[98-100] between old and young men for isometric fatigue protocols. These contrasting findings may be attributed to differences between the age ranges and health and habitual activity levels of participants, as well as the variety of different isometric fatigue protocols used between studies[101,102]. In a recent review, Avin and Law[101] have demonstrated that the age-related effects leading to greater fatigue resistance in older adults appear to be muscle group specific. Specifically, the muscles of the knee joint appeared to exhibit smaller age-related fatigue resistance effects favoring the older individuals, in comparison to other muscle groups that were examined (i.e., elbow and ankle joint muscles). However, the majority of studies examining the effects of fatigue and aging on the knee joint are almost exclusively limited to the knee extensors. No studies were found that have examined the effects of fatigue on the knee flexors across age groups, therefore making comparisons with the present findings not feasible. These findings are among the first to show that the knee flexors may exhibit relatively large age-related fatigue resistance characteristics favoring old compared to young men. Although the variability of muscle group specific effects regarding age-related fatigue resistance have been reported[95,101], collectively, there appears to be an overall consensus that older adults exhibit greater relative muscular endurance and/or fatigue resistance[101,102], and the present study both supports and highlights these effects particularly for the primary locomotor muscle groups of the anterior and posterior thigh. These observed effects may be attributed to physiological changes that occur during the aging process. For example, there is considerable evidence that muscle fiber type shifting occurs across the life span such that older adults exhibit increased type I fiber area relative to type II muscle area resulting from a preferential loss or atrophy of type II fibers[103-106]. It has thus been suggested by previous authors[29,98,102,103,107,108] that the larger proportion of type I compared to type II fibers in older adults may be a significant physiological contributor to the observed age-related fatigue resistance, given the lower fatigability and enhanced metabolic efficiency characteristics of type I muscle fibers and the correlations of this fiber type with muscle endurance performance[103,109]. Additionally, other age-related mechanisms including contractile factors, and neural and metabolic efficiency, have been proposed as being potential contributors to the suggested increased capacity for fatigue resistance in older healthy adults[29]. However, the specific mechanisms contributing to the age-related increased fatigue resistance are largely unknown, and at present the literature is still inconclusive regarding the certainty of a definitive advantage in fatigue for older adults[29,101,102]. Future research is needed to improve our understanding of the mechanisms of muscle fatigue and the influence of various interventional strategies aimed at improving fatigue resistance across the lifespan, and should also involve lesser studies muscles which are important for functional performance[102], such as the knee flexors.

The fatigue induced reductions in the absolute RTD variables across all time phases of the torque-time curve ranged from ~ 50 to 70% of Pre MVC values, which were relatively similar in magnitude (although greater in range) to the reductions observed for PT (62-63%). Previous studies show conflicting findings in which some support the present study demonstrating that PT and RTD were reduced to a similar magnitude following fatigue[62,67,69,110-114], whereas other studies contrastingly have revealed relatively greater fatigue induced reductions in rapid compared to maximal torque/force variables[65,115,116]. These discrepancies may be explained by differences in fatigue protocols, testing setups and methodologies used for determining maximal and rapid force/torque variables. The variety of fatigue protocols used among studies have resulted in varying degrees of fatigue attained following the fatigue tasks, resulting in varying magnitudes of declines in both maximal and rapid torque characteristics. For example, different fatigue protocols among studies involving squat[65,110,112], leg press[111], soccer[62,113] and handball [115] match play and maximal[114,116] and submaximal[67,117] isometric leg extension protocols reveal markedly different declines in maximal (range = 7.1 - 55.6%) and rapid (3.5 – 56.6%) torque characteristics between studies and participants. Also, testing setup differences between studies include bilateral[67,117] vs. unilateral[114,116] isometric MVC testing, and a wide variety of methods of calculating RTD/RFD which include RFDpeak[65,69,112,114-116], RFD at varying percentages of maximal force[65,110], RFD at absolute varying time intervals (i.e. 30, 50, 100,200 [62,113,115] and the amount of average force produced in an absolute time period (i.e. 100ms intervals)[69,110,111]. These differences along with the variety of study populations examined (strength trained vs. non-trained; young vs. old; men vs. women), are likely contributors to the fatigue related discrepancies among studies for both maximal and rapid torque variables. Taken together, however, particularly when examining fatigue induced via isometric contractions, these findings seem to suggest that fatigue-related mechanisms resulting in both decreased maximal and absolute rapid force/torque characteristics immediately following fatigue, may be similar, and thus potentially stemming from common or shared physiological impairment mechanisms. The mechanisms contributing to neuromuscular fatigue may stem from changes in one or many stages in a complex chain of central and peripheral physiological processes[81,118] influencing neuromuscular activation and contractile processes and ultimately force producing capacities. Factors resulting in fatigue due to muscular activity have been suggested to involve one or several of a variety of potential failure sites which may include metabolic perturbations, neuromuscular transmission impairments, central activation and/or peripheral/contractile failure[27,29]. Previous authors, however, have suggested that the specific mechanisms involved with fatigue are highly task dependent[2,119]. Specifically, the fatigue related mechanisms pertaining to sustained maximal or submaximal contractions appear to be different than those that are involved in intermittent submaximal contractions. For instance, central fatigue has been reported to be a primary factor in sustained maximal contractions[84,119,120], however submaximal and intermittent contractions appear to primarily involve peripheral fatigue mechanisms[2,119,121-123]. Thus, given there is considerable support from previous studies with protocols similar to the present study, in which central fatigue was not observed with submaximal intermittent fatiguing contractions[1,2,81,119], it would appear that this is an unlikely candidate as a contributor to the observed fatigue-related force impairments. Furthermore, previous authors have shown that neither neuromuscular transmission failure[2,123,124] nor metabolic factors[81,125] can explain the fatigue observed during submaximal intermittent contractions. Thus, the observed fatigue related declines in muscle function from this type of fatigue task are likely peripheral related mechanisms and previous authors have revealed that E-C coupling impairment is the most likely cause[8,81,125-127].

In the current study there were differential recovery patterns for the knee extensors and flexors for PT and the early RTD variables (30 and 50ms) whereas there was no recovery differences between muscle groups for the late RTD period (100-200ms). The recovery period for both muscle groups for all variables examined required at least a minimum of 15 min, while incomplete recovery was still observed for several variables at 30 min post fatigue task. In agreement with these findings, Bilodeau et al.[84] and Allman and Rice[2] have reported an incomplete recovery of PT of the elbow flexors at 20 and 60 min post fatigue task, respectively. However, in contrast to these findings, other studies have demonstrated shorter recovery, where isometric PT had recovered at between 3 and 10 min post fatigue task[67,114,116]. These discrepancies are likely a result of differences between muscle groups and fatigue tasks between studies. For example, Bilodeau et al.[84] and Allman and Rice[2] both investigated the elbow flexors, in comparison to the leg extensors for the other previous studies[67,114,116], and it is possible that the effects of fatigue on the smaller elbow flexors are more pronounced than on the larger leg extensors[73]. Also, the Zhou[114] and Bilodeau et al.[84] studies utilized MVCs for the fatigue task, in comparison to Allman and Rice[2] and the present study, in which submaximal fatigue tasks were used. It is believed that fatigue tasks using maximal contractions involve different mechanisms compared to submaximal fatiguing contractions (see above). A novel finding of the present study was the slower recovery in the knee flexors and the early rapid torque characteristics, in comparison to the knee extensors and later rapid torque variables. The early rapid torque (30 and 50ms) variables demonstrated markedly lower values throughout the duration of the recovery period for the knee flexors. For example, whereas RTD100-200 had recovered to 93.9 – 101.9% of baseline by 30 min of recovery, the RTD30 had only increased to 75-81.9% of baseline values in the knee flexors. Several previous studies are in agreement with the observed slower recovery pattern of the rapid torque characteristics (in comparison to PT/PF), following a fatigue-inducing task[67,114,116]. For example, Zhou[114] revealed that PF had recovered to pre fatigue values by 10 min of recovery, but Peak RFD had not recovered at 20 min of recovery.

Interestingly, the early vs. late vs. PT differential effects were almost exclusively limited to the knee flexors muscle group, while this differential recovery pattern was not observed in the knee extensors. There is a paucity of data examining the effects of isometric fatigue tasks and the knee flexors, and no studies were found that examined these effects on rapid torque characteristics (i.e. RTD) during a recovery period, thus comparisons of these findings are limited. However, the present findings for PT are supported by previous authors who have suggested that the knee flexors may exhibit greater fatigue-induced effects compared to the extensors[73,128]. Emery et al.[73] have demonstrated that the knee flexors fatigued more than the extensors during a fatigue task and Kawabata et al.[128] have revealed that the knee flexors were slower to recover, in comparison to the extensors, following a fatigue task involving both muscle groups simultaneously. Muscle specific differences exist between the knee extensors and flexors that may contribute to these results which could render the knee flexors more vulnerable to the effects of fatigue/exercise-induced consequences in comparison to the knee extensors. Compared to the extensors, the flexors exhibit a smaller total muscle mass[33,34,73,129], a higher proportion of Type II fibers[31,36], longer fibers[32-34], and potentially smaller pennation angles[31]. A smaller muscle mass has been suggested as being a factor that may limit physical work abilities due to poor perfusion of these muscles[130], and there is considerable evidence that type II fibers are more adversely affected during fatiguing tasks compared to Type I fibers[27,116]. Additionally, daily activity patterns of the knee flexors may differ from the extensors such that the flexors may not be significant contributors in various daily living activities involving low levels of locomotor exertion[31,35]. The sustained effects of fatigue-induced reductions in maximal and early rapid torque characteristics for the knee flexors may have adverse performance and injury risk consequences. Given the knee flexors have been demonstrated to be important for athletic related tasks[19,50,74,75,131] and functional performances such as balance recovery[132], as well as play a major role in injury prevention of the knee and ACL[133-135]; a significant impairment and/or delayed recovery in the neuromuscular performance of this muscle group may increase the risks for adverse performance and injury events, for a sustained time period during recovery following the onset of exercise induced fatigue. These effects may prove to be particularly detrimental for elderly individuals, where minor detriments to performance may yield large functional performance and health related consequences.

Overall, the normalized rapid torque characteristics were reduced following the fatigue task to a lesser degree than the absolute rapid torque variables and differential effects occurred at early and late periods of the normalized torque-time curve. Specifically, a differential muscle group effect was observed at the early (nRTD1/6) period, whereas the later (nRTD2/3) period revealed different age-related effects. For the early period, there was no observed effect of fatigue for the knee extensor muscle group at Post nor during the recovery period. However, the knee flexors exhibited a delayed effect of fatigue, where they were not reduced at immediately Post, but had declined to lower than Pre values at 7 minutes of recovery and remained significantly lower than baseline during the remainder of the recovery period. Similar to the previously described differential muscle group effects of fatigue on maximal and absolute rapid torque variables, the normalized rapid torque qualities may be due to these physiological, structural, and physical activity characteristic differences between muscle groups. The physiological differences between muscle groups may result in smaller normalized rapid torque effects from fatigue, for the extensors compared to the flexors. Previous authors have suggested the normalized rapid torque characteristics represent "qualitative" factors, which include motor unit discharge rates and behavior, stiffness, fiber type, pennation angles, etc.[11,12], and therefore have been deemed "useful to study physiological mechanisms…independent of the maximal generated force"[14]. Thus, the qualitative factors involving physiological and structural differences among these muscles could contribute to the differential fatigue-induced rapid force deficits for the early normalized rapid torque variables. Although the actual fiber type differences between extensors and flexors are somewhat uncertain, some evidence suggests there is a higher amount of type II fibers in the flexors compared to the extensors[36]. Since, the type I fibers have been suggested to have greater stiffness[136-138] and fatigue resistant capacities[139] compared to the type II fibers, it is possible a relatively higher amount of type I vs. type II fibers in the knee extensors may exhibit different fatigue-induced effects. Also, other factors which are independent of muscle size and strength, such as shorter muscle fiber lengths and perhaps greater pennation angles observed in the knee extensors may contribute to the different fatigue-induced effects between muscle groups. Several of these qualitative factors appear to predominantly influence the early portion[13,140-142] of the normalized torque-time curve, therefore, possibly rendering enhanced resilience to substantial adverse effects of fatigue-induced physiological disruptions, and thereby possibly mitigating reductions in rapid torque production. Moreover, differences in activity patterns between muscle groups, where the flexors may be less involved in lower levels of activities of daily life[31,35], may contribute to the fatigue-induced discrepancies that show a larger effect for the flexors perhaps resulting from deficiencies in overall conditioning of the muscle. Collectively, given the aforementioned qualitative and muscle group factors (i.e. fiber type, long muscle fibers, lower activity pattern, etc.), perhaps the flexors may be more vulnerable to EC coupling mechanism impairment, which is the primary factor involved in low frequency fatigue and has been shown to exhibit slower and longer duration fatigue related effects[3,8]. This could further support and help explain the delay in the significant reduction of the knee flexor normalized rapid torque characteristics until minute 7 of recovery, and the maintained reduction, throughout the remaining duration of the recovery period. This would also align with the fiber type theory as the type II fibers appear to be more prone to LFF fatigue compared to type I fibers[3,143-145]. These proposed impairment mechanisms are supported by the similar long duration recovery pattern of the knee flexors that was observed in the absolute PT and RTD variables.

The later normalized torque time period (nRTD2/3) was not adversely effected immediately following fatigue nor during recovery in the old men, however, the young men experienced reductions at Post fatigue and early recovery (at 7 minutes). Perhaps these findings may be explained by similar qualitative factors as previously described for the muscle group discrepancies. The physiological and structural alterations in tendon and muscle that are suggested to occur during aging processes could influence qualitative factors associated with rate of rise in force production. These changes include fiber type shifting towards relatively greater proportions of type I compared to type II fibers[105,106], slower contractile characteristics[146,147] and greater musculotendinous stiffness[138,148]. It is possible these age-related physiological and structural changes may yield more “fatigue resilient” qualitative rapid force capabilities for normalized rate of tension development due to the positive relationship between these qualitative factors and normalized RTD[11,12,142,149]. For example, the greater amount of type I fibers, higher stiffness, and slower contractile qualities may potentially be less influenced by common mechanisms associated with fatigue, such as impaired EC coupling or LFF. Further, it has been suggested[27,29] that the slower contractile properties which are observed in old adults[146,147], may allow the older muscle to produce similar relative force even at lower motor unit discharge rates allowing for a greater degree of tetanic fusion[27] and better metabolic economy[29] in the muscle. This proposed age-related neuromuscular efficiency may explain the negligible and even absent effects of fatigue on normalized rapid torque production in the old men.

Interestingly, the expression of the normalized rapid torque to PT capacities (nRTD50/PT ratios) across time periods and age groups revealed, 1) the ratios increased following fatigue for both groups, but to a greater extent for the old than the young (significant group × time interaction), and 2) the ratios were greater at all time periods for the old compared to the young men. The increase in this ratio immediately following fatigue suggests that PT declined to a greater extent compared to the relative rapid torque capacities. A potential explanation for this occurrence may be that the factors that largely constitute the normalized RTD capabilities, were less affected by the fatigue, in comparison to the mechanisms that resulted in the proportionally greater reductions in PT. As mentioned above, these "qualitative" factors are independent of muscle strength and these findings suggest that because they were influenced less by the consequences of muscle fatigue compared to maximal strength, differential fatigue-related mechanisms may be involved between qualitative and quantitative force production. This also provides further support, that the fatigue-related loss of absolute torque production was related to the quantitative factors involved in the loss of maximal torque production, and thus, these mechanisms appear to be shared, at least in the present type of fatigue task. The greater normalized rapid to maximal torque values observed for the old compared to the young men suggests that PT declines are greater during aging than the relative capacity to develop force rapidly. This may be due to the aforementioned structural changes (increased musculotendinous stiffness), and the more efficient tetanus at lower frequencies as a function of slower muscle contractile properties[146,147]. These age-related adaptations could allow the muscle to maintain the "qualitative" characteristics to a relatively high degree to offset the markedly large declines in quantitative muscle characteristics that occur during old age. Perhaps this could be a compensatory mechanism, such that a lower rate of decline in relative rapid force capacities across the lifespan may help counteract the larger decreases in maximal strength related characteristics, which could enhance efficient and reduce the effects of fatigue on rapid force production yielding lower overall relative functional performance consequences resulting from fatigue-related mechanisms.

It is noteworthy to highlight that these findings did not show any age effect on the magnitude of declines in absolute RTD variables, following fatigue nor during recovery. This finding is in agreement with Valkeinen et al.[150] who revealed no age related differences in maximal or rapid torque declines between young and older adults following a fatigue task of the neck extensors and flexors. Few studies have examined the influences of aging and fatigue on rapid force/torque characteristics, with the only study the author is aware of examining the neck muscles. Thus, the influence of fatigue in older adults for the functionally important locomotor muscles is largely unknown. Although the present study has shed some light on these effects, further research is warranted investigating the effects of a variety of fatigue tasks on the muscles of the lower limb specifically pertaining to the effects on rapid force qualities. Further research in this area is necessary to elucidate and quantify these effects, and to help better clarify and understand the age-related physiological mechanisms involved in such tasks.

CHAPTER VI

CONCLUSION

The present study was designed to test the hypothesis that a fatigue inducing bout of intermittent submaximal contractions would exhibit larger effects on the rapid torque characteristics compared to maximal torque characteristics and that these effects would be exacerbated in older men. A second aim was to examine the influence of a recovery period on these force and age characteristics, and to make comparisons between antagonistic locomotor muscle groups of the anterior and posterior thigh (knee extensors and flexors). Overall, these hypotheses were not supported in this study. The rapid force characteristics declined to a similar magnitude as the maximal strength characteristics and these effects were no different in the old compared to the young men for all absolute rapid torque variables. Also, the normalized rapid torque variables were reduced to a lesser extent than the absolute variables across all time periods (nRTD1/6-nRTD2/3). Taken together, these findings suggest that the fatigue-induced reduction in both maximal and rapid torque characteristics may share or stem from common physiological mechanisms, and that this was independent of age, in healthy men. It was also concluded that the “qualitative” neuromuscular mechanisms, which are representative of the normalized rapid torque properties are minimally effected from this type of fatigue task. In addition to adding to the paucity of data available regarding the influence of aging and fatigue on rapid torque properties, the present study also revealed novel differential muscle group effects on the recovery of maximal and rapid torque characteristics. Overall, despite a similar reduction in magnitude of both maximal and rapid torque immediately following a fatigue task, the knee flexors muscle group exhibited slower and sustained reductions in these characteristics during recovery, compared to the extensors. These findings suggest muscle group specific differences pertaining to the effects of fatigue. To the authors' knowledge, this is the first study to investigate these age-related effects, for the knee flexor muscles, and to make these comparisons to their antagonistic muscle group. These muscle group specific differences may be attributed to the structural, morphological, physiological and activity dependent differences inherent between these muscle groups. The observed fatigue-induced sustained reductions of maximal and rapid torque properties for the leg flexors has substantial performance and injury risk implications. Given the importance of the knee flexors in athletic related tasks, functional living tasks such as balance recovery, and injury risks including knee stabilization and prevention of ACL injuries, these sustained adverse force decrements may be of large practical and functional significance to a variety of populations and settings. Further, because older individuals operate nearer their functional independent living thresholds compared to younger adults, any decrements in performance may be particularly detrimental to the elderly where minimal changes in performance may result in rather large effects on independent living abilities, and quality of life.

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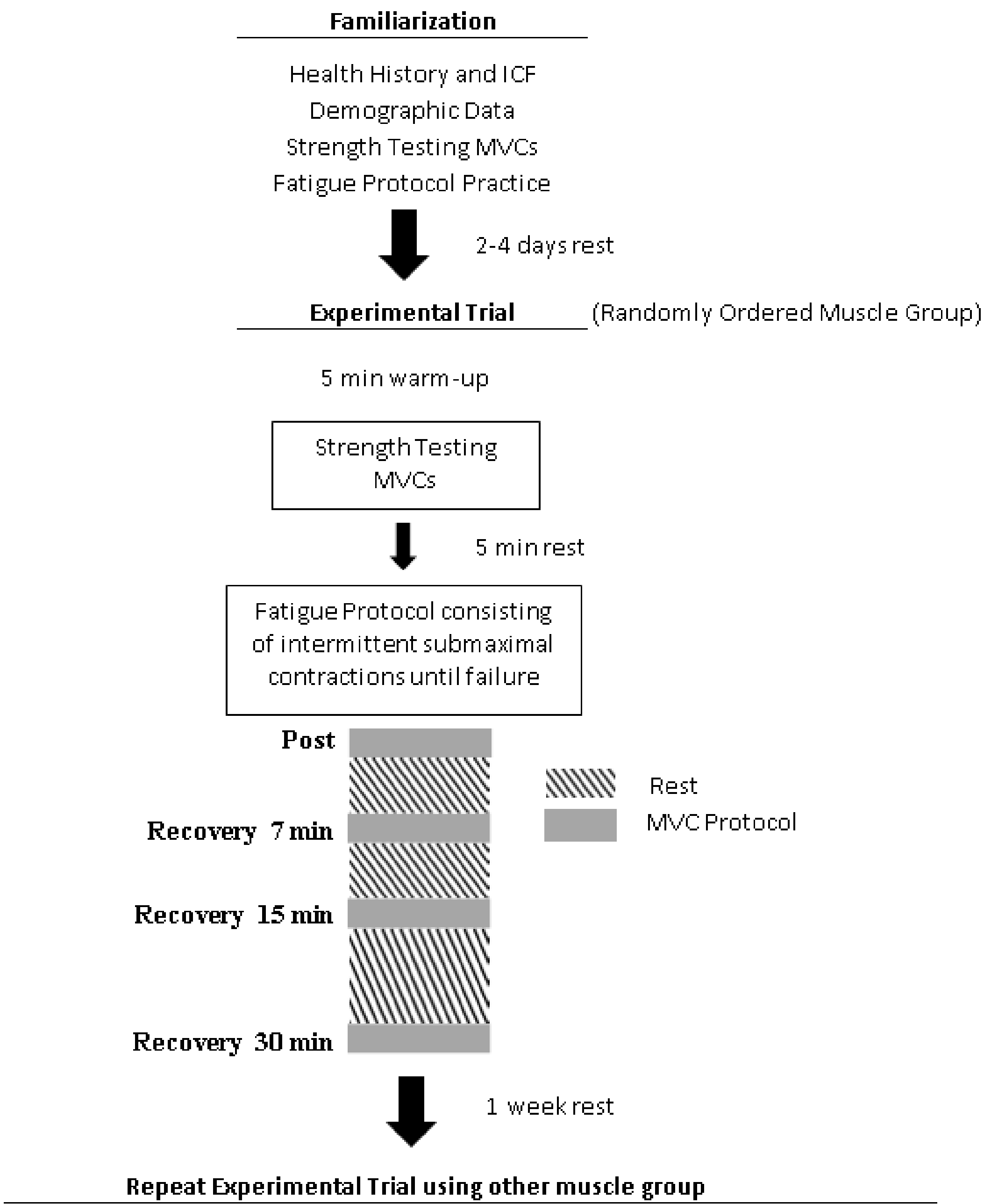
APPPENDICES

APPENDIX A

RESEARCH DESIGN



APPENDIX B

MUSCLE STRENTH AND FATIGUE DYNAMOMETRY TESTING SETUP

APPENDIX C

HEALTH HISTORY QUESTIONNAIRE

PRE-EXERCISE TESTING HEALTH & EXERCISE STATUS QUESTIONNAIRE

HEALTH AND HUMAN PERFORMANCE DEPARTMENT

Participant ID# ______________________________ Date_______________

Email: ____________________________________ Cell Phone _________________________

Other Phone _________________ Home Address_______________________________________

Person to contact in case of emergency ____

Emergency Contact Phone _______________________ Birthday (mm/dd/yy)____/_____/_____

Personal Physician ______________________________ Physician's Phone________________

Gender_________ Age ______(yrs) Height ______(ft)______(in) Weight______(lbs)

A. JOINT-MUSCLE STATUS (✓Check areas where you currently have problems)

Joint Areas
( ) Wrists
( ) Elbows
( ) Shoulders
( ) Upper Spine & Neck
( ) Lower Spine
( ) Hips
( ) Knees
( ) Ankles
( ) Feet
( ) Other______________________

Muscle Areas
( ) Arms
( ) Shoulders
( ) Chest
( ) Upper Back & Neck
( ) Abdominal Regions
( ) Lower Back
( ) Buttocks
( ) Thighs
( ) Lower Leg
( ) Feet
( ) Other_____________________

B. HEALTH STATUS (✓Check if you currently have any of the following conditions)

( ) High Blood Pressure
( ) Heart Disease or Dysfunction
( ) Peripheral Circulatory Disorder
( ) Lung Disease or Dysfunction
( ) Arthritis or Gout
( ) Edema
( ) Epilepsy
( ) Multiply Sclerosis
( ) High Blood Cholesterol or Triglyceride Levels
( ) Allergic reactions to rubbing alcohol
( ) Acute Infection
( ) Diabetes or Blood Sugar Level Abnormality
( ) Anemia
( ) Hernias
( ) Thyroid Dysfunction
( ) Pancreas Dysfunction
( ) Liver Dysfunction
( ) Kidney Dysfunction
( ) Phenylketonuria (PKU)
( ) Loss of Consciousness

C. EDUCATION HISTORY (✓ Check your highest formal education)

( ) Graduate of Middle School (8^{th} grade)
( ) Highschool graduate
( ) Associates degree
( ) Bachelors degree
( ) Masters degree
( ) Doctoral degree

D. PHYSICAL EXAMINATION HISTORY

Approximate date of your last physical examination_______________________________
Physical problems noted at that time____

Has a physician ever made any recommendations relative to limiting your level of physical exertion? _________YES __________NO
If YES, what limitations were recommended?___________________________________
____

E. CURRENT MEDICATION USAGE (List the drug name and the condition being manag

MEDICATION	CONDITION
___________________________	_____________________________________
___________________________	_____________________________________
___________________________	_____________________________________

F. PHYSICAL PERCEPTIONS (Indicate any unusual sensations or perceptions. ✓Check have recently experienced any of the following during or soon after *physical activity* (PA) during *sedentary periods* (SED))

PA	SED		PA	SED	
( )	( )	Chest Pain	( )	( )	Nausea
( )	( )	Heart Palpitations	( )	( )	Light Headedness
( )	( )	Unusually Rapid Breathing	( )	( )	Loss of Consciousness
( )	( )	Overheating	( )	( )	Loss of Balance
( )	( )	Muscle Cramping	( )	( )	Loss of Coordination
( )	( )	Muscle Pain	( )	( )	Extreme Weakness
( )	( )	Joint Pain	( )	( )	Numbness
( )	( )	Other________________________	( )	( )	Mental Confusion

G. FAMILY HISTORY (✓Check if any of your blood relatives . . . parents, brothers, sisters uncles, and/or grandparents . . . have or had any of the following)

( ) Heart Disease
( ) Heart Attacks or Strokes (prior to age 50)
( ) Elevated Blood Cholesterol or Triglyceride Levels
( ) High Blood Pressure
( ) Diabetes
( ) Sudden Death (other than accidental)

H. EXERCISE STATUS (Please provide a **precise** estimation of your previous exercise hat

Do you regularly engage in aerobic forms of exercise (i.e., jogging, cycling, walking, etc.)? YES

How long have you engaged in this form of exercise? ______ years ______ months

How many *hours per week* do you spend for this type of exercise? _______ hours

Do you regularly lift weights? YES

How long have you engaged in this form of exercise? ______ years ______ months

How many *hours per week* do you spend for this type of exercise? _______ hours

Do you regularly play recreational sports (i.e., basketball, racquetball, volleyball, etc.)? YES

How long have you engaged in this form of exercise? ______ years ______ months

How many *hours per week* do you spend for this type of exercise? _______ hours

PRE-EXERCISE TESTING
HEALTH & EXERCISE STATUS
QUESTIONNAIRE

HEALTH AND HUMAN PERFORMANCE DEPARTMENT

Subject ID ______________________________ Date________________

EXCLUSION CRITERIA:

1. Participants have indicated they have current (within past 6 months) joint-muscle problems with their hips, legs or knees that would prevent them from satisfactorily completing the testing.
2. If they have any specific condition or a physician has specified they are not able to perform muscular exertion in which case they would not be allowed to complete the testing
3. They perform resistance training exercise more than 3 times per month.

APPENDIX D: IRB APPROVAL

Oklahoma State University Institutional Review Board

Date:	Tuesday, June 19, 2012
IRB Application No	ED1291
Proposal Title:	The Influence of a Bout of Muscle Fatigue on Torque and Rapid Torque Characteristics of the Leg Flexors and Extensors
Reviewed and Processed as:	Expedited

Status Recommended by Reviewer(s): Approved   Protocol Expires: 6/18/2013

Principal Investigator(s):

Brennan Thompson
192A Colvin Center
Stillwater, OK 74078

Douglas Smith
197 Colvin Center
Stillwater, OK 74078

The IRB application referenced above has been approved. It is the judgment of the reviewers that the rights and welfare of individuals who may be asked to participate in this study will be respected, and that the research will be conducted in a manner consistent with the IRB requirements as outlined in section 45 CFR 46.

☒ The final versions of any printed recruitment, consent and assent documents bearing the IRB approval stamp are attached to this letter. These are the versions that must be used during the study.

As Principal Investigator, it is your responsibility to do the following:

1. Conduct this study exactly as it has been approved. Any modifications to the research protocol must be submitted with the appropriate signatures for IRB approval. Protocol modifications requiring approval may include changes to the title, PI, advisor, funding status or sponsor, subject population composition or size, recruitment, inclusion/exclusion criteria, research site, research procedures and consent/assent process or forms.
2. Submit a request for continuation if the study extends beyond the approval period of one calendar year. This continuation must receive IRB review and approval before the research can continue.
3. Report any adverse events to the IRB Chair promptly. Adverse events are those which are unanticipated and impact the subjects during the course of this research; and
4. Notify the IRB office in writing when your research project is complete.

Please note that approved protocols are subject to monitoring by the IRB and that the IRB office has the authority to inspect research records associated with this protocol at any time. If you have questions about the IRB procedures or need any assistance from the Board, please contact Beth McTernan in 219 Cordell North (phone: 405-744-5700, beth.mcternan@okstate.edu).

Sincerely,

Shelia M. Kennison

Shelia Kennison, Chair
Institutional Review Board

APPENDIX E
INFORMED CONSENT FORM

INFORMED CONSENT FOR PARTICIPATION IN THE STUDY

Project Title: The influence of muscle fatigue on torque and rapid torque characteristics of the quadriceps and hamstrings muscles.

Investigators: Brennan Thompson, M.S.
Doug Smith Ph.D.
Eric Conchola, M.S.
Kazuma Akehi, M.S.
School of Applied Health & Educational Psychology
Oklahoma State University

Purpose: Muscle fatigue may result from a wide variety of sport related and daily living activities. There are many functional consequences relating to muscle fatigue that may adversely affect performance outcomes for many populations. The purpose of this investigation is to examine the effects of a single bout of muscular fatigue on strength and explosive strength qualities for the hamstrings and quadriceps muscles.

Procedures:

- As a participant you will visit the lab on 3 occasions, for a total of about 2 hours over the course of 1-2 weeks with a minimum of 1 week between testing day 2 and day 3.

Day 1 (40 minutes)

- During the 1st visit you will complete this form and one other brief form that will give us an idea of your current health and physical activity status.
- You will have your height, weight, percent body fat measured, and we will also take girth measurements of your thigh, calf and forearm.
- You will then practice the vertical jump, strength and fatigue protocols that will be performed on the following 2 lab visits.

Day 2 (40 minutes)

- Perform a light 5 min warm-up on a bike.
- Perform a vertical jump test in which you jump as high as you can three times.
- Perform strength assessments of your hamstring or quadriceps muscles with sensor electrodes taped to your skin to see how "active" the muscles are. You will be asked to push or pull as hard as you can against a padded lever arm
- Perform a fatigue protocol which involves contracting your muscles at a sub-maximal intensity until you can no longer attain/maintain the required force output.
- Repeat the strength measures immediately following the fatigue protocol, and at 7, 15 and 30 minutes of passive recovery following the bout of fatigue.

Day 3 (40 minutes)

- Perform a light 5 min warm-up on a bike.
- Perform strength assessments of your quadriceps or hamstrings muscles with sensor electrodes taped to your skin to see how "active" the muscles are. You will be asked to push or pull as hard as you can against a padded lever arm
- Perform a fatigue protocol which involves contracting your quadriceps muscles at

maximal intensity until you can no longer attain/maintain the required force output.

- Repeat the strength measures immediately following the fatigue protocol, and at 7, 15, and 30 minutes of recovery following the bout of fatigue.

Lab Location: 192 Colvin Recreation Center, Stillwater, OK.

Exclusion Criteria: you will be unable to participant if you have:

- A specific health condition that would not allow you to complete the testing.
- If your physician has suggested you should not partake in general fitness testing.

Risks of Participation: Possible risks include muscle soreness and temporary blood pressure elevation due to muscle contractions as well as potential injury (muscle sprain or strain) to the knee or ankle joint as a result of muscular exertion. Medical records will only be used during the screening process. In case of injury or illness resulting from this study, emergency medical treatment will be available (CPR certified investigators and 911). No funds have been set aside by Oklahoma State University to compensate you in the event of illness or injury.

Benefits: These findings may help researchers and clinicians better understand the influences of muscle fatigue on muscle strength and explosive strength functional and performance qualities and it may also help them to provide more appropriate recommendations for athletes, the general population, ACL injured and/or aging individuals pertaining to these measurements.

Confidentiality: Confidentiality will be maintained by coding all information with individual identification numbers. The master list will be kept in a locked file cabinet in the PI's office. Only qualified research personnel and the Oklahoma State University Institutional Review Board (IRB) will have access to the database containing study information. All study data entered into statistical analyses and publication reports will have no identification to participants. Only mean (average) values will be reported. No individual or group other than the research team will be given information, unless specifically requested by the IRB. All primary data sources will be kept in the locked file cabinet located in the PI's office. It is possible that the consent process and data collection will be observed by research oversight staff responsible for safeguarding the rights and wellbeing of people who participate in research.

Contacts: This study has been reviewed and approved by the Oklahoma State University Institutional Review Board (IRB). If you have questions about the research project you may contact Brennan Thompson, M.S. at brennan.thompson@okstate.edu, Doug Smith, Ph.D, at doug.smith@okstate.edu, Eric Conchola M.S. at eric.conchola@okstate.edu, or Kazuma Akehi M.S. at kazuma.akehi@okstate.edu
If you have questions about your rights as a research volunteer, you may contact Dr. Shelia Kennison, IRB Chair, 219 Cordell North, Stillwater, OK 74078, 405-744-3377 or irb@okstate.edu

Participation Rights: Participation in the study is voluntary and you are free to withdraw completely from the study at any time. There is no penalty for refusal to participate or failure to complete the study.

I have read and fully understand the consent form. I sign it freely and voluntarily.

______________________________ Date:__________

Signature of Participant

I certify that I have personally explained this document before requesting that the participant sign it.

______________________________ Date:__________

Signature of Researcher

APPENDIX F
RECRUITMENT FLYER

HEALTH AND HUMAN PERFORMANCE DEPARTMENT

Hello,

My name is Brennan Thompson and I am a doctoral student in the Health and Human Performance Department at Oklahoma State University. We are conducting a study in our laboratory which examines the influence of short term muscle fatigue on strength and explosive strength characteristics of the leg muscles. We are looking for male or female participants between the ages of 18-30 and males of the age of 55 and older. We are trying to examine and understand how short term muscle fatigue effects performance based on a comprehensive assessment of your leg strength and how aging affects these characteristics.

What types of testing will you do?

Body Composition: We will assess your percent body fat and muscle composition
Strength: How strong your lower body muscles are.
Power: How much power you can generate based on a vertical jump test
Muscle Endurance: How well you can perform on a brief muscle fatigue test

The study involves only 3 visits to the laboratory. The visits will take approximately 40 minutes each for a total time of about 2 hours.

If you are interested we can be reached at the following:

Lab Phone: 405-744-9373

Email: brennan.thompson@okstate.edu

Thank you for your interest in supporting Oklahoma state university, the human performance laboratory and the students as well as your contribution in furthering our understanding of the physiological responses of fatigue and muscle strength across the life span.

Kind Regards,

Brennan Thompson, M.S.
Applied Musculoskeletal & Human Physiology Laboratory
Health & Human Performance Department
Oklahoma State University
Email: brennan.thompson@okstate.edu

APPENDIX G
RECRUITMENT SCRIPT

Verbal Recruitment Script

Hello, my name is Brennan Thompson, and I am doctoral student in Health and Human Performance at Oklahoma State University. I am involved in a research study entitled "the influence of a bout of muscle fatigue on torque and rapid torque characteristics of the leg flexors and extensors". We are trying to determine how a short term fatigue protocol influences basic lab strength and explosive strength muscle characteristics across the life span.

Testing will consist of three visists to the Health and Human Performance Lab within the Colvin Recreation Center (room 192). The sessions will last approximatetly 40 minutes each.

During the visit you will fill out forms that will provide specific details of the study and require you to answer questions about your health status. You will then have your body composition, height, weight and girth measurements taken. Following a light warm-up you will perform three maximal vertical jump assessments. Following this, you will be performing strength assessments of your right hamstrings and quadriceps muscles. During these assessments surface EMG sensors will be placed on the surface of your skin to measure how active the muscle is.

During the strength testing assessments you will be asked to push or pull as hard as you can against a padded lever arm on an isokinetic dynamometer (Physical Therapy testing device) for a total of 2-4 seconds. Following the initial strength testing, you will perform a brief fatigue protocol of the right quadriceps or hamstrings muscles until you can no longer attain the required force. You will then perform the same strength assessments again immediatelv following the fatigue protocol and at 7, 15 and 30 minutes of the recovery period.

You will be required to sign an informed consent document showing that you understand all of the procedures and your rights as a research participant. As a partic will contribute to the understanding of the physiological relationships between muscl and basic strength and explosive strength characteristics and functional dynamic jump abilities which may be an indicator of performance and also a useful screening tool us clinicians, researchers, coaches and practitioners in a variety of settings. I would be happy to answer any additional questions that you may have about the study. Do you think you might be interested?

Thank you.

VITA

Brennan J. Thompson

Candidate for the Degree of Doctor of Philosophy

Dissertation: AGE-RELATED EFFECTS OF NEUROMUSCULAR FATIGUE AND RECOVERY ON VOLUNTARY MAXIMAL AND RAPID TORQUE CHARACTERISTICS OF THE LEG FLEXORS AND EXTENSORS IN YOUNG AND OLD MEN

Major Field: Health, Leisure, & Human Performance

Biographical:

I was born and reared in blossom, UT. I spent many years working on a ranch, in north-central Minnesota, with my family. I enjoy the great outdoors and traveling as well as horseback riding and spending time with my family. I look forward to what my future in higher education will bring.

Education:

Completed the requirements for the Doctor of Philosophy in Health & Human Performance at Oklahoma State University, Stillwater, Oklahoma in May, 2013.

Completed the requirements for the Master of Science in Health, Physical Education, and Recreation at Utah State University, Logan, Utah in May, 2008.

Completed the requirements for the Bachelor of Science in Exercise Science/Nutrition Education at Weber State University, Ogden, Utah in May, 2004.

Experience:
Graduate Assistant, Oklahoma State University
August 2009-May 2013
Graduate Assistant, Utah State University
August 2006-May2008
Worked as a trainer, and lead exercise therapist at various gyms and wellness centers

Professional Memberships:
National Strength and Conditioning Association (2007 – Present)
American College of Sports Medicine (2011 – Present)