AGE-RELATED DIFFERENCES IN RAPID TORQUE PRODUCTION: INFLUENCE OF MUSCLE SIZE, QUALITY, ARCHITECTURE, AND ACTIVATION

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A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Arts in the department of Exercise and Sport Science in the College of Arts and Sciences (Exercise Physiology).

Chapel Hill
2014

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ABSTRACT

JOSEPH G. ROSENBERG: Age-Related Differences in Rapid Torque Production: Influence of Muscle Size, Quality, Architecture, and Activation
(Under the direction of Eric Ryan)

Rapid torque production is important for many activities of daily living and has been shown to decrease in older adults. The purpose of the present study was to examine the age-related differences in the rate of torque development (RTD) and the influence of muscle size (CSA), muscle quality (EI), pennation angle (PA), fascicle length (FL) and the rate of electromyographic rise (RER) on RTD. Ultrasonography was used to examine muscle architecture and RTD and RER were examined with surface electromyography during a maximal isometric strength assessment in 35 young and 22 older men. Absolute peakRTD (*a*RTDpeak) and PA were lower and EI was greater in the older men (P<0.05), with no differences in CSA, FL and RER (P>0.05). With groups combined, CSA, EI, and PA were related to *a*RTDpeak (P<0.05). These findings may suggest that the age-related reductions in *a*RTDpeak may be related to alterations in muscle quality and PA.

ACKNOWLEDGEMENTS

I would first like to thank my advisor, Dr. Eric Ryan, for your patience, wisdom, and help with all aspects of this thesis. I have learned so much about the writing process and what it takes to be a productive researcher. I would also like to thank my committee members, Dr. Abbie Smith-Ryan and Mr. Eric Sobolewski, for taking the time to review my document and for providing invaluable insight and advice. Finally, I would like to thank Gupper, Ed, Andrew, Craig, and Brennan for all your help both in and out of the lab.

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LIST OF ABBREVIATIONS

*a*RTDpeak	Absolute peak rate of torque development
CSA	Cross-sectional area
EI	Echo intensity
EMG	Electromyography
FL	Fascicle length
MG	Medial gastrocnemius
MVC	Maximal voluntary contraction
*n*RTDpeak	Normalized peak rate of torque development
PA	Pennation angle
RER	Rate of electromyographic rise
RFD	Rate of force development
RTD	Rate of torque development
ttRER	Time to peak rate of electromyographic rise
ttRTDpeak	Time to peak rate of torque development

CHAPTER I

INTRODUCTION

Previous work by Andersen and colleagues (3) have suggested that "explosive muscle strength is one of the single most important physiological parameters for successful performance in many sports". These characteristics are often examined *in vivo* during a rapid maximal isometric contraction, whereby the rate of torque or force production is examined from the onset of the muscle action at specific time intervals (i.e 0-30 ms, 100-200 ms) along the torque-time curve (57). Although rates of torque development (RTD) are commonly evaluated in athletic settings (57), previous studies have demonstrated that rapid contractile variables are markedly reduced (25-64%) with aging and may result in serious mobility limitations and/or an increased risk of falling in older adults (14, 18, 23). These variables are of particular importance as many rapid movements (i.e. recovering from a fall) occur within 50–200 ms, which is significantly less time than it takes to reach maximal torque (≥300 ms) (3). For example, Bento et al. (6) demonstrated that older women without a previous fall history (non-fallers) generated greater leg flexion RTD than those who experienced a fall despite no difference in peak strength. In a three-year prospective study, Pluijm et al. (43) found that of the 55.3 percent of adults who reported a fall, 20.9 percent reported three or more falls. In addition, Clark et al. (12) recently showed that maximum walking speed in healthy older adults was limited by impaired rates of force development (RFD). Andersen and Aagaard (4) have shown that from the onset of torque production, RTD is increasingly dependent on maximal voluntary contraction (i.e. maximal muscle strength) and less dependent on neural drive as the time from the onset of muscle action increases. Furthermore, previous studies have indicated that RTD decreases to a greater extent in aging adults than maximal strength (18, 26, 56). Collectively, these findings demonstrate that the age-related decline in rapid contractile variables may significantly contribute to the functional decline observed in older adults.

Previous research has shown that reductions in muscle mass (i.e. sarcopenia) with increasing age may correspond to a decline in maximal strength (18, 20, 56). In a study by Sipilä et al. (50) involving the quadriceps muscle, significant correlations between muscle strength and CSA were observed, with non-significant correlations between strength and muscle thickness. Similarly, Thompson et al. (56) reported that both estimated thigh CSA and RTD were significantly lower in older compared to young adults, indicating a possible relationship between these two variables. For example, Suetta et al. (53) found that changes in rapid force characteristics of the quadriceps among older adults were accompanied by alterations in muscle CSA.

The age-related loss of contractile tissue has also been associated with a quantifiable increase in intramuscular noncontractile tissue. Previous studies examining muscle quality among older adults have demonstrated a negative relationship between muscle tissue quality and isometric strength. For example, Kent-Braun et al. (25) reported an increase in the non-contractile area in older adults when compared to the younger adults, in addition there was a significant inverse association between the percent of dorsiflexor muscle noncontractile area and habitual physical activity level. These findings may indicate that older adults with lesser muscle quality may possess a greater infiltration of intramuscular adipose and connective tissue, which may result in lower levels of muscular strength (17). Echo intensity (EI), an index of muscle quality obtained through the gray-scale analysis of individual pixels within an ultrasound (US) image has previously been correlated with skeletal muscle infiltration of fat and fibrous tissue (42). Despite a lack of available data concerning longitudinal reductions in muscle quality, there appears to be a general consensus that the increase in EI, indicative of reduced skeletal muscle quality, predominantly occurs among those adults over 60 years of age (5). Furthermore, the prevalence of sarcopenia may range from 13-24% in persons aged 65-70 years and nearly 50% for those over 80 years of age (15). Thus, despite non-significant changes in overall CSA between young and older adults, muscle quality may decline with age as lean muscle mass becomes increasingly replaced with fat and fibrous tissue (24, 45). This reduction in muscle quality may be attributed to neuromuscular aging - the progressive neurogenic process whereby a diminished re-innervation capacity causes a permanent denervation and loss of the fiber (32). Until recently, ultrasonography EI analysis has utilized individual slices of muscle cross-sections, rather than a composite image of the entire muscle (5, 9, 17). While EI can still be obtained in this manner, panoramic ultrasonography allows for quantification of a complete region or muscle of interest (2, 41). As the presence of intramuscular adipose and fibrous tissue may not necessarily be evenly distributed throughout the muscle, a panoramic analysis of the entire cross-section of the muscle may provide a better estimate of skeletal muscle quality.

Additionally, muscle architectural properties have been proposed as the primary determinants of muscle function with regard to shortening velocity and force transmission, where increases in both these parameters enhance movement efficiency, thereby improving rapid force production (33). For example, Moreau et al. (37) reported that rectus femoris fascicle length and pennation angle were significant predictors of peak RFD in healthy young children. Furthermore, peak RFD was found to be related to sport and physical functioning performance to a greater degree than maximal strength. While Narici and colleagues (40) have previously shown that both fascicle length and pennation angle decrease with increasing age, the possible relationship between these architectural features and RTD warrants further investigation in older adults.

Aging-related atrophy and subsequent loss of rapid force generation and functionality may be caused by a loss of muscle fibers beginning at 25 years of age, with a subsequent reduction in the size of the remaining type II fibers (32). Specifically, because type II fibers are capable of producing up to 10-20 times the isometric tension as type I fibers, performance of rapid movements may become impaired (8). For example, Roos et al. (45) suggested that because muscle force output depends on both contractile properties and firing rates, examination into both these factors might elucidate the mechanisms of frailty and motor control in older adults. Recently, Thompson et al. (56) reported significantly lower maximal and rapid torque characteristics among older men when compared to young and middles-aged men. However, these authors did not examine EMG data and were unable to determine if these differences were attributed to alterations in muscle activation. For example, Klass et al. (26) reported that the age-related reduction in RTD was accompanied by a reduction in the number of doublet discharges and motor unit discharge frequency particularly for the second and third interspike intervals. However, recent papers by Clark and colleagues (10, 11) demonstrated no differences in rapid muscle activation (i.e. rate of EMG rise) of the quadriceps between healthy middle-aged and older adults. These findings highlight the following: (a) future studies are needed to elucidate the influence of agonist rapid muscle activation on RTD variables, and (b) other factors in addition to muscle size and rapid muscle activation patterns may contribute to the age-related reduction in RTD variables.

In summary, the ability to examine muscle architecture *in vivo* is important for assessing changes associated with exercise interventions (2), neuromuscular diseases (38), and aging (47). Falls are the largest single cause of restricted activity days among the elderly, at 18% (48). Accordingly, identifying the mechanisms responsible for falls among older adults may allow for more specialized training programs among older patients, potentially reducing the number of restricted activity days. Rapid torque characteristics hold significant functional relevance among the aging population, because many functional movements last less than 250 ms (56). LaRoche and colleagues (30) suggest that neuromuscular as well as strength and RTD deficits in the ankle musculature may be present in adults with a history of falling, and that strength, speed of movement, and power of the ankle plantarflexors should be examined as potential contributors to falls in older adults. Therefore, the purpose of the present study was to examine the age-related differences in muscle quantity, muscle quality, pennation angle, fascicle length and the rate of EMG rise on the RTD.

<u>Purpose</u>

1. The primary purpose of this study was to 1) investigate the age-related differences in medial gastrocnemius (MG) muscle size (CSA), muscle quality (EI), pennation angle (PA), fascicle length (FL), the rate of EMG rise (RER) and normalized (*n*RTDpeak) and absolute (*a*RTDpeak) peak rate of torque development, 2) to determine the relationship between these variables in young and older adults, and 3) to determine the relative contributions of MG size, quality, architecture, and activation on relative and absolute plantar flexor RTD in young and older adults.

<u>Research Questions</u>

1. Do CSA, EI, PA, FL, RER, *n*RTDpeak and *a*RTDpeak decline with increasing age?

2. Are CSA, EI, PA, FL and RER related to either *n*RTDpeak or *a*RTDpeak in young adults, older adults, and all ages combined?
3. Which parameters are most predictive of *n*RTDpeak and *a*RTDpeak separately and combined amongst age groups.

<u>Hypotheses</u>

1. CSA, EI, PA, FL, RER, *n*RTDpeak and *a*RTDpeak will decline with increasing age.
2. CSA, EI, PA, FL and RER will be related to *n*RTDpeak and *a*RTDpeak in both groups separately, and when groups are combined.
3. CSA, EI, and RER will significantly contribute to *n*RTDpeak and *a*RTDpeak in both groups separately, and when groups are combined.

<u>Delimitations</u>

1. Participants in the young and older groups were between the ages of 18-30 years and 65-74 years, respectively.
2. Muscle activity of the medial gastrocnemius was measured using bipolar surface electrodes and the BIOPAC system.

<u>Limitations</u>

1. Participant recruitment took place throughout various departments on the UNC campus. Therefore, participant selection was not truly random.
2. The sample included volunteers, therefore not meeting the underlying assumption of random selection.

<u>Theoretical Assumptions</u>

1. Participants provided accurate health and exercise history on the enrollment questionnaire.

2. All participants gave maximal effort when performing isometric contractions.
3. Each participant's right leg was completely relaxed during all US assessments.
4. All equipment was calibrated and accurate for all testing sessions.

Statistical Assumptions

1. The population from which the samples were drawn was normally distributed.
2. The data were based on a parametric scale, either interval or ratio.
3. The within-group variability of the samples in the experiment was equal or nearly so (homogeneity of variance).

Operational Definitions

Surface Electromyography (EMG) – an electrical recording of the muscle action potential potentials that sweep across the sarcolemma and pass through the surface electrode recording areas during a skeletal muscle action; representative of motor unit recruitment and firing frequency; the raw signal is expressed in microvolts (μV) (16).

Recreationally Active – 1-5 hours per week of structured and/or recreational exercise, excluding competitive athletes.

Maximum Voluntary Contraction (MVC) – the maximum voluntary torque produced by a muscle or group of muscles under isometric conditions.

Panoramic Ultrasound – an image fitting method that extends the field of view of the ultrasound probe through real-time generation of a cross-sectional image.

Echo Intensity (EI) – an index of muscle quality obtained through computer aided gray-scale analysis of the individual pixels within an ultrasound image; representative of the amount of adipose and/or connective tissue in a given cross-sectional scan of skeletal muscle.

CHAPTER II

REVIEW OF LITERATURE

This literature review will include previous research studies that are most related to the influence of neuromuscular function on the age-related reduction in RTD. Additionally, the results of each study along with the conclusions suggested by the authors will provide a more in-depth understanding of the concepts expressed later in Chapter V of this thesis. This review will begin with an overview of the mechanisms suggested to be responsible for changes in RTD, and then move to an overview of the effects that aging may have on these mechanisms.

The influence of age on various mechanisms of RTD

<u>Thelen, Schultz, Alexander, and Ashton-Miller (1996)</u>

The purpose of this study was to examine the effects of aging on rapid torque development of the ankle during dorsiflexion (DF) and plantarflexion (PF). Twenty-four healthy young (YA, 19-29 years) and 24 healthy older (OA, 65-86 years) adults, with equal numbers of males and females in the two age groups participated in this study. All tests were performed with an isokinetic dynamometer (MERAC, Universal Gym Equipment, Cedar Rapids, IA) with the subjects laying in the supine position and dominant foot attached to the footplate. During all trials, the participants knee angle was maintained at 20º below full extension, with an ankle angle of 100º and 85º during isometric DF and PF muscle actions, respectively. Isometric and isokinetic (30, 60, 120, 190, and 240º/s) muscle actions were initiated by a visual cue, and concluded after 3 seconds through an audible digital tone. Following six submaximal and maximal warm-up trials, torque data were recorded during three sets of six muscle actions with 30 seconds between trials and five minutes between sets. Each set consisted of one isometric muscle action followed by one isokinetic muscle action at each of the five velocities. Surface electromyographic (EMG) signals were recorded from the tibialis anterior, soleus, and medial and lateral gastrocnemius muscles using bipolar surface electrodes. Maximum isometric voluntary strength (MVS) and absolute rate of torque development (MRTD) were significantly lower among the OA compared to the YA for isometric plantarflexion ($P<0.01$). MVS and MRTD were significantly lower among the OA compared to the YA for isometric dorsiflexion ($P<0.05$), with the exception of MVS among the male participants ($P>0.05$). The loss in MRTD with age was 25% and 29% in the dorsiflexors and plantarflexors, respectively. While the normalized RTD (NRTD) in the dorsiflexors and plantarflexors was greater for the YA than the OA, the difference was not significant ($P>0.05$). Additionally, YA developed significantly larger maximum isokinetic torques than OA at all angular velocities examined ($P<0.05$). The authors (54) suggested that the ability of healthy older adults to recover their balance following a perturbation or to complete time-critical actions that require at least moderate strength may be considerably degraded by the reductions in the elderly to develop ankle torque rapidly. Furthermore, the authors posit that these age related declines in RTD may result from changes in muscle activation or adaptations of muscle mechanics.

<u>Izquierdo, Aguado, Gonzalez, López, and Häkkinen (1999)</u>

The purpose of this investigation was to examine age-related changes in balance, as well as maximal and explosive force production characteristics of the leg extensor muscles during isometric and dynamic muscle actions. Thirty-two healthy men divided into young (M20, n=12), middle-aged (M40, n=10) and older groups (M70, n=10) volunteered for this study. All participants were tested for their maximal bilateral isometric leg extension force (MIF) and maximal rate of force development (RFD) during the complete muscle action from a squatted isometric condition using a force platform (Dinascan 600M). MIF testing consisted of three trials lasting 2.5-4 s with a 90 s rest period. Dynamic explosive force was measured on the force platform through a maximal vertical squat jump (SJ), counter movement jump (CMJ), and standing long jump (SLJ). Balance performance was measured as the transition time (TT), percentage of time inside center with respect to the overall time lit (TC), and straightness of trajectory (ST) for the participant to achieve a bull's-eye by moving their body. MIF in M70 was significantly lower ($P<0.001$) than both M40 and M20. Similarly, M70 demonstrated significantly lower values ($P<0.001$) than both M40 and M20 in SJ, CMJ, and SLJ protocols. Both maximal RFD and the force produced during the first 500 ms of the MIF were significantly lower in M70 ($P<0.001$-0.01, respectively) than in M40 and M20. Maximal RFD values between M40 and M20 did not differ significantly from one another ($P>0.05$). Specifically, the maximal RFD in M70 was 64% lower than in M20, while MIF in M70 was only 46% lower than in M20. Regarding balance performance, TT between the lit centers in M20 was significantly shorter than in M70 ($P<0.001$), while TC was greater in M20 than in M70 ($P<0.001$). The authors (23) concluded that explosive force production of the leg extensor muscles, examined through RFD, significantly declines with age to a greater extent than maximal muscle strength. Further, this loss of explosive force may contribute to the age-related impairments in postural control and balance.

<u>Aagaard, Magnusson, Larsson, Kjær, and Krustrup (2007)</u>

The purpose of this investigation was to examine maximum isometric muscle strength (MVC), rapid force development (RFD), and muscle fiber characteristics in lifelong strength (S) or endurance (E) trained and untrained (U) old participants. Twenty-four old (age: 70.5-73.9 years) males (E, n=9; S, n=7; U, n=8) volunteered for this experiment. All strength measurements were preceded by a warm-up including 5 min of ergometer cycling at 100 W and five to seven maximal vertical jumps. Maximal voluntary contraction (MVC) force and RFD (*d*Force/*d*time) and impulse were obtained at a 70º knee joint angle using an isokinetic dynamometer (KinCom, Kinetic Communicator, Chattecx Corp., Chattanooga, TN). The MVC protocol consisted of three to five maximal isometric quadriceps contractions, each separated by a 45-s pause. RFD and impulse parameters measured at the time intervals 0-30, 50, 100, and 200 ms were obtained from the trial with the largest contractile impulse at 0-200 ms relative to force onset. Normalized RFD was calculated as RFD normalized to MVC (RFD/MVC) Muscle morphology and fiber type composition were obtained from the vastus lateralis of the dominant limb. The results suggested that MVC normalized to body mass was significantly greater in S and E than U (P<0.01), with no significant differences in time to reach one-half and two-thirds MVC between S, E, and U (P>0.05). Both RFD and impulse at each time interval were significantly greater in S compared with U (P<0.05). Further, normalized RFD was greater in S but not E compared with U at the earliest phase of the muscle action (determined at one-sixth MVC) (P<0.05). In conjunction with the finding that muscle fiber CSA and RFD did not differ between E and U (P>0.05), these results indicate that qualitative factors (muscle architecture and neuromuscular control) may be responsible for the age-related reduction in rapid muscle action. This study demonstrated that elderly subjects chronically exposed to either endurance or strength training activities have higher maximal muscle strength than do untrained, age-matched individuals. Thus, the authors (1) suggested that the rapid muscle force exertion observed within this study may have been retained at a higher level in physically active older individuals, particularly when exposed to chronic strength training.

Klass, Baudry, and Duchateau (2008)

The purpose of this investigation was to examine the relationship between the rate of torque development (RTD) and maximal motor unit discharge frequency in young and old adults during rapid muscle actions of the ankle dorsiflexors. Ten healthy young (mean ± SD: age = 20.2 ± 1.6 years, n=5) and older adults (age = 75.6 ± 5.7 years, n=5) participated in this study. Each participant performed 2-3 maximal voluntary contractions (MVCs) separated by 2-3 min of rest, followed by 10 fast isometric voluntary muscle actions around each of the three target torques (25, 50, and 75% MVC) as indicated by a visual feedback display. Each fast muscle action was separated by at least 3-5 s and 3-5 min of rest between motor unit recordings from the different electrode locations. The isometric force developed by the dorsiflexor muscles was measured using a force transducer (model TC 2000-500, Kulite, Basingstoke, UK) attached to a footplate. Motor unit potentials were recorded by a selective electrode that comprised diamel-coated nichrome wires glued into the lumen of a hypodermic needle. The electrode was inserted into the middle part of the tibialis anterior muscle and during each experimental session the needle was inserted in at least three separate locations. A difference in recruitment threshold of at least 10% was considered to represent distinct motor units. The MVC torque was determined from the trial that yielded the largest value and the average rectified EMG (aEMG) amplitude was measured for a 1-s period during the plateau of the MVC. Peak torque, time to peak torque, and peak RTD were obtained from each fast muscle action. The mean MVC torque was significantly greater (28%) in the young compared with the older adults ($P<0.05$). While the average time to peak torque during the fast muscle actions was 26% longer ($P<0.01$) in the older adults, there was no difference (P=0.38) between the two groups when peak torques were expressed relative to the respective MVC torques. The fast muscle action was accompanied by a 48% decrease in absolute peak RTD (P<0.01) and by a 33% decrease in relative peak RTD (P<0.01). Peak RTD was linearly related to the peak torque achieved during the fast muscle actions produced at different torque levels in both young and old men. The results indicated that regardless of the torque achieved during the fast muscle action, the peak RTD was significantly (P<0.01) lower in older adults. Additionally, there was a significant age-related decline (P<0.001) in motor unit discharge frequency during the fast voluntary muscle action, with the discharge frequency of the third interspike interval significantly lower than the second (P<0.05) among the older adults. The percentage of motor units that discharged doublets (interspike intervals <5 ms) was significantly greater for young (8.4%) than for old (4.6%) adults (P<0.05). The authors (26) suggested that healthy aging involves neural impairments that likely limit the maximal capacity of motoneurons to discharge at very high rates, illustrated with the decline in interspike intervals and doublets, which consequently may limit maximal RTD.

Thompson, Ryan, Sobolewski, Conchola, and Cramer (2013)

The purpose of this investigation was to examine the age-related differences in maximal and rapid torque variables of the leg extensor and flexor muscle groups in young, middle-aged, and old men. Sixty-five healthy, recreationally active young (mean ± SD: age = 24.9 ± 3.0 years, n=25), middle-aged (age = 50.6 ± 4.0 years, n=22), and old (age = 66.8 ± 4.5 years, n=18) men volunteered for this investigation. Maximal isometric strength testing was performed on the right leg using a Biodex System 4 isokinetic dynamometer (Biodex Medical Systems, Inc. Shirley, NY, USA). All isometric torque assessments were performed at a leg flexion angle of 60º below the horizontal plane. Two isometric maximal voluntary contractions (MVCs) of the leg flexors and extensors were performed with one minute of recovery between muscle actions and three minutes between muscle groups. All torque signals were sampled with a Biopac data acquisition system (MP150WSW, Biopac Systems, Inc., Santa Barbara, CA, USA). Estimated total thigh muscle cross-sectional area (eThighCSA) was calculated from midthigh circumference and anterior thigh skinfold measurements. Isometric MVC peak torque (PT) was determined as the highest 0.5 s epoch during the 3-4 s MVC plateau. Rate of torque development (RTD) was quantified from the linear slope of the torque-time curve at time intervals of 30 (RTD30), 50 (RTD50), 100 (RTD100), and 200 ms (RTD200) from the onset of torque production. Contractile impulse (IMPULSE) was determined as the integrated area under the torque-time curve for the previously described time intervals (see above). Finally, relative RTD values were computed on the normalized torque-time curve at 10, 20, 30, 40, and 50% of the MVC. PT was greater for the young ($P<0.001$) and middle-aged ($P=0.001$) men when compared to the older men. RTD50 was significantly greater for the young compared to the old men for the leg extensors ($P=0.024$). While both RTD30 ($P=0.003$) and RTD50 ($P=0.002$) were greater for the middle-aged men compared to the older men, only RTD50 was significantly greater for the young men compared to the older men. Peak RTD ($P<0.001$), RTD100 (young, $P<0.001$; middle-aged, $P=0.002$), and RTD200 ($P<0.001$) were significantly greater for the young and middle-aged men than the older men. No significant differences between age groups were observed for relative RTD ($P>0.05$), IMPULSE30 ($P=0.004$), IMPULSE50 ($P=0.002$), and IMPULSE100 ($P=0.003$) were significantly greater for the middle-aged men than the older men, while IMPULSE200 was greater for both the young ($P<0.001$) and middle-aged men ($P=0.001$) compared to the older men. Additionally, eThighCSA was significantly lower for the old men compared to the young ($P=0.001$) and middle-aged men ($P=0.016$). The results of this study indicated that maximal and rapid torque variables were significantly lower in the older men when compared to young and middle-aged men for both leg extensor and flexor muscle groups ($P<0.05$). These findings demonstrated that there might be an age-related neuromuscular adaptation at the early phases (RTD30 and RTD50) of the torque-time curve, as well as an age-related reduction in muscle mass, as indicated by the lower eThighCSA among the older men. The authors (56) concluded that because the maximal and rapid torque variables were maintained in the middle-aged compared to younger men, these age-related declines of the lower extremities may not present prior to age 50. Additionally, because relative RTD was not significantly different between age groups, the authors suggest that strength and muscle mass may be critical for improving RTD among older adults.

Factors influencing rate of torque development

Skelton, Greig, Davies, and Young (1994)

The purpose of this investigation was to compare the strength, power and functional ability of healthy older adults (65 – 89 years) and to assess the effects of aging on muscular and functional performance. Fifty independent, healthy men volunteered for this investigation, with ten men in each half-decade from 65 – 89 years. Maximal voluntary contraction (MVC) of the leg extensors was measured with the subject seated in an adjustable straight-back chair, the lower leg unsupported and the knee flexed to 90º. Each MVC was determined as the peak force obtained for at least one second from the best of three attempts with 30 s rest periods. Leg extensor power (LEP) over five trials was measured using a modified Nottingham Power Rig, with the subject seated with a 90º knee angle while pressing on a footplate as hard and fast as possible. Box stepping (progressively 10, 20, 30, 40, and 50 cm) without the use of handrails was utilized as a functional ability measure, with the highest step recorded. The results suggested that the age-related loss of LEP was significantly greater than the rate of loss of MVC (P=0.0001). The differences in isometric strength and leg extensor power over the age range were equivalent to reductions of 1-2% and 3.5% per year, respectively. Age and LEP relative to body weight each accounted for 33% of the variance in step height (P=0.04). These findings suggested that reductions in functional performance may be due to inactivity and disease rather than strength or power. The authors (51) suggested identification of those adults most at risk for becoming dependent might only be possible through comparisons with healthy older adults, and that strength and power may play a role in changes in functional performance.

Andersen and Aagaard (2006)

The purpose of this study was to determine if the rate of force development (RFD) at different time points from the onset of muscle action is influenced by different mechanisms. The authors examined the relationship between voluntary contractile RFD at different time intervals (0 – 10 ms to 0 – 250 ms) from onset of muscle action with maximum strength and electrically evoked muscle twitch contractile properties (time to peak torque, peak torque, peak twitch RFD, and half relaxation time). Twenty-five (mean ± SD: age = 23 ± 3 yrs) healthy sedentary males participated in this study. Voluntary and evoked muscle force was assessed across multiple isometric strength tests of the leg extensors. Participants completed four maximal muscle actions of 3 s each with a rest period of 60 s using a strain gauge load cell (Bofors KRG-4, Bofors, Sweden) at a static knee joint angle of 90º. Peak force produced from the MVC was defined as the highest peak torque value of the four maximal attempts. Electrically evoked contractile properties of the vastus lateralis during leg extension were measured with the subjects at rest using surface stimulation electrodes (Bioflex, model PE3590) placed over the distal and proximal part of the vastus lateralis muscle. The results demonstrated no correlation between twitch time to peak torque (r=-0.26-0.11), half relaxation time (r=-0.10-0.01), and twitch peak torque with voluntary RFD (r=0.01-0.14) (P>0.05). At time intervals later than 90 ms from muscle action onset, maximal muscle strength could account for 52-81% of the variance in voluntary RFD, indicating that factors other than maximal strength may be responsible for early RFD. Specifically, a significant relationship was observed between both voluntary RFD at 30 ms (r=0.57, P<0.01) and 200 ms (r=0.89, P<0.001) from the onset of muscle action and twitch RFD. These findings suggested that voluntary RFD becomes increasingly dependent on maximal strength and less dependent on twitch RFD and intrinsic muscle contractile properties when RFD is calculated later from the onset of muscle action. The authors (4) suggest that RFD at later phases of muscle action (150-250 ms) may be influenced by muscle cross-sectional area, a component of maximal muscle strength, as well as the neural drive to the muscle fibers.

Andersen, Andersen, Zebis, and Aagaard (2010)

The purpose of this investigation was to examine the change in contractile rate of torque development (RTD) in the early (<100 ms) and later phases (>200 ms) of a maximal voluntary contraction in response to high-intensity resistance training. Fifteen healthy sedentary males (mean ± SD: age = 23.5 ± 3.2 years) participated in the resistance training intervention, with ten participants matched as a control group (mean ± SD: age = 23.9 ± 3.1 years). Resistance training was performed for 14 weeks with three session/week following a linear progression model for the leg press, hack squat, knee extension and hamstring curl with four to five sets for each exercise. During the first 15 sessions, the relative exercise loading included a 10-12 repetition maximum (RM) load (four sets), followed by 8-10 RM load (four sets) during sessions 16-25 and a 6-8 RM load (five sets) during sessions 26-38. Maximal voluntary isometric contractions (MVC) of the leg extensors were performed at a static knee joint angle of 70º using a KinCom dynamometer (Kinetics Communicator, Chattecx Corp., Chattanooga, Tennessee, USA). MVC testing, preceded by a 15 min dynamic and isometric submaximal contraction warm-up, consisted of three maximal isometric attempts lasting 3 s with 60 s rest periods. MVC was defined as the highest peak torque of the three maximal attempts, while RTD was defined as the slope of the torque-time curve in increasing time-intervals from onset of muscle action to 250 ms. The results indicated that in the resistance training group, the RTD increased 11% at 250 ms from onset of muscle action ($P<0.05$) whereas no significant changes occurred in the earlier time intervals. Relative RTD (RTD/MVC) significantly decreased 10-18% ($P<0.05$) from the onset of muscle action to 140 ms in the resistance training group. MVC increased 18% in the resistance training group, while no change occurred in the control group ($P<0.001$). The training-induced increase in RTD observed at 250 ms was positively correlated to the gain in MVC (r=0.69, $P<0.01$), with an explained variance of 48% ($P<0.05$). The authors (3) suggested that because contractile RTD in the early and later phases of rising muscle torque respond differently to resistance training, training to improve early RTD should be performed with the intention of maximal acceleration regardless of the actual movement velocity.

<u>Moreau, Falvo, and Damiano (2012)</u>

The purpose of this study was to examine the relationship between rate of torque development (RTD), impulse, muscle architecture, and strength of the knee extensors on functional mobility. Twelve ambulatory children with cerebral palsy (CP) (mean ± SD: age = 11.9 ± 2.9 years) and 11 with typical development (TD) (mean ± SD: age = 11.3 ± 3.0 years) participated in this study. Ultrasound analysis of the rectus femoris (RF) and vastus lateralis (VL) at each muscles midpoint were obtained using a 6-12 MHz linear array transducer in 2D B-Mode (Voluson 730 Expert, GE Healthcare, Kretztechnik, Zipf, Austria), with the average of three measurements of each variable used for subsequent analysis. All measurements were performed on the right limb with the participants in the supine position with the leg at 10º of flexion. Muscle thickness (MT), fascicle angle (FA), and estimated fascicle length (FL) were obtained with the probe held in the longitudinal plane, while anatomical cross-sectional area (CSA) of the RF was obtained along the transverse plane. Each participant performed three maximal voluntary isometric contractions (MVC) on an isokinetic dynamometer (System 3 Pro, Biodex Medical Systems, Shirley, NY) in the seated position with a hip angle of 85º of flexion above horizontal and knee angle of 60º of flexion. Each MVC was performed for 3 s, with 60 s rest periods between trials, from which the highest MVC was used for subsequent analysis. RTD was calculated as the mean slope of the torque-time curve from onset of muscle action to 30, 50, 100, and 200 ms. Peak RTD (RTD_{peak}) was calculated as the maximum slope during the 0 – 200 ms time period, with RFD_{50} calculated as the slope at 50% of MVC. Impulse was obtained from the area under the torque-time curve during the same time periods described above. Gait (velocity, cadence, step length, stride length) was analyzed using a Vicon motion capture system (Vicon, Oxford Metrics, Oxford, UK) over ground level at a self-selected walking speed. Finally, functional mobility was assessed with the Pediatric Outcomes Data Collection Instrument (PODCI) parent report and the Activities Scale for Kids performance version (ASKp). All knee extensor RTD and impulse values among the CP group were significantly lower (P=0.001 – 0.002) than those in the TD group. The results indicated significant differences for normalized RTD (RTD/MVC) between the CP and TD groups at 0 – 30 ms, 0 – 50 ms, and 0 – 100 ms relative to onset of muscle action (P = 0.01 – 0.02), with no significant differences for normalized RTD at 0 – 200 ms, RTD_{peak}, or RTD_{50} (P = 0.054 – 0.64). While VL MT in the CP group was the only significant (P<0.05) predictor of RTD_{peak} (R^2 = 0.35) and impulse (0 – 100 ms) (R^2 = 0.50), all muscle architectural variables in the TD group were significant predictors of RTD_{peak} (R^2 = 0.46 – 0.71) and impulse (0 – 100 ms) (R^2 = 0.37 – 0.70). RTD_{peak} and impulse were the strongest predictors of PODCI Sports and Physical Functioning (r = 0.82, R^2 = 0.67, $P<0.05$). Additionally, while RTD_{peak} was shown to be a better predictor of sports and higher level activities (R^2 = 0.66, $P<0.05$), MVC was shown to be a better predictor of gait (R^2 = 0.50, $P<0.05$). VL MT was the primary predictor of RTD and impulse in the CP group, while all muscle architectural variables were predictors of impulse and RTD in the TD group across all time periods. The authors (37) suggest that RTD may be more closely related to strength during the later phases of the torque-time curve.

Changes in fiber type distribution and size with age

<u>Lexell, Taylor, and Sjöström (1988)</u>

The purpose of this study was to examine the age-related changes in muscle area, total number, size, proportion and distribution of fiber types of the vastus lateralis muscle in men. Forty-three previously healthy male cadavers (age = 15 - 83 years) that were less than three days post mortem were included in this study. Thin cross-sections (15 μm) taken from a 10 mm sample of the vastus lateralis half way between the origin and insertion were stained for myofibrillar adenosine triphosphatase and used for analysis. Muscle cross-sectional area (CSA), fiber density (mean fiber number per mm^2), total number of fibers and proportion of fiber types was measured using a 1 × 1 mm square grid placed over the muscle cross-section. The mean muscle CSA of type I and II fibers was calculated from 125 fibers of each type, taken from five different regions of the muscle cross-section. Each region included fibers in superficial, deep and central parts of the muscle cross-section. While muscle fibers in the younger men (age = 15 - 56 years) were tightly packed in fascicles of normal size and shape, fibers from the older men (age = 70 - 83 years) were less tightly packed with visible differences in fiber size and shape. Additionally, fiber type grouping was greater among the older men compared to the younger men. The largest muscle CSA was observed at 23.7 years of age, with a 40% reduction from age 20 to 80 years. There was a significant reduction (*P*<0.01) in size with increasing age of type II fibers only, with a 26% reduction from 20 to 80 years of age. Interestingly, the results indicated that muscle fibers comprised only 50% of muscle CSA among the older men, while muscle fibers in the younger men comprised 70% of muscle CSA. The authors (32) suggested that denervated and inactive fibers might be the cause for the change in fiber size and number, particularly in type II fibers, and that the replacement of those impaired fibers by fat and fibrous tissue may be responsible for the decrease in fiber density.

Lee, Cheung, Qin, Tang, and Leung (2006)

The purpose of this investigation was to examine the age-related changes in the number, size, and area percentage of different types of skeletal muscle fibers and connective tissues. Sixty-five men and women between 17 and 96 years of age participated in this study. Participants with neuromuscular diseases or injuries or damage affecting normal muscle structure and functions in the sampling region of the lower limbs were excluded. Biopsy specimens (5 mm^3) were obtained from the hamstring, vastus lateralis, gluteus, or tensor fascia lata. Ten sections from each biopsy specimen were cut, with the three highest quality sections analyzed following alkaline triphosphatase (ATPase) staining. Average muscle fiber area percentage, fiber number percentage, mean fiber area, and area percentage of connective tissues were analyzed. Based on the clinical criteria of aging recommended by the World Health Organization, the overall distribution of all skeletal muscle types and connective tissue proportions were compared between participants less than or greater than 65 years of age. The ratio of type IIa and IIb muscle fibers significantly decreased as age increased ($P<0.05$), with respect to total area, number, and mean fiber area. Alternatively, type I fibers increased in total area and number ($P<0.05$) with increasing age. Type IIa and IIb muscle fibers decreased in fiber number percentage (r=-0.282, $P=0.027$; and r=-0.552, $P<0.001$, respectively), and significantly increased in type I muscle fiber (r=0.597, $P<0.001$) with increasing age. Mean fiber area of type IIa and IIb fibers were smaller with increased age (r=-0.503, $P<0.001$; and r=-0.454, $P<0.001$, respectively), with no difference in type I muscle fibers (r=0.185, $P=0.151$). The area percentage of intramuscular connective tissue also increased with increasing age (r=0.401, $P=0.002$). Additionally, the type IIb muscle fibers appeared flattened and small with an aspect ratio (maximum length/maximum width) of 1.60 ± 0.40 for those participants less than 65 years of age, and 1.95 ± 0.60 for those greater than 65 years of age. These results indicated that type II muscle fiber number and size decrease with age, with concomitant increases in type I fiber number and connective tissue. The authors (31) suggested that lack of physical activity or regular exercise may have resulted in the differences in size and shape of the fast-twitch fibers to a greater extent than the deterioration seen with normal aging.

<u>Narici, Maganaris, Reeves, and Capodaglio (2003)</u>

The purpose of this investigation was to examine the age-related changes of the medial gastrocnemius (MG) anatomical cross-sectional area (ACSA), volume (Vol), fascicle length (FL), and pennation angle (PA). Thirty healthy, recreationally active young (age = 27 - 42 years, n=14) and old (age = 70 - 81 years, n=16) men participated in this study. MG ACSA and Vol were measured by computerized tomography (General Electric, ProSpeed Sx power), while resting FL and PA were assessed by ultrasonography (HDI-3000). ACSA was computed as the mean of three consecutive measurements on the same 10-mm slice from the MG muscle, with the maximum ACSA ($ACSA_{max}$) of the MG selected for subsequent data analysis. For MG muscle Vol calculation, all slices were fitted with a spline algorithm to interpolate for missing slices and total Vol was calculated by adding the individual ACSA of each image and multiplying the sum by the slice thickness. FL and PA were measured at the midbelly of the MG along the longitudinal plane. When the fascicle extended off the ultrasound image, the length of the missing portion of the fascicle was estimated by extrapolating linearly both the fascicular path and the aponeurosis. The results indicated significant differences between the older and younger groups for $ACSA_{max}$ (19.1%, $P<0.005$), Vol (25.3%, $P<0.001$), FL (10.2%, $P<0.01$), and PA (13.2%, $P<0.01$), with a significant correlation observed between ACSA and PA ($r = 0.432$, $P<0.05$). Additionally, a significant difference was observed between the older and younger groups for PCSA (15.2%, $P<0.05$). Because both $ACSA_{max}$ and PCSA of the MG were found to decrease with increasing age, the authors speculated that the aging process may include a loss of muscle fibers in series as well as parallel. Specifically, no difference was observed between the ratios of $ACSA_{max}$ to PCSA of the young (0.30 ± 0.04) and of the older (0.29 ± 0.06) ($P>0.05$). Combined between the young and old men, $ACSA_{max}$ and PCSA were found to be significantly correlated ($r=0.759$, $P<0.01$). The authors (40) suggested that the reductions in muscle size and architecture in the older group may not have been altered by disuse, because the older individuals selected in the study had similar physical activity and daily energy expenditure values to those of the younger group.

The influence of intramuscular fat and connective tissue on muscle quality

<u>Reimers, Reimers, Wagner, Paetzke, and Pongratz (1993)</u>

The purpose of this study was to examine the relative contributions of interstitial fat and fibrous tissue on muscle echogenicity values. In 82 participants between 11-71 years of age, 86 muscle biopsies were taken from the tibialis anterior (n=54), biceps brachii (n=14), rectus femoris (n=12), vastus lateralis (n=4), and medial gastrocnemius (n=2). Biopsy samples with a minimum of 100 fibers were included in the investigation (n=83). Total content of triglycerides in the muscle biopsy sample was determined enzymatically in 29 muscles. Ultrasonographic analyses of the muscles were performed in both transverse and longitudinal planes using a real-time scanner with a 3.75 MHz linear array transducer (Toshiba SSA 90-A, Tokyo, Japan). Echo intensities were determined using computer-assisted gray-scale analysis. The results indicated a significant correlation ($r=0.46$, $P<0.001$) between the content of intramuscular fat and the mean echogenicity. However, the degree of muscular fibrosis did not significantly influence the echogenicity ($P>0.05$). The authors (44) suggested that fat replacement, or increased intramuscular fat rather than increased fibrous tissue, constitutes the main cause of increased muscle echogenicity.

<u>Pillen, Tak, Zwarts, Lammens, Verrijp, Arts, Van Der Laak, Hoogerbrugge, Van Engelen, and Verrips (2009)</u>

The aim of this study was to examine the influence of fibrosis on muscle echo intensity (EI) obtained through ultrasound. Ultrasound measurements of 14 muscles were performed in two golden retriever dogs with muscular dystrophy, in order to obtain samples with variable amounts of fibrosis and small amounts of interstitial fat. EI of a region-of-interest that comprised the entire muscle without the surrounding fascia was measured through Adobe Photoshop (Adobe Systems Inc., San Jose, CA, USA) and obtained using a Sonos 2000 Phased Array Imaging System (Hewlett-Packard Co., Andover, MA, USA). Two ultrasound images were made in the transverse plane along the muscle belly and at 1 cm proximal and distal of the muscle belly. Following the ultrasound assessment, muscle cross-sectional specimens were collected at the site of the ultrasound examination. The largest cross-sectional area of each specimen was selected and cut in 4 μm thick sections. The percentage of perimysial and endomysial tissue were measured using digital image analysis, whereby microscopic fields of vision were digitized using a (Red Green Blue) CCD camera, and multiple sections of each image were randomly chosen for analyses. For each section, the 4 to 10 digitized images were analyzed and the mean percentage of fibrous tissue was calculated, while the percentage of interstitial fat was determined manually. Muscle EI was significantly correlated to the amount of fibrous tissue (r=0.87; P<0.001), and remained after correction for fat content (r=0.88; P<0.001). No significant correlation between fat and EI were observed (P>0.05), however the authors suggest that this may have been due to the low levels of fat within the specimens. The authors (42) conclude that increased echo intensity is both caused by the infiltration of fat and fibrous tissue. However, through ultrasound alone, the relative contributions of fat and fibrous tissue on mean EI may not possible.

<u>Delmonico, Harris, Visser, Park, Conroy, Velasquez-Mieyer, Boudreau, Manini, Nevitt, Newman, and Goodpaster (2009)</u>

The purpose of this investigation was to examine the relationship between muscle cross-sectional area (CSA) and intramuscular fat (IMF) with age-related changes in muscle strength over a five year period. In total, 1678 men and women between the ages of 70 and 79 years at baseline participated in this study. Body composition at baseline and five years was measured with DXA (QDR 4500A; Hologic Inc, Waltham, MA). The CSA and IMF of the right thigh were measured at baseline and five years later at the level of the midthigh using computed tomography. IMF was determined from subcutaneous fat by manually tracing along the deep fascial plane surrounding the thigh muscle, with the total area of non-adipose and non-bone tissues encompassed within the selection used to determine muscle area (cm^2). Average maximum isokinetic torque of the knee extensors was measured at baseline and at year six with a

Kin-Com 125 AP Dynamometer (Chattanooga, TN) at 60º/s on the right leg. The average of the three most similar trials was used for subsequent analysis. In both men and women, total thigh CSA, average torque (both $P<0.001$), and subcutaneous fat ($P<0.05$) all decreased significantly. There was also a significant increase in IMF area in both men and women ($P<0.001$). Muscle quality, defined as muscle torque relative to quadriceps muscle area and a measure of relative performance, decreased significantly with increasing age over the five year period ($P<0.001$). In the men, average torque decreased 16.1% ± 20.6, while muscle CSA decreased 4.9% ± 7.4. These findings suggested that IMF of midthigh skeletal muscle in men and women increase with age, with age-related decreases in strength exceeding the loss of muscle size. The authors (13) suggest that progressive weakness and the increase in infiltrating fat with age occur independent of changes in muscle quantity or subcutaneous fat.

The relationship between muscle size, muscle quality, muscle strength, and rate of torque development

<u>Visser, Goodpaster, Kritchevsky, Newman, Nevitt, Rubin, Simonsick, and Harris (2005)</u>

The purpose of this investigation was to determine whether low muscle mass, low muscle strength, and greater intramuscular fat predict incident mobility limitation. A total of 2631 participants (1286 men and 1345 women) participated in this study. Each participant performed maximal isokinetic leg extensions on a KinCom 125 AP Dynamometer (Chattanooga, TN) at 60º/s. Muscle strength was calculated from the average of three trials of a maximum of six trials. Thigh muscle cross-sectional area (CSA) and fat infiltration were measured by computed tomography (CT) at the midthigh. Intermuscular and visible intramuscular adipose tissue were measured by manually drawing a line along the deep fascial plane surrounding the muscle. Total area of non-adipose, non-bone tissue within the selection was used as a measure of muscle CSA

(cm^2). Fat infiltration was measured through mean attenuation of the thigh muscle, where lower attenuation indicated greater fat infiltration. Mobility limitations were assessed by self-reported level of difficulty walking one-quarter mile and climbing 10 steps without resting. Hazard ratios for men and women ranged between 1.68 ($P<0.01$) – 2.02 ($P<0.001$) for muscle strength and muscle attenuation. When muscle strength was accounted for, low muscle area did not remain a significant factor associated with incident mobility limitations. Additionally, those participants with the greatest amount of intramuscular fat (within the lowest quartile of all participants) were 50-80% more likely to develop mobility limitations over time, independent of muscle CSA, strength, or total body fat mass ($P<0.001$). The results indicated that only muscle attenuation and muscle strength independently predicted mobility limitation. The authors (59) suggest the association between low muscle mass and incident mobility limitations to be a function of lower muscle strength. Specifically, older persons with low muscle mass may be at increased risk of functional decline due to overall frailty.

Fukumoto, Ikezoe, Yamada, Tsukagoshi, Nakamura, Mori, Kimura, and Ichihashi (2012)

The purpose of this investigation was to determine if muscle quality assessed from echo intensity (EI) is related to maximal isometric strength of the knee extensors independent of age and muscle thickness (MT), and to determine if there is a relationship between EI and body composition. Ninety-two healthy women (mean ± SD: age = 70.4 ± 6.6 years) participated in this study. EI, MT, and subcutaneous fat (FT) of the quadriceps femoris at the midpoint of the right leg were measured with a Brightness-mode ultrasound device (LOGIQ e; GE Healthcare UK Ltd., Chalfont, Buckinghamshire, England) and multi-frequency linear transducer (8-12 MHz) with the participant relaxed and seated with 60º of knee flexion. EI was digitally assessed using Adobe Photoshop Elements. Regions of interested that included as much of the rectus femoris as possible without the surrounding fascia were selected for EI analysis. Percent body fat (%BF) was assessed using segmental bioelectrical impedance analysis with 12 pre-gelled electrocardiogram electrodes (2x2 cm, Red Dot, 3 M). Strength testing of the knee extensors on the right side was performed using an isometric dynamometer (Isoforce GT-330; OG GIEN Co., Okayama, Japan). The participants were tested in a seated position with 60º of knee flexion. Isometric strength was measured twice for 3 s, with a 30 s rest period between trials. The results indicated that while significantly positively correlated with age (r=0.34, $P<0.01$), EI was also significantly correlated with muscle strength when age and MT were controlled (r=−0.26, $P<0.05$). Additionally, EI showed no significant correlation with %BF (r=0.08) and FT (r=-0.19) ($P>0.05$). Muscle strength was significantly negatively correlated with age (r=−0.32, $P<0.01$). Finally, MT was significantly correlated with muscle strength (r=0.32, $P<0.01$) when age, BMI, and EI were controlled. These findings suggested that muscle size and muscle quality independently contribute to muscle strength, although together they only account for a majority of the variance in muscle strength, which may have resulted from the already compromised muscle quality among these older adults. The authors (17) also suggest that age-related decreases in muscle strength may be associated with factors other than muscle quality, including decreased neural activation of the agonist muscle, specifically among older adults.

<u>Cadore, Izquierdo, Conceição, Radaelli, Pinto, Baroni, Vaz, Alberton, Pinto, Cunha, Bottaro, and Kruel (2012)</u>

The purpose of this investigation was to examine the relationship between both echo intensity (EI) and muscle thickness (MT), and isometric and isokinetic peak torque in older men. Thirty-one healthy older men (mean ± SD: age = 64.7 ± 4.1 years) volunteered for this study. Maximal isometric and isokinetic peak torques (PT) were obtained using an isokinetic dynamometer (Biodex, New York, USA) with the subjects seated at a hip angle of 85º and right leg at 120º of knee extension. Maximal isometric protocols consisted of three maximum voluntary contractions (MVC) of the knee extensors lasting 5-s each, while isokinetic PT at 60, 180, and 360º/s was assessed as the PT achieved from five dynamic repetitions (2-min rest intervals) of concentric knee extension/flexion at each angular velocity. EI of the rectus femoris (RF) and MT of the vastus lateralis (VL), vastus medialis (VM), vastus intermedius (VI), and RF were measured using B-mode ultrasound (Philips, VMI, MG, Brazil) with a 7.5 MHz probe placed perpendicular to the skin, and analyzed using Image-J (National Institute of Health, USA, version 1.37). Regions of interested that included as much of the muscle as possible without the surrounding fascia were selected for EI analysis. The sum of the four lower-body muscles MT was represented in subsequent analyses as the quadriceps femoris (QF). The results indicated significant negative correlations between individual RF EI and corresponding isometric PT and isokinetic PT values at 60, 180, and 360º/s (range from $r=-0.48$ to $r=-0.64$, $P<0.05$). MT was also significantly correlated with isometric and isokinetic PT values (range from $r=0.44$ to $r=0.62$, $P<0.001$ to $P<0.05$). Additionally, a significant relationship between muscle EI and explosive strength, represented as isokinetic performance, was observed (range from $r=-0.64$ to $r=-0.67$, $P<0.001$). The authors (9) concluded that both muscle size and muscle quality (i.e. the amount of connective and adipose tissues in the muscle) are associated with high-speed isokinetic performance, or rapid force muscle actions.

Strasser, Draskovits, Praschak, Quittan, and Graf (2013)

The purpose of this investigation was to compare muscle thickness (MT), pennation angle (PA), and echo intensity (EI) of the quadriceps muscle between young and older adults, and examine the relationship between MT and EI with isometric maximum voluntary contraction force (MVC). Fifty-two young (mean ± SD: age = 24.2 ± 3.7 years, n=26) and old (age = 67.8 ±

4.8 years, n=26) adults participated in this investigation. MVC performance during three maximal leg extensions with two minutes rest between each trial was assessed using a load cell (DFS Ametek Inc., Chatillon, USA) with participants seated with their hips and knees at 90º of flexion. MT and EI of the quadriceps muscles at 50% of the femur length of a randomly assigned leg of each participant were obtained through brightness mode ultrasonography with a 7.25 MHz linear array transducer and assessed using Image-J (National Institutes of Health, USA). PA was measured from each longitudinal US image, with the average PA obtained from the three separate fascicles. Maximal MT was measured as the distance between the superficial and deep fascia at the widest point, with a region of interest excluding surrounding fascia from a longitudinal scan used to examine EI. MT of the rectus femoris, vastus intermedius, vastus lateralis, and vastus medialis between the young and old groups was significantly reduced in the older group (P<0.0001, P<0.05, P<0.01, and P<0.05, respectively). EI was also significantly reduced in the older group (P<0.01). PA was significantly different between the young and old groups in both the vastus lateralis and vastus medialis (P<0.001). Furthermore, PA was significantly correlated with MVC in the vastus intermedius in the young group only (r=0.68, P<0.001). Mean MVC of the older group was significantly lower than that of the younger group (-31.1%, P<0.001). In both groups, a significant relationship between MT (r=0.75-0.92, P<0.001) and MVC was observed. There was no significant relationship between EI and MVC within the old group, however EI in this study was evaluated through longitudinal ultrasound scans, in contrast to most others that measure transverse scans. The authors (52) concluded that MT of the quadriceps is significantly correlated with MVC. Thus, assessment of muscle thickness of the quadriceps through ultrasonography can be used to examine the effects of sarcopenia in neuromuscular unimpaired patients. Because PA was different between groups, and significantly correlated with MVC in the young group, the relationship between PA and MVC among different ages may be significant in other muscle groups. Furthermore, because EI was evaluated in longitudinal compared to transverse ultrasound scans, the significance of this measure on MVC among older adults may still be present. Because EI provides an indirect measure of skeletal muscle tissue quality (accumulation of connective tissue and/or intramuscular fat) an increased EI may indicate a reduction in skeletal muscle quality. Additionally, because EI is based on the gray-scale of each ultrasound image, the cross-sectional view of the muscle fibers permitted during a transverse scan may provide an alternative view of the muscle.

The influence of rapid contractile variables on lower extremity muscular performance

Lamoureux, Sparrow, Murphy, and Newton (2001)

The purpose of this investigation was to examine the age-related changes in maximal strength of the major muscle groups of the lower extremity, explosive force production characteristics, muscle activation of the knee extensors, and lean tissue in old (<70 years) and older (≥70 years) adults. Thirty old (mean ± SD) (age = 63.3 ± 2.6 years, n=15) and older (age = 75.7 ± 3.9 years, n=15) adults participated in this study. Maximal strength and rate of torque development (RTD) of the knee extensor muscles was measured through a maximal voluntary isometric contraction (MVC) of the dominant leg using a Cybex II (New York, NY) isokinetic dynamometer. MVC testing consisted of five maximal muscle actions with a two minute rest period between trials. Dual energy x-ray absorptiometry (DXA) was used to measure bone-free lean tissue mass (BFLT). Muscle activation was assessed using surface electromyography (EMG), whereby EMG activity was determined by integrating the rectified EMG signal over a 100 ms time period. The integrated EMG of each 100 ms interval was expressed as a percentage of individual peak integrated EMG activity. Absolute RTD was determined from the time taken to increase torque in 50 Nm intervals from 50 to 250 Nm. The relative torque-time curve was taken from the times needed to increase torque from 10 to 20%, 30%, and 40% of MVC. The results suggest that both MVC and RTD_{peak} of the old group were significantly greater than the older group ($P<0.01$). Mean BFLT of the thigh was significantly greater ($P<0.05$) in the old group than in the older group. BFLT was significantly correlated to MVC of the knee extensors in both groups (r=0.851, $P<0.001$). In addition, the older group took significantly longer to reach each torque level than the old group ($P<0.05$). No significant differences were observed between groups among the relative torque-time responses. Additionally, the old group produced significantly higher integrated EMG values ($P<0.01$) at each 100 ms epoch from the start of muscle activation up to 500 ms. Together, these findings indicate that reduced neuromuscular activity, size and number of functional motor units, and excitable muscle mass may be possible mechanisms for age-related changes in MVC and RTD. The authors (29) suggested that the age-related reductions in muscle strength and explosive force characteristics of the neuromuscular system may contribute to increased fall related injuries and limitations of activities of daily living among older adults. This may be due to decreased ability to activate functional motor units, as well as decreased proportion of type II muscle fibers.

Granacher, Gruber, and Gollhofer (2010)

The purpose of this study was to investigate maximal and explosive force production, functional reflex activity (FRA) during gait perturbations, and the relationship between variables of force production capacity and FRA in young and old men. Twenty-eight healthy young (mean ± SD; age = 27 ± 3 years, n=14) and old men (age = 67 ± 4 years, n=14) participated in this study. Treadmill perturbation impulses and maximal isometric voluntary contractions (MVC) were assessed for all participants on a leg-press, whereby the characteristics of the leg-extensors were evaluated. During all assessments, circular bipolar surface electrodes (Hellige, Ag/AgCl, Freidburg, Germany) positioned over the tibialis anterior (TA), soleus (SO) and vastus medialis (VM) of the right leg measured mean amplitude voltage (MAV), which was normalized on the swing and stance phases of ten regular gait cycles. Gait perturbation protocol used to determine FRA consisted of random decelerating perturbation impulses at separate phases of the gait cycle, with the decelerating perturbation impulses 120 ms after the first biomechanical response to the perturbation impulse used for FRA analysis. The MVC was performed following a warm-up of 3-5 submaximal muscle actions with each foot on individual force platforms (Kistler, Winterthur, Switzerland). RFD_{peak} was defined as the maximal slope at the deflection point on the force-time curve, while RFD30 and RFD100 were determined over the time intervals 0-30 ms and 0-100 ms, respectively. MVC, RFD_{peak}, RFD30, and RFD100, as well as MAV of SO and VM, were significantly lower in the old compared with the young men ($P<0.01$). Regarding gait perturbations, only the decelerating perturbation impulse (functional reflex activity) was significantly reduced for the TA in the old compared to young men ($P<0.05$), with a no significant differences in coactivation between groups ($P=0.07$). The results suggested that older men experience reduced maximal and explosive force production capacity, with impairments in neural activation of select muscles. The authors (18) hypothesized that strength performance and functional reflex activity, or neuromuscular activation, in older adults must be trained complementarily.

LaRoche, Cremin, Greenleaf, and Croce (2010)

The purpose of this investigation was to compare reaction time to a visual cue, rate of torque development (RTD), and neuromuscular activation of lower-extremity muscles in older fallers and non-fallers. Twenty-three women aged 65-85 participated in this study. Fallers (mean ± SD; age = 71.3 ± 5.4 years, n=11) were identified as women who had fallen or nearly fallen three or more times within the last year, while non-fallers (age = 71.2 ± 6.2 years, n=12) had no history of unexplained falls. All measures were obtained during maximal voluntary isometric contractions (MVC) of the dominant limb using a HUMAC Norm dynamometer (CSMI, Stoughton, MA, USA) in conjunction with a BIOPAC MP100 data acquisition system and were performed separately for the leg flexors (LF), leg extensors (LE), ankle plantarflexors (PF) and ankle dorsiflexors (DF). During LE and LF testing, participants were seated with a hip angle of 90º and knee angle of 75º. DF and PF testing occurred in the prone position with a 90º angle between the foot and the leg. Participants completed three trials for each of the four muscle groups during which a MVC (2 s) was initiated in response to a visual cue (2 s), with a 60 s rest period. Electromyograms (EMG) were recorded from disposable, surface, Ag-AgCl, wet gel electrodes with a 1 cm diameter (Vermed, Inc., Bellows Falls, Vermont, USA). Total reaction time was measured as the time between the start of the visual cue until a torque threshold of 0.5 Nm was exceeded, while motor time was the time from the beginning of the EMG burst until the 0.5 Nm torque threshold. Time to peak torque (TPT) was defined as the duration of time between the visual stimulus and peak torque (PT) achieved during the muscle action. The results suggested that only dorsiflexion and plantarflexion strength scores (summation of PT, RTD and impulse) were significantly different between fallers and non-fallers (P=0.049, P=0.014 respectively). Specifically, RTD was not significantly different between groups (P=0.212). Similarly, composite scores of PT and motor time summed across the four muscles were significantly different between fallers and non-fallers (P=0.021, P=0.014 respectively). When each temporal component (motor time, total reaction time, and TPT) was summed across muscle groups and examined independently, motor time was 22 ms longer (29%) in fallers. However, no differences in any variable were found between groups for the leg extensors or leg flexors, independently. The authors (30) hypothesized that neuromuscular as well as strength and RTD deficits in the ankle musculature may be present in those adults within the fall group. The authors further suggest that strength, speed of movement, and power of the ankle dorsiflexors and plantarflexors should be examined as potential contributors to falls in older adults.

Bento, Pereira, Ugrinowitsch, and Rodacki (2010)

The purposes of this investigation were to compare muscle peak torque (PT) and rate of torque development (RTD) of the lower limb joints in older adults with and without fall history, and to determine whether PT and RTD are related to the number of falls. Thirty-one women with a mean age of 67.1 years volunteered for this study. Participants were divided into three groups determined through a customized health risk questionnaire: no fall history (GI; n=13), one fall (GII; n=8) and two or more falls (GIII; n=10). No significant differences in physical characteristics were present between groups ($P>0.05$). Hip, knee, and ankle flexion and extension maximal voluntary isometric contractions (MVC) were assessed in a recumbent position, while hip abduction and adduction tests were performed with the participants in a standing position. Torque-time curves were determined with a load cell (Model CZC500, Kratos, São Paulo, Brazil) attached to an adjustable pole aligned perpendicular to the tested limb segment. Torque testing consisted of three maximal trials during which the participants were instructed to produce torque as fast and hard as possible for 2-3 s with the highest PT used for subsequent analysis. PT and RTD were not significantly different between groups ($P>0.05$) in any joint of the lower limbs, except the knee flexors, which showed significantly larger ($P<0.05$)

RTD in the non-fallers than in the other two groups of fallers. However, there were no differences in knee flexor PT between GII and GIII (*P*>0.05). The authors (6) concluded that because RTD rather than PT was more closely related to falls among the older participant, exercises designed to develop muscle power may be more beneficial to reduce the risk of falls than exercises designed to improve strength.

Clark, Patten, Reid, Carabello, Phillips, and Fielding (2010)

The purpose of this investigation was to determine the effect of movement velocity on torque and power production in healthy (OH) and mobility limited (OML) older relative to middle-aged (MH) adults, and whether these factors were associated with differences in neuromuscular activation of the agonist and antagonist muscle groups. Eighty-nine participants (MH, n=29; OH, n=28; OML, n=32) volunteered for this study (MH: age = 40-55 years, OH, OML: age = 70-85 years). OML and OH groups were assigned using a Short Physical Performance Battery assessment, with a score ≤ 9 out of a possible 12 indicating mobility limitations. Maximal voluntary leg extension was performed using a Cybex-II dynamometer (Cybex, Ronkonkoma, NY) with muscle activation of the knee extensors and knee flexors assessed by surface electromyography (Delsys, Boston, MA). Five consecutive maximal isokinetic knee extensions (60º/s, 90º/s, 180º/s, 240º/s) followed by three static maximal voluntary contractions for both knee extension and flexion at 60º of knee flexion were performed with one minute rest intervals. Computed tomography (CT) scans of the non-dominant thigh were obtained at the midpoint of the femur using Siemens Somatom Scanner (Erlangen, Germany), and anterior compartment muscle cross-sectional area (CSA) was determined through manual tracing. The results suggested that at faster velocities (240º/s), OML produced significantly lower specific torque (torque/muscle CSA) than both the MH and OH groups

(*P*<0.05), with the MH producing the greatest power followed by OH and OML (*P*<0.0001) groups. Normalized torque (expressed as a percentage of maximal voluntary contraction) in the OML was significantly lower than the MH and OH groups at 90, 180, and 240º/s (*P*<0.0001). Anterior compartment thigh muscle CSA was significantly greater in the MH group than the OH and OML groups (*P*<0.001). The OML group produced significantly less absolute power than both the MH and OH groups at each velocity (*P*<0.05). In contrast to agonist activation amplitude in MH and OH, which was positively associated with velocity (*P*<0.05), no significant associations were observed for OML (*P*>0.05). Furthermore, the rate of normalized quadriceps activation was significantly greater in the OH group compared to the OML (*P*=0.03), indicating that reduced activation may have contributed to mobility limitations. Additionally, there were significant correlations between agonist activation and torque production for all groups as velocity increased (r=0.56-0.62, *P*<0.001). The authors (11) suggested that impaired power and neuromuscular activation, specifically of the agonist muscle groups, may contribute to compromised mobility function in older adults.

<u>Clark, Manini, Fielding, and Patten (2013)</u>

The purpose of this investigation was to examine the extent to which maximum walking speed was affected by neuromuscular function of the lower extremities in older adults. Twenty healthy adults participated in this investigation. Each participant was assigned to a faster (n=12) or slower (n=8) walking group, with assignment to the slower group defined as a <0.6 m/s difference between usual and maximum 10 meter walking speed, and the faster group as >0.6 m/s difference. Plantarflexion force production during a rapid bilateral heel-rise task at maximal voluntary effort performed while the participant was standing upright was assessed through the vertical ground reaction force recorded by a pair of force plates (Bertec, Columbus, OH).

Neuromuscular activation was assessed using surface electromyography (EMG) from the right triceps surae muscles, specifically the soleus (SO) and medial gastrocnemius (MG). Muscle cross-sectional area (CSA) was determined by 3D-magnetic resonance imaging using a Philips 3.0 T magnet (Philips Medical Systems, Bothell, WA). Plantarflexion rate of force development (RFD) was 38% lower (*P*=0.002) in the slower compared to the faster group, while only MG rate of EMG rise was significantly lower among the slower group (34%, *P*=0.01). Moreover, MG rate of EMG rise across all participants was significantly positively associated with plantarflexion RFD (*P*=0.02, r=0.62) and maximum walking speed (r=0.54, *P*=0.04). In addition, muscle CSA was non-significantly different between the slower and faster groups. The authors (12) conclude that maximum walking speed in healthy, well-functioning older adults is associated with age-related neuromuscular activation impairment. Additionally, because RFD and rate of EMG rise were different between groups, these measures may help identify those older adults at-risk for future decrements in functionality and possibly reduce their risk of injury.

CHAPTER III

METHODOLOGY

Participants

Thirty-five (18-30 yrs) and 22 older males (65-74 yrs) were recruited from the University of North Carolina at Chapel Hill (UNC-CH) and the surrounding area. Participants were excluded if they accumulated more than 5 hours of exercise per week or had a current or recent injury of the low back, hip, knee, or ankle within the past three months, or a neuromuscular disease that may have affected their ability to produce maximum torque. Prior to any testing, participants completed a health history and exercise status questionnaire detailing various resistance and aerobic training modalities and the average time each week spent performing each activity, along with a written informed consent document approved by the University's Institutional Review Board.

Experimental Design

Each participant visited the UNC-CH Neuromuscular Research Laboratory on two separate occasions (including the familiarization day) for approximately 60 minutes each. The experimental trial was held 2-7 days after the familiarization trial at the same time of day (± 2 hrs), and consisted of the identical procedure as the familiarization trial. Participants refrained from any vigorous physical activity for 24 hrs prior to the experimental trial.

Familiarization Trial

During the familiarization trial, each participants height and body mass were measured using a stadiometer (Detecto, Webb City, MO, USA) and underwent a musculoskeletal ultrasound (US) assessment of their right medial gastrocnemius (MG) to examine muscle size and quality, fascicle length, and pennation angle. In addition, each participant practiced the isometric maximum strength testing protocol.

Isometric Maximal Voluntary Contraction

Isometric testing was conducted on a calibrated, HUMAC Norm dynamometer (Computer Sports Medicine Inc., Stoughton, MA, USA). All participants were seated at a 135° angle between the thigh and torso, measured using a handheld goniometer model G300 (Whitehall Manufacturing, City of Industry, CA, USA), with a Velcro restraining strap (90 mm width) across the thigh and the participants' arms crossed in front of their chest. The participants' right leg was fully extended (0° below the horizontal plane) with their foot secured in a thick rubber heel cup and held against a custom steel foot plate (36 x 17 cm) with straps over the toes and metatarsals (25 mm width), and the lateral malleolus of the fibula aligned with the axis of rotation of the dynamometer. The isometric strength testing was conducted at a neutral ankle joint angle (0˚ dorsiflexion). Each participant performed 2-3 maximal voluntary contractions (MVCs) with 2 min of recovery between trials. During each MVC, participants received strong verbal encouragement and instructed to plantarflex “as hard and fast as possible” for a total of 3-4 s (58).

Electromyography

Prior to electrode placement, the skin at the location of the medial gastrocnemius and soleus muscles was shaved, lightly abraded and cleansed with rubbing alcohol. Pre-amplified, bipolar surface electrodes (EL254S Biopac Systems, Santa Barbara, CA, USA) were placed on the prominent bulge of the medial gastrocnemius and at a 2/3 distance between the medial condyles of the femur to the medial malleolus for the soleus, parallel to the muscle fiber orientation in accordance with the SENIAM guidelines (22). A single, pre-gelled, disposable reference electrode was placed over the tibial tuberosity (Ag Cl Quinton Quick Prep; Quinton Instruments Co, Bothell, WA, USA).

Signal Processing

The EMG (μV) and torque (Nm) signals were sampled at 2.5 KHz and recorded simultaneously with a Biopac MP150WSW data acquisition system and AcqKnowledge software (Biopac Systems, Inc., Santa Barbara, CA, USA). All digitized signals were stored on a personal computer (Think Pad T420, Lenovo, Morrisville, NC, USA) and processed off-line with custom-written software (Labview 8.5, National Instruments, Austin, TX, USA). The torque signals were filtered using a fourth order, zero phase shift low pass Butterworth filter with a 10 Hz cutoff frequency, while the EMG signal were bandpass filtered with a zero phase shift 4th order Butterworth filter with cutoff frequencies of 10–500 Hz. Normalized (*n*RTDpeak) and absolute (*a*RTDpeak) peak rates of torque development were quantified from the first derivative of the normalized and absolute torque-time signals, respectively, during the initial ascent of the torque-time curve. For the rate of EMG rise (RER), the filtered signals were rectified prior to being low pass filtered using a 10 Hz linear EMG envelope. Peak EMG amplitude was determined as the maximum value of the filtered EMG-time curve and subsequently used to derive a normalized EMG-time curve. The RER was calculated as the peak linear slope of the normalized EMG-time curve from onset. To be consistent with the torque-time curve, the onset of RER was manually determined from the normalized EMG-time curve at the inflection point corresponding to the onset of the exponential phase (apex of the first trough). The instant of torque onset was confirmed by also displaying the first derivative of the torque-time curve, with any noticeable active baseline discarded from further analyses.

Ultrasound Assessment

Muscle cross-sectional area (CSA), echo intensity (EI), fascicle length (FL) and pennation angle (PA) of the MG were examined on the right limb at approximately 1/3 the distance from the articular cleft between the femur and tibia condyles to the lateral malleolus, measured using a Gulick tape measure (AliMed, Dedham, MA, USA) (36) with a portable brightness mode (B-mode) US imaging device (LOGIQ e 5, General Electric Company, Milwaukee, WI, USA) and a multi-frequency linear-array probe (12L-RS; 5-13 MHz; 38.4 mm FOV) (General Electric Company, Milwaukee, WI, USA). To ensure the US probe was moved perpendicular to the skin and along the transverse plane (from medial to lateral) during panoramic imaging assessment of muscle CSA and EI, a custom made probe support composed of high-density foam padding was positioned perpendicular to the longitudinal axis of the plantarflexor muscles and secured with an adjustable strap. Image acquisition of FL and PA used a similar protocol to acquisition of panoramic muscle CSA and EI, but occurred without a probe support and in the longitudinal plane. During muscle CSA and EI assessments, equipment settings including gain (68 dB), depth (4 cm), and frequency (10 MHz) were optimized for image quality using the musculoskeletal mode prior to testing and then held constant between tests and across participants. During FL and PA scans, depth was adjusted between participants to ensure both deep and superficial fascia remained visible in the field-of-view. During all US measurements, participants remained prone on a padded wooden table with their legs fully extended and completely relaxed. In order to prevent rotation and movement of the leg during the assessments, an adjustable strap was used to securely attach the right foot to a vertical post at a 90° joint angle between the foot and leg. All measurements were performed following a 10 min rest period to allow for any fluid shifts to occur (7). A generous amount (1 - 2 oz.) of hypoallergenic water-soluble transmission gel was applied to the skin to reduce possible near field artifacts and enhance acoustic coupling (Aquasonic 100, Parker Laboratories, Inc., Fairfield, NJ, USA). LogicView™ software (General Electric Company, Milwaukee, WI, USA) was used to generate real-time panoramic cross-sectional images of the MG, as previously in detail by Rosenberg et al. (46). Following each scan, each image was reviewed to ensure appropriate image quality.

Muscle Size and Quality Analysis

All US imaging analyses were performed using Image-J software (version 1.46r, National Institutes of Health, USA). Prior to analysis, each image was individually scaled from area in pixels to centimeters using the straight-line function. CSA of the MG were determined using the polygon function by selecting a region of interest that included as much of the muscle as possible without any surrounding fascia. EI was assessed by computer-aided gray-scale analysis using the standard histogram function. The same pre-selected region of interest used for the calculation of muscle CSA was used to determine the mean EI value and corresponding index of muscle quality ranging between 0 and 255 arbitrary units (a.u.) (black = 0; white = 255). Test-retest reliability for CSA and EI yielded intraclass-correlation coefficients ($ICC_{2,1}$) of 0.95 and 0.77 for the young, and 0.88 and 0.65 for the older adults, respectively.

Fascicle Length and Pennation Angle Analysis

Using the segmented-line function, two fascicles were traced continuously from their origin (superficial aponeurosis) to insertion (deep aponeurosis) just inside the surrounding fascia of the MG, with the average FL used for subsequent analysis. PA was measured using the angle tool in Image-J and defined as the angle between muscle fibers and the deep aponeurosis for two separate fascicles, with the average PA used for subsequent analysis. Test-retest reliability for FL and PA yielded intraclass-correlation coefficients ($ICC_{2,1}$) of 0.91 and 0.89 for the young, and 0.94 and 0.80 for the older adults, respectively.

Statistical Analyses

All descriptive statistics are presented as mean ± standard deviation unless the assumptions of normality were violated. Normality of the data was confirmed with the Shapiro-Wilk test and homogeneity of variances was verified using Levene's test. Eight independent t-tests were performed to examine any differences between the young and older groups for muscle CSA, EI, PA, FL, RER, *n*RTDpeak, *a*RTDpeak, and age. A correlation matrix for all outcome variables was performed for the young and older groups separately and combined among both age groups. Further, stepwise regression was used to determine the contributions of muscle CSA, EI, PA, FL, and RER on *n*RTDpeak and *a*RTDpeak in the young and older groups, as well as the combination of groups. The alpha level was set at $P \leq 0.05$, and all analyses were performed with SPSS version 20.0 (SPSS, Inc., Chicago, IL, USA).

CHAPTER IV

RESULTS

Thirty-five young (mean ± SD: age = 20 ± 2 years) and 22 older (age = 69 ± 3 years) males were used for statistical analyses. Body mass, EI, and age were significantly greater in the older males than the young males ($P<0.001$). CSA and *n*RTDpeak were not significantly different between groups ($P=0.693$ and $P=0.789$, respectively). PA and *a*RTDpeak were significantly lower in the older males than the young males ($P<0.001$ and $P<0.05$, respectively) (Table 1). Due to differences in body mass between groups, analyses of covariance (ANCOVAs) were used to examine differences in *a*RTDpeak and CSA between groups with body mass as the covariate and showed no difference ($P=0.317$) between groups for CSA, and a significant difference ($P=0.001$) between groups for *a*RTDpeak when controlling for body mass. The observed power value for *a*RTDpeak was 0.92.

Among the young males, there was a significant ($P<0.05$) positive and negative relationship with *a*RTDpeak for CSA (r=0.41) and EI (r=-0.37), respectively. There was also a significant negative relationship between EI and PA (r=-0.39; $P<0.05$) and a positive relationship between CSA and FL (r=0.67;$P<0.01$) (Table 2). Among the older males, there was a significant negative relationship between CSA and EI (r=-0.58;$P<0.01$) (Table 3). No significant relationships were found between *n*RTDpeak and the outcome variables in either group separate or when combined. CSA, EI, and PA were significantly related (r=0.34, r=-0.40 and r=0.34, respectively) to *a*RTDpeak (*P*=0.009, *P*=0.002 and *P*=0.011, respectively) when groups were combined (Table 4).

Stepwise regression analyses identified CSA as a significant predictor of *a*RTDpeak (*P*=0.014) among young males accounting for 16.8% of the total variance (Table 5). Among the older males, no outcome variables significantly predicted *a*RTDpeak. When both groups were combined, both PA and CSA were significant predictors of *a*RTDpeak (*P*=0.024 and *P*=0.021, respectively), accounting for 19.7%, of the total variance (Table 6). Lastly, no significant differences between groups were found for time to peak RTD (ttRTDpeak) and time to peak rate of EMG rise (ttRER) (*P*=0.729 and *P*=0.925, respectively).

CHAPTER V

DISCUSSION

The main findings of the present study indicated the older men had lower *a*RTDpeak, a smaller PA, and poorer muscle quality (higher EI) when compared to the younger men. However, there were no age-related differences in *n*RTDpeak, CSA, FL, or RER. Furthermore, only CSA and EI of the MG were significantly correlated with *a*RTDpeak in the young group, no variables were correlated to *a*RTDpeak in the old, however, CSA, EI, and PA were related to *a*RTDpeak when both groups were combined. Groups were combined in order to provide a larger sample size as well as assist in assessing collectively which variables contributed to *a*RTDpeak and *n*RTDpeak independent of age (60). In addition, CSA was the only significant predictor of *a*RTDpeak in the young group while both CSA and PA had a significant cumulative effect on the prediction of *a*RTDpeak when young and older groups were combined. Taken together, these results illustrate that in addition to muscle size and architectural features which have previously been correlated to rapid torque production (4, 37), intrinsic qualitative features of the muscle (i.e. EI) may also correlate with these measures. The results of this study may contribute to our current understanding of underlying causes for age-related reductions in functional performance.

The finding in the present study that there was a reduction in *a*RTDpeak between the young and older adults is in agreement with similar previous studies (14, 19, 23, 56). Despite discrepancies in the magnitude of the age-related decline in *a*RTDpeak between each of these studies (approximately 62-67%, 37%, 64%, and 27-36%, respectively), the overall findings support those from the present study (18%). Differences in the magnitude of *a*RTDpeak may be due to differences in the muscles examined (i.e. thigh vs. calf) and activity status of participants. The present finding that the relative capacity for rapid torque production was preserved in older men for the plantar flexors is in agreement with previous studies examining the plantar flexors (54), dorsiflexors (54), leg flexors (56), and leg extensors (56). However, other previous studies have also reported that relative or normalized RTD is lower in the old when compared to the young men for the plantar flexors (55) and leg extensors (27). Similar to *a*RTDpeak, the conflicting results among previous studies for *n*RTDpeak may be due to the muscles assessed, as well as activity status. For example, because all of the older men in the current study were ambulatory and recreationally active, the degree muscular atrophy and fat and fibrous tissue infiltration in the GM may have been less than their older frail counterparts (1).

In the present study, CSA was significantly related to *a*RTDpeak with both groups combined, however there were no significant differences between groups. These findings may suggest that muscle CSA may not be responsible for the age-related changes in *a*RTDpeak. Previous studies have also shown a significant relationship between muscle size and RTD (1, 56). In addition, a recent study by Moreau et al. (37) found that vastus lateralis muscle thickness was a significant predictor of RTDpeak in children with cerebral palsy, a neuromuscular disorder with similar degenerative symptoms of excitable muscle mass and motor units as seen with normal aging. Recent studies have suggested that the quality of the tissue or the amount of excitable muscle mass within a given area (29), may also contribute to age-related reductions in explosive strength. For example, a classic study by Lexell et al. (32) found that between 20 and 80 years of age, excitable muscle mass decreases within a given area. Specifically, a 20%

reduction of excitable muscle mass within a given CSA was observed between young (70%) and older (50%) men. The authors suggested that denervated and inactive fibers, particularly the larger type II fibers, along with the replacement of those fibers by fat and fibrous tissue, may be responsible for the decrease in fiber density. Similarly, in our study, the reduction in muscle quality as indicated by a greater EI in the older men despite no significant difference in muscle CSA illustrates that the replacement of type II muscle fibers with fat and fibrous tissue may have contributed to the lower *a*RTDpeak. The simultaneous increase in EI and lack of change in CSA is similar to the findings reported by McNeil et al. (35) who reported no differences in total CSA of the anterior compartment of the lower limb between young and older adults, but did reveal an increase in the non-contractile CSA in the older adults. With respect to the influence of contractile and non-contractile CSA on RTD, Wilhelm et al. (61) also reported a significant correlation between the individual quadriceps muscles EI and RTD during leg extension, but also stated that these correlations decrease at earlier time-points from the onset of contraction (<200ms). Given the functional implications for a reduction in RTD, it is important to note that Visser et al. (59) found that among older participants (70-79 years), increased intramuscular fat significantly increased the probability of developing mobility limitations, independent of muscle CSA, strength, or total body fat mass. These results indicate that older adults with a greater increase of intramuscular fat and/or connective tissue may be at increased risk of functional impairments.

A recent study by Moreau et al. (37) indicated that muscle thickness, PA, and FL were all significant predictors of RTDpeak in typically developed children. Thus, it is possible that age-related reductions in *a*RTDpeak may also be due to alterations in muscle architecture. In contrast to the present study where PA, not FL, was different between groups, Narici et al. (40)

reported significant differences between young and older groups for CSA, FL, and PA. These findings suggest that as muscle size decreases with age, FL and PA experience similar reductions. While actual fiber density may decline with age, a similar or even reduced CSA has been shown to result in no change in FL (32, 39). Therefore, it is possible that a reduction in PA, with no change in CSA or FL, may result in an increase in the vertical component of the muscle force vector (49). In contrast to our findings, Kubo et al. (28) reported no significant reduction in PA of the MG with increasing age. It is important to note however that these results were obtained from sedentary adults, likely with greater muscular atrophy than the adults used in our study. These findings present further evidence for why activity levels and health status should be taken into account when comparing age groups. Specifically, in order to better evaluate these age-related changes, healthy and recreationally active males from both young and older age groups must be assessed in order to reduce any changes that may have occurred from inactivity and disease (31, 40, 51).

Klass et al. (26) have reported that independent of maximal torque, the age-related decline in RTD among older men coincided with a reduction in motor unit discharge frequency, indicating a diminished capacity for rapid neuromuscular activation. These findings suggest that healthy aging involves neural impairments that may limit the maximal capacity for motor neurons to discharge at high rates, subsequently limiting maximal RTD (29). The results of the present study did not support these findings and reported no age-related reductions in RER. Previous studies (10, 11, 55) have also demonstrated that the rate of muscle activation, when examined with surface EMG, is not different between young and older healthy adults. For example, recent findings by Thompson et al. (55) indicated RER was not different between young and older men, despite an age-related decrease in relative RTD. Furthermore, our findings demonstrated no relationship between RER and RTD, which are in contrast to the results reported by Thompson et al. (55) who demonstrated a significant positive relationship between RER and RTD. These discrepancies are likely due to the time at which RER and RTD were calculated. For example, Thompson et al. (55) examined the relationship between RER and RTD at 50ms, whereas the ttRER and ttRTDpeak were examined at approximately 75ms and 155ms, respectively. In addition, the rate of muscle activation is likely more related to RTD at time intervals earlier then what was examined in the current study. While maximal strength is crucial for sit-to-stand tasks and climbing stairs, virtually all postural stability tasks depend on the ability to rapidly produce force (12, 18, 21). The results of the present investigation revealed that absolute rapid torque production of the plantar flexors was reduced in the older men when compared to the young men, and was related to muscle size, muscle quality, and pennation angle of muscle fascicles. The preservation of normalized rapid torque production in the older compared to the young men, and the lack of differences in the rate of muscle activation, indicate that increased accumulation of fat and fibrous tissue, and reduced pennation angle may contribute to the age-related decline in rapid torque production. These findings may help explain the greater incidence of fall related injuries and loss of functional independence (30, 34, 59) in older adults. In light of the functional implications associated with a reduction in RTD, resistance training programs aimed to improve RTD should be performed with the intention of maximal acceleration (1, 3).

Table 1: Physical characteristics and outcome variables for both young and older groups. (Mean ± SD)

	Group	
Variable	Young Males	Older Males
n	35	22
Age (years)	20 ± 2	69 ± 3**
Height (cm)	175.6 ± 7.1	176.5 ± 5.2
Body Mass (kg)	73.4 ± 9.9	82.0 ± 10.8**
CSA (cm^2)	13.5 ± 3.3	13.8 ± 2.8
EI (a.u.)	73.7 ± 5.6	89.1 ± 8.5**
PA (deg)	20.0 ± 2.8	17.1 ± 2.5**
FL (cm)	5.6 ± 0.9	5.8 ± 1.0
aRTDpeak (Nm/s)	610.2 ± 192.1	500.9 ± 168.6*
nRTDpeak (Nm/s)	437.1 ± 106.8	445.5 ± 129.3
ttRER (ms)	71.4 ± 58.2	78.5 ± 96.6
ttRTDpeak (ms)	155.3 ± 72.8	153.2 ± 92.1
RER	1407.3 ± 428.4	1449.3 ± 462.5

CSA: Cross-sectional Area; EI: Echo Intensity; PA: Pennation Angle; FL: Fascicle Length; aRTDpeak: Absolute Peak Rate of Torque Development; nRTDpeak: Normalized Peak Rate of Torque Development; ttRER: Time to Normalized Peak Rate of EMG Rise; ttRTDpeak: Time to Absolute Peak Rate of Torque Development; RER: Rate of EMG Rise

* $P<0.05$, ** $P<0.005$

Table 2: Correlation coefficients between physical characteristics, RTD, and EMG variables of young males (n=35).

	CSA	EI	PA	FL	aRTDpeak	nRTDpeak	RER
CSA	-	-0.44**	0.32	0.67**	0.41*	0.15	-0.15
EI		-	-0.39*	-0.18	-0.37*	-0.17	0.01
PA			-	-0.23	0.25	-0.13	-0.06
FL				-	0.18	0.12	-0.10
aRTDpeak					-	0.63**	-0.12
nRTDpeak						-	0.16
RER							-

CSA: Cross-sectional Area; EI: Echo Intensity; PA: Pennation Angle; FL: Fascicle Length; aRTDpeak: Absolute Peak Rate of Torque Development; nRTDpeak: Normalized Peak Rate of Torque Development; RER: Rate of EMG Rise

* $P<0.05$, ** $P<0.01$

Table 3: Correlation coefficients between physical characteristics, RTD, and EMG variables of older males (n=22).

	CSA	EI	PA	FL	aRTDpeak	nRTDpeak	RER
CSA	-	-0.58**	-0.01	0.17	0.29	0.23	-0.10
EI		-	-0.15	-0.11	-0.23	-0.18	0.18
PA			-	0.18	0.21	0.11	-0.42
FL				-	0.28	0.17	-0.35
aRTDpeak					-	0.80**	-0.04
nRTDpeak						-	0.22
RER							-

CSA: Cross-sectional Area; EI: Echo Intensity; PA: Pennation Angle; FL: Fascicle Length; aRTDpeak: Absolute Peak Rate of Torque Development; nRTDpeak: Normalized Peak Rate of Torque Development; RER: Rate of EMG Rise

* $P<0.05$, ** $P<0.01$

Table 4: Correlation coefficients between physical characteristics, RTD, and EMG variables of all participants (n=57).

	CSA	EI	PA	FL	aRTDpeak	nRTDpeak	RER
CSA	-	-0.28*	0.16	0.47**	0.34**	0.18	-0.13
EI		-	0.51**	-0.01	-0.40**	-0.09	0.09
PA			-	-0.11	0.34*	-0.05	-0.19
FL				-	0.17	0.15	-0.21
aRTDpeak					-	0.65**	-0.10
nRTDpeak						-	0.19
RER							-

CSA: Cross-sectional Area; EI: Echo Intensity; PA: Pennation Angle; FL: Fascicle Length; aRTDpeak: Absolute Peak Rate of Torque Development; nRTDpeak: Normalized Peak Rate of Torque Development; RER: Rate of EMG Rise

* *P*<0.05, ***P*<0.01

Table 5: Factors associated with *a*RTDpeak on stepwise regression analysis among young males (n=35)

Dependent variables	Independent variables	Coefficient	Standardized coefficient	*t* value	*P* value	95% Confidence interval	
						Lower	Upper
*a*RTDpeak (Nm/s) $R^2 = 0.168$	CSA	24.1	0.41	2.58	<0.05	5.12	43.1

CSA: Cross-sectional Area; PA: Pennation Angle; *a*RTDpeak: Absolute Peak Rate of Torque Development

Table 6: Factors associated with *a*RTDpeak on stepwise regression analysis among all participants (n=57)

Dependent variables	Independent variables	Coefficient	Standardized coefficient	*t* value	*P* value	95% Confidence interval	
						Lower	Upper
*a*RTDpeak (Nm/s)	PA	18.0	0.29	2.32	<0.05	2.44	33.5
R^2 = 0.197	CSA	18.2	0.30	2.39	<0.05	2.90	33.5

CSA: Cross-sectional Area; PA: Pennation Angle; *a*RTDpeak: Absolute Peak Rate of Torque Development

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