Jonathan R. Gomez. INCREASED ANTAGONIST COACTIVATION-RELATED HAMSTRING TORQUE REDUCES MAXIMAL KNEE EXTENSION TORQUE IN HEALTHY OLD ADULTS. (Under the direction of Tibor Hortobágyi, Ph.D.) College of Health and Human Performance, Spring 2010

As humans age, the ability to produce maximal voluntary torque decreases due to muscle atrophy (sarcopenia) and it is also known that advancing age alters the neural control of voluntary movement. One manifestation of the neural changes is that old adults execute voluntary movements with heightened antagonist muscle coactivation. Previous studies have examined the roles of increased coactivation but none have examined the effects of coactivation on motor output *per se*. In a simple knee extension task, it is possible to estimate the torque generated by the knee extensor and hamstring muscle groups using an electromyography- (EMG) driven model. The purpose of this study was to determine if the higher hamstring coactivation during knee extension in old adults would produce proportional reductions in knee extension torque. The hypothesis was that old compared with young adults have higher levels of antagonist hamstring muscle coactivation at all velocities, producing greater reductions of torque during knee extensions in the old adults.

Peak torque was measured in the quadriceps and hamstrings and surface EMG activity were collected from the vastus lateralis, vastus medialis, semitendinosus, and biceps femoris during knee extension at 30°/s, 90°/s, and 150°/s using concentric (shortening) and eccentric (lengthening) contractions of the hamstrings. Outputs of the EMG-driven model were: 1) net concentric knee extension torque (summation of the torque computed from EMG activity of the quadriceps and hamstrings), 2) agonist torque (torque calculated from the EMG activity of the quadriceps), and 3) antagonist torque (torque calculated from the EMG activity of the hamstrings). We compared these three measures of torque during controlled knee extension at

30°/s, 90°/s, and 150°/s between old (mean age 76.2, n=10) and young adults (age 20.7, n=13) using a speed (3) by group (2) ANOVA followed by a Tukey's post-hoc contrast at $p < 0.05$.

Measured peak torque was 31% lower in old vs. young adults. Old adults had greater coactivation during knee extension at all three contraction velocities. The calculated torques revealed that young vs. old adults produced more calculated net concentric torque and that old vs. young adults had significantly greater calculated antagonist hamstring torque production. The difference in calculated net concentric torque was attributed to increased calculated antagonist hamstring torque in old adults, since calculated agonist quadriceps torque was similar between the two groups. There was a significant speed-related increase in calculated antagonist hamstring torque production. In conclusion, while the age-related loss of maximal voluntary torque has been primarily attributed to sarcopenia, the present data suggest that such reductions may also include decreases in torque due to hyperactivity of antagonist muscle that increase the counteracting torques produced by the agonist prime movers.

Increased Antagonist Coactivation-Related Hamstring Torque Reduces Maximal Knee Extension Torque in Healthy Old Adults

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Jonathan R. Gomez

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Due to the after effects of the baby boom after the Second World War, the US is at risk to have a disproportionate amount of old people represented in the total population of the US within the next 40 years. By the year 2050, the amount of people aged 85 and over will increase by a staggering 388.9%, rising from 1.5% of the total 282,125,000 in 2000 to 5% of the projected 419,854,000 people in 2050 (US Census Bureau, 2008). Research is in demand to help understand the effects of aging on the neuromuscular system to meet the health needs of the increasing population of old Americans.

Advancing age profoundly modifies structures of most organ systems, including the Central Nervous System (CNS) and muscles. Bones, muscles, and tendons are all affected by the aging of the musculoskeletal system. Changes in the central nervous system are also evident: a loss of brain and spinal cord mass, nerve cells are less likely to propagate an action potential, and the structure of neurons can change (Hagood, Solomonow, Baratta, Zhou, & D'Ambrosia, 1990; Vandervoort, 2002).

Changes in the nervous and muscular systems due to age are evident, resulting in changes in mobility and the control mechanisms of locomotion. One adaptation developed in old individuals to overcome this impairment is for old adults to co-activate their muscles more (Hsu, Wei, Yu, & Chang, 2007; Mian, Thom, Ardigo, Narici, & Minetti, 2006). This involves the activation of an antagonist muscle on a joint during the activation of an agonist muscle. This phenomenon has been studied in a variety of conditions ranging from complex tasks, such as gait and stair walking, to simple tasks, such as knee extensions, finger abduction, and elbow flexion (Burnett, Laidlaw, & Enoka, 2000; Hortobagyi & DeVita, 2000; Hortobagyi et al., 2009; Hsu,

Wei, Yu, & Chang, 2007; Klein, Rice, & Marsh, 2001; Larsen, Puggaard, Hamalainen, & Aagaard, 2008; Macaluso et al., 2002; Simoneau, Martin, Porter, & Van Hoecke, 2006; Suzuki, Shiller, Gribble, & Ostry, 2001). It has been shown that young adults do co-activate their muscles, although this phenomenon is observed in old adults much more frequently and with more intensity.

More and more research is being done to understand how the neuromuscular system adapts with age. One research tool for understanding the neuromuscular system is electromyography (EMG). The use of this measurement tool in conjunction with isokinetic dynamometry has been shown to be a useful and reliable tool for the study of the musculoskeletal system activation (Aagaard et al., 2000; Amiridis et al., 1996; Barnes, 1980; Thorstensson, Grimby, & Karlsson, 1976). Isokinetic dynamometry allows for the researcher to examine the behavior of the musculoskeletal system in a single joint model. By using this simple model, the mechanical role of coactivation can be more precisely quantified when compared to more dynamic models such as gait, where inverse dynamics analysis of gait ignores coactivation in joint torque computation therefore ignoring the behavioral effect of coactivation during gait. The role of coactivation in open kinetic exercises, such as isokinetic knee extension, is to stabilize the joint against anterior shear forces acting on the knee as the joint approaches full extension (Beynnon, Howe, Pope, Johnson, & Fleming, 1992; Escamilla et al., 1998; Hirokawa, Solomonow, Lu, Lou, & D'Ambrosia, 1992; Kaufman, An, Litchy, Morrey, & Chao, 1991). This stabilizing benefit accounts for the need for coactivation observed in both young and old groups during isokinetic testing. It has also been shown that coactivation increases with contraction velocity to compensate for the need for quicker limb deceleration near extension in a variety of populations (Aagaard, Simonsen, Trolle, Bangsbo, & Klausen, 1995; Hagood,

Solomonow, Baratta, Zhou, & D'Ambrosia, 1990; Kellis & Baltzopoulos, 1998; Osternig, Hamill, Lander, & Robertson, 1986; Schlinkman, 1984; Weir, Keefe, Eaton, Augustine, & Tobin, 1998).While many researchers have seen comparable differences in muscle activation patterns between young and old, relatively few (Izquierdo et al., 1999; LaRoche, Roy, Knight, & Dickie, 2008; Macaluso et al., 2002) have examined the difference between these groups during isokinetic movement.

While many previous studies have observed coactivation during a variety of tasks and have proposed reasons for this phenomenon, none have examined how this adaptation affects motor function. The proposed study will attempt to observe the effect of coactivation on function by examining the effect of coactivation on the torque production of the knee extensors using an EMG based method. Theoretically, antagonist hamstring muscle coactivation during knee extension would reduce knee extension force scaled in proportion to the level of EMG activity. Previous studies did show that a significant reduction in torque production due to coactivation during knee extension (Aagaard et al., 2000; Amiridis et al., 1996; Baratta et al., 1988; Kellis & Baltzopoulos, 1997; Osternig, Hamill, Lander, & Robertson, 1986), but whether such a systematic effect is also present due to age is unknown. Further, whether there an interaction between age and contraction velocity with respect to the magnitude in reduction in knee extension force due to hamstring coactivity, has not been examined.

Hypothesis

It is hypothesized that old compared with young adults will have higher levels of antagonist hamstring muscle coactivation at all velocities, producing greater reductions of torque during knee extensions in the old adults

Purpose

The purpose of this study was to determine if the higher hamstring coactivation during knee extension in old adults would produce proportional reductions in knee extension.

Delimitations

1. All subjects will be adults, 18-25 years or ≥60

2. All subjects will be healthy: without lower leg injury within the last year, able to walk with no discomfort, or no diseases that would prevent the performance of normal daily activities

4. The BMI of the subjects will not exceed 30 kg/m^2

5. This study is designed for evaluation in the right leg using isokinetic dynamometry only.

Limitations

1. Body composition may hinder the EMG signal

2. Muscle fatigue during the course of a trial may skew torque production.

Assumptions

1. Torque output will be measured reliably during data collection.

2. Subjects will produce a maximal effort during each trial.

Operational Definitions

1. Coactivation: activation of an antagonist muscle concurrently with the activation of an agonist muscle.

2. Young adult 18-25 years
3. Old adults ≥ 60 years

REVIEW OF LITERATURE

Antagonist Muscle Coactivation during a Single-joint Movement

The human nervous system controls voluntary movement. By controlling the muscular system, the nervous system is able to produce movements ranging in complexity from as simple as moving a limb to as complex as gait. The nervous system accomplishes this task by the rhythmic activation of muscles. For every joint, there are both agonist and antagonist muscles that act in opposition to one another. In order for any productive movement to occur, the nervous system must either excite or inhibit muscle groups that act on the same joint. According to Sherrington's law of reciprocal innervations (Crone, 1993), a muscle will relax when its opposite muscle is activated. This phenomenon is called reciprocal inhibition. This is the expected behavior of muscles acting upon a similar joint during simple and dynamic movements. Crone and Nielson showed that the initiation of inhibition originated in supraspinal structures and is mediated by propriospinal structures. These results were found by looking at the timing of ankle muscle activity during dorsiflexion. The results showed that inhibition of the soleus h-reflex occurred 50 ms before the onset of tibialis anterior EMG activity and this inhibition increased during onset of ramp-and-hold dorsiflexion of the foot (Crone & Nielsen, 1989). Since Ia inhibitory interneurons only become active 20-40 ms after onset of voluntary movement (Vallbo, 1971),control of inhibition must be initiated by a cortical mechanism.

For the neuromuscular system to make movement efficient, it utilizes reciprocal inhibition. Yet, the muscle activation patterns during movement do not faithfully follow this. During movement, antagonist and agonist groups of the same joint are activated at the same time and this phenomenon is known as co-activation. The pattern of muscle activation during

movement is usually observed as two large bursts of activity followed by smaller bursts of activity. This activation pattern has been observed in many studies (Kellis, Arabatzi, & Papadopoulos, 2003; Shapiro, Prodoehl, Corcos, & Gottlieb, 2005). The first burst signifies the onset of the agonist muscle and the initiation of the muscle movement, while the second is representative of the onset of the antagonist muscle activation. This second activation is attributed with decelerating and stopping the limb. Utilizing this strategy, the neuromuscular system uses coactivation as a way to perform normal activities while minimizing the risk of damage.

Coactivation, defined as initiation of movement of the joint by the agonist muscle while the antagonist muscle activates mildly, provides added benefits, such as providing joint stability, slowing the limb during rapid movements, and increasing joint stiffness. Many studies have been done to further determine the effects of this co-activation (Hagood, Solomonow, Baratta, Zhou, & D'Ambrosia, 1990; Suzuki, Shiller, Gribble, & Ostry, 2001). These studies have shown that by increasing the stability of a joint, risk of injury is decreased (Hagood, Solomonow, Baratta, Zhou, & D'Ambrosia, 1990). This occurs because the antagonist muscle group is more activated, as there is an increase in intensity of the type of movement. Another benefit of coactivation is that this leads to longer durability of the joint (Goodwin, Zhou, Baratta, Solomonow, & Keegan, 1997). Co-activation around joints also varies with velocity of movement. Studies have shown that as velocity of the movement increases, the amount of co-activation around the joint also increases (Hagood, Solomonow, Baratta, Zhou, & D'Ambrosia, 1990; Suzuki, Shiller, Gribble, & Ostry, 2001).

The behavior of the activation of the muscular system is dependent of any changes in the task being performed, in regards to action, velocity, load**,** and contraction mode. One noted

difference is attributed to the type of contraction being done. Burnett et al. showed that lengthening contractions required more co-activation than shortening contractions (Burnett, Laidlaw, & Enoka, 2000). The velocity of the movement also plays a role in the behavior of activation of the muscles. One such study by Prilutsky and Gregor examined the relationship of muscle activation during the walk-run transition in seven subjects. They found that muscle activation increases with the transition from walk to run (Prilutsky & Gregor, 2001). Differences in loads also can impact the mode of activation. Shields et al. examined the muscle co-activation of the leg muscles between single leg squats with different levels of resistance, and found that co-activation between the quadriceps and hamstring decreased with increased load (Shields et al., 2005).

Coactivation during Isokinetic Movement

Isokinetic dynamometry can be defined as the dynamic muscular contraction when the velocity of movement is controlled and maintained constant by a special device. This method of experimentation has been used to measure various function of the musculoskeletal system. It is used to measure torque production of the muscles, the relationship between angular position and maximal strength output, the torque velocity relationship, and/or reciprocal muscle activation (Barnes, 1980; Dibrezzo, Gench, Hinson, & King, 1985; Thorstensson, Grimby, & Karlsson, 1976). Dibrezzo et al. examined the number of trials needed to find a valid measurement of torque output. This study showed that only two trials of maximal effort were needed to determine maximal torque output. Because of these findings, the current study will use three maximal torque output trials for data analysis. Although the findings by Dibrezzo et al. provided support for the number of trials to be collected, their study ignored the effects of velocity on maximal torque output in the muscle. Barnes, 1980, examined the contraction velocity effect on

torque output during isokinetic contractions. This study showed that during testing, torque production from the lower limb decreased with increases in velocity. This study attributed this effect to the torque-length relationship. Yet this is not the only factor known to decrease torque production, reciprocal muscle coactivation has been shown to contribute to decreases in torque production (Amiridis et al., 1996). While coactivation may hinder maximal torque production, many studies have shown that there is a need for coactivation during isokinetic exercise. One such study by Escamillia et al. quantified the knee forces of an open kinetic chain exercise. Their findings indicate that during a seat knee extension anterior shear forces of 400 Nm were observed (Escamilla et al., 1998). This result further supported other studies that have shown large levels of anterior shear forces acting on the knee during isokinetic exercise near full extension of the joint (Beynnon, Howe, Pope, Johnson, & Fleming, 1992; Hirokawa, Solomonow, Lu, Lou, & D'Ambrosia, 1992; Kaufman, An, Litchy, Morrey, & Chao, 1991). Other studies have also shown that there is a contraction velocity effect on coactivation during isokinetic exercise. Schlinkman, 1984 measured torque production in high school football players. This study found that with increases in velocity, coactivation of the hamstring muscles increased (Schlinkman, 1984). While this study examined a specialized population this result has been observed in different populations including, elite athletes and healthy sedentary young adults (Aagaard, Simonsen, Trolle, Bangsbo, & Klausen, 1995; Hagood, Solomonow, Baratta, Zhou, & D'Ambrosia, 1990; Kellis & Baltzopoulos, 1998; Osternig, Hamill, Lander, & Robertson, 1986; Schlinkman, 1984; Weir, Keefe, Eaton, Augustine, & Tobin, 1998). Factors thought to contribute to this increase are the need for quicker limb deceleration at the faster velocities and it is suggested that the active force generated by the quadriceps is larger than the passive force generated by the hamstrings, therefore requiring hamstring coactivation (Osternig,

Hamill, Lander, & Robertson, 1986). By looking at the findings of these previous studies, it can be seen that torque decreases with velocity due to the force length relationship along with contributions from increased muscle coactivation, and that reliable torque values can be measured from two experimental trials.

In the present study, subjects will perform isokinetic contractions during which the quadriceps and hamstring muscles' neural activation will be recorded with surface electromyography. Thus it is pertinent to understand, the coactivation patterns associated with these movements. Many studies have utilized this type of movement in their assessment of coactivation (Aagaard et al., 2000; Amiridis et al., 1996; Baratta et al., 1988; Carolan & Cafarelli, 1992; Osternig, Hamill, Lander, & Robertson, 1986). Baratta et al. showed that there were measureable levels of coactivation during knee extension and flexion. They also showed that activation levels of the antagonist muscles were different between muscle groups. They found that the quadriceps had small measures of antagonist activity, while the hamstring had higher amounts of activity. This finding was further supported by Aagard et al. who also showed that hamstring coactivation accounted for 30-70% of measured knee extensor moment in the 10-30˚ range of motion. These results have been shown to be similar in most studies examining coactivation in the leg muscles using isokinetic dynamometry and should be reproducible in this current study. While these previous studies have been able to show that muscle coactivation is easily observed using EMG and isokinetic dynamometry, none of these studies have examined how levels of coactivation differ between young and old adults during isokinetic movements.

Changes In Coactivation due to Age

Age-Related Differences in Coactivation during Dynamic Movements

The aim of the current study is to examine differences between young and old in coactivation levels during isokinetic movements. In order to justify this aspect of the study, it is pertinent to look at the activation pattern differences between young and old groups during dynamic movements. Many studies have looked at the muscle activation patterns in old individuals during a variety of different functional tests (Burnett, Laidlaw, & Enoka, 2000; Hortobagyi & DeVita, 2000; Izquierdo et al., 1999; Manchester, Woollacott, Zederbauer-Hylton, & Marin, 1989; Patten & Kamen, 2000). A review article by Hortobagyi and Devita, 2006, quantified the coactivation difference between the young and old subjects from results from many different studies. Their computations showed variable differences between the two groups, ranging from no difference between the two groups to as high as 148% higher coactivation in the old. Of these aforementioned studies, only two, Manchester et al. 1989, and Patten and Kamen, 2000, showed significant differences between groups (Hortobagyi & Devita, 2006). Manchester et al. examined muscle activation patterns in the lower limb muscles between young and old in a balance activity on a tilting platform. This study showed that the old group had higher levels of antagonist muscle activation in the ankle. This level of coactivation was determined to be 21% percent higher in the old individuals (Hortobagyi & Devita, 2006). The other study by Patten and Kamen also examined muscle activation patterns during force modulation in the ankle muscles. The quantification of the coactivation differences between the young and old by Hortobagyi and Devita was calculated to be 118% higher in the old individuals than in the young. By examining the results of these studies, it can be seen that old individuals exhibit higher levels of coactivation regardless of the activity being performed.

Age-Related Differences in Coactivation during Isokinetic Movement

Knowing that coactivation levels are higher in old individuals than young regardless of activity, it is plausible to predict that this same pattern will occur during isokinetic contractions. This pattern has been shown in multiple studies using isokinetic dynamometers(Izquierdo et al., 1999; Klein, Rice, & Marsh, 2001; Kuruganti, Parker, Rickards, & Tingley, 2006; LaRoche, Roy, Knight, & Dickie, 2008; Macaluso et al., 2002; Simoneau, Martin, Porter, & Van Hoecke, 2006). All of these studies have shown that old individuals have high levels of muscle coactivation during isokinetic contractions. Of these mentioned studies, only 4 examined the muscle differences between young and old individuals (Izquierdo et al., 1999; LaRoche, Roy, Knight, & Dickie, 2008; Macaluso et al., 2002). The first of these studies Izquierdo et al. looked at the muscle activation patterns of the knee extensors and knee flexors. Their results show that old individuals have higher levels of coactivation for all extensor conditions, with the highest levels of coactivation being measured during dynamic isokinetic contractions. Macaluso et al. examined muscle torque production of the lower limb during isometric contractions using a dynamometer. Their results were similar to the previous study finding that the old group had higher levels of coactivation across all testing protocols. They also found that the flexors were more activated when acting as an antagonist than when the extensors acted as antagonist. The results of these studies show that old individuals have higher levels of coactivation across all testing conditions and that this pattern is more profound during extension contractions. One relevant study by Klein et al. did examine coactivation differences between young and old in the upper limb during isokinetic exercise. Although there are methodological differences, this study did also show that the old group had higher levels of coactivation in all muscles of the elbow. While all of these studies specifically examined the coactivation differences between young and

old, the study by LaRoche et al. examined the mechanisms for muscle force production differences between the young and the old after a training intervention. This study also showed that levels of coactivation were higher in the old group, but even after the training exercise, the difference in coactivation between the young and old group remained constant. By examining the results of these studies, a difference in coactivation levels can be predicted between old and young for isometric and dynamic contractions. While many of the previous studies have examined the difference in coactivation between young and old, none have examined how this difference is affected by the contraction velocity or how this factor influences muscular strength. Therefore the aim of the present study is to examine if the differences in coactivation between the young and the old is affected by velocity during isokinetic dynamometry.

Quantification of Torque during Isokinetic Dynamometry

While many of the previously mentioned studies examined the phenomenon of coactivation in aging, none have examined how this neural adaptation alters function in neuromuscular system. One way to examine this is to observe the effects of coactivation on torque production during isokinetic dynamometry. Isokinetic dynamometry is widely used to obtain maximal torque efforts of the muscles (Aagaard et al., 2000; Amiridis et al., 1996; Appen & Duncan, 1986; Dibrezzo, Gench, Hinson, & King, 1985; Jenkins, Thackaberry, & Killian, 1984; Johnson & Siegel, 1978). This measured output during isokinetic testing is representative of the net torque produced by both the agonist muscle and antagonist muscle. Therefore, the positive torque generated by the agonist muscle is underrepresented. In order to correct for this, multiple studies (Aagaard et al., 2000; Amiridis et al., 1996; Baratta et al., 1988; Kellis & Baltzopoulos, 1997; Osternig, Hamill, Lander, & Robertson, 1986) have utilized a method to estimate the individual torque contributions of both the agonist and antagonist muscles using an EMG based equation.

Amiridis, et al. found that the net torque measured during the maximal concentric action of the knee extensors underrepresented the actual extensor knee moment throughout the range of motion by about 25 Nm due to the antagonist torque generated by the knee flexors. By utilizing this same method of analysis, the current study can quantify the effect of the increased coactivation in aging on torque production.

Summary

The previous literature has shown that antagonist muscle coactivation differs between movements. The literature has also shown that the level of coactivation increases with age. With the use of isokinetic dynamometry, it is possible to examine the velocity and contraction type effect on the differences in levels of coactivation between young and old individuals. The anticipated effects of velocity and contraction type are that they will greatly increase muscle coactivation in the old. By estimating the torque output using an EMG based method, the present study will be able to quantify how the associated increase in coactivation in aging affects the capabilities of the muscles to produce torque.

METHODOLOGY

Subject Characteristics

Two groups of participants performed the experimental protocol. One group consisted of young individuals serving as the control group. The other group consisted of old individuals.

Group	Number	Height (cm)	Weight (kg)	Age (years)	SPPB
Young	13	172.3±7.4	69.5±14.1	20.7±1.7	12±0
Old	10	169.7±9.1	69.1±11.1	76.2±6.8	11.6±0.5

Table 1. Showing Subject Characteristics

Inclusion Criteria:

1. Apparently healthy and mobile with no previous musculoskeletal injuries or conditions.
2. Free of pain or difficulty performing activities of daily living (ADLs).
3. BMI less than or equal to 30.0 kg/m^2
4. Are able to perform all procedures without difficulty.
5. Provide written informed consent.
6. Able to pass the Short Physical Performance Battery (SPPB)
7. Be right-leg dominant.

Exclusion Criteria:

1. Difficulty performing ADLs including the use of an ambulatory device or experiencing a fall within the past year.

2. Currently smoking cigarettes.
3. Neurological problems including stroke, dementia, epilepsy, Parkinson's disease, etc.
4. Musculoskeletal problems including arthritis, osteoporosis, joint replacement, lower extremity or back surgery.
5. Cardiovascular problems including heart attack, high cholesterol, uncontrolled high blood pressure, pace maker, coronary artery disease, peripheral artery disease.
6. Other health problems including cancer, diabetes, vision problems, etc.

Study Design

Between groups comparisons were made using EMG data from agonist and antagonist muscle activation of the knee flexors and knee extensors during isokinetic contractions. The data were used to determine the levels of co-activation of the muscles in the right leg of subjects during different experimental conditions.

Equipment

The EMG data was collected on a Bortec (Bortec Biomedical Ltd., Canada) unit using 4 channels and a ground. Torque data was collected with the use of an isokinetic dynamometer (Humac Norm, Computer Sports Medicine, Inc, Ma). Qualisys Track Manager (QTM) (Qualisys, Sweden) software was used for data collection. Data were collected at a frequency of 960Hz.

Experimental Protocol

Subjects in the control group were recruited from campus. The old individuals were recruited by telephone from a database of potential subjects. Subjects were informed to wear

proper athletic attire, which included closed toe shoes, shorts, and a comfortable shirt. Subjects were then given an informed consent that was signed after the experimenter explained it, detailing the experiment and its associated risks. The informed consent was reviewed and accepted by the university's advisory board for safety and clarity before any testing was conducted.

Subjects' skin was prepared for EMG electrodes: they were shaved, skin was cleaned with an alcohol wipe to remove skin oils, and then an abrasive cream was used for exfoliation of the skin, thus improving the impedance of the skin. Four pre-gelled (Ag, Ag/Cl) electrodes and one ground were placed on the upper right leg: two quadriceps and two hamstring muscles were used in this study. The ground electrode was placed on the lateral condyle of the femur. The EMG wires were then connected to the transmitter pack. The transmitter pack was temporarily tied around the subject's waist while warming up.

The subject was placed on a stationary bike for five minutes for a five-minute warm-up. Next, the transmitter pack was removed from the subject's waist and carried. Subjects were seated in the Humac Norm and strapped in place to prevent any movement of the right thigh. The subject then began the testing trials of the experiment. Knee extension movements were collected with different agonist muscles: maximal concentric knee extensions (quadriceps driven) and maximal eccentric knee extensions (hamstrings driven). One practice trial was given followed by seven maximal trials. Three of the seven trials were selected for analysis. The three trials were chosen by assessing the torque values throughout the range of motion and qualitatively choosing the trials that were similar. These trials were considered representative of maximal effort. Each trial type (concentric and eccentric) was collected at three contraction

velocities: 30 Deg/Sec, 90 Deg/Sec, and 150 Deg/Sec. Trials were randomized by contraction mode and contraction velocity.

Data Analysis

Raw EMG data was collected in QTM. The data was then filtered with a 10-300 Hz band pass filter and rectified. A RMS function with a 20 ms window was then applied to the filtered data. Filtered data was exported to Excel (Microsoft Corp, Seattle, WA) for further analysis. In Excel, position data was used to create 10-degree bins for the range of motion. Mean EMG values were calculated for each muscle group in each 10-degree bin. Quadriceps and Hamstring moments were calculated individually during the concentric knee extension trials by creating an EMG-to-force constant as explained below. The total net concentric moment is found using the following equation (Aagaard et al., 2000):

$$M_1 = K_1 \cdot EMG_{Q,agon} - K_2 \cdot EMG_{H,antag}$$

where M_1 is the net moment during the concentric knee extension condition and K_1 and K_2 are EMG-to-force constants. The equation shows that the total extensor concentric moment is calculated by subtracting the antagonist flexor moment from the agonist extensor moment. The total net eccentric moment is calculated using the following:

$$M_2 = K_2 \cdot EMG_{H,agon} - K_1 \cdot EMG_{Q,antag}$$

where M_2 is the net moment during the eccentric knee extension condition of the hamstrings. The equation shows that the total flexor eccentric moment is calculated by subtracting the antagonist extensor moment from the agonist flexor moment. By solving for K in either equation, the EMG-to force constants can be isolated into the following equations:

$$K_1 = \frac{(A_1 + A_2)}{(B_2 - B_1)}$$

$$K_2 = \frac{A_1}{(1 - B_1)}$$

where A_1 is a ratio of the net eccentric moment to the agonist Ham EMG activity ($M_2/EMG_{H,agon}$), A_2 is a ratio of the net concentric moment to the antagonist Ham EMG activity ($M_1/EMG_{H,antag}$), B_1 is a ratio of the antagonist Quad EMG activity to the agonist Ham EMG activity ($EMG_{Q,antag}/ EMG_{H,agon}$), and B_2 is a ratio of the agonist Quad EMG activity to the antagonist Ham ($EMG_{Q,agon}/ EMG_{H,antag}$). By using the angular position data, extensor and flexor moments for each position bin can be calculated using the following formulas:

$$M_{Qext}(\Theta) = K_1(\Theta) \cdot \mathrm{EMG_Q}(\Theta)$$

$$M_{Hflex}(\Theta) = K_2(\Theta) \cdot \mathrm{EMG_H}(\Theta)$$

which state that the net quadriceps extensor moment at a given angular position can be calculated by multiplying the EMG activity of the Quads by the EMG-to-torque constant, and that the net hamstrings flexor moment at a given angular position can be calculated by multiplying the EMG activity of the Hams by the EMG-to-torque constant.

Statistical Analysis

The main analysis consisted of an age (young, old) by velocity (30, 90, 150 °/s) analysis of variance (ANOVA) with repeated measure on velocity to determine if there an age by velocity interaction in a) the EMG activity of the antagonist hamstring muscles and b) in the magnitude of force produced by this EMG activity to reduce the knee extension force. A secondary analysis consisted of an age (young, old) by velocity (30, 90, 150) by position (10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, 90°) ANOVA with repeated measure on velocity to determine if there are age by

velocity by position interactions in the magnitude of force produced by antagonist hamstrings EMG activity to reduce the knee extension force. A significant interaction was followed by Tukey's post-hoc contrast at $p < 0.05$.

As appropriate for critical statistical analysis of effects and interactions, effect sizes were evaluated and reported as: small (0-0.2), medium (0.2-0.8), and large (>0.8) (Cohen, 1988).

RESULTS

It was hypothesized that old compared with young adults will have higher levels of antagonist hamstring muscle coactivation at all velocities, producing greater reductions of torque during knee extensions in the old adults. The purpose of this study was to determine if the higher hamstring coactivation during knee extension in old adults would produce proportional reductions in knee extensor torque. This chapter is divided into the following sections: 1) Measured Torque-Velocity Relationships in Young and Old in the Quadriceps and Hamstring muscles, 2) Agonist EMG activity and Antagonist EMG Coactivation, 3) Calculated Net Extension Torque, 4) Calculated Agonist Quadriceps Torque, 5) Calculated Antagonist Hamstring Torque, and 6) Summary

Measured Torque-Velocity Relationships in Young and Old in the Quadriceps and Hamstring Muscles

Raw data for two representative subjects shown (Figure 1). This graph shows the raw torque in mV, raw position data in mV, as well as EMG data for the VL, VM, BF, and ST. These graphs show that the range of motion between the subjects was similar (90°). These data also show qualitatively that the raw EMG of the quadriceps in the old individual was smaller than that of the young individual, while hamstrings EMG were similar between the two individuals.

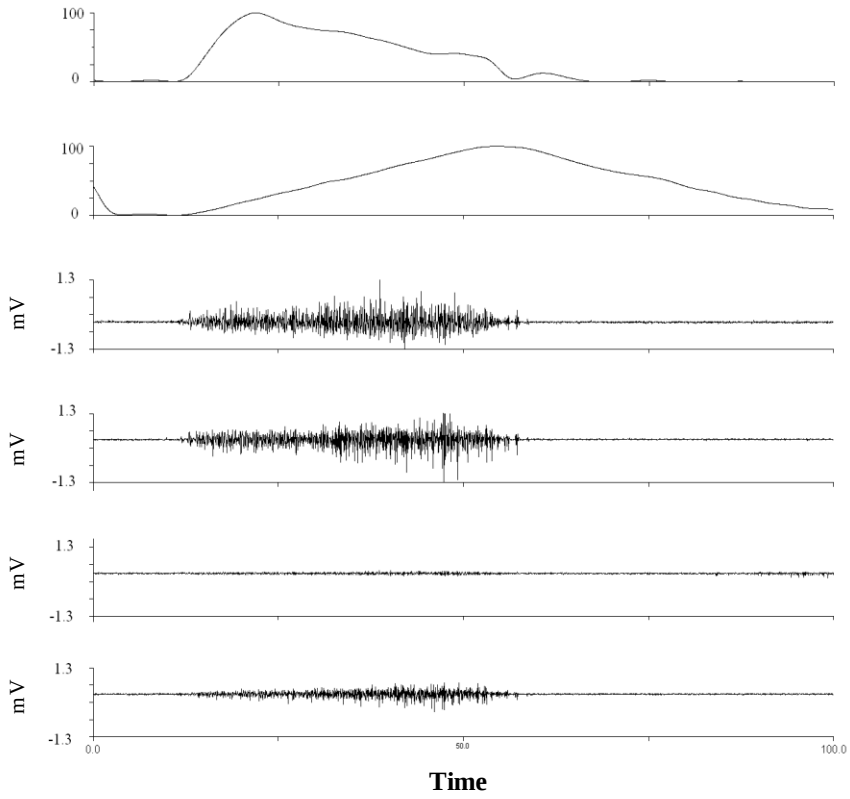

Figure 1 Raw Torque, Position, VL, VM, BF, ST data for one subject

Constant	Speed	Young	ST DEV	Old	St DEV	Δ	St Dev	Δ%
K_1	30	354.3	92.8	470.1	84.3	-115.7	72.2	-32.668859
	90	287.0	67.1	544.5	177.2	-257.5	166.7	-89.697621
	150	194.6	45.0	368.1	118.9	-173.5	86.6	-89.18792
K_2	30	340.1	145.2	402.6	146.7	-62.5	34.5	-18.363546
	90	476.3	405.8	543.9	315.7	-67.5	191.9	-14.178787
	150	268.0	303.6	420.4	181.9	-152.4	296.9	-56.847143

Table 2 Mean Data for EMG-to-Torque Constants

The data for the EMG-toTorque constants are given in Table 2. This data shows that there were differences between the young and the old constants during the concentric and eccentric conditions, and that there was an increase in the difference with increasing contraction velocity.

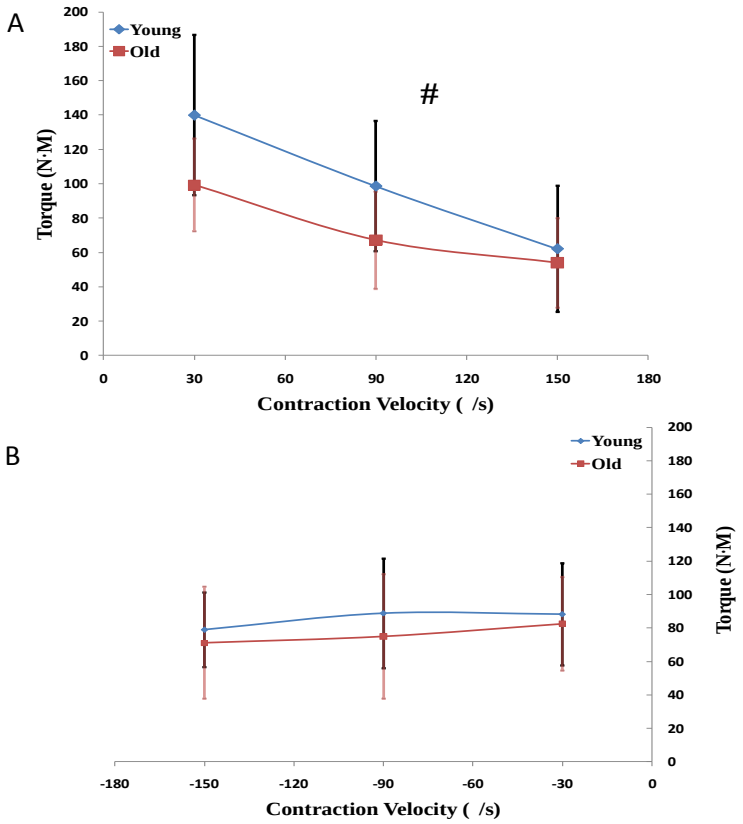

Figure 2 Grouped (A) measured quadriceps torque velocity curves during concentric knee extension and (B) measured hamstrings torque velocity curves during eccentric knee extension for young (blue) and old (red). Error bars are SD. # indicates significant main effect $p < 0.05$

The actual torque data measured by the Humac dynamometer was used to create torque-velocity curves for the young and old groups during concentric and eccentric knee extension. There was a significant (F = 3.9, p = 0.028) interaction effect on measured quadriceps torque during the concentric condition. These measured torque-velocity curves show that during concentric knee extension, the young group was borderline significantly stronger (F = 3.9, p = .060, ES = .48) than the old group by 30.8% (Figure 2a). There was no significant (p = .68) speed by group interaction for the measured hamstrings torque during the eccentric condition. During eccentric knee extension the young group was 11.2% stronger than the old group but was not significantly (F = .57, p = .460) different (Figure2b).

Agonist EMG activity and Antagonist EMG

There was no significant speed by group interaction for the EMG activity of the hamstrings (p = .42) or quadriceps (p = .63) during the eccentric condition. Grouped mean agonist quadriceps EMG activity during concentric knee extension was greater, by 28.1%, across all three contraction velocities in the young when compared with the old (Figure 3a), but this difference was not significantly (F = 1.2, p = .282) different. Grouped mean antagonist hamstrings EMG activity during concentric knee extension was not significantly (F = 0.0, p = .991) different between the two groups, 0%, when compared across all three contraction velocities (Figure 3b).

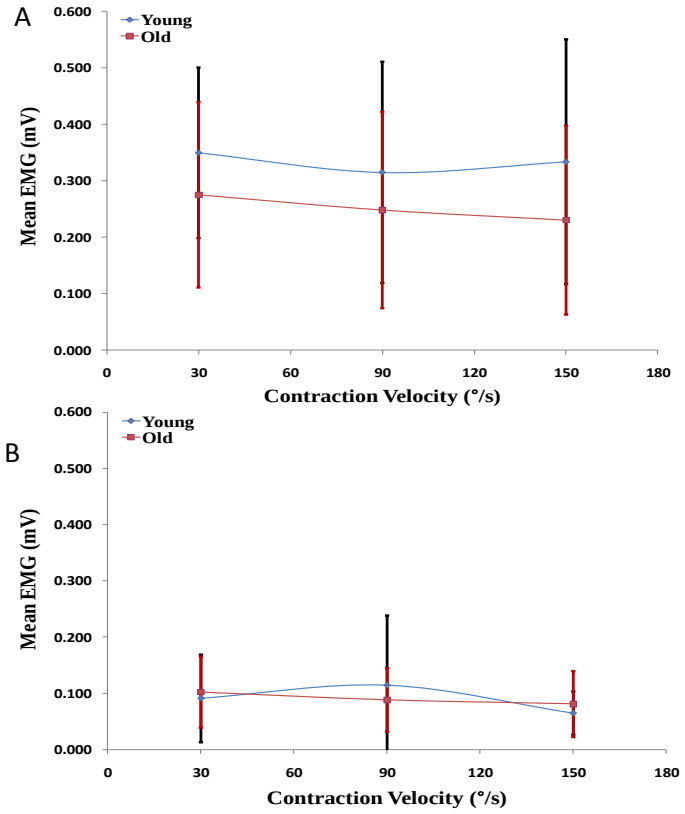

Figure 3 Grouped (A) quadriceps and (B) hamstrings activation during concentric condition for young (blue) and old (red) during concentric knee extension. Error bars are SD.

There was no significant speed by group interaction for the EMG activity of the hamstrings (p = .19) or quadriceps (p = .98) during the eccentric condition. Grouped mean antagonist quadriceps EMG activity was significantly (F = 5.7, p = .027) different between the two groups, 46.6%, when compared across all three contraction velocities during eccentric knee extension (Figure 4a). Grouped mean agonist hamstrings EMG activity was not significantly (F = 2.2, p = .156) different across all three contraction velocities between the two groups although there was a difference of 26.7 % during eccentric knee extension (Figure 4b).

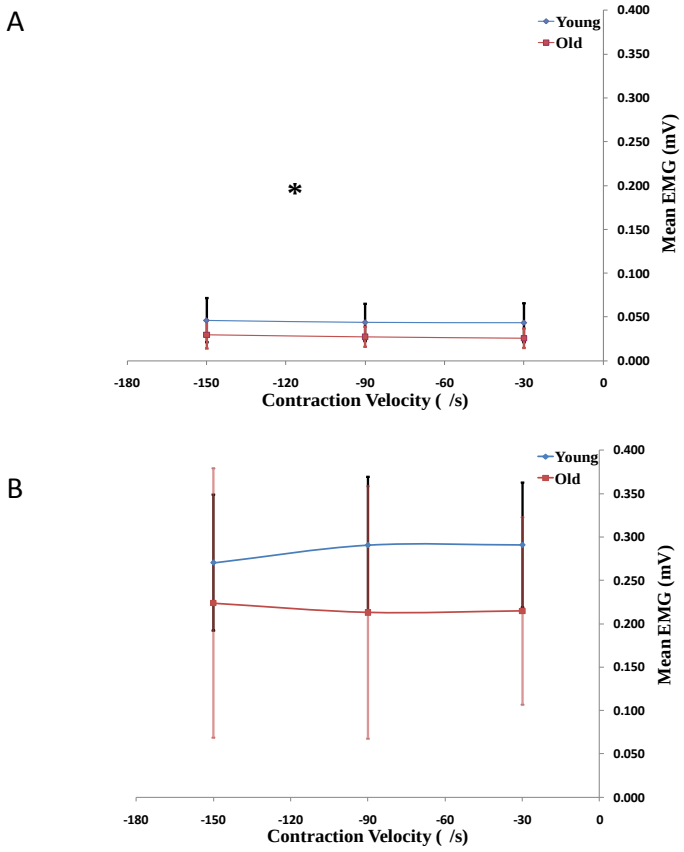

Figure 4 Grouped (A) quadriceps and (B) hamstrings activation during eccentric condition for young (blue) and old (red) during eccentric knee extension. Error bars are SD. * indicates significant main effect $p < 0.05$

There was no significant speed by group interaction for the coactivation ratios during the concentric (p = .82) and eccentric (p = .40) conditions. The coactivation ratio during concentric

knee extension was significantly (F = 13.6, p = .001) greater, 63.7%, in the old group when compared to the young for all three contraction velocities (Figure 5a). Coactivation ratio during eccentric knee extension was not significantly (F = 0.02, p = .898) different, 1.9%, between the young group and old across all three contraction velocities (Figure 5b).

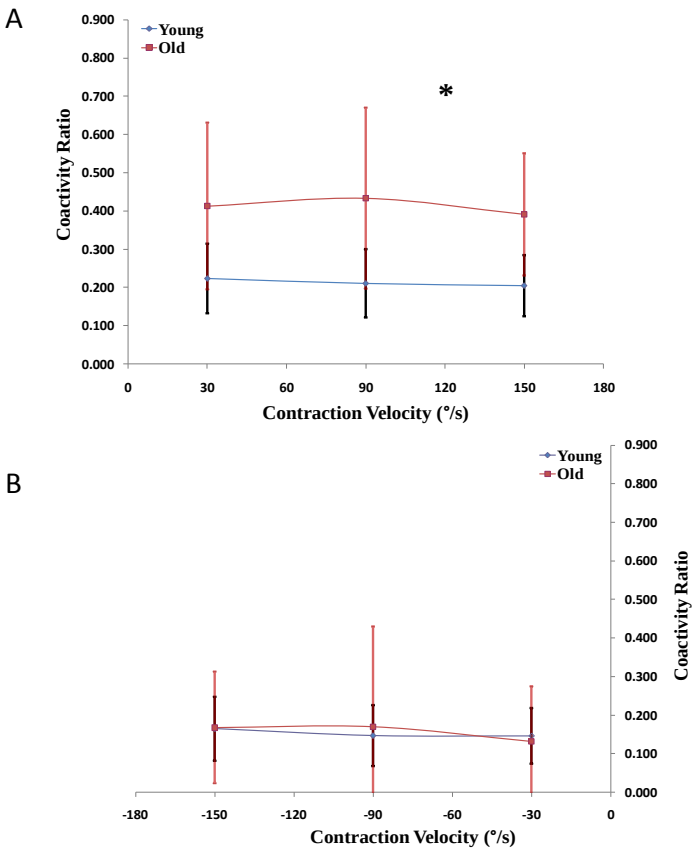

Figure 5 (A) Grouped coactivation ratio during concentric knee extension for young (blue) and old (red). (B) Grouped coactivation ratio during eccentric knee extension for young (blue) and elderly (red). Error bars are SD. * indicates significant main effect $p < 0.05$

Calculated Net Extension Torque

The EMG-driven method used to estimate the individual muscle torques produced torques that followed the expected torque-velocity pattern for the quadriceps and hamstrings muscles based on the measured torque velocity curve (Figures 6a & 6b).

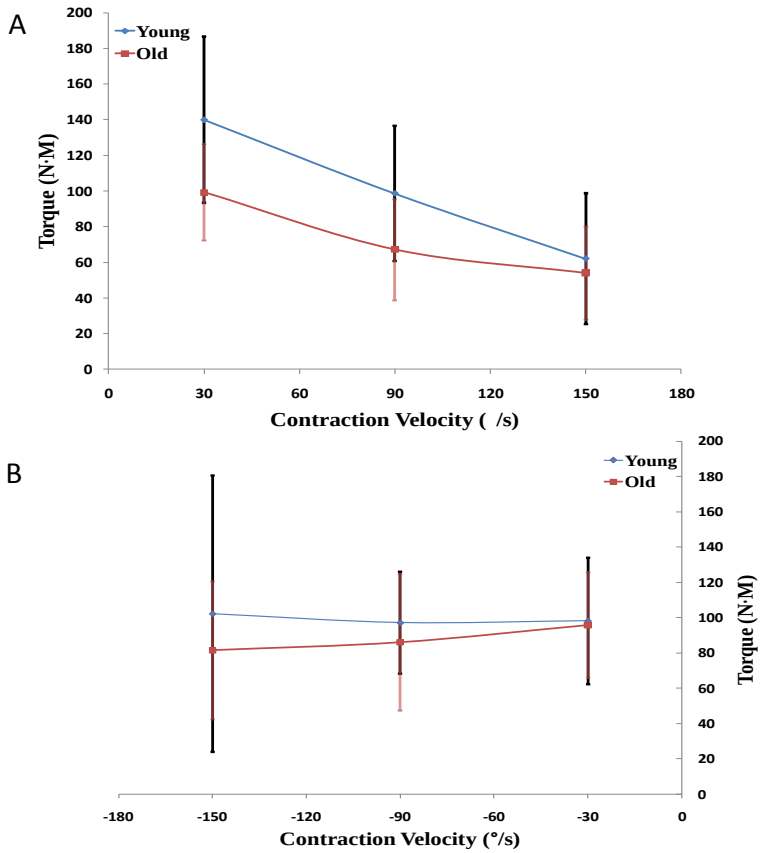

Figure 6 Grouped (A) calculated quadriceps torque velocity curves during concentric knee extension and (B) calculated hamstrings torque velocity curves during eccentric knee extension for young (blue) and old (red). Error bars are SD.

The peak calculated torque-position curves were similar to the peak measured torque-position curves at all three speeds for young and old (Appendix). For concentric knee extension there was a 3.8% difference for young and 2.7% difference for old between measured and calculated torques. For eccentric knee extension there was a 15.0% difference for young and 4.4% difference for old between measured and calculated torques. When comparing peak calculated concentric torque production across all speeds; the young group produced greater amounts of net torques (Appendix)

A borderline significant (F= 2.8, p = 0.07, ES = .53) speed by group interaction was observed for peak calculated net concentric torque (Figure 7A). The peak calculated net

concentric torque for the young group was significantly (F= 172.1, $p < .001$) different, 29.8% greater, from the old group (Figure 7B). A speed main effect was observed (F= 54.8, $p < 0.001$) for the peak calculated concentric net torque with torque increasing 35.8% between 30 °/s and 90 °/s, and increasing 30.1% between 90 °/s and 150 °/s (Figure 7C).

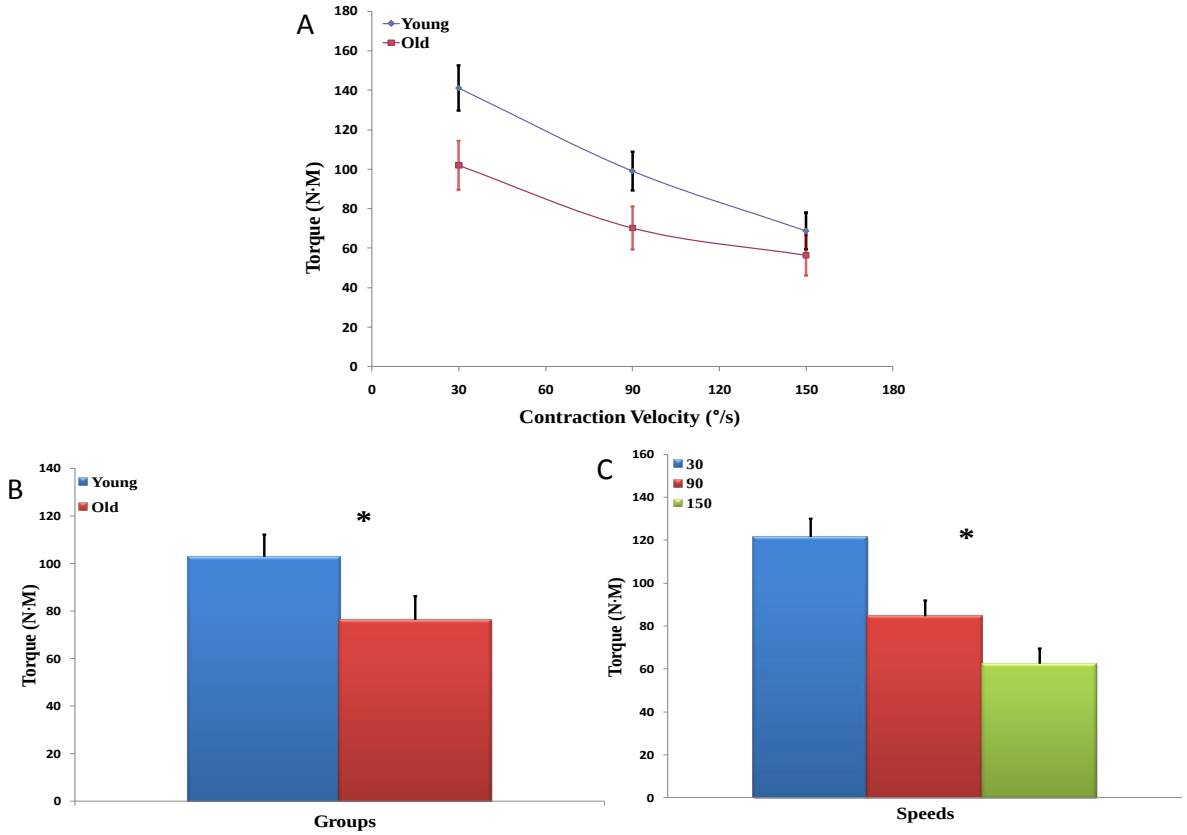

Figure 7 (A) Torque velocity curve for the calculated net torque in young (blue) and old (red). Error bars are SE. (B) Group Main effect on torque. Error bars are SE. (C) Speed main effect on net torque. Error bars are SE. * significant main effect $p < 0.05$.

Calculated Agonist Quadriceps Torque

There was no significant (F= 0.9, $p = .405$) speed by group interaction observed for peak calculated quadriceps torque (Figure 8A). The peak calculated quadriceps torque for the young group was not significantly (F= .002, $p = 0.967$) different from the old group (Figure 8B). A speed main effect was observed (F= 28.4, $p < 0.001$) for the peak calculated quadriceps torque

with torque increasing 30.0% between 30 °/s and 90 °/s, and increasing 22.0% between 90 °/s and 150 °/s (Figure 8C).

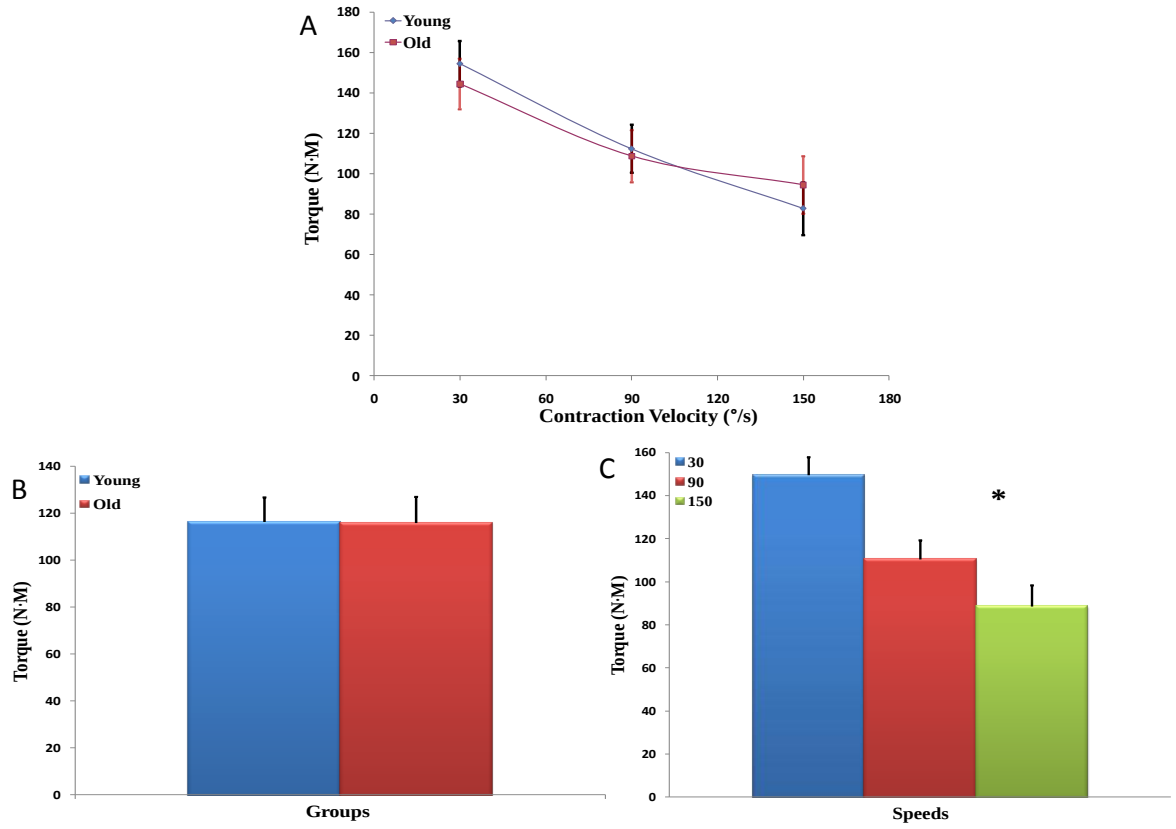

Figure 8 (A) Torque velocity curve for the calculated quadriceps torque during concentric condition in young (blue) and old (red). Error bars are SE. (B) Group Main effect on torque. Error bars are SE. (C) Speed main effect on net torque. Error bars are SE. * indicates significant main effect $p < 0.05$.

Calculated Antagonist Hamstring Torque

There was no significant (F= 2.0, p = .173) speed by group interaction observed for peak calculated hamstring torque (Figure 9A). The peak calculated hamstring torque for the young group was significantly (F= 5.8, p <0.001) different, 54.5% lower, from the old group (Figure 9B). There was no significant (F= .02, p = 0.894) speed main effect observed for the peak calculated hamstrings torque (Figure 9C).

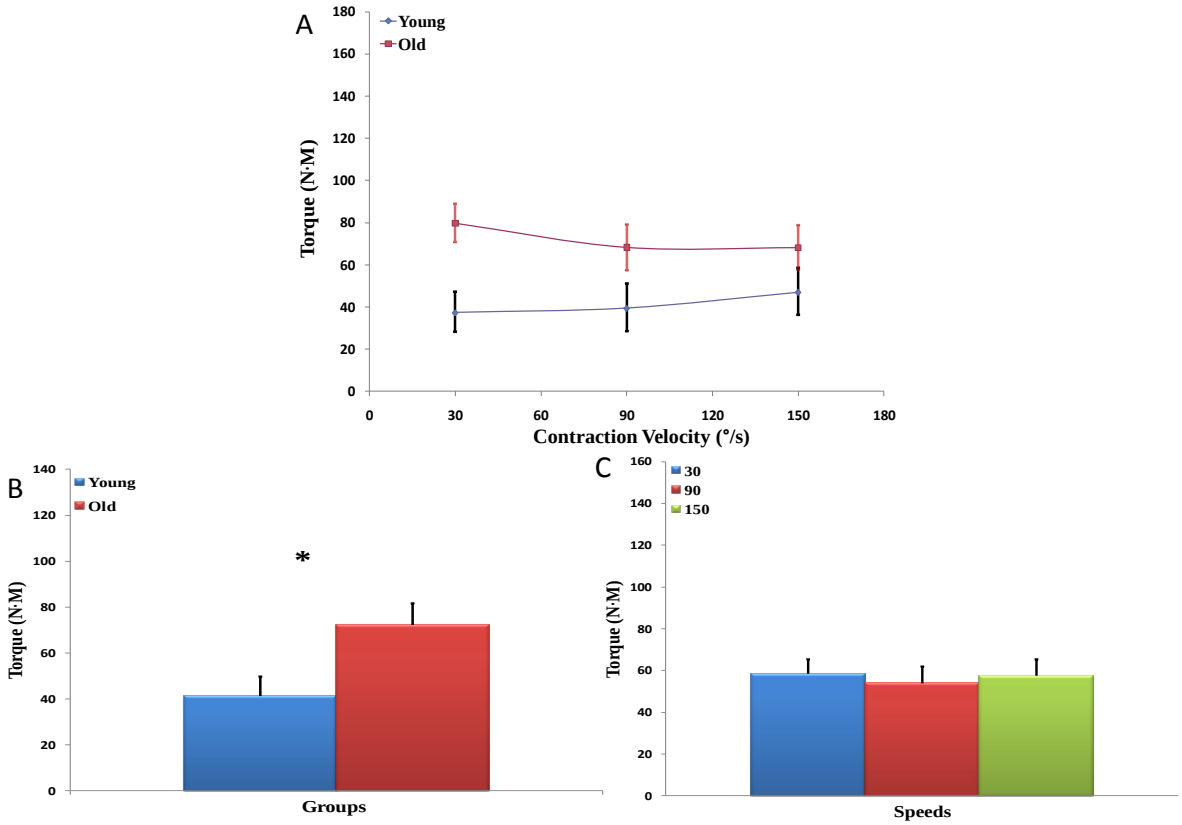

Figure 9(A) Torque velocity curve for the calculated hamstrings torque during concentric contraction in young (blue) and old (red). Error bars are SE. (B) Group Main effect on torque. Error bars are SE. (C) Speed main effect on net torque. Error bars are SE. * indicates significant main effect $p < 0.05$.

When mean calculated antagonist hamstring torque was observed across position there was no significant (F= .367, p = .983) 3-way interaction (speed by group by bin) observed (Figure 10A). A significant (F = 4.3, p< 0.001) group by bin interaction was observed (Figure 10B). No significant (F = 1.7, p = .198) speed by group interaction was observed for mean calculated hamstrings torque across position (Figure 10C).

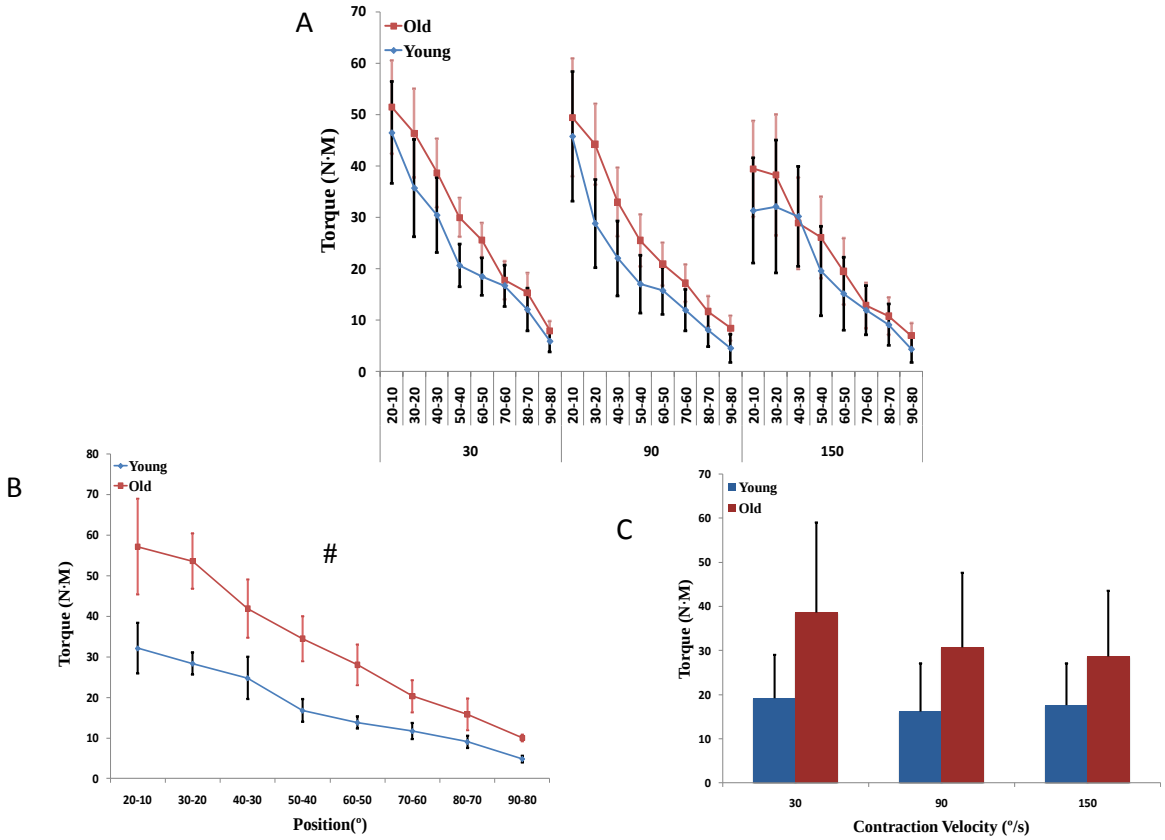

Figure 10 (A) Torque velocity curve for the calculated hamstrings torque during concentric condition in young (blue) and old (red) across position. Error bars are SE. (B) Group x Bin interaction on antagonist torque. Error bars are SE. (C) Group x Bin interaction effect on antagonist hamstring torque across position. Error bars are SE. # indicates significant interaction $p < 0.05$.

There was a borderline significant (F= 3.1, p = 0.054, ES =) speed main effect observed with mean calculated hamstrings torque increasing 21.0% between 30 °/s and 90 °/s, and then showing no significant increase between 90 °/s and 150 °/s (Figure 11A). A significant (F = 38.4, p< 0.001) bin main effect was observed with mean calculated hamstrings torque increasing 142% from the 90°-80° bin to 20°-10° bin (Figure 11B). A significant (F = 62.9, p< 0.001) group main effect was observed with the old group producing 67.3 % more mean calculated hamstrings torque than the young (Figure 11C).

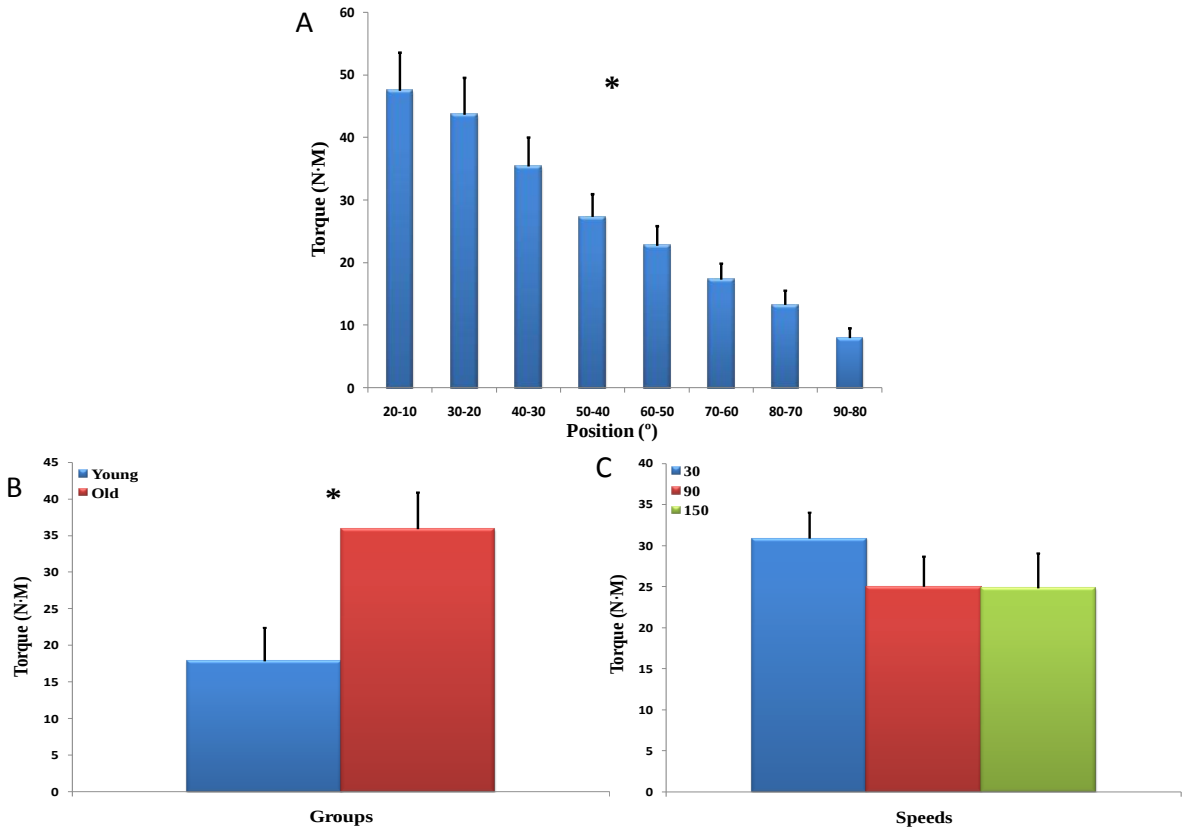

Figure 11(A) Bin main effect for calculated hamstrings torque across position. Error bars are SE. (B) Group Main effect on torque. Error bars are SE. (C) Speed main effect on antagonist hamstring torque across position. Error bars are SE. * indicates significant main effect $p < 0.05$.

Summary

In summary, the old group had greater levels of hamstring coactivation during knee extension. This increased coactivation in turn caused the old group to produced greater amounts of antagonist hamstring torque. While quadriceps agonist torque between the two groups was similar, the discrepancy in hamstrings antagonist torque caused a difference in total net concentric torque production. It was also observed that knee joint position had an effect on antagonist torque production.

DISCUSSION

The purpose of this study was to determine if the higher hamstring coactivation during knee extension in old adults would produce proportional reductions in knee extension. The hypothesis leading to this purpose was that old compared with young adults have higher levels of antagonist hamstring muscle coactivation at all velocities, producing greater reductions of torque during knee extensions in the old adults. The magnitude of hamstring coactivation torque was calculated using an EMG-driven model (Aagaard et al., 2000). By quantifying hamstring antagonist torque, the effect due to the increased hamstring coactivation in old adults during concentric knee extension torque production can then be observed.

This study was designed to compare the neuromuscular differences in young and old adults during isokinetic knee extensions at various contraction velocities. This chapter will discuss the results as they related to the literature and hypothesis and is organized as follows: 1) Development of the Hypothesis, 2) Discussion of Results, 3) Summary, 4) Conclusions, and 5) Future Recommendations.

Development of the Hypothesis

Coactivation is a mechanism that is utilized by the neuromuscular system to reduce the risk of injury and increase the durability of joints (Goodwin, Zhou, Baratta, Solomonow, & Keegan, 1997; Hagood, Solomonow, Baratta, Zhou, & D'Ambrosia, 1990). This mechanism has been observed during various tasks in both the upper and lower extremities (Hagood, Solomonow, Baratta, Zhou, & D'Ambrosia, 1990; Suzuki, Shiller, Gribble, & Ostry, 2001). While in healthy, young adults coactivation occurs when there is mild activation of the antagonist muscle during agonist muscle activation, in old adults the level of coactivity is

increased (Hortobagyi & Devita, 2006). This neuromuscular adaptation is thought to be caused by the diminishment of spinal reciprocal inhibition in the old (Hortobagyi & Devita, 2006).

The increased levels of coactivation in the old are thought to be associated with the increased need for joint stability and joint stiffness, thus leading to longer durability of the joint (Izquierdo et al., 1999; Patten & Kamen, 2000). There are theorized detriments of this mechanism, such as increased metabolic cost and decreased torque production, but the effect of increased coactivation on neuromuscular function has yet to be determined.

One method to examine the effects of coactivation on function is to observe muscle torque production in isokinetic dynamometry, which has been shown to be an effective tool for observing maximal torque efforts (Amiridis et al., 1996; Appen & Duncan, 1986). By using isokinetic dynamometry, the behavior of the musculoskeletal systems can be observed in a single joint model. Using this model, the role of coactivation can be isolated when compared to dynamic models such as gait, where coactivation is not accounted for. In isokinetic dynamometry, increased coactivation has been observed in the old when compared to young in both upper and lower extremities (Klein, Rice, & Marsh, 2001; LaRoche, Roy, Knight, & Dickie, 2008). It has also been observed in healthy, young individuals that the level of coactivation increases with contraction velocity (Osternig, Hamill, Lander, & Robertson, 1986).

By utilizing isokinetic dynamometry and EMG, previous studies have shown that when quantifying torque production of the knee extensors using an EMG based method, there is a significant reduction in torque production due to coactivation of the knee flexors (Aagaard et al., 2000; Amiridis et al., 1996; Baratta et al., 1988). But it is unknown if this effect is changed with aging. The observed increase in antagonist muscle coactivation associated with aging, led to the

hypothesis that the old group would have higher levels of antagonist hamstring coactivation when compared to the younger group at all velocities, and the increased antagonist hamstring coactivation will produce a greater reduction of torque during knee extensions in the old group

Discussion of Results

This section will discuss the results in regards to the hypotheses that old compared with young adults have higher levels of antagonist hamstring muscle coactivation at all velocities, producing greater reductions of torque during knee extensions in the old adult.

Measured Torque

Torque data, as measured by the Humac dynamometer, were used to create torque-velocity curves for the young and old group during concentric and eccentric knee extension. Measured torque from the young group was 30.8% greater than the old group, however this result was borderline significantly greater ($p < .060$). The magnitude of difference in torque between groups has been observed in other studies. Overend et al., examined the strength differences between young and old individuals during isokinetic knee extensions. They found that the old group was 32% significantly weaker than the young during concentric knee extension (Overend, Cunningham, Kramer, Lefcoe, & Paterson, 1992). Another relevant study found a significant difference in torque production, about 20%, when comparing groups of healthy, adults aged 45-54 and 65 and over (Frontera, Hughes, Lutz, & Evans, 1991). Previous studies have observed a difference of 20-30% in torque production between young and old during a variety of tasks (Raj, Bird, & Shield).

It has also been observed that old men are significantly stronger than old women. Frontera et al. examined the difference in specific force production, the capacity of muscle to

generate force, of muscle, in young and old muscle. They found that old muscle has lower levels of specific force than young and that old male muscle was stronger than old female muscle (Frontera, Hughes, Lutz, & Evans, 1991).

Speed	Group	M	F	M/F Ratio	Δ% Y & O
30	Y	109.7	67.2	1.631476377	7.085191
	O	75.8	50.0	1.515883165	
90	Y	82.4	50.1	1.646716505	-1.21596
	O	55.8	33.5	1.6667399	
150	Y	44.6	24.7	1.803819782	-34.7318
	O	58.0	23.8	2.430318821	

Table 3 Strength Data for Young and Old Subjects by Sex

Our study found similar results with older males producing more torque than females across all speeds. It was also observed that the ratio of male to female (M/F) strength between the young and old groups were similar during 2 of the 3 speeds (Table 3). Because of this similarity between young and old group M/F strength ratio, it is believed that sex had no role in preventing any statistical significance from being observed.

These previous studies attributed the difference in net torque production as a limitation of the physiological muscular differences observed in older individuals regardless of sex, i.e. smaller CSA and decreased muscle mass. However, decreased strength is not only caused by muscular degradation. Macaluso et al. found that the loss of strength can also be attributed to increased antagonist muscle coactivation i.e. a neural adaptation associated with aging (Macaluso et al., 2002). Therefore the interpretation of the result of the current study is that the decrement of torque production may be attributed to both muscular and neurological

mechanisms. Since physiological muscle characteristics were not examined in the current study, this discussion will simply discuss the role of neurological mechanisms on torque production.

Agonist Quadriceps EMG Activity and Antagonist Hamstring EMG Coactivation

The two mechanisms thought to limit maximal torque production during isokinetic knee extension are diminished neural drive to agonist muscle and increased antagonist muscle drive. Both mechanisms result in an increase in antagonist muscle coactivity. The grouped mean agonist quadriceps EMG activity was higher, by 28.1%, in the young than the old group. This result was not significantly different, but this non-significance maybe caused by a power issue in the study. The grouped mean antagonist hamstring activity between the two groups was similar but the proportion of antagonist-to-agonist muscle activity, which is the coactivation ratio, was 63.7%, significantly higher in the old vs. the young during knee extension. These results support the idea that the mechanism for increased coactivation in old adults is due to a decrease in the agonist neural drive. This mechanism is attributed to a diminishment in motor unit firing frequency and recruitment as well as a prolonging of twitch time (Narici, Maffulli, & Maganaris, 2008). This mechanism accounts for the similar levels of antagonist hamstring EMG activity between the two groups while the old group still exhibited higher levels of coactivation. This result of increased coactivation in the old groups supports previous findings that have found increased magnitude of coactivation, 20-118%, in old groups when compared to young during a variety of tasks (Burnett, Laidlaw, & Enoka, 2000; Hortobagyi & DeVita, 2000; Izquierdo et al., 1999; Klein, Rice, & Marsh, 2001). One study that examined similar muscle groups as the current study found 55% more coactivation in the old group when compared to the young during isokinetic knee extension (Macaluso et al., 2002). These results support the hypothesis that the

old group would have higher levels of coactivation across all contraction velocities when computed as the antagonist-to-agonist muscle activity ratio.

Comparison of Measured Torque and EMG-Driven Calculated Net Extension Torque

This study utilized an EMG-driven model to calculate individual agonist quadriceps and antagonist hamstring torques during concentric knee extension to determine the role of the individual muscle groups during knee extension. Using the EMG-driven model, we calculated 1) net concentric knee extension torque (summation of the torques computed from EMG activity of the quadriceps and hamstrings), 2) agonist torque (torque calculated from the EMG activity of the quadriceps), and 3) antagonist torque (torque calculated from the EMG activity of the hamstrings). We used a comparison between calculated net torque and experimentally measured torque for validation of our calculation method. During concentric knee extension there was a 3.8% difference between the young group and a 2.7% difference for the old group between measured and calculated net extension torque. This relatively low percent difference allows us to confidently draw conclusions on the individual behaviors of the two muscle groups being examined in this study.

The Role of Increased Antagonist Hamstring Coactivation in Calculated Torques

By examining the role of the individual muscle groups during the isokinetic action, we can determine which of the two mechanisms responsible for increased coactivation contributes to the difference in torque production between young and old. The result of the diminished neural drive to the agonist muscle is that during voluntary maximal effort there is a failure to recruit all of the available muscle fibers (Clark, Condliffe, & Patten, 2006). Our results indicate that there was no significant difference in calculated agonist torque between young and old. Since our

results were computed using an EMG-driven equation, implications for the neural drive of the quadriceps can be made. Therefore diminished agonist neural drive cannot be the sole mechanism of increased coactivation since there was no difference between the two groups in the calculated quadriceps torque.

Both decreased agonist drive and increased antagonist muscle activation may have occurred during isokinetic knee extension to lead to the diminishment in calculated extension torque production in the old group. Our results show that there was significantly ($p < 0.001$) greater, 54.5%, calculated antagonist torque in the old group compared to the young. This result verifies that increased antagonist coactivation occurred in the old group.

But since there was no difference in antagonist hamstring activity between groups, hyperactivity of the antagonist muscle did not occur during the extension task. This contrary finding can be explained by our calculation of individual torques, which accounts for the eccentric action of the antagonist hamstring muscles during concentric knee extension. This is accomplished by comparing the EMG activity of the hamstring muscles during concentric and eccentric knee extension.

During eccentric knee extension, the young group was not significantly stronger than the old group. Since the old group had lower levels of agonist hamstring activation during eccentric knee extension while producing a similar level of torque to the young group, the corresponding calculated antagonist hamstring torque during concentric knee extension was higher in the old than the young. This result is supported by previous studies that have shown eccentric strength is relatively preserved in aging (Hortobagyi et al., 1995) and that there is an increase in muscular stiffness and an accumulation of elastic elements associated with aging (Roig et al., 2010),

accounting for the decreased EMG activity during eccentric contractions in old individuals. This finding supports the hypothesis that increased antagonist hamstring coactivation will produce a greater reduction of torque during concentric knee extensions in the old group.

The Role of Contraction Velocity and Joint Position on Antagonist Torque

Another aspect of this study examined the role of joint position and contraction velocity on antagonist hamstrings coactivation. This was accomplished by examining the calculated antagonist torque production in 10° bins throughout the range of motion for each contraction velocity, from 30 °/s to 150 °/s. For calculated antagonist torque, a significant speed effect was observed with torque production increasing between 30 °/s and 90 °/s, and then showing no significant increase between 90 °/s and 150 °/s. The speed effect on torque production has been reported in previous studies examining agonist torque production (Osternig, 1986). But the result of the current study describes the effect of speed on antagonist torque production. This result can be explained by increases in coactivation with increases in contraction velocity. This phenomenon has been examined in previous studies, which have observed increases in coactivation with increases in contraction velocity in healthy, young adults (Aagaard, Simonsen, Trolle, Bangsbo, & Klausen, 1995; Kellis & Baltzopoulos, 1998; Osternig, Hamill, Lander, & Robertson, 1986; Schlinkman, 1984; Weir, Keefe, Eaton, Augustine, & Tobin, 1998).

For calculated antagonist torque, a significant bin effect was observed with torque production. Moving from the flexed position (90°-80°) to the extension position (20°-10°) calculated antagonist torque production increased 142%. This finding corroborated previous studies that calculated individual torques in the same manner, which found calculated antagonist torque production increasing 74.6% from flexion to extension (Aagaard et al., 2000). This

finding further supported previous findings where calculated antagonist torques were greater at the termination of knee extension than at the initiation of the movement (Kellis & Baltzopoulos, 1997; Snow, Cooper, Quanbury, & Anderson, 1993). The reason for the difference in the magnitudes of the findings is that this previous study examined this effect only in healthy, young individuals where the expected coactivation ratio would be smaller and therefore lower levels of calculated antagonist hamstrings torque would be estimated than in the current study. This finding is validated by previous studies, which have shown that joint position alters the level of antagonist coactivity in healthy, young adults (Baratta et al., 1988; Osternig, Hamill, Lander, & Robertson, 1986; Remaud, Cornu, & Guevel, 2009).

Summary

Statistical analysis showed that there were age-related differences in net concentric torque production during isokinetic knee extension. The effects of age were seen in antagonist hamstrings torque production. Because of this significant increase in antagonist torque production, net concentric torque was significantly decreased in the old group. The results of this study support our hypothesis that old compared with young adults have higher levels of antagonist hamstring muscle coactivation at all velocities, producing greater reductions of torque during knee extensions in the old adult.

Conclusion

It was hypothesized was that old compared with young adults have higher levels of antagonist hamstring muscle coactivation at all velocities, producing greater reductions of torque during knee extensions in the old adult. This increased coactivation has been observed in many different tasks when comparing young and old individuals. While many different studies have observed benefits of increased coactivation, no study has previously determined the effect of increased coactivation of old individuals on neuromuscular function. Therefore, this functional effect was tested by examining the role of coactivation on torque production using an EMG driven computation during isokinetic knee extension.

Torque production between the young and old group was compared to determine the effect of antagonist hamstring coactivation. Age-related differences were observed in mean EMG activity between the young and old groups. This age-related difference in coactivation caused an observable significant difference in antagonist hamstring torque production and this increased antagonist hamstring torque in turn caused a diminishment in net concentric torque production. These findings support the hypotheses that there would be increased coactivation associated with aging and that this increased coactivation causes a diminishment in neuromuscular function.

In conclusion, this thesis identified a detrimental effect of coactivation on neuromuscular function. Although coactivation provides benefits that help prevent the risk and reduce the gravity of injury, the findings of this study have negative implications for strength capacity in aging. . In conclusion, while the age-related reduction in the ability to produce forceful muscle contractions is due to sarcopenia, the present data suggest that this reduction may include

reductions due to altered neural control of voluntary movement, causing an increase in counteracting torques arising from the antagonist muscle during a simple knee extension task.

Future Recommendations

The physiological adaptations associated with aging are becoming more understood. Many of the mechanisms of the compensatory adaptations in aging are finally becoming well studied. But what is not well known is the time course of the manifestations of these compensatory adaptations. While there have been a few cross-sectional studies to look at time course of changes in strength, by using the methods used in this thesis the time course or the neurological adaptations attributed to aging may be observed.

Another aspect to investigate would be to determine the effects of such compensatory adaptations on less healthy older individuals. Old adults that perform similarly to young adults are said to have different cortical motor strategies than frail individuals(Sailer, Dichgans, & Gerloff, 2000). One manifestation of the healthy, old adult cortical motor strategy is increased coactivation. Pilot data from another study in our lab has shown that the increased coactivation associated with aging is associated with increased metabolic demand. Therefore it would be worthwhile to investigate the cortical motor strategy and functional discrepancies between healthy old and less than healthy old groups. By examining the role of coactivation on function, future studies can determine if there are more beneficial modes of therapy available for clinical populations that manifest increased coactivation.

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APPENDIX A: INFORMED CONSENT

Consent Form
Mechanical Plasticity in Locomotion with Age

Investigator: Paul DeVita, Ph.D., Tibor Hortobagyi, Ph.D.
Address: 332 Sports Medicine Building
Biomechanics Laboratory
East Carolina University, Greenville, NC 27858
Telephone: (252) 737 – 4563, (252) 737 - 4564

I am being asked to voluntarily participate in this research project conducted by Paul DeVita, Ph.D. and Tibor Hortobágyi, Ph.D. The **purpose** is to examine the effects of exercise on muscle strength and mobility. Depending on my group assignment, the study involves up to 4 sessions of testing 1 hour each **or** these testing sessions plus supervised exercise training of the leg muscles 3 times per week for 10 weeks. There will be about 40 participants in this study.

I understand that my written consent is required before I can participate in this project. I may not participate in this project if: I had a falling accident in the past; I have had lower extremity surgeries or neurological conditions (i.e. stroke) or I have orthopedic conditions that substantially modify my walking pattern; I am afraid of ascending and descending stairs; I am on medication that causes dizziness; I am a smoker; I have a body mass/height ratio greater than 28; I have high blood pressure (140 systolic and 90 mm Hg diastolic) or I have a heart condition.

Procedures: I understand that I will be told which procedures apply to me:
1. Testing procedures: After 2-3 minutes of quiet sitting, my resting blood pressure and heart rate will be measured. In preparation, certain areas of the skin on my legs will be shaved and cleaned with alcohol. To determine the exact location of the muscle belly, water-soaked probe will be placed on the skin through which a very brief (100-millisecond) electrical stimulus will be applied to the skin. The stimulus may be applied 1-4 times per muscle site. Because the stimulation is very brief, I will feel no pain. EKG sensors will then be placed on 4 muscles of my right leg over the cleaned areas. These electrodes do not emit electricity but record muscle activity. The EKG electrodes will be connected to cables that lead to a small box secured on a waist-belt. As a warm-up for the subsequent tests, I will ride a stationary bicycle ergometer at a light resistance for about 5 minutes.

A. Position sense test. I will be seated on the seat of a computerized device. This is a precision test. For this experiment I will wear a blindfold. There will be no resistance applied to my leg throughout this test. I will be asked to move my leg from the starting position to a designated position, try to remember this position, return my leg to the starting position, then resume this position the best I can remember. After a few practice trials, I will be asked to repeat this test for 5 different positions using my right leg and my right ankle, respectively.

B. Steadiness test. This test will be done with eyes open. This is a matching test. I will be asked to extend my right knee and try to match a target force level that appears in front of me on a computer screen. The force I need to match will be just a few pounds. After some practice trials, I will perform 5 trials at a very low force and 5 trials at a somewhat greater force using my knee and my ankle, respectively.

C. Maximal leg strength test. This test will be done with eyes open. As a specific warm-up, I will perform 2 light, 2 medium, and 2 harder efforts. I will be tested for maximal knee extension and flexion and ankle extension and flexion strength of the right leg using a computerized strength-measuring device. Three repetitions of static effort (effort without actual movement) and 3 repetitions of dynamic efforts (effort with movement at the joint) with 1 minute of rest between conditions.

D. Walking test. Level walking: I will be asked to walk 10 yards as fast as I safely can. My movement will be video taped from the side. I will perform 5 trials. Then I will perform 5 trials at 1.5 m/s speed which is a comfortably slower speed. Walking on a Ramp: I will be asked to walk up a wooden ramp, stop at the end, turn around and walk down. The ramp is about 15 feet long and its slope is similar to a handicap ramp. Walking with ankle weights: I will be asked to walk with weights attached to my left or right ankle with Velcro. The weights are very light and correspond to only 5% or 10% of body weight.

Consent Form
Mechanical Plasticity in Locomotion with Age
(Page 2 of 3)

E. Ascending and descending stairs. I will be asked to walk up at a self selected pace 4 steps, stop on the top of the stairwell, turn around, and descend. My movement will be video taped from the side. I will perform 5 trials.

F. Balance test. This test will be done under 7 conditions as listed below. A person will stand behind me to hold me, should I lose my balance. I will be asked to stand on a level platform that is even with the floor and try to maintain my balance for 30 seconds, 3 trials each of the following conditions:
1. Standing on the platform eyes open; 2. Standing on the platform eyes open head extended;
3. Standing on the platform eyes closed head extended; 4. Standing on the platform eyes open wearing the hat and head extended; 5. Standing on foam placed on the platform eyes open head extended; 6. Standing on foam placed on the platform eyes closed head extended, and 7. Standing on foam placed on the platform with hat on and head extended. The 'hat' refers to a dome that will be block my view but lets light through.

G. Other mobility tests. The following tests will be administered by staff members who will rate my mobility for time and quality of movement. I will wear no electrodes and I will not be video taped.
1. Arising from a chair without an arm rest. 2. Immediate standing balance after arising from a chair. 3. Nudged on sternum 3 times at maximal standing height. 4. Pick up a pencil/pen from floor. 5. Turn 360°. 6. Arise from a chair and turn 360°. 7. Arise from a chair and walk 15 m in a carpeted hallway. 8. Ascend about 20 stairs. 9. Descend about 20 stairs. 10. Reaching for maximal length without losing balance or making a step.

H. Maximal leg press strength. In supine position, the weight I can move with my legs one time, will be measured in a leg press weight lifting machine. I will perform warm up trials at very light and medium loads to reach my maximum gradually.

I. Step length test. I will walk across the level walkway about 25 times using steps ranging from short to long in length. My movements will be recorded with a camera system and my muscles will be measured with electrodes placed on four muscles in the right leg.

2. Training procedures: If I am selected to be in the exercise training group, I will report to the Biomechanics Laboratory 3 times per week for 10 weeks to undergo a supervised weight lifting exercise program with an emphasis on leg strength. I will exercise by performing 4 to 6 bouts of 10 to 15 repetitions at 40-50% of my maximal weight or by performing 4 to 6 bouts 5 to 10 repetitions at 80-90% of my maximal weight. As I improve, the weights will be gradually adjusted every week. I will exercise my thigh and hip muscles and my calf muscles. A 'bout' refers to a unit of exercise during which I perform a given number of repetition. There will be 2 minutes of rest between each exercise bout. My blood pressure will be monitored before, during, and after exercise. Optional upper body exercises will be available but not required.

Risks: Because the forces produced during the Position and Steadiness tests are very low, there are minimal risks associated with these tests. In contrast, any tests that require maximal effort represent risks in terms of high blood pressure, stroke, heart attack, temporary pain, and muscle strain or joint sprain. Such tests are the Maximal leg strength and Maximal leg press tests. The Walking tests represent low risks although during rapid walking temporary breathlessness or dizziness may develop. Ascending and especially descending stairs can be hazardous for elders in terms of falling. The Balance tests represent some risk of falling when my eyes are closed or wearing the vision-blocking hat. The Mobility tests represent some risks of losing balance, falling, rapid rise in blood pressure, and dizziness. The Training procedures represent risks of elevated blood pressure, dizziness, shortness of breath and my legs may become tired.

All these risks will be reduced by: allowing subjects to participate who have been previously cleared by their physicians; carefully screening for the various risk factors prior to testing; monitoring blood pressure and heart rate; having a spotter monitor the tests that are associated with risks for falling; carefully explaining and demonstrating the tasks, and by having subjects properly warmed up for and thoroughly familiarized with the tests.

UMCIRB
APPROVED
FROM 7·15·09
TO 7·14·10

Consent Form
Mechanical Plasticity in Locomotion with Age
(Page 3 of 3)

Benefits: All results will be explained to me. I will be entitled to $50 if my assignment is a non-exercising control subjects. In this case I will be asked to perform the tests twice about 8-10 weeks apart. If my assignment places me in the exercise group, I will be entitled to $150. To receive this benefit, I will be asked to perform the tests twice, once before and once after the exercise training program. The payment will be available to me upon the completion of the study or will be prorated in proportion to the extent of participation.

Withdrawal, Injury, Confidentiality: The nature and purpose of the procedures, the known risks involved, and the possibility of complications have been explained to me, and I understand them. I understand that not all risks and side effects of these procedures are foreseeable.

I understand that participation in this experiment is voluntary and refusal to participate will involve no penalty or loss of benefits to which I am otherwise entitled, and I may discontinue participation at any time without penalty. The policy of East Carolina University does not provide for compensation or medical treatment
for subjects because of physical or other injury resulting from this research activity. However, every effort will be made to make the facilities of the School of Medicine available for treatment in the event of such physical injury.

I understand that my personal data will be held in strict confidence by the investigators. I understand that if any publications result from this study my name or any identifiable codes will not be used. The video tape footages will be seen only by the researchers involved in data analysis. The video tapes will be destroyed after all data had been extracted.

Contact person. If I have any questions about the research or possible research-related injury, I may contact Dr. DeVita at home ([252] 756 – 8070) or at work ([252] 737 – 4563) or Dr. Hortobágyi at home ([252] 355-7715) or work ([252] 737-4564). Also, if questions arise about my rights as a research subject, I may contact the Chair of the University Policy and Review Committee on Human Research ([252] 816-2914).

I have read the above material and it has been explained to me by Dr. DeVita or Dr. Hortobagyi. I have been encouraged to ask questions about the study and all inquiries have been answered to my satisfaction. A copy of this consent form shall be given to the person signing as the subject or as the subjects authorized representative.

_____
Patient's name (Print)

_____ Date _____
Patient's signature

Auditor witness: I confirm that the contents of this consent form were orally presented.

_____
Auditor's name (Print)

_____ Date _____
Auditor's witness signature

_____
Principal investigator's name (Print)

_____ Date _____
Principal investigator's signature

_____
Family physician's name (Print)

_____ Date _____
Family physician's signature

UMCIRB
APPROVED
FROM 7.15.09
TO 7.14.10

APPENDIX B: INSTITUTIONAL REVIEW BOARD APPROVAL

University and Medical Center Institutional Review Board
East Carolina University • Brody School of Medicine
600 Moye Boulevard • Old Health Sciences Library, Room 1L-09 • Greenville, NC 27834
Office **252-744-2914** • Fax **252-744-2284** • **www.ecu.edu/irb**
Chair and Director of Biomedical IRB: L. Wiley Nifong, MD
Chair and Director of Behavioral and Social Science IRB: Susan L. McCammon, PhD

TO: Paul DeVita, PhD, Dept of EXSS, ECU—332 Ward Sports Medicine Building

FROM: UMCIRB

DATE: July 15, 2009

RE: Expedited Continuing Review of a Research Study

TITLE: "Mechanical Plasticity in Locomotion with Age"

UMCIRB #98-044

The above referenced research study was initially reviewed and approved by the convened UMCIRB on 9.1.1998. This research study has undergone a subsequent continuing review using expedited review on 7.15.09. This research study is eligible for expedited review because it is on collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving x-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing. (Studies intended to evaluate the safety and effectiveness of the medical device are not generally eligible for expedited review, including studies of cleared medical devices for new indications.) Examples: (a) physical sensors that are applied either to the surface of the body or at a distance and do not involve input of significant amounts of energy into the subject or an invasion of the subject's privacy; (b) weighing or testing sensory acuity; (c) magnetic resonance imaging; (d) electrocardiography, electroencephalography, thermography, detection of naturally occurring radioactivity, electroretinography, ultrasound, diagnostic infrared imaging, doppler blood flow, and echocardiography; (e) moderate exercise, muscular strength testing, body composition assessment, and flexibility testing where appropriate given the age, weight, and health of the individual. It is also a research involving materials (data, documents, records, or specimens) that have been collected, or will be collected solely for nonresearch purposes (such as medical treatment or diagnosis). (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(4). This listing refers only to research that is not exempt.) The Chairperson (or designee) deemed this **NIH/ECU grant funded** study **no more than minimal risk** requiring a continuing review in **12 months**. Changes to this approved research may not be initiated without UMCIRB review except when necessary to eliminate an apparent immediate hazard to the participant. All unanticipated problems involving risks to participants and others must be promptly reported to the UMCIRB. The investigator must submit a continuing review/closure application to the UMCIRB prior to the date of study expiration. The investigator must adhere to all reporting requirements for this study.

The above referenced research study has been given approval for the period of **7.15.09** to **7.14.10**. The approval includes the following items:

- Continuing Review Form (dated 7.9.09)
- Informed Consent (dated 11.11.04) (received 7.10.09)

The Chairperson (or designee) does not have a conflict of interest on this study.

The UMCIRB applies 45 CFR 46, Subparts A-D, to all research reviewed by the UMCIRB regardless of the funding source. 21 CFR 50 and 21 CFR 56 are applied to all research studies under the Food and Drug Administration regulation. The UMCIRB follows applicable International Conference on Harmonisation Good Clinical Practice guidelines.

APPENDIX C: SHORT PHYSICAL PERFORMANCE BATTERY FORMS

Study ID _____ Date _____ Tester Initials _____

SCORING:

A. Side-by-side-stand
Held for 10 sec ❒ 1 point
Not held for 10 sec ❒ 0 points
Not attempted ❒ 0 points
If 0 points, end Balance Tests

Number of seconds held if less than 10 sec: ___._ _sec

If participant did not attempt test or failed, circle why:
Tried but unable 1
Participant could not hold position unassisted 2
Not attempted, you felt unsafe 3
Not attempted, participant felt unsafe 4
Participant unable to understand instructions 5
Other (specify) _____ 6
Participant refused 7

B. Semi-Tandem Stand
Held for 10 sec ❒ 1 point
Not held for 10 sec ❒ 0 points
Not attempted ❒ 0 points *(circle reason above)*
If 0 points, end Balance Tests

Number of seconds held if less than 10 sec: ___._ _sec

C. Tandem Stand
Held for 10 sec ❒ 2 points
Held for 3 to 9.99 sec ❒ 1 point
Held for < than 3 sec ❒ 0 points
Not attempted ❒ 0 points (circle reason above)

Number of seconds held if less than 10 sec: ___._ _sec

D. Total Balance Tests score_____(sum points)

Comments: _____

Study ID _____ Date _____ Tester Initials _____

GAIT SPEED TEST SCORING:

Length of walk test course: Four meters ❒ Three meters ❒

A. Time for First Gait Speed Test (sec)

1. Time for 3 or 4 meters __ __.__ __sec
2. If participant did not attempt test or failed, circle why:

Tried but unable	1
Participant could not walk unassisted	2
Not attempted, you felt unsafe	3
Not attempted, participant felt unsafe	4
Participant unable to understand instructions	5
Other (Specify) _____	6
Participant refused	7

Complete score sheet and go to chair stand test

3. Aids for first walk.....None ❒ Cane ❒ Other ❒

Comments:_____

_____

_____

B. Time for Second Gait Speed Test (sec)

1. Time for 3 or 4 meters __ __.__ __ sec
2. If participant did not attempt test or failed, circle why:

Tried but unable	1
Participant could not walk unassisted	2
Not attempted, you felt unsafe	3
Not attempted, participant felt unsafe	4
Participant unable to understand instructions	5
Other (Specify)	6
Participant refused	7

3. Aids for second walk..... None ❒ Cane ❒ Other ❒

What is the time for the faster of the two walks?
Record the shorter of the two times __ __.__ __ sec
[If only 1 walk done, record that time] __ __.__ __ sec

If the participant was unable to do the walk: ❒ **0 points**

For 4-Meter Walk:		**For 3-Meter Walk:**	
If time is more than 8.70 sec:	❒ **1 point**	If time is more than 6.52 sec:	❒ **1 point**
If time is 6.21 to 8.70 sec:	❒ **2 points**	If time is 4.66 to 6.52 sec:	❒ **2 points**
If time is 4.82 to 6.20 sec:	❒ **3 points**	If time is 3.62 to 4.65 sec:	❒ **3 points**
If time is less than 4.82 sec:	❒ **4 points**	If time is less than 3.62 sec:	❒ **4 points**

Study ID _____ Date _____ Tester Initials _____

SCORING
Single Chair Stand Test

	YES	NO
A. Safe to stand without help	❒	❒

B. Results:

Participant stood without using arms	❒	→ Go to Repeated Chair Stand Test
Participant used arms to stand	❒	→ End test; score as 0 points
Test not completed	❒	→ End test; score as 0 points

C. If participant did not attempt test or failed, circle why:

Tried but unable	1
Participant could not stand unassisted	2
Not attempted, you felt unsafe	3
Not attempted, participant felt unsafe	4
Participant unable to understand instructions	5
Other (Specify) _____	6
Participant refused	7

Repeated Chair Stand Test

	YES	NO
A. Safe to stand five times	❒	❒

B. If five stands done successfully, record time in seconds.

Time to complete five stands __ __.__ __ sec

C. If participant did not attempt test or failed, circle why:

Tried but unable	1
Participant could not stand unassisted	2
Not attempted, you felt unsafe	3
Not attempted, participant felt unsafe	4
Participant unable to understand instructions	5
Other (Specify)	6
Participant refused	7

Scoring the Repeated Chair Test

Participant unable to complete 5 chair stands or completes stands in >60 sec:	❒ 0 points
If chair stand time is 16.70 sec or more:	❒ 1 points
If chair stand time is 13.70 to 16.69 sec:	❒ 2 points
If chair stand time is 11.20 to 13.69 sec:	❒ 3 points
If chair stand time is 11.19 sec or less:	❒ 4 points

Study ID _____ Date _____ Tester Initials _____

Scoring for Complete Short Physical Performance Battery

Test Scores

Total Balance Test score	**_____ points**
Gait Speed Test score	**_____ points**
Chair Stand Test score	**_____ points**
Total Score	**_____ points (sum of points above)**

APPENDIX D: SUPPLEMENTAL GRAPHS

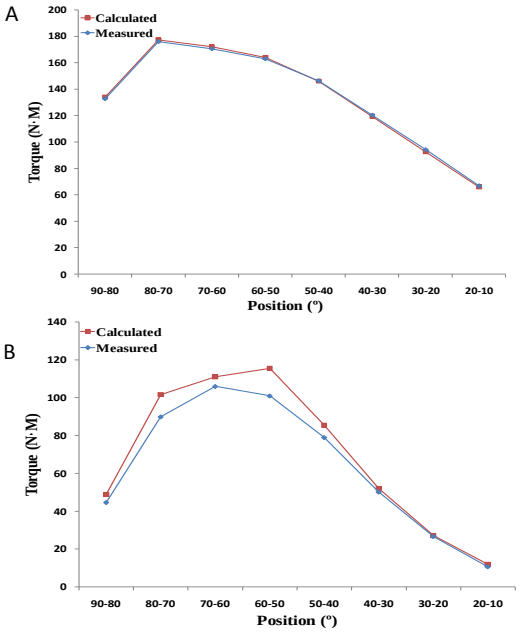

Figure 13 (A) Concentric knee extension and (B) eccentric knee extension torque velocity curves for measured (blue) vs. calculated (red) net torques at 30 /s.

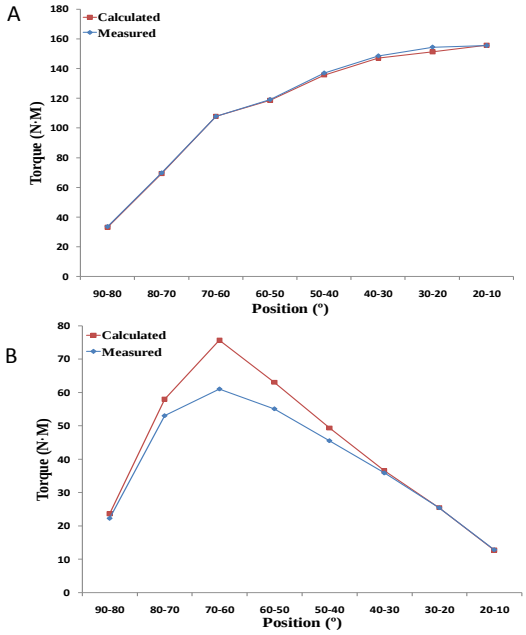

Figure 14 (A) Concentric knee extension and (B) eccentric knee extension torque velocity curves for measured (blue) vs. calculated (red) net torques at 90 /s.

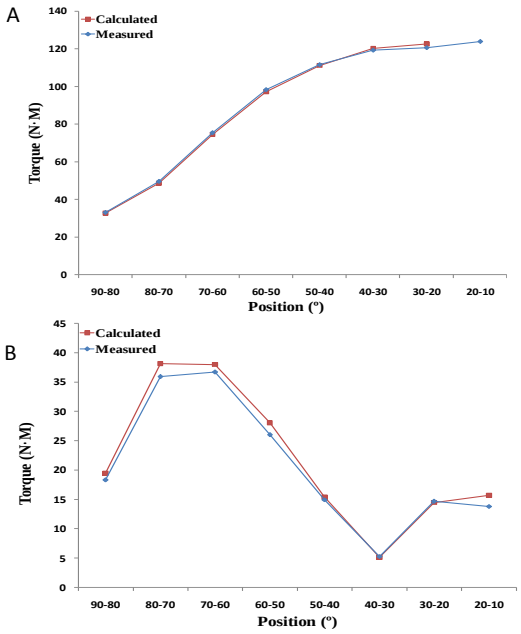

Figure 15 (A) Concentric knee extension and (B) eccentric knee extension torque velocity curves for measured (blue) vs. calculated (red) net torques at 150 /s.

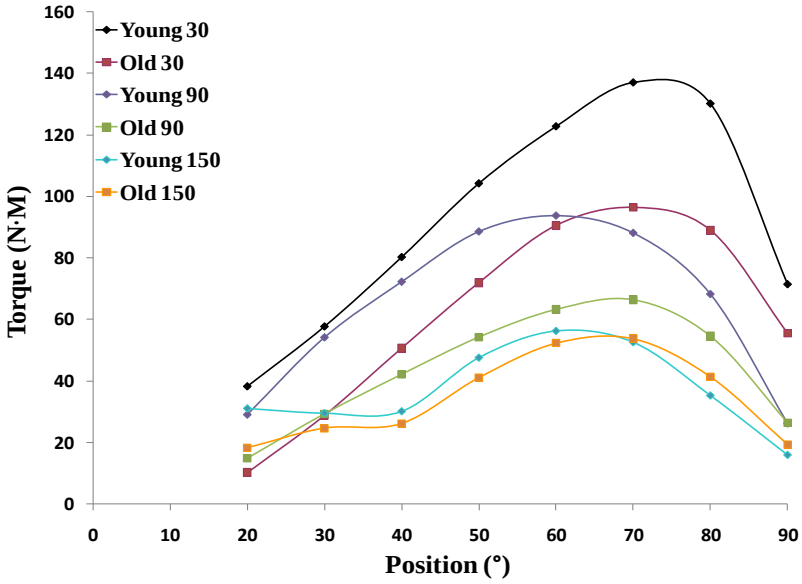

Figure 16 (A) Concentric knee extension torque velocity curves for calculated net torques of young and old at 30, 90, and 150 /s.

APPENDIX E: SUPPLEMENTAL TABLES

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	5.579	1	5.579	62.369	.000
GRP	.109	1	.109	1.221	.282
Error	1.789	20	.089		

Table 4 Statistical Data for Agonist Quadriceps EMG

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	.085	1	.085	103.911	.000
GRP	.005	1	.005	5.668	.027
Error	.016	20	.001		

Table 5 Statistical Data for Antagonist Quadriceps EMG

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	4.108	1	4.108	123.043	.000
GRP	.073	1	.073	2.172	.156
Error	.668	20	.033		

Table 6 Statistical Data for Agonist Hamstring EMG

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	.534	1	.534	48.714	.000
GRP	1.419E-6	1	1.419E-6	.000	.991
Error	.219	20	.011		

Table 7 Statistical Data for Antagonist Hamstring EMG

A

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	6.392	1	6.392	133.023	.000
GRP	.653	1	.653	13.597	.001
Error	.961	20	.048		

B

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	1.565	1	1.565	115.201	.000
GRP	.000	1	.000	.017	.898
Error	.272	20	.014		

Table 8 Statistical Data for (A) Concentric and (B) Eccentric Coactivation

A

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	492938.801	1	492938.801	167.767	.000
GRP	11702.883	1	11702.883	3.983	.060
Error	58764.690	20	2938.235		

B

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	426776.964	1	426776.964	180.649	.000
GRP	1339.894	1	1339.894	.567	.460
Error	47249.279	20	2362.464		

Table 9 Statistical Data for (A) Concentric and (B) Eccentric Knee Extension Torque

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Speed	Sphericity Assumed	38756.797	2	19378.399	54.829	.000
	Greenhouse-Geisser	38756.797	1.737	22309.149	54.829	.000
	Huynh-Feldt	38756.797	1.983	19541.984	54.829	.000
	Lower-bound	38756.797	1.000	38756.797	54.829	.000
Speed * GRP	Sphericity Assumed	2007.644	2	1003.822	2.840	.070
	Greenhouse-Geisser	2007.644	1.737	1155.638	2.840	.079
	Huynh-Feldt	2007.644	1.983	1012.296	2.840	.071
	Lower-bound	2007.644	1.000	2007.644	2.840	.107
Error(Speed)	Sphericity Assumed	14137.327	40	353.433		
	Greenhouse-Geisser	14137.327	34.745	406.886		
	Huynh-Feldt	14137.327	39.665	356.417		
	Lower-bound	14137.327	20.000	706.866		

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	526584.668	1	526584.668	172.072	.000
GRP	11487.028	1	11487.028	3.754	.067
Error	61205.076	20	3060.254		

Table 10 Statistical Data for Calculated Net Extension Torque

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Speed	Sphericity Assumed	41433.183	2	20716.591	28.426	.000
	Greenhouse-Geisser	41433.183	1.454	28490.483	28.426	.000
	Huynh-Feldt	41433.183	1.617	25618.564	28.426	.000
	Lower-bound	41433.183	1.000	41433.183	28.426	.000
Speed * GRP	Sphericity Assumed	1349.510	2	674.755	.926	.405
	Greenhouse-Geisser	1349.510	1.454	927.956	.926	.379
	Huynh-Feldt	1349.510	1.617	834.416	.926	.388
	Lower-bound	1349.510	1.000	1349.510	.926	.347
Error(Speed)	Sphericity Assumed	29152.048	40	728.801		
	Greenhouse-Geisser	29152.048	29.086	1002.284		
	Huynh-Feldt	29152.048	32.346	901.251		
	Lower-bound	29152.048	20.000	1457.602		

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	882731.579	1	882731.579	231.922	.000
GRP	6.703	1	6.703	.002	.967
Error	76123.077	20	3806.154		

Table 11 Statistical Data for Calculated Agonist Torque

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Speed	Sphericity Assumed	266.836	2	133.418	.255	.776
	Greenhouse-Geisser	266.836	1.835	145.450	.255	.758
	Huynh-Feldt	266.836	2.000	133.418	.255	.776
	Lower-bound	266.836	1.000	266.836	.255	.619
Speed * GRP	Sphericity Assumed	1259.297	2	629.649	1.202	.311
	Greenhouse-Geisser	1259.297	1.835	686.432	1.202	.309
	Huynh-Feldt	1259.297	2.000	629.649	1.202	.311
	Lower-bound	1259.297	1.000	1259.297	1.202	.286
Error(Speed)	Sphericity Assumed	20947.728	40	523.693		
	Greenhouse-Geisser	20947.728	36.691	570.922		
	Huynh-Feldt	20947.728	40.000	523.693		
	Lower-bound	20947.728	20.000	1047.386		

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	210080.861	1	210080.861	78.507	.000
GRP	15591.034	1	15591.034	5.826	.025
Error	53519.138	20	2675.957		

Table 12 Statistical Data for Calculated Antagonist Torque

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Speed	Sphericity Assumed	4119.111	2	2059.556	3.139	.054
	Greenhouse-Geisser	4119.111	1.200	3432.436	3.139	.083
	Huynh-Feldt	4119.111	1.298	3173.576	3.139	.079
	Lower-bound	4119.111	1.000	4119.111	3.139	.092
Speed * GRP	Sphericity Assumed	2211.539	2	1105.770	1.685	.198
	Greenhouse-Geisser	2211.539	1.200	1842.865	1.685	.209
	Huynh-Feldt	2211.539	1.298	1703.884	1.685	.208
	Lower-bound	2211.539	1.000	2211.539	1.685	.209
Error(Speed)	Sphericity Assumed	26243.534	40	656.088		
	Greenhouse-Geisser	26243.534	24.001	1093.431		
	Huynh-Feldt	26243.534	25.959	1010.969		
	Lower-bound	26243.534	20.000	1312.177		
Bin	Sphericity Assumed	93834.464	7	13404.923	38.371	.000
	Greenhouse-Geisser	93834.464	1.606	58425.556	38.371	.000
	Huynh-Feldt	93834.464	1.812	51779.892	38.371	.000
	Lower-bound	93834.464	1.000	93834.464	38.371	.000
Bin * GRP	Sphericity Assumed	10478.010	7	1496.859	4.285	.000
	Greenhouse-Geisser	10478.010	1.606	6524.080	4.285	.030
	Huynh-Feldt	10478.010	1.812	5781.993	4.285	.024
	Lower-bound	10478.010	1.000	10478.010	4.285	.052
Error(Bin)	Sphericity Assumed	48908.698	140	349.348		
	Greenhouse-Geisser	48908.698	32.121	1522.638		

Table 13 Statistical Data for Velocity and Position Effects