AGE-RELATED TIME COURSE EFFECTS OF CONSTANT-ANGLE AND CONSTANT-TORQUE STRETCHING ON THE PASSIVE RESISTIVE PROPERTIES OF THE POSTERIOR HIP AND THIGH MUSCLES IN YOUNG AND OLD MEN

By

TY B. PALMER

Bachelor of Science in Kinesiology
Texas Lutheran University
Seguin, TX
2009

Master of Education in Exercise Science
Texas State University
San Marcos, TX
2011

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Graduate College of the
Oklahoma State University
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Dissertation Approved:

Dr. Doug Smith

Dissertation Adviser

Dr. Aric Warren

Dr. Matthew O'Brien

Dr. Jennifer Shaw

Outside Committee Member.

Name: TY PALMER

Date of Degree: MAY, 2015

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Abstract: The purpose of the present study was to examine the acute effects of static stretching at a constant angle (CA) and constant torque (CT) on the passive resistive properties of the posterior hip and thigh muscles in young and old men. Twenty young (mean±SD: age = 24.60 ± 2.98 years) and seventeen old (age = 71.88 ± 3.86 years) men performed 16, 30-s bouts of CA and CT stretching of the posterior hip and thigh muscles using an instrumented straight-leg raise (SLR). SLRs were then performed again at 10, 20, and 30 min following the completion of the stretching protocol. During each SLR, passive stiffness, passive torque, and electromyographic (EMG) amplitude were determined at the second to last common joint angle of the angle-torque curve, and maximum range of motion (ROM) was determined as the point of discomfort but not pain, as indicated by the participant. Three-way mixed factorial ANOVAs (group [young vs. old] × treatment [CA vs. CT] × time [stretch 1 vs. stretch 2 vs. stretch 4 vs. stretch 8 vs. stretch 16 vs. Post10 vs. Post20 vs. Post30]) were used to analyze all passive resistive variables. The present findings revealed that the older men had greater passive stiffness values compared to the young men. No differences were observed between the CA and CT treatments across stretches for passive torque and ROM; however, differential time course effects were observed between treatments for passive stiffness. The CT treatment decreased passive stiffness following one 30-s bout of stretching, whereas for the CA treatment, passive stiffness did not decrease until stretch 8 (4 min of stretching). Moreover, during the first 4 min of stretching, greater reductions in passive stiffness were observed for the CT treatment than the CA treatment. Both treatments showed lower passive stiffness and torque and higher ROM at Post10, Post20, and Post30 for both age groups; however, the old men exhibited significantly greater changes for these variables compared to the young men when collapsed across treatment and time. These findings may have important stretch-related performance and injury risk implications for a variety of populations and settings.

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CHAPTER I

INTRODUCTION

Stretching prior to athletic competition or exercise has traditionally been performed by athletes and recreationally-active individuals for many years[1]. Previous studies have suggested that stretching prior to exercise may reduce passive stiffness and increase range of motion (ROM), which in turn, may help enhance athletic performance and lower the risk of injury[2,3]. However, the efficacy of pre-exercise stretching as a performance-enhancing and injury-reducing modality has recently been questioned, as previous authors have suggested that there may not be enough evidence to support the claims that stretching improves performance and/or reduces the risk of injury[4-7]. Nevertheless, stretching is still considered an integral component of fitness[2] and because most recreationally-active individuals incorporate some form of stretching into their training routines prior to participating in strenuous exercise[8,9], previous research studies[10-14] have been heavily focused on identifying the types of stretching techniques that are most effective for altering the passive stiffness and ROM characteristics of the muscle-tendon unit (MTU).

The majority of previous studies investigating the efficacy of stretching at increasing ROM and decreasing passive stiffness have primarily examined the effects of static[10-17], proprioceptive neuromuscular facilitation[16,17], ballistic[15], and/or dynamic[18,19] stretching, with the most common being static stretching[11]. Static stretching typically involves stretching the MTU to the point of slight discomfort but not pain and holding this position for an extended period of time at a constant angle (CA)[11]. These CA types of stretches display a time-dependent property called "stress relaxation," which refers to the decrease in passive tension that is observed over time[11,12]. CA static stretching (i.e. for a duration of ~2-8 min) has been shown to be an effective stretching technique at increasing ROM and decreasing passive resistance in both sedentary and recreationally-active individuals[10-14]. Additionally, recent studies have demonstrated that constant-torque (CT) stretching may also be an effective method for altering the passive resistive properties (i.e., ROM, passive stiffness, passive torque) of the MTU in these populations[1,10-14,20]. Similar to CA stretching, CT stretching also elicits time-dependent changes to the MTU. However, unlike CA stretching, these changes cause small increases in the joint angle referred to as "muscle creep," which may allow for greater tension and work to be applied to the MTU, potentially leading to greater decreases in passive musculotendinous stiffness[12,21]. Although CT stretching is technically not static because of the slight movement that occurs from muscle creep, it is still considered a static stretch by most studies[11,12].

Many stretching studies have used maximum ROM as the primary outcome variable to determine the ability of a MTU to withstand strain-related injuries[8]. However, ROM provides limited information regarding the physiological changes to the MTU[22]. On the contrary, the passive mechanical properties of the MTU (i.e., expressed as stiffness) may provide more valid evidence concerning the effectiveness of stretching at increasing muscle fascicle length, which could help in decreasing the risk of injury[1,2]. Passive musculotendinous stiffness is a measure of the mechanical properties of the MTU and is typically calculated as the slope of the angle-torque curve at a specified joint angle recorded during passive ROM[12,23,24]. It is believed that a decrease in passive stiffness at the same absolute joint angle following an acute bout of stretching is the result of less passive tension recorded from the MTU[2,25-27]. However, recently previous studies have suggested that passive stiffness may be more complex than simple decreases in the passive resistance to stretch (i.e., passive torque)[11,12]. Although the measurements are closely related, Herda et al.[12] reported that CT stretching decreased passive stiffness and passive torque, while CA stretching only decreased the passive resistance of the MTU. Thus, decreases in passive torque at a given position on the angle-torque curve may not necessarily reflect a decrease in passive stiffness. However, it is possible that because passive stiffness is calculated from the slope of the angle-torque curve, changes in the shape of the curve (rather than changes in passive torque) may be more indicative of changes in passive stiffness[12].

Stretching-induced changes in the shape of the angle-torque curve may be related to changes in the viscoelastic properties of the MTU[11]. Viscoelasticity describes the MTU's loading response, which shows a combination of both elastic and viscous properties, where elastic deformation depends on the load of the applied stretch and viscous deformation depends on the rate of load application[28-30]. Gajdosik[28] suggested that the stress relaxation response during CA stretching may only affect the viscosity of the MTU, while the muscle creep response during CT stretching may affect both the MTU's viscous and elastic behavior. Thus, in theory, it is possible that CT stretching, because of muscle creep, may result in greater changes to the passive stiffness characteristics of the MTU compared with CA stretching. In support of this hypothesis, Herda et al.[11] recently demonstrated decreases in passive stiffness after a single 30-s bout of CT stretching with subsequent decreases in stiffness for up to 4 min of stretching; however, no decreases in passive stiffness were reported following CA stretching. Moreover, although Cabido et al.[10] showed that both CA and CT static stretching caused significant decreases in passive stiffness and increases in ROM, greater changes in these variables were reported after CT stretching than CA stretching. Thus, CT stretching may elicit greater changes in the passive properties of the MTU than CA stretching; however, it is unclear whether differences between techniques exist in the time course responses of these variables after stretching[11]. Determining how long changes in the passive properties of the MTU will last following practical durations (i.e. ~2-8 min) of static stretching may provide important information regarding recommendations for when stretching should be performed in relation to the start of competition or exercise[1].

Although a number of studies have investigated the effects of CA and CT static stretching on the passive mechanical properties of the MTU, the majority of these studies have been conducted in young[10-12] and middle-aged[13,14] adults. Very limited research, however, has been conducted on the effects of static stretching on the passive resistive properties of the MTU in older populations. Gajdosik[31] reported significant decreases in passive resistance of the plantar flexor muscles following a single 60-s CA static stretch in healthy older males and females. More recently, Sobolewski et al.[32] compared the viscoelastic responses between young and old men following 4, 30-s CA and CT static stretches of the plantar flexors. The authors reported no differences in the muscle creep responses between the young and old men following the CT stretching; however, they did report significantly greater relative changes in stress relaxation for the young compared to the old men after the initial 30 seconds of CA stretching[32]. Taken together, these findings suggest that although CT static stretching may be equally effective at altering the viscoelastic properties of the MTU in young and old men, CA stretching may be more effective at decreasing passive resistance in a younger population. On the contrary, a recent study by Ryan et al.[20] demonstrated that CT stretching of the plantar flexors caused greater increases in ROM and decreases in passive torque in older versus younger men. Although the authors did not examine the effects of stretching on passive stiffness, they hypothesized that the greater changes in ROM and passive torque in the older men may have been due to age-related increases (i.e. old > young) in tendon compliance[20], which may affect the shape of the angle-torque curve. Thus, based on these findings, it is possible that differences in the passive stiffness responses to stretch may exist between young and old adults. However, given the paucity of studies relating to stretching, passive stiffness, and aging, more studies are warranted to further elucidate the acute effects of stretching on passive stiffness characteristics across the life span.

The majority of previous studies investigating the effects of CA and CT static stretching on the passive properties of the MTU have primarily been conducted on the plantar flexor[13,14] and hamstring[10-12] muscle groups during passive ankle dorsiflexion and knee extension movements, respectively. However, to our knowledge, no previous studies have investigated the ability of CA and CT stretching to decrease passive stiffness and increase ROM of the posterior hip and thigh muscles during a passive straight-leg raise (SLR). Currently, the passive SLR is the most widely used method of stretching in both young and elderly populations[33,34] and has been reported to be a safe and reliable means for assessing the passive properties of the posterior hip and thigh muscles[2]. Thus, given the SLR's widespread use as an assessment tool of the passive musculotendinous resistive properties, and because of the limited amount of research investigating the acute effects of SLR CA and CT static stretching in young and older individuals, further research is warranted to examine whether aging has an effect on the passive stiffness responses of the MTU during these types of stretches. Identification of the type of static stretching that is most effective at decreasing passive stiffness and increasing ROM in both young and older individuals may provide important insight regarding implications for the type of SLR stretch that is to be performed prior to exercise (or rehabilitation) as well as shed light on the relationships between aging and the number of static stretches that are necessary for effectively altering the passive resistive properties of the MTU.

Statement of Purpose

The purpose of the present study was to examine the acute effects of static stretching at a constant angle and constant torque on the passive resistive properties of the posterior hip and thigh muscles in young and old men.

Hypotheses

1. H_0: There will be no stretching-induced differences in the time course responses for passive stiffness, passive torque, and ROM between the CA and CT static stretching protocols.

H_A: The CT stretching will cause greater and/or more rapid changes in passive stiffness, passive torque, and ROM than the CA stretching.

2. H_0: There will be no differences in the stretching-induced time-course effects on passive stiffness and passive torque between the young and old men during and/or following the static stretching.

   H_A: Older men will exhibit greater and/or more rapid stretching-induced changes in passive resistive properties compared to the younger men.

3. H_0: There will be no differences in passive stiffness between the young and old men.

   H_A: The old men will exhibit greater passive stiffness compared to the young men.

Definitions

Passive Torque: The resistance of the muscle-tendon structures measured during passive stretch.

Passive Stiffness: A measure of the mechanical properties of the MTU and is typically calculated as the slope of the angle-torque curve at a specified joint angle recorded during passive ROM.

Constant Angle Stretching: A type of static stretching which displays a time-dependent property called “stress relaxation,” which refers to the decrease in passive tension that is observed over time.

Constant Torque Stretching: A type of static stretching that causes small increases in the joint angle referred to as “muscle creep,” which may allow for greater tension and work to be applied to the MTU.

Viscoelasticity: Describes the MTU’s loading response, which shows a combination of both elastic and viscous properties, where elastic deformation depends on the load of the applied stretch and viscous deformation depends on the rate of load application.

Delimitations

This study will be delimited to convenience samples of participants between the ages of 18 – 30 and 60 – 85 years of age. Additionally, all participants will be required to be male and recreationally active based on their response to a health history questionnaire. Participants will be ineligible to participate in the study if they have had any recent (6 month) or ongoing neuromuscular disorders of the lower extremities, based on an initial health screening questionnaire. Participants will also be excluded from the study in the event that they are not capable of performing the CA and/or CT static stretching protocols.

Assumptions

1. The samples will be normally distributed and representative of their respective populations.
2. Participants' responses to the health history questionnaire will be accurate and valid.
3. The equipment will be appropriately calibrated and functioning properly.
4. There will be no data collection, data analyses, data entry or statistical processing errors.
5. The samples for the younger and older groups will be similarly represented in terms of the population, skeletal composition, and their relative physical fitness levels when compared to the norms for their respective age groups.

Limitations

1. Differences in the activity levels of participants both between and within the groups may have an effect on the responses to the CA and CT static stretching protocols.
2. Differences in motivational levels and pain tolerance between participants may produce varying levels of maximum tolerable torque thresholds.

CHAPTER II

REVIEW OF LITERATURE

The purpose of this review of literature is to present, synthesize, and integrate the available and pertinent research in the areas of range of motion (ROM), passive torque, and passive stiffness characteristics pertaining to constant-angle (CA) and constant-torque (CT) static stretching and the influence of aging on these parameters.

Passive Straight-Leg Raise

Passive musculotendinous resistive properties are commonly assessed via the application of a dynamic stretch[24,28,30,35,36]. For the hamstrings specifically, the utilization of a straight-leg raise (SLR) movement to assess passive resistive properties, such as passive stiffness, passive torque, and ROM may be important for determining athletic[23,37,38] and health[39] status and predicting lower-body injuries[40]. For example, Palmer et al.[23] showed that passive stiffness coefficients measured from a SLR were effective at discriminating between athletic status in college-aged athletes and non-athletes. Tafazzoli and Lamontagne[39] demonstrated that passive torque values as measured during a SLR were effective at differentiating between health status in individuals with and without low back pain. Furthermore, Witvrouw et al.[40] reported that the maximum ROM achieved during a SLR could be used to identify athletes who were at risk for developing strain-related injuries to the hamstrings.

The passive SLR was first described by Forst[41] in 1881 as a test for assessing passive tension of the hamstrings[42]. Forst credited his teacher Laségue with the hypothesis that the SLR could be used to diagnose impaired movement of the peripheral nerves (i.e. sciatic nerve) in the lower body[43]. Over time, specific procedures have been developed for performing the passive SLR, which may be summarized in the following sequence:[42,44] 1) A firm, level plinth with the participant lying in a relaxed, supine position. 2) Participant's trunk and hips placed in a neutral position without lateral flexion or rotation. Hips neither adducted nor abducted. 3) Primary investigator ensuring that the participant's knee remains extended, with the foot in a vertical plane as the leg is slowly elevated to the onset of pain.

Passive Resistive Properties

Passive musculotendinous properties contributing to the resistance to stretch are thought to be influenced by several factors, including the stable cross-links between the actin and myosin filaments (series elastic component), resistance from the actin and myosin filaments directly (series elastic component), noncontractile proteins of the endosarcomeric and exosarcomeric cytoskeletons (series elastic component), and deformation of the connective tissues located within and surrounding the muscle belly (parallel elastic component)[28,45]. Of these factors, the collagen fibers within the connective tissues, particularly the perimysium, are considered to be the major contributors to the resistance of passive stretch[30,46]. Gajdosik[28] suggested that the crimped arrangement of the collagen fibers becomes "uncrimped" as the muscle-tendon unit (MTU) lengthens, which, in turn, causes a mechanical deformation and realignment of the perimysium that may partially explain why the slope of the latter portion of the angle-torque curve tends to be greater than the slope of the initial portion. Future studies are needed to test these hypotheses with in vivo human musculotendinous models.

Eliciting the stretch reflex may also be a potential factor that contributes to increases in the resistance measured during passive stretch[36]. Lamontagne et al.[47] indicated that stretch reflex excitation is velocity-dependent; therefore, passive SLR assessments performed at higher stretch velocities may elicit a higher stretch reflex excitation, thereby, causing increased activation of the stretched muscles and possible contamination (with both active force production and passive tension) of the passive resistive measurements[36]. The need for a device to control for stretch velocity has been addressed by several authors who have used isokinetic dynamometers when performing SLR assessments[2,35,48-50]. Indeed, previous studies have suggested that the utilization of an isokinetic dynamometer during a SLR assessment provides reliable, and quantitative measurements of the passive resistive characteristics of the posterior muscles of the hip and thigh by controlling for the velocity of stretch[2,36]. On the contrary, some studies have used manual techniques to perform SLR-related movements[29,51]. These manual assessments typically consist of the primary investigator applying resistance against a load cell positioned immediately posterior to the heel while the leg is moved toward the head. Although these manual techniques have been shown to provide equally reliable passive stiffness and ROM measures as compared to those from an isokinetic dynamometer[2], they are often performed at high stretch velocities[36], and because higher stretch velocities may evoke a higher stretch reflex excitation[2], it is possible that manual techniques have a greater potential for eliciting the stretch reflex, and consequently higher electromyographic (EMG) activity than automated techniques using an isokinetic dynamometer.

Moreover, previous studies examining the passive resistive properties during dynamic stretch have used EMG amplitude signals to ensure that the stretches are performed passively[2,11,12,23,30,36]. Specifically, these studies have taken EMG amplitude values during passive stretching and have normalized them to the peak EMG amplitude that is recorded during pre-stretch isometric maximal voluntary contractions (MVCs). Normalized EMG signals are typically expressed as a percentage of the MVC peak EMG amplitude[12,52]. Many studies[2,11,12,23,30,36] have set a threshold to where ROM assessments cannot be considered passive if the corrected and normalized EMG amplitude is greater than 5% of MVC.

Stretching prior to athletic competition or exercise has traditionally been performed by athletes and physically-active individuals for many years[1]. Previous studies have suggested that stretching prior to exercise may reduce passive stiffness and increase ROM, which in turn, may help enhance athletic and functional performance and lower the risk of injury[2,3]. However, the effectiveness of pre-exercise stretching as a performance-enhancing and injury-reducing modality has recently been questioned, as previous authors have suggested that there may not be enough evidence to support the claims that stretching improves performance and/or reduces the risk of injury[4-7]. Nevertheless, stretching is still considered an integral component of fitness[2] and because most physically-active individuals incorporate some form of stretching into their training routines prior to participating in strenuous exercise[8,9], previous studies[10-14] have been heavily focused on identifying the types of stretching techniques that are most effective for altering the passive stiffness and ROM characteristics of the MTU.

Passive stiffness is a measure of the mechanical properties of the MTU and is often displayed in graphic form as the relationship between passive resistive torque and joint angle displacement (i.e., passive angle-torque curve)[24]. It is believed that a decrease in passive stiffness at the same absolute joint angle following an acute bout of stretching is the result of less passive torque recorded from the MTU[2,25-27]. However, recent studies have suggested that passive stiffness may be more complex than simple decreases in passive torque[11,12]. Although the measurements are closely related, Herda et al.[12] reported that CT stretching decreased passive stiffness and passive torque, while CA stretching only decreased the passive resistance (i.e. passive torque) of the MTU. Thus, decreases in passive resistance at a given position on the angle-torque curve may not necessarily reflect a decrease in passive stiffness. However, it is possible that because passive stiffness is calculated from the slope of the angle-torque curve, changes in the shape of the curve, rather than changes in passive torque, may be more indicative of changes in passive stiffness[12].

The loading response of the MTU during dynamic stretch is characterized by viscoelastic behavior[30]. Viscoelasticity is a combination of both elastic and viscous properties, where elastic deformation depends on the load of the applied stretch, and viscous deformation depends on the rate of load application[28,29]. McHugh et al.[29] was the first study to investigate the effects of viscoelastic stress relaxation in human skeletal muscle, in vivo, during a passive stretch of the hamstrings. The concept of viscoelastic stress relaxation suggests that when a muscle is under stress due to tension from stretch, the tissue begins to 'relax,' causing decreased tension at a CA. In order to test viscoelastic stress relaxation of the hamstrings in human skeletal muscle, McHugh et al.[29] developed an apparatus using a load cell (to measure force) in series with a chain that was attached to the subject's ankle. An electrogoniometer was attached at the hip joint to measure ROM. During testing, the primary investigator stood behind the subject and pulled slowly on the chain attached at the ankle, placing tension on the hamstrings. The investigator continued to pull at an approximate 90 degree angle in relation to the ankle until maximum ROM was reached. At this point, the investigator continued to pull for a count of 45 s so that the subject's hamstrings were held under stress at a CA. Results showed that when held at a CA, passive tension from the hamstrings significantly decreased during a 45 s stretch at both maximum ROM and at a sub-maximal ROM position. These findings demonstrated the capacity for viscoelastic stress relaxation in human skeletal muscle, in vivo.

More recently, other studies have demonstrated the capacity for viscoelastic creep in human skeletal muscle[53,54]. Viscoelastic creep is the resulting increase in joint angle caused by the CT applied to the MTU during stretch. Ryan et al.[53] recently characterized viscoelastic creep in the human skeletal MTU by having participants perform a single 30-s CT stretch of the plantar flexors. The authors found that position increased over the entire 30 s stretch, while the majority of the increases in position took place during the initial 15-20 s. Intraclass correlation coefficients of ≥0.994 and standard error of measurement values (expressed as a percentage of the mean) of ≤1.54% indicated that the viscoelastic creep responses in human skeletal MTUs may be reliable for future studies.

Passive Stiffness, Muscle Size, and Static Stretching

Gajdosik[28] suggested that the number of passive components (series and parallel elastic components) within a muscle is related to the size of the muscle and, therefore, an increase in passive component quantity and thus muscle size may, in theory, lead to greater passive stiffness. Many studies have presented evidence in support of this hypothesis by demonstrating significant linear relationships between passive stiffness and muscle cross-sectional area (CSA)[55-58]. For example, Ryan et al.[58] examined the relationship between CSA of the plantar flexors and the passive properties of the MTU. The authors measured the CSA of each participant's plantar flexor muscles using a peripheral quantitative computed tomography (pQCT) scanner. The passive properties of the MTU were assessed by examining passive stiffness and passive energy absorption of the plantar flexors using an isokinetic dynamometer. Passive stiffness was determined from the slope of the final 5° of the length-tension curve during passive dorsiflexion of the foot at the ankle. Passive energy absorption was calculated from the area underneath the length-tension curve during the same final 5°. Results showed significant positive relationships between muscle CSA and passive stiffness and energy absorption. These findings suggest that individuals who possess greater muscle CSA may also have greater passive stiffness and energy absorption values than those who possess lower muscle CSA.

In addition to the significant relationship reported by Ryan et al.[58] between passive stiffness and muscle CSA of the plantar flexors, other investigations have also demonstrated significant positive relationships between passive stiffness and muscle CSA of the forearm flexors[56] and hamstrings[55,57]. Given these significant relationships, previous authors have revealed that normalizing measurements of stiffness to muscle CSA may effectively remove the influence of muscle size[24,59], thereby improving the comparisons made between the passive resistive properties in participants whose muscles are of different thicknesses[60]. Based on these findings, future studies comparing groups of individuals with varying muscle thickness should consider normalizing measurements of passive stiffness to muscle CSA.

At present, the most common technique used to increase ROM and decrease passive stiffness of the MTU involves the use of static stretching[11,12]. Static stretching typically involves stretching the MTU to the point of slight discomfort but not pain and holding this position for an extended period of time at a constant joint angle[11]. These CA types of stretches display a time-dependent property called "stress relaxation," which refers to the decrease in passive tension that is observed over the time under stretch[11,12]. CA static stretching has been shown to be an effective stretching technique at altering the passive resistive properties in both sedentary and recreationally-active individuals[10-14]. For example, Herda et al.[12] reported that 8 min of CA stretching increased ROM and decreased passive torque in a group of college-aged, recreationally-active males. Although CA stretching has been shown to be an effective modality for increasing ROM and decreasing the resistance to stretch (i.e. passive torque), few studies have demonstrated its ability to decrease passive stiffness. Indeed, several authors have suggested that CA static stretching may be an ineffective modality at decreasing the passive stiffness properties of the MTU[11,12]. The need for a static stretching technique to effectively alter passive stiffness has been suggested by previous studies that have used CT static stretching[1,10-14,20]. Similar to CA stretching, CT stretching also elicits time-dependent changes to the MTU. However, unlike CA stretching, these changes cause small increases in the joint angle referred to as "muscle creep," which may allow for greater tension and work to be applied to the MTU, potentially leading to greater decreases in passive stiffness[12,21]. Although it could be argued that CT stretching is technically not static because of the slight movement that occurs during the stretch (from muscle creep), it typically falls under the category of static stretching[11,12].

Gajdosik[28] suggested that the stress relaxation response during CA stretching may only affect the viscosity of the MTU, while the muscle creep response during CT stretching may affect both the MTU's viscous and elastic behavior. Therefore, it is possible that CT stretching, because of muscle creep, may result in greater decreases to the passive stiffness characteristics of the MTU compared with CA stretching[11]. In support of this hypothesis, many previous studies[10-14] investigating the effects of CA and CT stretching have demonstrated greater decreases in passive stiffness following CT stretching.

Although a number of studies have presented evidence that CT stretching elicits greater decreases in passive stiffness than CA stretching, conflicting findings have been reported regarding differences in the effects of CA and CT stretching on ROM and passive torque[10-14]. For example, Herda et al.[12] recently demonstrated that CT stretching did not result in greater ROM or passive torque changes compared with CA stretching, whereas Yeh et al.[14] reported that CT stretching caused greater changes in ROM and passive torque than CA stretching. It was suggested that the discrepancies in these findings between studies may have been due to differences in the dosages of stretching[12]. Yeh et al.[14] applied stretches continuously for 30 min, whereas Herda et al.[12] performed cyclical stretching for a total time under stretch of 8 min.

Effects of Aging and Stretching

Previous authors that have investigated the effects of aging (i.e. young versus older adults) on passive ROM have reported contrasting findings[20,32,61-63]. For example, Sobolewski et al.[32] reported no differences in ROM of the plantar flexors between young and old men, whereas Gajdosik[63] reported that ROM of the plantar flexors decreased with increasing age groups in young, middle-aged, and older women. While it is uncertain why age-related differences in ROM have been reported in some studies but not in others, various theories have been proposed to explain the increases in ROM that are typically observed following an acute bout of static stretching[60]. Most of these theories attribute increases in ROM to changes in the mechanical properties of the MTU[11,27,64]. For example, Herda et al.[11] suggested that the decreases in the passive mechanical properties (i.e. passive torque, passive stiffness) of the MTU during static stretching may have accounted for the observed increases in ROM. Moreover, McHugh et al.[64] reported that maximum ROM as measured from a SLR was negatively related to increases in passive torque during the initial portion of the angle-torque curve. Thus, it is possible that increases in ROM after stretching may be attributable to decreases in passive resistance.

Magnusson et al.[65] suggested that stretching-induced increases in ROM without changes in passive stiffness or passive torque may be the result of an enhanced capacity to tolerate a greater amount of stretch. Thus, changes in stretch tolerance may be another possible mechanism that explains for the increases in ROM that are observed after stretching in both young and old adults. Indeed, many previous studies[66-68] have reported no changes in the shape of the passive angle-torque curve following an acute bout of stretching; however, these studies did report increases in ROM, which could be due to alterations in stretch tolerance.

Similar to ROM, the effects of aging on passive stiffness have previously been reported with conflicting results[32,61-63,69]. For example, Chesworth and Vandervoort[69] reported no differences in passive stiffness of the plantar flexors between young, middle-aged, and older women, whereas Sobolewski et al.[32] reported that passive stiffness of the plantar flexors was significantly higher in older compared to younger men. Discrepancies in the findings between these studies may be due to differences in the type of stiffness values that were reported. For example, Chesworth and Vandervoort[69] reported absolute stiffness values (i.e. stiffness was measured in Nm·deg^{-1}), whereas Sobolewski et al.[32] reported relative stiffness values that were normalized to calf girth measurements (i.e. stiffness was measured in Nm·deg^{-1}·cm^{-1}). Differences in muscle CSA between young and older individuals may have a significant effect on the age-related differences in passive stiffness. Therefore, future aging studies should consider normalizing passive stiffness to muscle CSA (or girth) to provide a better comparison of the passive resistive properties between different age groups[60].

Because Sobolewski et al.[32] normalized passive stiffness values to muscle CSA (i.e. calf girth), it is possible that their findings of greater passive stiffness for older compared to younger men may have been due to qualitative factors (i.e., increases in collagen/fibrous tissue content and the amount of cross-linking) rather than changes in muscle size[70]. Previous studies have suggested that ultrasound (US) measurements of echo intensity (EI) may provide an index of muscle quality[71,72]. EI measurements are typically obtained through gray-scale analysis of individual pixels within the US image and have been correlated with skeletal muscle infiltration of fat and fibrous tissue[71]. Although there are no studies to date that have examined the relationships between EI and passive stiffness, it is possible that potential increases in intramuscular fat and fibrous tissue content across the lifespan may be reflected by decreases in muscle quality (i.e. increased EI values as measured from US), which could be a potential contributor to the greater passive stiffness values observed in older compared to younger men.

Very few studies have investigated the effects of aging on the efficacy of static stretching at decreasing passive stiffness (and/or passive torque) and increasing ROM[20,31,32]. Recently, Sobolewski et al.[32] compared the viscoelastic responses between young and old men following 4, 30-s CA and CT static stretches of the plantar flexors. No differences in the muscle creep responses between the young and old men were reported following the CT stretching; however, the authors did report significantly greater relative changes in stress relaxation for the young compared to the old men after the initial 30 s of CA stretching[32]. Collectively, these findings suggest that although CT static stretching may be equally effective at altering the viscoelastic properties of the MTU in young and old men, CA stretching may be more effective at decreasing passive torque in a younger population. On the contrary, a more recent study by Ryan et al.[20] showed that CT stretching of the plantar flexors caused greater increases in ROM and decreases in passive torque in older versus younger men. It was hypothesized that the greater changes in ROM and passive torque in the older men may have been due to age-related increases in tendon compliance, which may have an effect on the shape of the angle-torque curve[20]. Although Ryan et al.[20] did not examine the effects of CT stretching on passive stiffness, based on their findings, it is possible that differences in the time course responses of passive stiffness to stretch may exist between young and older adults.

Time Course of Passive Stiffness Responses to Stretching

Limited research has been conducted on the time course of passive stiffness responses following various durations of static stretching[1,11,21,73]. Ryan et al.[1] used a randomized, repeated-measures design (time [pre-stretching versus post-stretching versus 10 min versus 20 min versus 30 min post-treatment] x condition [control versus 2 min versus 4 min versus 8 min] x joint angle [1° versus 5° versus 9° versus 13° for the final 13° of the ROM]) to investigate the time course of passive stiffness responses to various durations of CT static stretching of the plantar flexor muscles. Results from this study indicated a significant decrease in passive stiffness (relative to the control (i.e. no stretching treatment)) immediately following 2 min, 4 min, and 8 min of acute static stretching. Passive stiffness returned to baseline following 10 min post-stretching for the 2 min condition; however, stiffness did not return to baseline until 20 min post-stretching for both the 4 min and 8 min conditions. Based on these results, it was suggested that there may be a threshold necessary for decreases in passive stiffness, which may be approximately 2 min of static stretching. In addition, longer acute stretching bouts (4 minutes and 8 minutes) may have a prolonged effect on suppressing passive stiffness before returning to baseline. If reductions in passive stiffness aid in the prevention of strain-related injuries, these results suggest that practical durations of stretching (2 – 8 min) for the plantar flexors should be performed within 10 – 20 min of the start of competition or exercise.

A recent study by Herda et al.[11] also used a randomized, repeated-measures design (treatment [CA vs CT] × stretch (1 vs 2 vs 4 vs 8 vs 16)] to examine the time course responses of the passive properties during 8 min (i.e. 16, 30 s stretches) of CA and CT static stretching of the hamstrings. The authors reported a significant decrease in passive stiffness after a single 30 s bout of CT stretching with subsequent decreases in stiffness for up to 4 min of stretching; however, no decreases in passive stiffness were reported following CA stretching. Furthermore, passive torque decreased and ROM increased following one 30 s bout of static stretching (collapsed across CA and CT stretching) with additional decreases and increases for up to 4 and 8 min of stretching, respectively. Based on these findings, the authors suggested that CT stretching should be used for populations where decreases in stiffness are the objective and that a single 30-s bout of CT stretching can decrease stiffness with subsequent decreases for up to 4 min of stretching. However, it remains unknown how long changes in the passive properties will last following CA and CT stretching[11] and thus, future studies are needed to identify which stretching method is most effective at suppressing passive stiffness for an extended period of time before returning to baseline.

Conclusions

Passive musculotendinous resistive properties of the posterior hip and thigh muscles are commonly assessed via the application of a SLR[2,35,36]. Although the assessment of passive stiffness, ROM, and passive torque is commonplace in the literature, fewer studies have examined the influence of aging on these variables. It is believed that a decrease in passive stiffness at the same absolute joint angle following an acute bout of stretching is the result of less passive torque recorded from the MTU[2,25-27]. However, it is possible that because passive stiffness is calculated from the slope of the angle-torque curve, changes in the shape of the curve, rather than passive torque, may be more indicative of changes in passive stiffness[12]. Many studies have reported that CT caused greater decreases to the passive stiffness characteristics of the MTU compared with CA stretching[10-14]. However, given the paucity of studies relating to stretching-induced changes in passive stiffness and aging, more studies are warranted to further elucidate the acute effects of CA and CT stretching on passive stiffness characteristics across the age span. Improving our understanding of these functional consequences and processes may provide researchers, clinicians, coaches, athletic trainers, and other practitioners with the knowledge to better prescribe and evaluate pre-exercise stretching protocols, to improve functional performance, and reduce the risk of injuries in a wide variety of populations and settings.

CHAPTER III

METHODS

Participants

Twenty-one young and nineteen old healthy, recreationally-active males were recruited for participation in this study. None of the participants reported any acute or chronic neuromuscular diseases or musculoskeletal injuries specific to the ankle, knee, or hip joints. This study was approved by the institutional review board for human subjects research at Oklahoma State University, and prior to any testing, each participant completed an informed consent document and health history questionnaire.

Experimental Design

This study used a between-subjects randomized, repeated-measures crossover design to examine the acute time course responses of repeated CA and CT static stretching on passive stiffness, passive torque, and ROM of the posterior hip and thigh muscles in healthy young and old men. Each participant visited the laboratory three times, separated by 2 – 7 days at approximately the same time of day (± 2 h). The first visit was a familiarization trial, and the next two visits were experimental trials in randomized order (CA or CT stretching)[11]. During the familiarization trial, participants practiced the testing procedures by performing several CA and

CT SLR static stretches. In addition, panoramic US imaging assessments of the hamstrings muscle group were performed on the right leg, and the maximum tolerable torque threshold was determined for each individual as the point of discomfort but not pain as verbally acknowledged by the participant during a series of passive SLR assessments. This predetermined torque threshold was used during the experimental trial for the CT static stretching. For each experimental trial, participants completed pre-stretch maximal voluntary contractions (MVCs) followed by the stretching intervention and a post-stretching assessment at 10, 20, and 30 min after the intervention. Participants were instructed to maintain the same lifestyle between trials and to refrain from any vigorous physical activity or exercise within 24 h of testing.

Passive Stiffness, Passive Torque, and ROM

Passive stiffness, passive torque, and ROM of the posterior muscles of the hip and thigh were quantified during each SLR stretch and post-stretching assessment using a calibrated Biodex System 3 isokinetic dynamometer (Biodex Medical Systems Inc., Shirley, NY) programmed in passive mode to move the foot toward the head at $5°\cdot s^{-1}$. For each SLR, participants laid in a supine position, with the knee braced in full-extension and the ankle immobilized in a neutral 90° position (between foot and leg) with a custom-made cast that was fixed around the foot and held with straps above the ankle and over the toes and metatarsals. During the SLR, the input axis of the dynamometer was aligned slightly superior and anterior to the greater trochanter of the femur to account for movement of the greater trochanter and restraining straps were placed over the participants' left unstretched thigh and ankle. SLRs were performed on the right leg to the point of discomfort but not pain as indicated by the participant (regarded as maximum ROM for the CA stretching and post-stretching assessments) or to the point when the torque threshold of the isokinetic dynamometer was initially met (regarded as maximum ROM for the CT stretching)[12]. Stretches in both treatments (CA and CT stretching) were performed for 30-s bouts with a 20-s rest period between bouts, in which the leg was returned to the baseline position[11,12], which was a hip joint angle of 35° above the horizontal plane[2]. Each participant completed sixteen 30-s bouts of stretching totaling 8 min of time under stretch and lasting approximately 20 total min[11]. All participants experienced both stretching treatments in a random order[12]. The SLR post-stretching assessments were performed in a similar fashion to the SLR CA and CT stretches; however, once maximum ROM was reached, the leg was immediately returned to the baseline position.

Surface Electromyography

Surface electromyography (EMG) was recorded for the biceps femoris from bipolar pre-amplified electrodes (TSD150B, Biopac Systems Inc., Santa Barbara, CA) with a fixed center-to-center interelectrode distance of 20 mm and a gain of 350. The electrodes were taped directly to the skin and were placed at 50% of the distance between the ischial tuberosity and the lateral epicondyle of the tibia. The electrode placements were based on the recommendations of Hermens et al.[74]. To decrease the interelectrode impedance, the skin was shaved and cleansed with isopropyl alcohol before electrode placement. A single pregelled disposable electrode (EL502, Biopac Systems Inc., Aero Camino, CA) was placed on the palmar side of the right wrist to serve as a reference electrode.

EMG amplitude was calculated with a root-mean square (rms) function for 200-ms epochs corresponding to each whole-number degree during the ROM. According to the procedures of Herda et al.[12], EMG amplitude baseline noise values were subtracted from the EMG amplitude values recorded during the passive SLR stretches and post-stretching assessments. Furthermore, the corrected EMG amplitude values (µVrms) were normalized to the corresponding pre-stretch isometric MVCs and expressed as a percentage of the MVC EMG amplitude.

For the MVC assessments, participants performed two 5-s isometric MVCs of the posterior muscles of the hip and thigh while lying supine with restraining straps placed over the waist, left thigh, and ankle. During the MVCs, the thigh and leg were in the same 35° hip-flexion position as the starting point of the passive SLR stretches and post-stretching assessments. Participants were asked to extend the thigh as hard as possible for a total of 5-s. Isometric peak torque (PT) for each MVC was determined as the highest mean 500-ms epoch during the torque plateau, and the highest PT trial was selected for subsequent EMG normalization. EMG amplitude (µVrms) was quantified during the same 500-ms epoch used to calculate PT and was considered 100% (maximal) voluntary activation. The SLR stretches and post-stretching assessments could not be considered passive if the corrected and normalized EMG amplitude was greater than 5% of MVC in accordance with Gajdosik et al.[52] and Herda et al.[12]. Consequently, data from one young and two older participants were excluded from the analyses. All subsequent statistical analyses were performed on the data from the remaining 20 young and 17 older participants.

Panoramic Ultrasound Imaging Assessments

Participants laid on a padded wooden table in the prone position with the lower limbs extended and relaxed, while panoramic US imaging assessments were performed of the hamstring muscle group, which included the long head of the biceps femoris (BF), semitendinosus (ST), and semimembranosus (SM) muscles. To prevent rotation and movement of the leg during the assessments, an adjustable restraining strap was placed over the distal lower limb of the right leg while the foot was relaxed in a neutral position against the wall. All assessments were performed after participants had rested for 10 min to allow for any fluid shifts to stabilize[75].

Panoramic US images of the hamstring muscle group were obtained on the right leg using a portable B-mode US imaging device (GE Logiq S8, Milwaukee, WI) and linear-array probe (Model ML6-15-D; 4-15 MHz; 50 mm field-of-view). US settings were optimized for image quality, including gain (50 dB), depth (8 cm)[55], and frequency (12 MHz), and were set prior to testing and held constant between participants and across trials[72]. All US images were scanned in the transverse plane at 50% of the distance between the greater trochanter and the lateral joint line of the knee[57] and were marked while the participants were standing in an upright position[76]. For each scan, the primary investigator moved the probe manually at a slow and continuous rate along the surface of the skin from the lateral to the medial sides of the hamstring musculature using a special function on the US imaging device called LogiqView (GE Logiq S8). An adjustable, custom-made apparatus that was fitted over each participant's right thigh (at the midpoint of the thigh) was used during each assessment to assist with keeping the probe perpendicular to the skin, and a generous amount of water-soluble transmission gel was applied to both the probe and the skin to provide acoustic coupling without depressing the dermal surface[77]. For each participant, two panoramic US images were taken and the mean was calculated for each of the dependent variables which included muscle CSA and EI. The same experienced sonographer (T.B.P.) performed all assessments and following the completion of each scan, reviewed the images to ensure they were of sufficient quality[78].

All US images were analyzed using ImageJ software (version 1.47v; National Institutes of Health, USA). Prior to analysis, each image was scaled individually from area in pixels to centimeters with the straight-line function using a known distance of 1 cm[79]. Muscle CSA of the BF, ST, and SM were determined using the polygon selection function by selecting a region of interest (ROI) within each muscle that included as much of the muscle as possible without any surrounding bone or fascia[72]. Muscle quality was determined from the EI values assessed by gray-scale analysis using the standard histogram function of the same pre-selected ROIs that were used to calculate CSA for each muscle[72]. EI values in the ROIs were calculated in arbitrary units (AU) on a 0-255 scale (black = 0, white= 255). In addition to the individual hamstring muscles (BF, ST, and SM), whole hamstring muscle CSA and EI were also determined by taking the sum of the CSAs and the mean of the EIs of the BF, ST, and SM muscles, respectively.

All passive stiffness and torque values were normalized to whole muscle CSA of the hamstrings $\left(i.e. \frac{\text{passive stiffness}}{\text{muscle CSA}}\ and\ \frac{\text{passive torque}}{\text{muscle CSA}}\right)$ per the recommendation of Ryan et al.[24].

Signal Processing

During each SLR CA and CT static stretch and post-stretching assessment, torque (Nm), joint angle position (°), and EMG (µV) signals were sampled simultaneously at 1 kHz (MP100WSW; Biopac Systems, Inc, Santa Barbara, CA), stored on a personal computer (Dell Inspiron 8200; Dell, Inc, Round Rock, TX), and processed off-line using custom-written software (LabVIEW, Version 11.0; National Instruments, Austin, TX). Torque and position signals were low-pass filtered, with a 10-Hz cutoff (zero-phase lag, fourth-order Butterworth filter). The EMG signal was scaled and bandpass filtered (zero-phase lag, fourth-order Butterworth filter) from 20 to 400 Hz. All subsequent analyses were conducted on the scaled and filtered signals.

For passive torque, gravity correction was performed during each SLR stretch and post-stretching assessment using a cosine function in which the limb mass was subtracted from the torque signal across the ROM. The scaled and gravity-corrected torque and joint angle signals were plotted as passive angle-torque curves and fitted with a fourth-order polynomial regression model based on the equation reported by Nordez et al.[80] (Figure 1). Passive stiffness, passive torque, and EMG were quantified at the second to last common joint angle (θ) among selected stretches (i.e., stretch 1, stretch 2, stretch 4, stretch 8, and stretch 16) and at 10 (Post10), 20 (Post20), and 30 (Post30) min post-stretching for each participant[1,11]. Consequently, the same absolute joint angle was used for each participant to calculate passive stiffness, passive torque, and EMG for each SLR stretch and post-stretching assessment. Passive stiffness values were calculated with the following equation, where m, n, o, p, and q were coefficients and θ denotes the joint angle in the fourth-order polynomial regression model that was fitted accordingly with the passive angle-torque curve:

$$\text{passive torque} = m\theta^4 + n\theta^3 + o\theta^2 + p\theta + q$$

Passive stiffness was subsequently calculated with the following equation:

$$\text{passive stiffness }(\theta) = 4m\theta^3 + 3n\theta^2 + 2o\theta + p$$

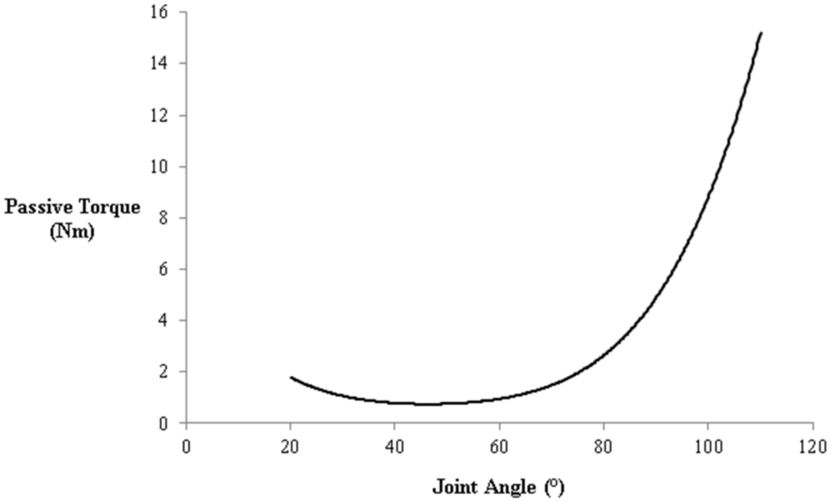


Figure 1. An example of a single, passive angle-torque curve tracing taken from a participant during an instrumented straight-leg raise. Passive stiffness, passive torque, and EMG were quantified at the second to last common joint angle (θ) among selected stretches and post-stretching assessments.

Statistical Analyses

Independent samples *t*-tests were used to analyze differences in demographic characteristics and muscle CSA and EI of the BF, ST, SM, and whole hamstrings between the young and old men. Four separate two-way mixed factorial analysis of variances (ANOVAs) (group [young vs. old] × treatment [CA vs. CT]) were used to analyze all baseline (i.e. stretch 1) passive resistance characteristics. Pearson product-moment correlation coefficients (*r*) from the pooled data of all participants (young and old men, *n* = 37) were calculated to examine the relationships between passive stiffness at baseline (collapsed across treatment) and the EI values for each muscle. In addition, four separate three-way mixed factorial ANOVAs (group [young vs. old] × treatment [CA vs. CT] × time [stretch 1 vs. stretch 2 vs. stretch 4 vs. stretch 8 vs. stretch 16 vs. Post10 vs. Post20 vs. Post30]) were performed using the relative percentage scores (% of stretch 1 values)[81,82] to analyze the effects of the stretching treatments on passive stiffness, passive torque, ROM, and EMG amplitude. When appropriate, follow-up analyses included lower-ordered ANOVAs and Bonferroni-corrected independent and dependent samples *t*-tests. Statistical analyses were performed using IBM SPSS Statistics v. 21.0 (SPSS Inc., Chicago, IL, USA), and an alpha level of $P \leq 0.05$ was used to determine statistical significance. All data are presented as mean ± standard deviation (SD), except for in the figures, where data are mean ± standard error of the mean (SEM) for clarity of presentation.

CHAPTER IV

RESULTS

Baseline Passive Resistance Characteristics and Muscle Size and Quality

All participants' demographic characteristics and hamstring CSA and EI values are presented in Table 1. Table 2 lists the baseline values (mean ± SD) for passive stiffness, passive torque, ROM, and EMG amplitude and Table 3 shows the relative percentage scores (% of stretch 1) across all time periods. There was a significant difference in age ($P < 0.001$), but not body mass ($P = 0.673$) and height ($P = 0.406$) between the young and old men (Table 1). The old men exhibited lower CSA and higher EI values than the young men for the BF ($P \leq 0.001$), ST ($P \leq 0.019$), SM ($P \leq 0.002$), and whole hamstring muscle ($P \leq 0.001$) (Table 1). For passive stiffness at baseline, there was no two-way interaction ($P = 0.881$) and no main effect for treatment ($P = 0.795$), but there was a main effect for group ($P = 0.030$). The old men demonstrated higher passive stiffness values compared to the young men when collapsed across treatment (Figure 2). In addition, significant positive relationships were observed between passive stiffness (collapsed across treatment) and EI values for the BF ($r = 0.411$; $P = 0.012$), ST ($r = 0.373$; $P = 0.023$), SM ($r = 0.453$; $P = 0.005$), and whole hamstring musculature ($r = 0.441$; $P = 0.006$; Figure 3). For passive torque, ROM, and EMG amplitude at baseline, there were no interactions ($P = 0.560$-

0.952), no main effects for treatment (*P* = 0.214-0.998), and no main effects for group (*P* = 0.096-0.901).

Passive Stiffness

For passive stiffness, there was no three-way interaction (*P* = 0.904) and no two-way interactions for group × treatment (*P* = 0.584) or group × time (*P* = 0.404), but there was a two-way interaction for treatment × time (*P* = 0.001). There was also a significant main effect for group (*P* = 0.034), such that the older men had lower stiffness values than the younger men when collapsed across treatment and time (Figure 4). Follow up analyses for the treatment × time interaction (Figure 5) revealed that for the CA stretching treatment, stretch 1 was greater than stretches 8, 16, and Post10, Post20, and Post30 ($P \leq 0.002$); however, no differences were observed between stretch 1 and stretches 2 and 4 ($P > 0.999$). For the CT stretches, stretch 1 was greater than stretches 2, 4, 8, 16, and Post10, Post20, and Post30 ($P < 0.001$); stretch 2 was greater than stretches 8 (*P* = 0.003), 16 (*P* = 0.016), and Post10 (*P* = 0.038); however, no differences were observed between any of the other CT static stretches ($P \geq 0.415$). In addition, dependent samples *t*-tests indicated that passive stiffness was greater for the CA stretching treatment than the CT stretching treatment for stretches 2, 4, and 8 ($P \leq 0.039$).

Passive Torque

For passive torque, there was no three-way interaction (*P* = 0.852), no two-way interactions for group × treatment (*P* = 0.692), group × time (*P* = 0.171), or treatment × time (*P* = 0.802), and no main effect for treatment (*P* = 0.588), but there were main effects for group (*P* = 0.010) and time ($P < 0.001$) (Figure 6). The old men had lower values than the young men when collapsed across treatment and time (Figure 4). Moreover, further analysis (collapsed across group and treatment) indicated that stretch 1 was greater than stretches 2, 4, 8, 16, and Post10, Post20, and Post30 ($P < 0.001$); stretch 2 was greater than stretches 4, 8, and 16 ($P < 0.001$);

stretch 4 was greater than stretches 8 and 16 (*P* < 0.001), and stretch 8 was greater than stretch 16 (*P* < 0.001). In addition, there were no significant differences between stretch 2 and Post10, Post20, and Post30 (*P* > 0.999); however, stretches 4, 8, and 16 were greater than all post-stretching time points (*P* < 0.001).

Range of Motion

For ROM, there was no three-way interaction (*P* = 0.699), no two-way interactions for group × treatment (*P* = 0.430), group × time (*P* = 0.133), or treatment × time (*P* = 0.911), and no main effect for treatment (*P* = 0.781), but there were main effects for group (*P* = 0.001) and time (*P* < 0.001) (Figure 7). The old men had greater values compared to the young men when collapsed across treatment and time (Figure 4). Further analysis (collapsed across group and treatment) indicated that stretch 1 was less than stretches 2, 4, 8, 16, and Post10, Post20, and Post30 (*P* < 0.001); stretch 2 was less than stretches 4, 8, 16 and Post10, Post20, and Post30 (*P* < 0.001); stretch 4 was less than stretches 8, 16, and Post10, Post20, and Post30 (*P* ≤ 0.002); stretch 8 was less than stretch 16 (*P* = 0.004); however, no differences were observed between stretches 8 and 16 and all post-stretching time points (*P* ≥ 0.070).

EMG Amplitude

For EMG amplitude, there was no three-way interaction (*P* > 0.999), no two-way interactions for group × treatment (*P* = 0.921), group × time (*P* = 0.999), or treatment × time (*P* > 0.999), and no main effects for group (*P* = 0.764), treatment (*P* = 0.891), or time (*P* = 0.998) (Figure 8). EMG amplitude was not different between the young and old men at any time point and did not change from baseline for both the young and old (Figure 4).

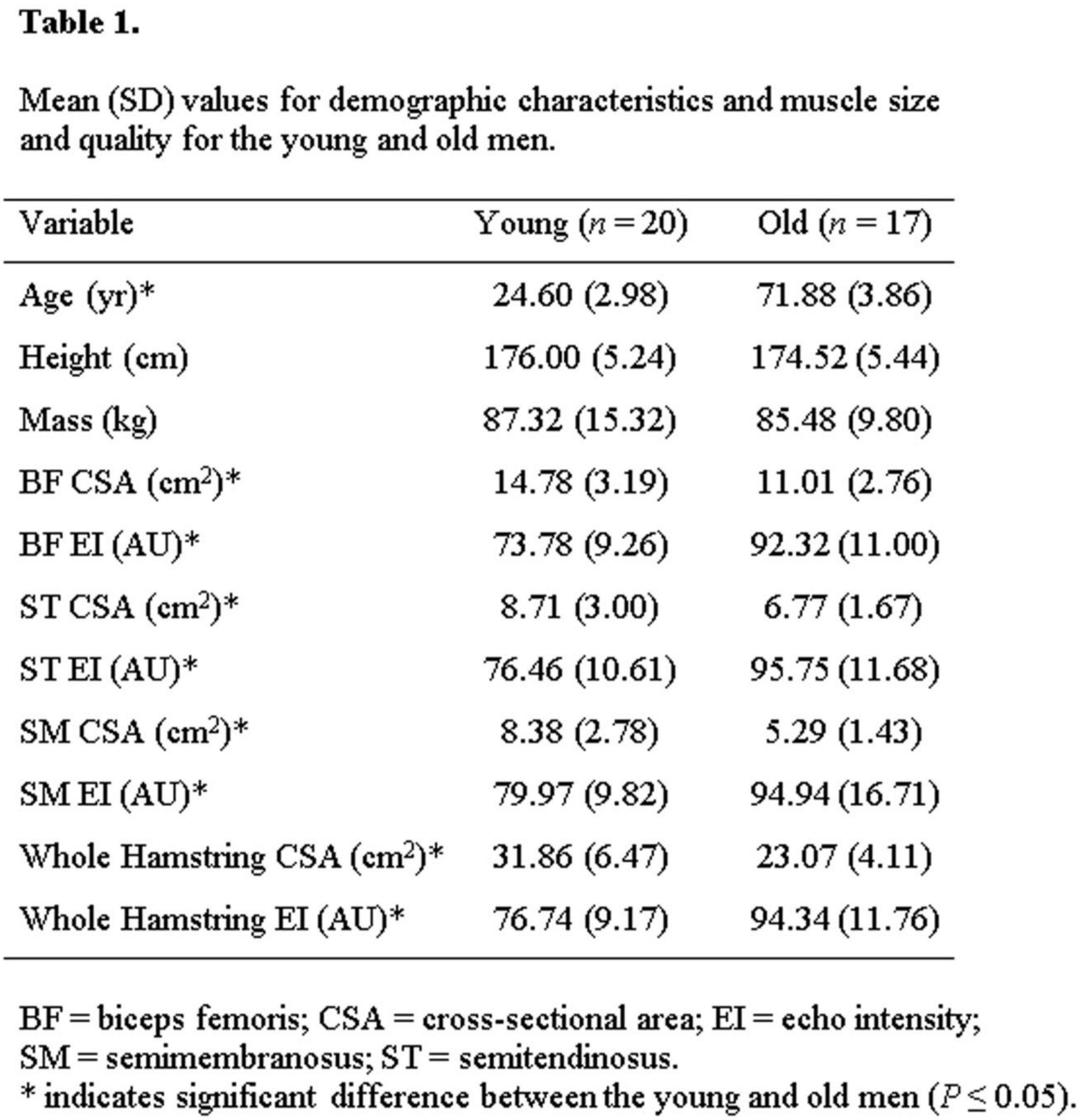


Table 1.

Mean (SD) values for demographic characteristics and muscle size and quality for the young and old men.

Variable	Young ($n = 20$)	Old ($n = 17$)
Age (yr)*	24.60 (2.98)	71.88 (3.86)
Height (cm)	176.00 (5.24)	174.52 (5.44)
Mass (kg)	87.32 (15.32)	85.48 (9.80)
BF CSA (cm^2)*	14.78 (3.19)	11.01 (2.76)
BF EI (AU)*	73.78 (9.26)	92.32 (11.00)
ST CSA (cm^2)*	8.71 (3.00)	6.77 (1.67)
ST EI (AU)*	76.46 (10.61)	95.75 (11.68)
SM CSA (cm^2)*	8.38 (2.78)	5.29 (1.43)
SM EI (AU)*	79.97 (9.82)	94.94 (16.71)
Whole Hamstring CSA (cm^2)*	31.86 (6.47)	23.07 (4.11)
Whole Hamstring EI (AU)*	76.74 (9.17)	94.34 (11.76)

BF = biceps femoris; CSA = cross-sectional area; EI = echo intensity; SM = semimembranosus; ST = semitendinosus.
* indicates significant difference between the young and old men ($P \leq 0.05$).

Table 2.

Mean (SD) values for baseline passive stiffness, passive torque, range of motion (ROM), and electromyographic (EMG) amplitude for the young and old men.

Variable	Group	Constant Angle	Constant Torque	Mean Treatment
Passive Stiffness ($\text{Nm}\cdot\text{deg}^{-1}\cdot\text{cm}^{-2}$)	Young	0.05 (0.03)	0.05 (0.03)	0.05 (0.03)
	Old	0.07 (0.04)	0.07 (0.03)	0.07 (0.04)*
	Mean Stiffness	0.06 (0.04)	0.06 (0.03)	
Passive Torque ($\text{Nm}\cdot\text{cm}^{-2}$)	Young	1.24 (0.73)	1.26 (0.73)	1.25 (0.72)
	Old	1.53 (0.92)	1.51 (0.81)	1.52 (0.85)
	Mean Torque	1.37 (0.82)	1.38 (0.77)	
ROM (deg)	Young	85.60 (20.56)	87.35 (19.88)	86.48 (19.98)
	Old	74.35 (17.03)	78.65 (18.23)	76.50 (17.51)
	Mean ROM	80.43 (19.60)	83.35 (19.38)	
EMG Amplitude (%max)	Young	0.62 (1.95)	0.64 (1.92)	0.63 (1.91)
	Old	0.51 (3.44)	0.55 (3.03)	0.53 (3.19)
	Mean EMG	0.57 (2.70)	0.60 (2.46)	

*** indicates significant difference between the young and old men when collapsed across treatment ($P \leq 0.05$).**

Table 3.

Mean (SD) relative percentage (% of Stretch 1) values for passive stiffness, passive torque, range of motion (ROM), and electromyographic (EMG) amplitude for both the constant angle (CA) and constant torque (CT) stretching treatments in the young and old men.

			Stretch 1	Stretch 2	Stretch 4	Stretch 8	Stretch 16	Post 10 min	Post 20 min	Post 30 min
CA Stretching Treatment	Young Men	Passive Stiffness †	100	99.83 (12.13)	95.60 (25.47)	81.15 (27.09)*	68.20 (29.68)*	74.15 (27.33)*	79.50 (35.41)*	82.00 (34.46)*
		Passive Torque	100	87.55 (6.76)*	75.40 (13.03)*‡	67.90 (10.46)*‡‖	62.45 (10.18)*‡‖§	86.35 (17.38)*‖§¶	88.50 (19.69)*‖§¶	87.60 (21.14)*‖§¶
		ROM	100	104.15 (6.12)*	107.85 (7.37)*‡	110.20 (8.32)*‡‖	113.40 (11.45)*‡‖§	116.45 (10.57)*‡‖	114.90 (9.90)*‡‖	115.55 (10.09)*‡‖
		EMG Amplitude	100	97.00 (50.11)	97.75 (46.98)	96.25 (70.84)	99.35 (65.50)	100.00 (63.20)	100.85 (75.16)	96.85 (61.69)
	Old Men	Passive Stiffness †	100	99.78 (23.29)	90.91 (25.86)	64.18 (22.50)*	57.47 (22.96)*	65.94 (27.66)*	70.65 (27.75)*	73.88 (21.76)*
		Passive Torque	100	77.00 (12.63)*	63.53 (13.18)*‡	55.82 (14.81)*‡‖	48.94 (14.22)*‡‖§	77.82 (18.65)*‖§¶	79.06 (18.73)*‖§¶	76.35 (23.08)*‖§¶
		ROM	100	110.18 (6.30)*	114.88 (10.04)*‡	119.29 (9.56)*‡‖	124.47 (8.77)*‡‖§	122.06 (11.63)*‡‖	123.47 (13.34)*‡‖	125.29 (13.43)*‡‖
		EMG Amplitude	100	102.29 (35.56)	103.47 (55.07)	100.18 (46.84)	103.76 (44.83)	104.00 (42.68)	102.59 (47.67)	96.12 (37.96)
CT Stretching Treatment	Young Men	Passive Stiffness †	100	85.65 (22.25)*	77.55 (27.36)*	68.75 (26.22)*‡	68.30 (42.63)*‡	69.85 (34.87)*	71.70 (32.94)*	77.55 (34.42)*
		Passive Torque	100	85.25 (15.30)*	72.65 (18.01)*‡	63.55 (18.23)*‡‖	57.75 (17.85)*‡‖§	83.20 (23.44)*‖§¶	88.75 (26.27)*‖§¶	87.55 (22.72)*‖§¶
		ROM	100	102.80 (6.62)*	108.50 (8.31)*‡	112.00 (8.84)*‡‖	113.75 (8.02)*‡‖§	118.25 (15.37)*‡‖	117.10 (15.94)*‡‖	118.75 (14.79)*‡‖
		EMG Amplitude	100	101.00 (62.93)	96.60 (61.99)	96.80 (76.20)	97.80 (71.13)	95.75 (52.71)	100.90 (79.03)	96.90 (53.74)
	Old Men	Passive Stiffness †	100	72.71 (16.67)*	63.12 (16.38)*	50.94 (22.19)*‡	50.24 (22.32)*‡	60.00 (16.50)*	64.94 (16.61)*	69.53 (19.92)*
		Passive Torque	100	73.82 (12.42)*	63.41 (15.47)*‡	57.88 (16.60)*‡‖	48.59 (15.29)*‡‖§	75.00 (15.64)*‖§¶	77.59 (13.94)*‖§¶	79.59 (15.80)*‖§¶
		ROM	100	107.82 (7.27)*	112.06 (13.33)*‡	117.82 (15.09)*‡‖	122.53 (16.99)*‡‖§	120.82 (15.74)*‡‖	119.41 (16.49)*‡‖	121.18 (16.29)*‡‖
		EMG Amplitude	100	100.71 (42.92)	101.53 (61.60)	98.12 (32.62)	101.29 (41.37)	99.12 (69.84)	98.29 (55.61)	99.35 (48.94)

† significant treatment × time interaction (collapsed across group); * significantly different than stretch 1; ‡ significantly different than stretch 2; ‖ significantly different than stretch 4; § significantly different than stretch 8; ¶ significantly different than stretch 16; ▨ shaded block indicates significant difference between treatment

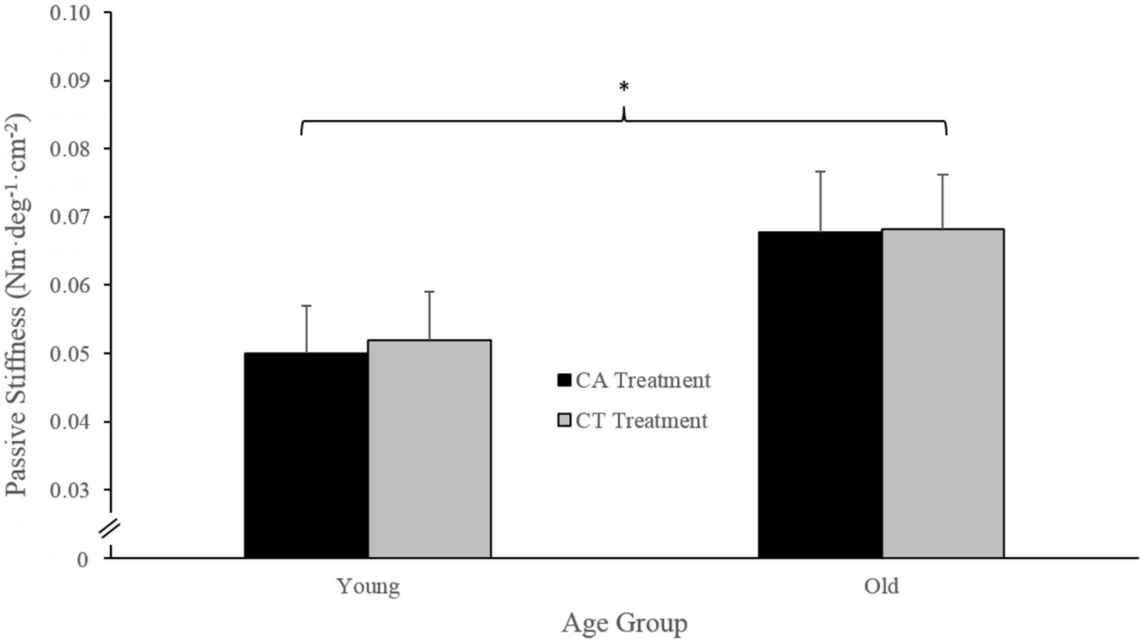


Figure 2. Baseline passive stiffness values for the young and old men for the constant angle (CA) and constant torque (CT) stretching treatments. * indicates a main effect for group showing that the old men were greater than the young. Values are mean ± SEM.

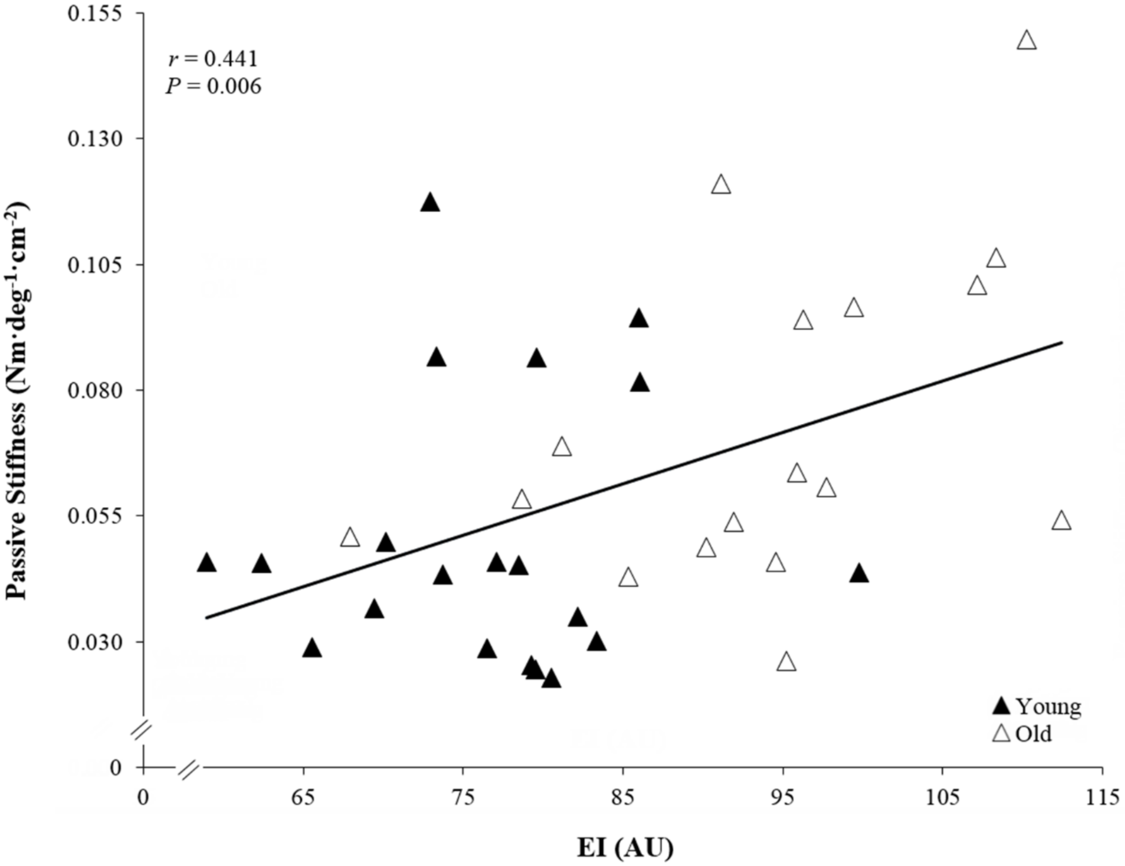


Figure 3. Relationship between passive stiffness at baseline (collapsed across treatment) and echo intensity (EI) of the whole hamstring muscle for the young and old men.

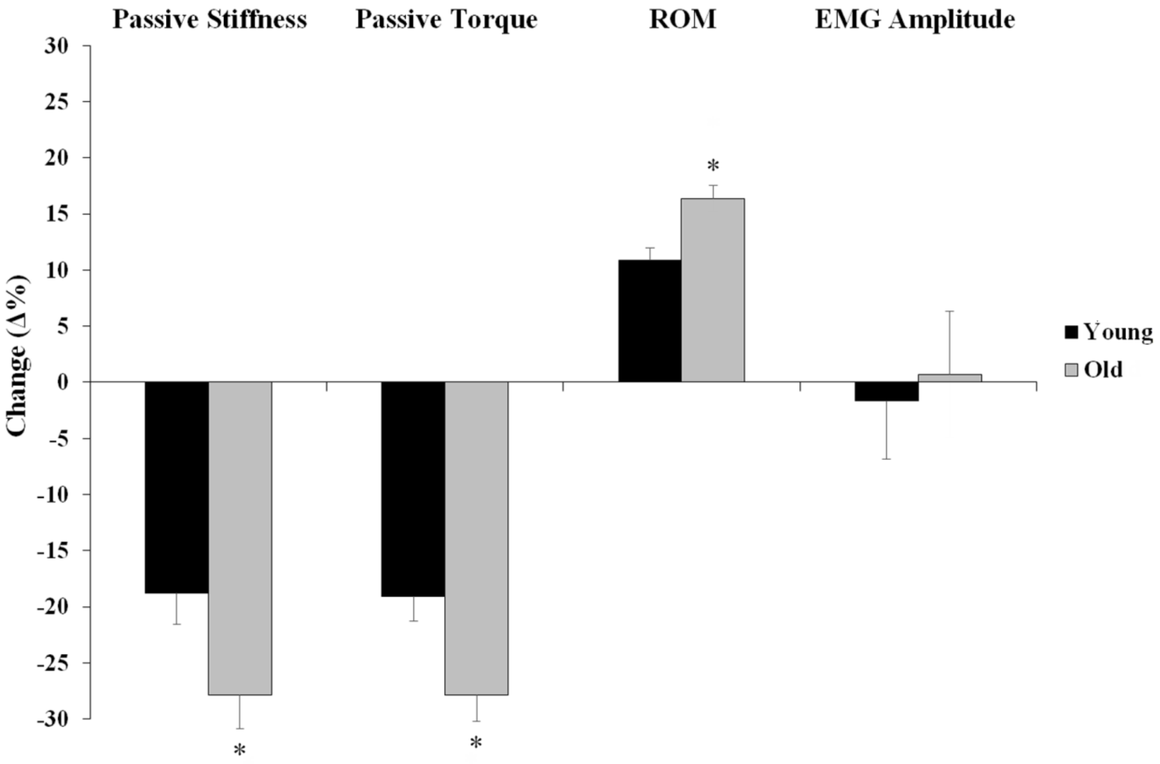


Figure 4. The percent change values from baseline (collapsed across treatment and time) for passive stiffness, passive torque, range of motion (ROM), and electromyographic (EMG) amplitude in the young and old men. * indicates a significant difference between groups. Values are mean ± SEM.

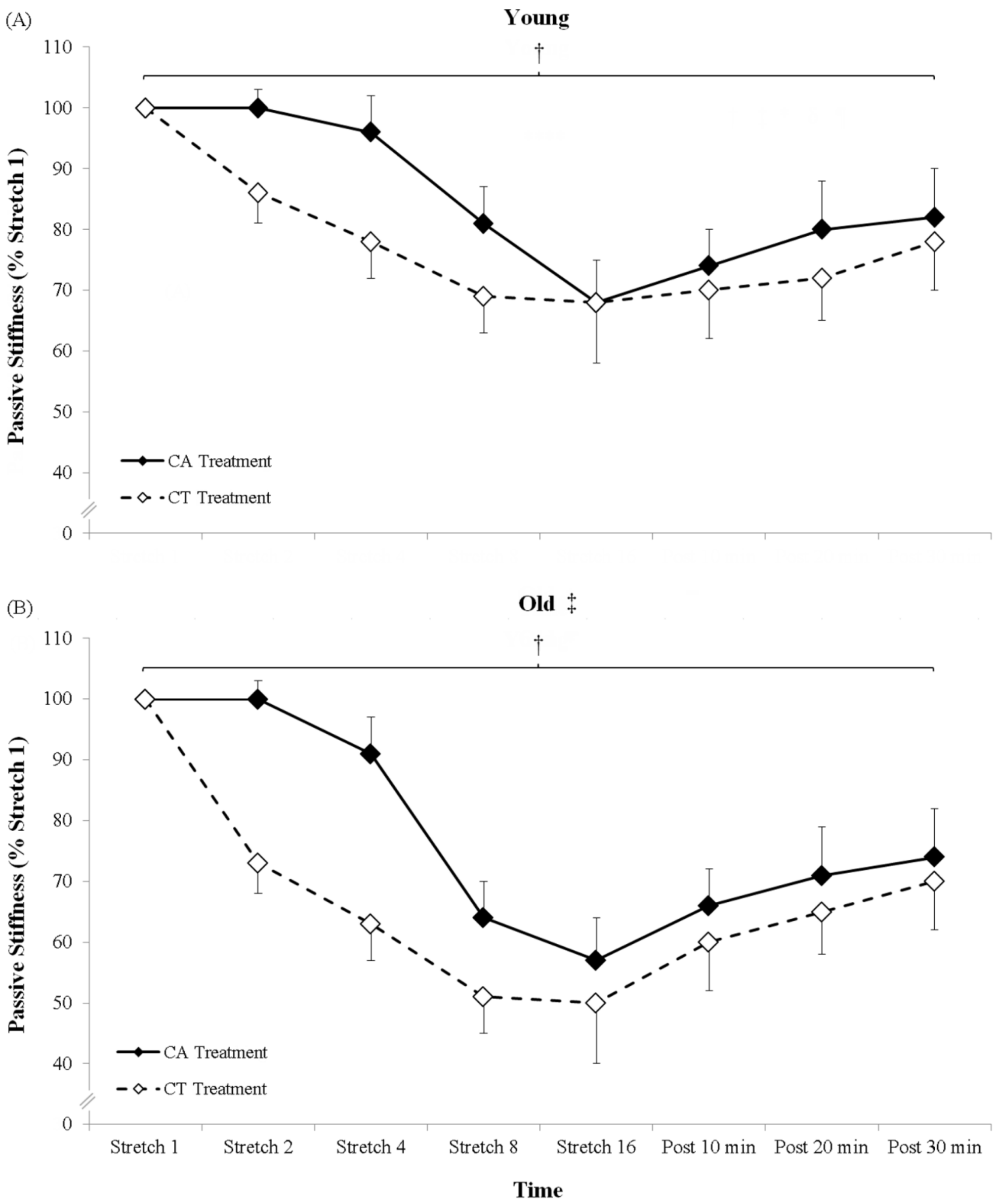


Figure 5. Passive stiffness values expressed relative to stretch 1 (%) for all time periods in the young (A) and old (B) men for the constant angle (CA) and constant torque (CT) stretching treatments. † indicates a significant treatment × time interaction where no differences were observed between stretch 1 and stretches 2 and 4 but there were differences between stretch 1 and stretches 8, 16, and Post10, Post20, and Post30 for the CA treatment; however, for the CT treatment, stretch 1 was higher than all subsequent stretches/time points. ‡ indicates a significant main effect for group, such that the older men had greater reductions in passive stiffness than the younger men when collapsed across treatment and time. Values are mean ± SEM.

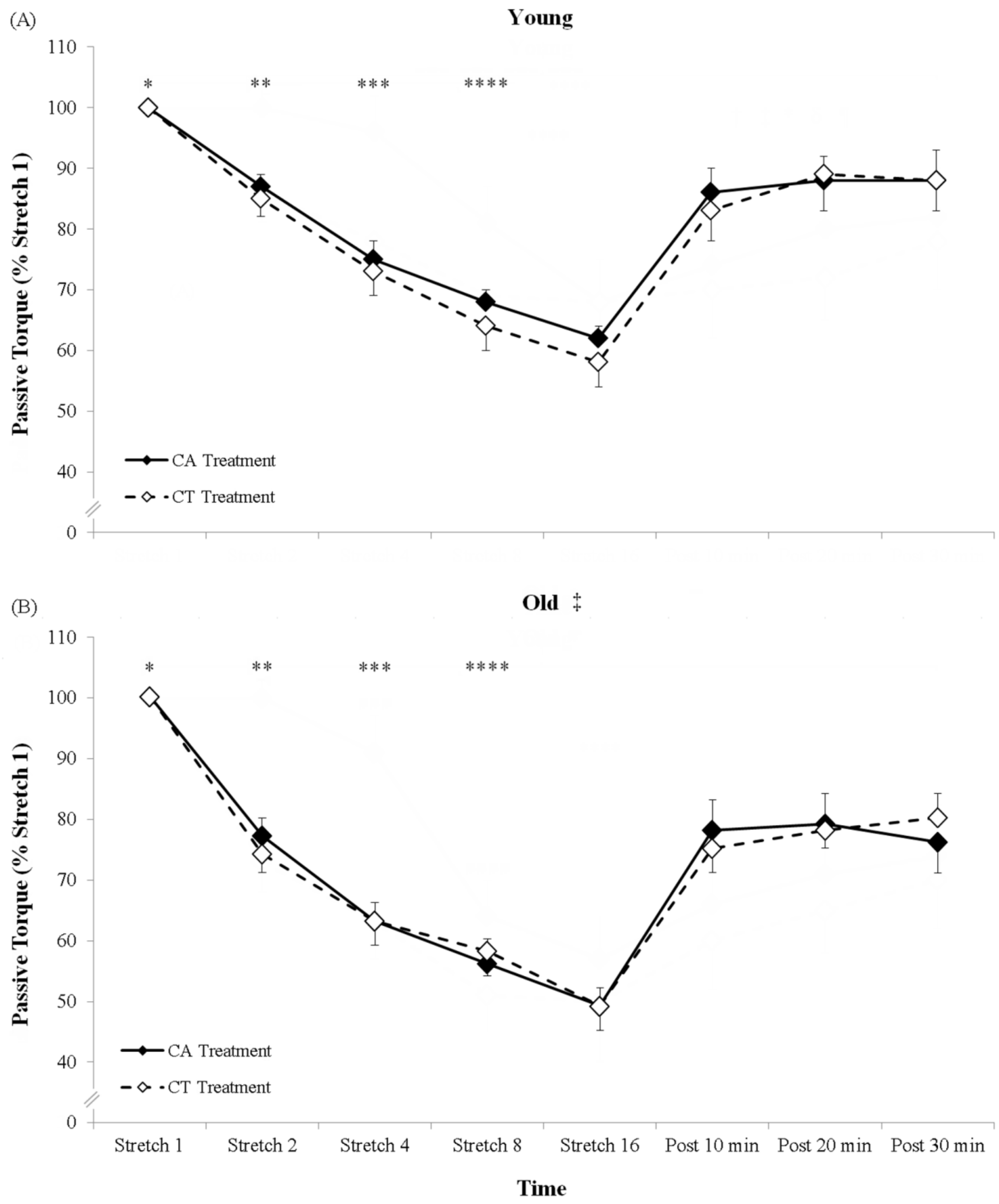


Figure 6. Passive torque values expressed relative to stretch 1 (%) for all time periods in the young (A) and old (B) men for the constant angle (CA) and constant torque (CT) stretching treatments. Collapsed across group and treatment: * stretch 1 was greater than stretches 2, 4, 8, 16, and Post10, Post20, and Post30; ** stretch 2 was greater than stretches 4, 8, and 16; *** stretch 4 was greater than stretches 8 and 16; **** stretch 8 was greater than stretch 16. ‡ indicates a significant main effect for group, such that the older men had greater reductions in passive torque than the younger men when collapsed across treatment and time. Values are mean ± SEM.

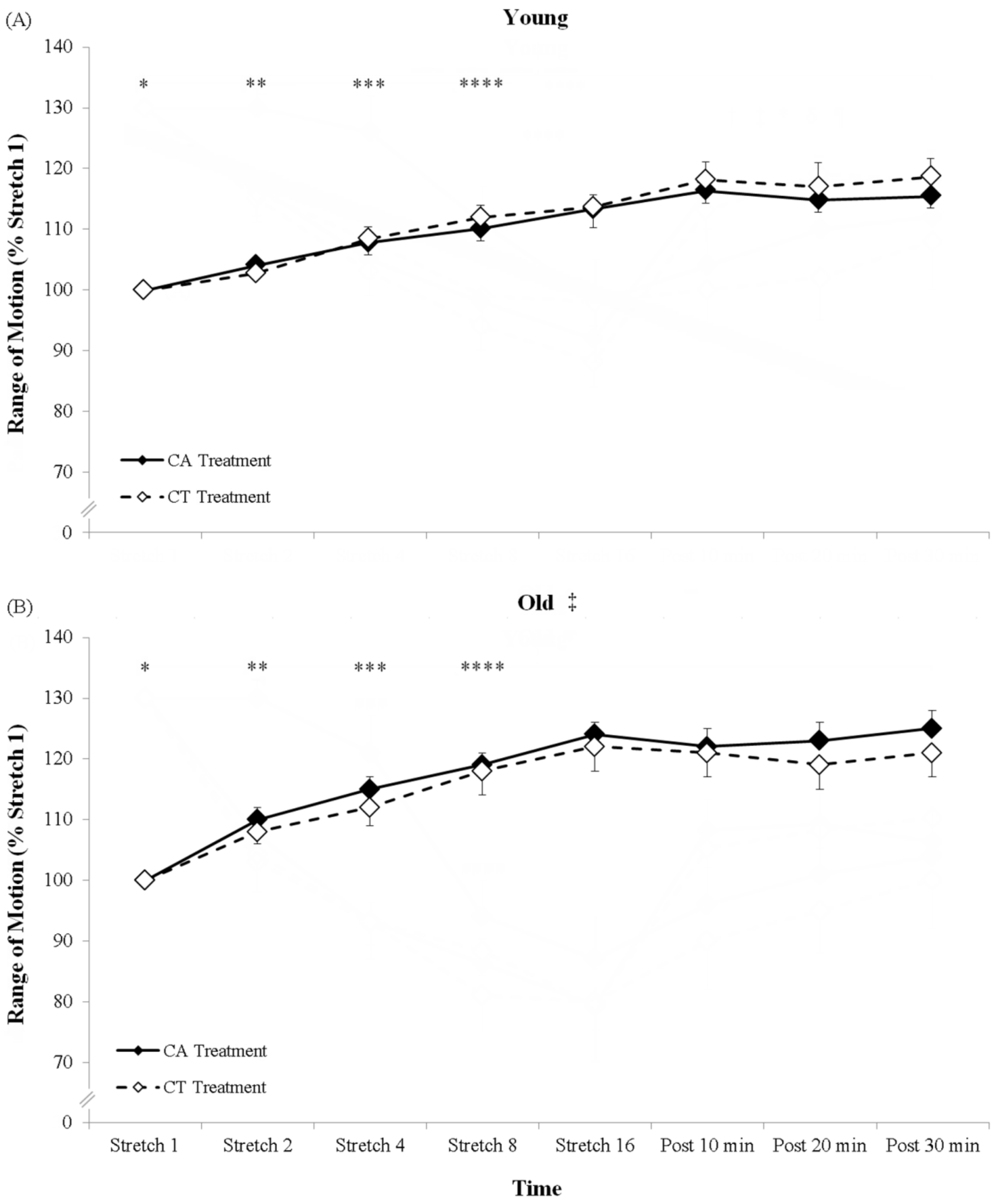


Figure 7. Range of motion (ROM) values expressed relative to stretch 1 (%) for all time periods in the young (A) and old (B) men for the constant angle (CA) and constant torque (CT) stretching treatments. Collapsed across group and treatment: * stretch 1 was less than stretches 2, 4, 8, 16, and Post10, Post20, and Post30; ** stretch 2 was less than stretches 4, 8, 16, and Post10, Post20, and Post30; *** stretch 4 was less than stretches 8, 16, and Post10, Post20, and Post30; **** stretch 8 was less than stretch 16. ‡ indicates a significant main effect for group, such that the older men had greater increases in ROM than the younger men when collapsed across treatment and time. Values are mean ± SEM.

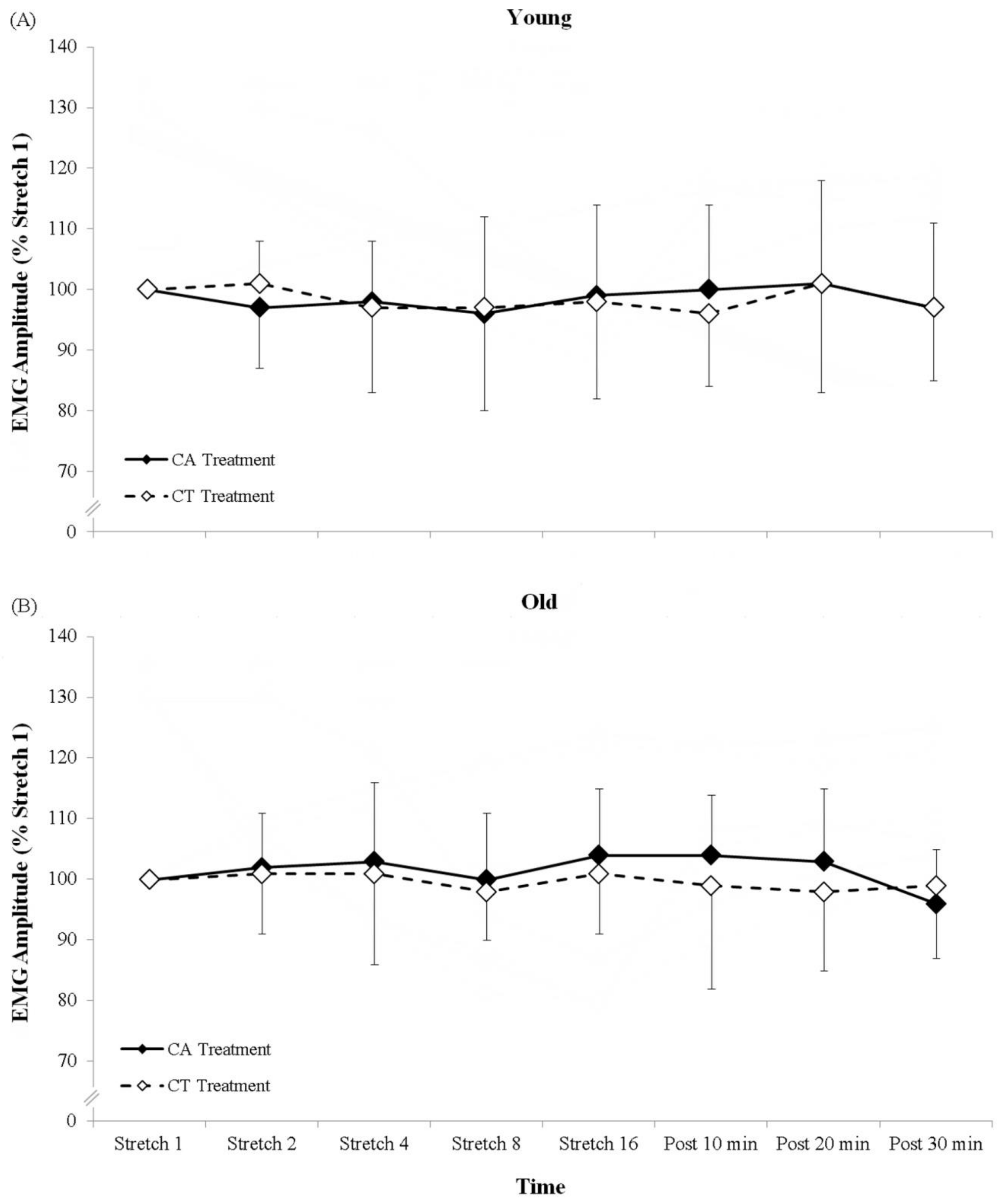


Figure 8. Electromyographic (EMG) amplitude values expressed relative to stretch 1 (%) for all time periods in the young (A) and old (B) men for the constant angle (CA) and constant torque (CT) stretching treatments. Values are mean ± SEM.

CHAPTER V

DISCUSSION

The primary findings of the present investigation showed that the older men had greater passive stiffness at baseline compared to the young men (Figure 2). The old men also exhibited lower CSA and higher EI values than the young men (Table 1), and based on pooled data from the two groups, significant positive relationships were observed between passive stiffness and EI values for all the hamstring muscles (Figure 3). Although the CA and CT static stretching elicited similar changes across stretches for passive torque and ROM (Figures 6 and 7), differential time course effects between the two treatments were observed for passive stiffness (Figure 5). Specifically, the CT treatment decreased passive stiffness following one 30-s bout of stretching, whereas for the CA treatment, passive stiffness did not decrease from baseline until stretch 8 (4 min of stretching). Moreover, during the first 4 min of stretching, greater reductions in passive stiffness were observed for the CT treatment than the CA treatment. However, despite these discrepancies, no differences in stiffness recovery patterns were observed between treatments after the stretching was completed. The CA and CT treatments showed lower passive stiffness and torque and higher ROM (relative to stretch 1) at Post10, Post20, and Post30 for both age groups; however, the old men exhibited significantly greater changes for these variables compared to the young men across all treatments and time points (collapsed together) (Figure 4).

The present findings showed that at baseline the old men exhibited greater (30.1%) passive stiffness compared to the young men (collapsed across treatments). These findings are in agreement with previous studies that have reported greater passive stiffness for old compared to young men for the elbow[83], knee[84], and plantar flexors[32,61,62]. Alternatively, however, other authors[69,85,86] examining some of the same muscle groups have reported no influence of age on passive stiffness. These discrepancies may be due to differences in the age and health status of the participants that were tested, passive stretching procedures, and/or the stiffness values that were examined. For example, the majority of studies reporting non-significant differences between young and old adults have used absolute stiffness values[69,85,86], whereas other studies[32,83] reporting significant differences between age groups have used relative stiffness values that were statistically adjusted for and/or normalized to measurements of muscle size (i.e., CSA, girth, body-mass index). Ryan et al.[24] suggested that passive stiffness of the MTU may be influenced by the quantity of muscle tissue; therefore, it is possible that the lower muscle CSA values typically observed in old compared to young men may influence absolute stiffness values, potentially masking any true differences in the passive mechanical properties between age groups. Thus, normalized stiffness values, which represent qualitative factors (i.e. collagen content and the amount of cross-linking)[24,87], may be useful for studying physiological mechanisms that are not confounded by CSA-related differences. In the present study, the old men had lower CSA values than the young men (Table 1); however, because passive stiffness was normalized to muscle CSA, it is possible that the differences observed in passive stiffness in this study were not due to changes in muscle size but rather changes in the quality of the musculotendinous tissue. Previous authors have suggested that changes in muscle quality (as assessed by EI) may influence the mechanical properties of the MTU[83,88] and, consequently, a decrease in muscle quality as indicated by higher EI values resulting from an increased infiltration of both intramuscular adipose and connective tissues[71,89], may provide for a higher passive stiffness during the performances of stretching-related movements[88]. Our results would support these hypotheses given the age-related differences in EI values (Table 1) and the significant positive relationships (*r* = 0.373-0.453) observed between passive stiffness and EI in the young and old men. Moreover, these findings are in agreement with those previously reported by Picelli et al.[90] who demonstrated significant positive relationships (*r* = 0.316-0.338) between passive resistance to stretch and EI values of the gastrocnemius muscles. Thus taken together, these findings suggest that muscle quality as assessed by EI may play an important role in the passive stiffness characteristics of the lower-body musculature. In addition, given the potential associations between increases in passive stiffness and EI values and the occurrence of falls and lower body injuries in young and old adults[91,92], the present findings provide support that passive stiffness and muscle quality characteristics may have important and promising implications for the assessment and treatment of balance-related injury risk. However, it is noteworthy that the present findings did not support differences in passive torque between age groups. Similar findings were reported by Such et al.[84] who observed an increase in passive stiffness but no differences in passive torque with age in the knee joint. The authors hypothesized that because tendons often become more compliant in old age, an increase in tendon compliance and a corresponding decrease in muscle compliance would result in a negligible change in passive torque between age groups[84]. Thus, the possibility of opposing changes in muscle and tendon compliances with age may explain why greater passive stiffness but no differences in passive torque were observed for the old compared to the young men in the present study. Although further research is needed to elucidate more specifically the functional importance of the relationships between age and tendon compliance, our findings may support the hypothesis that tendon compliance is greater in old compared to young adults which has recently been demonstrated in previous studies[93,94].

Similar to passive stiffness, the influence of age on ROM has previously been reported with conflicting results[20,32,61-63,95-97]. For example, Fukuchi et al.[95] reported no differences in hamstring ROM between young and old men and women, whereas Nonaka et al.[97] reported that hamstring ROM decreased with age in young, middle-aged, and older adults. Our findings add to these conflicting results by demonstrating that baseline ROM of the posterior hip and thigh muscles was similar between young and old men. The discrepancies between these findings and those reported by previous studies[62,63,96,97] may be the result of differences in muscle groups, ROM testing procedures, and/or the age and training status of the participants that were examined. While not significant, Charkravarty and Webley[98] reported substantial decreases in ROM may not occur in older adults until after the age of 75. Therefore, it is possible that because the majority of the older participants in the present study were less than 75 years of age (i.e. 12 of the 17 participants were < 75 years), there were no significant declines in flexibility, which may explain why the observed ROM values were similar between age groups. Moreover, it is also possible that the high physical activity levels of the older adults in the present study may have attenuated any declines in flexibility that might have occurred due to aging. This speculation may be supported by a previous study[99] examining changes in spinal ROM across a 5-year period in the elderly, where it was shown that older adults who reported high physical activity levels (several hours per week in conditioning exercises) also exhibited greater ROM and smaller age-related declines in flexibility than those who were sedentary. Magnusson et al.[57] suggested that the passive stiffness characteristics of the MTU may also play a significant role in flexibility, such that lower passive stiffness may allow for a greater ROM to be achieved. However, because of the lack of significant differences in ROM between the young and old men in the present study, our findings did not support these hypotheses. Nevertheless, it should be noted that when collapsed across treatment, the differences in ROM did approach statistical significance (P = 0.096) between age groups. Although these findings highlight a trend towards statistical significance for ROM, we do acknowledge that more research investigations with larger sample sizes are needed to further examine the effects of aging on flexibility-related measurements of the lower-body musculature.

This study showed that passive stiffness decreased as a result of CA and CT static stretching treatments in both young and old men. The declines in passive stiffness are similar to the findings of previous studies which also showed stretching-induced decreases in stiffness for the plantar flexor[13,14,73,100-103] and leg flexor[10-12,104] muscle groups. Because passive stiffness is thought to be influenced by the passive elastic components of muscle-tendon structure (i.e., tendon, contractile and noncontractile components, collagen fibers of the connective tissues)[23,105], the stretching-induced decreases in passive stiffness we observed may be a consequence of alterations in these physiological mechanisms. For example, Fowles et al.[73] revealed that a static dorsiflexion stretching protocol in a single subject elicited substantial increases in muscle fascicle length of the soleus and the lateral and medial gastrocnemius muscles, and because deformation of the contractile components (i.e. actin and myosin) of the muscle influences the resistance to passive stretch[28], it is possible that increases in muscle fascicle length due to stretching may result in decreases in passive stiffness of the MTU. Additionally, stretch-inducing alterations in intramuscular connective tissue may also contribute to the decreases in passive stiffness and help explain these findings. Morse et al.[102] reported that 5 min of static dorsiflexion stretching caused a significant reduction in passive stiffness of the plantar flexors, which was not attributed to increases in tendon compliance or muscle fascicle length. Alternatively, the authors suggested that the observed decrease in passive stiffness was likely due to the deformation of intramuscular connective tissues[102]. Although the precise mechanisms contributing to the stretch-induced decreases in passive stiffness cannot be determined from the present study, it is possible that the observed partial return to baseline for passive stiffness after stretching may be related to the connective tissues and viscoelastic recoil of the muscle[1,73]. Magnusson et al.[106] suggested that the rapid return to baseline in passive stiffness is an important property of the MTU that contributes to elastic recoil during locomotion. Future studies using more invasive measures are needed to test these hypotheses; however, the fact that our findings highlighted the presence of a time-related difference between stretch 1 but not stretch 2 and Post10, Post20, and Post30, suggest that passive stiffness in the present study recovered partially, but never completely returned back to baseline, which may be attributed to a combination of viscoelastic recoil and prolonged recovery from plastic deformation of the muscle[73].

Differential response patterns were observed between the CA and CT treatments for passive stiffness. Specifically, passive stiffness decreased following one 30-s bout of CT stretching, whereas for the CA stretching, passive stiffness did not decrease until stretch 8 (4 min of stretching). Moreover, during the first 4 min of stretching, greater reductions in passive stiffness were observed for the CT treatment than the CA treatment. Previous studies have reported similar findings regarding the superior efficacy of CT stretching over CA stretching at decreasing passive stiffness of the leg flexor[10,11] and plantar flexor[13,14] muscles. Ryan et al.[53] suggested that the muscle creep response that occurs during CT stretching may place more tension and/or apply more work on the MTU. Furthermore, Gajdosik et al.[28] reported that stretching at a CA affects the viscosity of the muscle-tendon structures but not the elasticity. Thus, taking these findings together, it is possible that the greater work performed by the CT stretching was enough to affect the viscosity and elasticity of the MTU, which may explain why greater decreases in passive stiffness of the posterior hip and thigh muscles were observed for the CT treatment than the CA treatment in the present study. It is interesting to note, however, that although the CA treatment was less effective, it still elicited significant decreases in passive stiffness following 4 min of static stretching. Previous studies[67,68,106] have reported that longer durations of CA stretching may be necessary to cause a decrease in passive stiffness. For example, Magnusson et al.[67,68,106] reported no changes in passive stiffness of the hamstrings following CA stretching durations of 1.5 to 2.25 min; however, Nordez et al.[80] and Matsuo et al.[104] showed that longer CA stretching durations (2.5 and 3 min, respectively) reduced passive stiffness in the hamstrings. Similar findings have been demonstrated in the plantar flexors[1], such that longer durations of CA stretching (5-30 min) reduced passive stiffness[73,102], while shorter durations (1-2 min) had no effect on stiffness[107,108]. Therefore, the present findings, in conjunction with those of previous studies[107,108], suggest that if there is a threshold necessary for the CA treatment to elicit a decrease in passive stiffness, it may be approximately 2 to 4 min of static stretching[1]. In contrast, however, the present findings showed that it only took one 30-s bout of CT stretching to significantly reduce passive stiffness. These findings are consistent with those of Herda et al.[11], who also demonstrated significant declines in passive stiffness after a single 30-s bout of CT stretching using a passive leg extension technique. However, unlike the present study, Herda et al.[11] showed no changes in passive stiffness after 4 and 8 min of CA stretching. It is possible, however, because of the limited number of participants in their study (*n* = 11)[11], that the lack of statistically significant decreases in passive stiffness at these time points may have been due to inadequate statistical power.

It is interesting that no differences in passive stiffness responses were observed between CA and CT treatments after the stretching was completed; both treatments showed reduced passive stiffness values at Post10, Post20, and Post30. This is a unique finding and perhaps suggests that in situations where time is not a factor, both CA and CT static stretching protocols can be used to effectively reduce and possibly maintain low passive stiffness values for up to 30 min post-stretching. Previous studies have reported conflicting results regarding the time-course responses of passive stiffness following CA and CT static stretching protocols[1,22,73,100,103]. For example, Ryan et al.[1] reported that after different durations (i.e., 2 min, 4 min, 8 min) of CT stretching, passive stiffness of the plantar flexors returned to baseline within 20 min post-stretching, whereas Magnusson et al.[22] demonstrated that passive stiffness of the hamstrings did not recover until 1 hour after the stretching protocol (i.e. 7.5 min of CA stretching) was completed. Some of the discrepancy between studies in stiffness responses may be attributed to differences in study methodology in which differences in the precision of resolution for the assessment of time-course responses following stretching prohibit accurate and precise determination of stiffness recovery. For example, Magnusson et al.[22] assessed passive stiffness at longer and less frequent time points (i.e. immediate and 1 hour post-stretching) following stretching, compared to Ryan et al.[1] who used more frequent recovery stiffness assessments (i.e., immediate and 10, 20, and 30 min post-stretching), which is consistent with the post-stretching time points reported in the present study. In addition, differences in stretching durations and intensities, the type of stretching treatment being performed (i.e. CA or CT), and/or the fiber compositions of the muscle groups that were examined are other possible explanations of the different recovery time-courses for passive stiffness that have been observed between studies. Power et al.[109] suggested that muscles that have a higher percentage of slow-twitch fibers may experience less severe stress from a stretching protocol. Therefore, because the plantar flexors have been documented on average to possess a greater percentage of slow-twitch fibers than the hamstrings and other thigh muscles[110,111], it is possible that for a given stretching duration/intensity, less stress may be placed on the plantar flexors, which could result in smaller and less prolonged changes in passive stiffness for these muscles during and after stretching, respectively. Consequently, the dose-response relationship between the duration of stretching and the passive stiffness response may be muscle-specific, such that the plantar flexors may require longer durations (i.e. >8 min) of stretching than the hamstrings to elicit substantial declines in passive stiffness that can be sustained for an extended period of time (i.e. ~30 min)[8]. From a practical standpoint, because stretching is often used in preparation for exercise or an athletic event, the present findings suggest that an 8 min bout of CA or CT static stretching for the posterior hip and thigh muscles should be performed within 30 min prior to the start of competition or exercise.

Although CT stretching placed more tension on the MTU compared with CA stretching, both stretching treatments elicited a similar time-course response for passive torque and ROM. In addition, the passive torque at the end range of motion was not significantly different between stretching treatments, suggesting that the initial torque at the beginning of CA stretching was similar to the torque threshold set for the CT stretching. Although these findings were inconsistent with those of Yeh et al.[13,14] and Cabido et al.[10] who reported greater changes in passive torque and ROM for the CT stretching than the CA stretching, they were in line with the results of Herda et al.[11] who reported no differences in passive torque and ROM between treatments (differences in the dosage of stretching, subject population, and the passive stretching procedures may account for the inconsistencies between Yeh et al.[13,14] and Cabido et al.[10] and the present study for ROM and passive torque). Herda et al.[11] reported that because greater declines were observed during the CT stretching for passive stiffness but not for passive torque and ROM, there may be a dissociation between these variables. The results of the present study indicated that passive torque significantly decreased following one 30-s stretch, regardless of the stretching treatment, and continued to decrease with subsequent stretches up to stretch 16 (8 min of stretching). After stretching, passive torque (collapsed across group and treatment) increased rapidly within the first 10 min post-stretching, but continued to remain below baseline at Post10, Post20, and Post30. For ROM (collapsed across group and treatment), significant increases were observed following one 30-s stretch with subsequent increases occurring up to stretch 16 (8 min of stretching); after stretching, ROM did not decrease but remained elevated above baseline at all post-stretching time points. Because mechanical factors, such as the passive resistance to stretch and passive stiffness of the MTU influence ROM[11], it is possible that the observed decreases in passive torque may have contributed to the increases in ROM that were observed during both the CA and CT static stretching. However, unlike passive torque, ROM did not show any sign of returning to baseline after stretching; therefore, it is likely that ROM may have also been influenced by other factors. Similarly, a recent study by Mizuno et al.[103] also reported that the retention time of the effects of stretching on passive torque (<15 min) was shorter than the retention time of the effects of stretching on ROM (>30 min) in the plantar flexors. The authors hypothesized that the increases in ROM immediately after stretching may have been attributable to changes in both the mechanical properties (i.e., passive torque, passive stiffness) of the MTU and to stretch tolerance; however, the changes in ROM at later post-stretching time points (i.e. 15 and 30 min) may have been attributable to changes only in stretch tolerance[103]. Therefore, it is possible that changes in the ability to tolerate a greater amount of stretch may have contributed to the sustained increases in ROM (at Post10, Post20, and Post30) that were observed in the present study. Finally, Ryan et al.[1] reported that even slow passive tension during a passive stiffness assessment can elicit the stretch reflex, thereby causing activation of the stretched muscles and contamination of the angle-torque curve (with both active force production and passive tension). Therefore, even though the stretching velocities during the CA and CT assessments in the present study were very slow (i.e. $5°\cdot s^{-1}$), they still may have elicited the stretch reflex, and caused an excessive EMG activity response. However, the inclusion criteria in this study was that the surface EMG amplitude never exceeded 5% of the MVC value during any of the passive stiffness values recorded at the final ROM (i.e. second to last common joint angle). Furthermore, there were no statistical differences between groups, treatments, or across time points for EMG, which suggested that the angle-torque curves in the present study were indeed passive and valid assessments of stiffness during both the CA and CT treatments.

Both groups in the present study experienced significant stretch-induced decreases in passive stiffness and passive torque and increases in ROM; however, interestingly, the old men experienced greater changes in these variables than the young men when collapsed across treatment and time. These findings are in agreement with the results reported by Ryan et al.[20] who also indicated greater stretching-induced changes in passive torque and ROM of the plantar flexors for old compared to young men. It was hypothesized that the greater stretching-induced changes that were observed among the old men may have been due to age-related increases in tendon compliance[20]. Wilson et al.[112] showed that tendon compliance (as assessed by the elastic modulus) of the hamstrings was greater in older adults than younger adults. Thus, the possibility of age-related increases in tendon compliance of the hamstrings and other thigh muscles may explain why greater changes in the passive musculotendinous resistive properties were observed for the old men in the present study. Moreover, it also possible, given the fact that a stiffer MTU may experience greater stress during stretching than a more compliant MTU[109], that the higher passive stiffness of the old men in the present study may have elicited greater stress to the tissue, resulting in greater stretching-induced changes in the mechanical properties of the muscle. However, given the scope of our study and the limited data available regarding these findings, it was not feasible to ascertain the underlying mechanisms resulting in the greater stretching-induced changes in passive properties for the old men than the young men. Thus, future research using ultrasound imaging in conjunction with passive stretching may be necessary to pin-point the exact mechanisms that may be responsible for influencing the stretching-related, passive-property differences displayed among groups of individuals with varying ages.

The results of the present study provide support that CT stretching should be used in both young and old men for research and clinical situations where rapid decreases in passive stiffness is the objective or there is a shortage of time before an exercise-related event or competition. It has been hypothesized that stretching-induced decreases in passive stiffness may reduce the risk of strain-related injuries to the MTU[25]. Garrett et al.[113] reported that 10 cycles of stretching to 50% of the determined failure length in rabbit MTUs resulted in greater muscle length before injury. The authors suggested that less force would be placed on the MTU throughout the required ROM after stretching, which would reduce the risk of muscle strains[113]. Although CT stretching elicited greater and more rapid decreases in passive stiffness than CA stretching, both treatments were equally effective at increasing ROM and decreasing passive torque and thus, it is unclear if either form of stretching would be more beneficial in reducing the risk of injury. Moreover, there is only a limited amount of evidence to directly support that acute static stretching does reduce injuries in the MTU[6,12,114]. Furthermore, many previous studies have demonstrated transient declines in muscle strength, strength endurance, power, and balance after an acute bout of static stretching[12,73,115-125]. Interestingly, however, we are aware of only one study[12] that has examined strength deficits specifically comparing CA and CT stretching treatments. Herda et al.[12] reported that maximal strength capabilities decreased to the same extent after 8 min of static stretching regardless of the treatment (CA or CT) that was performed. The authors recommended that although both treatments negatively affected muscle strength, CT stretching should be performed prior to performance to reduce passive stiffness with the understanding that it would not cause any greater decrement in strength compared with CA stretching[12]. While these recommendations could also be applied to the present study, it should be noted that Herda et al.[12] only examined young adult males, and thus, the effects of CA and CT static stretching on maximal and rapid strength in older adults are still unclear. Thus, future research studies should examine the effects of CA and CT static stretching on isometric peak torque and rate of torque development in both young and old adults to determine whether age has an effect on stretching-induced declines in these parameters.

CHAPTER VI

CONCLUSION

A very limited amount of previous research has investigated the effects of aging and stretching on the passive resistive properties of the MTU. The present study was designed to test the hypothesis that 8 min of stretching at a constant-torque would exhibit larger effects on the passive resistive properties compared to stretching at a constant-angle and that these effects would be greater in older men. A secondary aim was to examine the influence of a recovery period on these variables, and to make comparisons between age groups and treatments. Overall, these hypotheses were supported in this study. The CT treatment elicited greater decreases in passive stiffness than the CA treatment (collapsed across group) within the first 4 min of stretching and these effects were greater in the old compared to the young men when collapsed across treatment and time for all passive resistive measures (i.e., passive stiffness, passive torque, and ROM). However, interestingly, although CT stretching caused a greater and more rapid decrease in passive stiffness, both stretching treatments elicited a similar time-course response for passive torque and ROM. Collectively, these findings suggest a dissociation between the passive resistive properties and that the magnitude of stretching-induced changes in these variables may be influenced by the age of the participants. In addition to adding to the paucity of data available regarding the influence of aging and stretching on passive resistive measures, the present study also revealed novel differential effects on the recovery of these characteristics. Overall, despite a partial recovery in magnitude of both passive stiffness and passive torque after stretching, maximum ROM exhibited elevated and sustained increases in both groups and treatments (collapsed together). These findings suggest that decreases in passive stiffness and passive torque may contribute to the increases in ROM during and immediately after stretching; however, other factors, such as changes in stretch tolerance, may play a more significant role in the sustained increases in ROM at later post-stretching time points (10, 20, and 30 min after stretching). To the author's knowledge, this is the first study to investigate these changes specifically comparing CA and CT stretching treatments for both young and old men, and to make comparisons between these age groups. Age-specific differences in the effects of static stretching on the passive resistive properties may be attributed to changes in tendon and/or muscle compliance. The observed stretching-induced sustained reductions in passive stiffness of the posterior hip and thigh muscles has substantial performance and injury risk implications. Given the potential importance of these muscles in athletic related tasks, balance performance, and injury risks, these sustained decreases in passive stiffness may be of large practical and functional significance to a variety of populations and settings. Furthermore, because older adults have significantly greater passive stiffness values than younger adults, any stretch-induced decrease in stiffness may be particularly beneficial to the elderly, where a substantial decline in passive resistance in these populations may reduce the risk of falls and strain-related injuries to the muscle.

REFERENCES

1. Ryan ED, Beck TW, Herda TJ, et al. The time course of musculotendinous stiffness responses following different durations of passive stretching. J Orthop Sports Phys Ther 2008;38:632-639.

2. Palmer TB, Jenkins NDM, Cramer JT. Reliability of manual versus automated techniques for assessing passive stiffness of the posterior muscles of the hip and thigh. J Sports Sci 2013;31:867-877.

3. Safran M, Seaber A, Garrett W, Jr. Warm-up and muscular injury prevention. An update. Sports Med 1989;8:239-249.

4. Rubini EC, Costa AL, Gomes PS. The effects of stretching on strength performance. Sports Med 2007;37:213-224.

5. Shrier I. Does stretching improve performance? A systematic and critical review of the literature. Clin J Sport Med 2004;14:267-273.

6. Thacker SB, Gilchrist J, Stroup DF, Kimsey CD. The impact of stretching on sports injury risk: a systematic review of the literature. Med Sci Sports Exerc 2004;36:371-378.

7. Witvrouw E, Mahieu N, Danneels L, McNair P. Stretching and injury prevention: An obscure relationship. Sports Med 2004;34:443-449.

8. Hoge KM, Ryan ED, Costa PB, et al. Gender differences in musculotendinous stiffness and range of motion after an acute bout of stretching. J Strength Cond Res 2010;24:2618-2626.

9. Shehab R, Mirabelli M, Gorenflo D, Fetters MD. Pre-exercise stretching and sports related injuries: knowledge, attitudes and practices. Clin J Sport Med 2006;16:228-231.

10. Cabido CE, Bergamini JC, Andrade AG, Lima FV, Menzel HJ, Chagas MH. Acute effect of constant torque and angle stretching on range of motion, muscle passive properties, and stretch discomfort perception. J Strength Cond Res 2014;28:1050-1057.

11. Herda TJ, Costa PB, Walter AA, Ryan ED, Cramer JT. The time course of the effects of constant-angle and constant-torque stretching on the muscle-tendon unit. Scand J Med Sci Sports 2014;24:62-67.

12. Herda TJ, Costa PB, Walter AA, et al. Effects of two modes of static stretching on muscle strength and stiffness. Med Sci Sports Exerc 2011;43:1777-1784.

13. Yeh C-Y, Chen J-JJ, Tsai K-H. Quantifying the effectiveness of the sustained muscle stretching treatments in stroke patients with ankle hypertonia. J Electromyogr Kinesiol 2007;17:453-461.

14. Yeh C-Y, Tsai K-H, Chen J-J. Effects of prolonged muscle stretching with constant torque or constant angle on hypertonic calf muscles. Arch Phys Med Rehabil 2005;86:235-241.

15. Bacurau RFP, Monteiro GA, Ugrinowitsch C, Tricoli V, Cabral LF, Aoki MS. Acute effect of a ballistic and a static stretching exercise bout on flexibility and maximal strength. J Strength Cond Res 2009;23:304-308.

16. Marek SM, Cramer JT, Fincher AL, et al. Acute effects of static and proprioceptive neuromuscular facilitation stretching on muscle strength and power output. J Athl Train 2005;40:94-103.

17. Funk DC, Swank AM, Mikla BM, Fagan TA, Farr BK. Impact of prior exercise on hamstring flexibility: a comparison of proprioceptive neuromuscular facilitation and static stretching. J Strength Cond Res 2003;17:489-492.

18. Herda TJ, Herda ND, Costa PB, Walter-Herda AA, Valdez AM, Cramer JT. The effects of dynamic stretching on the passive properties of the muscle-tendon unit. J Sports Sci 2013;31:479-487.

19. Ryan ED, Everett KL, Smith DB, et al. Acute effects of different volumes of dynamic stretching on vertical jump performance, flexibility and muscular endurance. Clin Phys Funct Imaging 2014;34:485-492.

20. Ryan ED, Herda TJ, Costa PB, Herda AA, Cramer JT. Acute effects of passive stretching of the plantarflexor muscles on neuromuscular function: the influence of age. Age (Dordr) 2014;36:1-12.

21. Ryan ED, Beck TW, Herda TJ, et al. Do practical durations of stretching alter muscle strength? A dose-response study. Med Sci Sports Exerc 2008;40:1529-1537.

22. Magnusson SP, Simonsen, E.B., Aagaard, P., Kjaer, M. Biomechanical responses to repeated stretches in human hamstring muscle in vivo. Am J Sports Med 1996;24:622 - 628.

23. Palmer TB, Thompson BJ, Hawkey MJ, et al. The influence of athletic status on the passive properties of the muscle-tendon unit and traditional performance measures in division I female soccer players and non-athlete controls. J Strength Cond Res 2014;28:2026-2034.

24. Ryan ED, Thompson BJ, Herda TJ, et al. The relationship between passive stiffness and evoked twitch properties: the influence of muscle CSA normalization. Physiol Meas 2011;32:677-686.

25. Cross K, Worrell T. Effects of a static stretching program on the incidence of lower extremity musculotendinous strains. J Athl Train 1999;34:11-14.

26. Garrett WE. Muscle strain injuries: clinical and basic aspects. Med Sci Sports Exerc 1990;22:436-443.

27. Taylor DC, Dalton JD, Seaber AV, Garrett WE. Viscoelastic properties of muscle-tendon units. Am J Sports Med 1990;18:300-309.

28. Gajdosik RL. Passive extensibility of skeletal muscle: review of the literature with clinical implications. Clin Biomech 2001;16:87-101.

29. McHugh M, Magnusson S, Gleim G, Nicholas J. Viscoelastic stress relaxation in human skeletal muscle. Med Sci Sports Exerc 1992;24:1375-1382.

30. Palmer TB, Jenkins ND, Thompson BJ, Smith DB, Cramer JT. The relationship between passive stiffness and muscle power output: Influence of muscle cross-sectional area normalization. Muscle Nerve 2014;49:69-75.

31. Gajdosik RL. Influence of a low-level contractile response from the soleus, gastrocnemius and tibialis anterior muscles on viscoelastic stress-relaxation of aged human calf muscle-tendon units. Eur J Appl Physiol 2006;96:379-388.

32. Sobolewski EJ, Ryan ED, Thompson BJ, McHugh MP, Conchola EC. The Influence of age on the viscoelastic stretch response. J Strength Cond Res 2014;28:1106-1112.

33. Feland JB, Myrer JW, Schulthies SS, Fellingham GW, Measom GW. The effect of duration of stretching of the hamstring muscle group for increasing range of motion in people aged 65 years or older. Phys Ther 2001;81:1110-1117.

34. Jang J, Koh E, Han D. The effectiveness of passive knee extension exercise in the sitting position on stretching of the hamstring muscles of patients with lower back pain. J Phys Ther Sci 2013;25:501-504.

35. Marshall PWM, Mannion J, Murphy BA. Extensibility of the hamstrings is best explained by mechanical components of muscle contraction, not behavioral measures in individuals with chronic low back pain. PM&R 2009;1:709-718.

36. Palmer TB, Akehi K, Thiele RM, Smith DB, Warren AJ, Thompson BJ. Dorsiflexion, plantar flexion, and neutral ankle positions during passive resistance assessments of the posterior hip and thigh muscles. J Athl Train 2014[Epub: ahead of print].

37. Ekstrand J, Gillquist J. The frequency of muscle tightness and injuries in soccer players. Am J Sports Med 1982;10:75-78.

38. Kujala UM, Oksanen A, Taimela S, Salminen JJ. Training does not increase maximal lumbar extension in healthy adolescents. Clin Biomech 1997;12:181-184.

39. Tafazzoli F, Lamontagne M. Mechanical behaviour of hamstring muscles in low-back pain patients and control subjects. Clin Biomech 1996;11:16-24.

40. Witvrouw E, Danneels L, Asselman P, D'Have T, Cambier D. Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players a prospective study. Am J Sports Med 2003;31:41-46.

41. Forst J. Contribution a l'étude clinique sur la sciatique. University of Paris 1881;Thesis.

42. Rebain R, Baxter GD, McDonough S. A systematic review of the passive straight leg raising test as a diagnostic aid for low back pain (1989 to 2000). Spine 2002;27:E388-E395.

43. Andersson GB, Deyo RA. History and physical examination in patients with herniated lumbar discs. Spine 1996;21:10S-18S.

44. Breig A, Troup J. Biomechanical considerations in the straight-leg-raising test. Cadaveric and clinical studies of the effects of medial hip rotation. Spine 1979;4:242-250.

45. Ochala J, Lambertz D, Pousson M, Goubel F, Van Hoecke J. Changes in mechanical properties of human plantar flexor muscles in ageing. Exp Gerontol 2004;39:349-358.

46. Purslow PP. Strain-induced reorientation of an intramuscular connective tissue network: Implications for passive muscle elasticity. J Biomech 1989;22:21-31.

47. Lamontagne A, Malouin F, Richards CL, Dumas F. Evaluation of reflex- and nonreflex-induced muscle resistance to stretch in adults with spinal cord injury using hand-held and isokinetic dynamometry. Phys Ther 1998;78:964-975.

48. Göeken LN, Hof AL. Instrumental straight-leg raising: results in healthy subjects. Arch Phys Med Rehabil 1993;74:194-203.

49. Göeken LN, Hof AL. Instrumental straight-leg raising: results in patients. Arch Phys Med Rehabil 1994;75:470-477.

50. Marshall PWM, Cashman A, Cheema BS. A randomized controlled trial for the effect of passive stretching on measures of hamstring extensibility, passive stiffness, strength, and stretch tolerance J Sci Med Sport 2011;14:535-540.

51. Hall T, Zusman M, Elvey R. Adverse mechanical tension in the nervous system? Analysis of straight leg raise. Man Ther 1998;3:140-146.

52. Gajdosik RL, Vander Linden DW, McNair PJ, Williams AK, Riggin TJ. Effects of an eight-week stretching program on the passive-elastic properties and function of the calf muscles of older women. Clin Biomech 2005;20:973-983.

53. Ryan E, Herda T, Costa P, et al. Viscoelastic creep in the human skeletal muscle–tendon unit. Eur J Appl Physiol 2010;108:207-211.

54. Ryan ED, Herda TJ, Costa PB, Walter AA, Cramer JT. Dynamics of viscoelastic creep during repeated stretches. Scand J Med Sci Sports 2012;22:179-184.

55. Blackburn JT, Bell DR, Norcross MF, Hudson JD, Kimsey MH. Sex comparison of hamstring structural and material properties. Clin Biomech 2009;24:65-70.

56. Chleboun, GS, Howell, JN, Conatser, RR, Giesey, JJ. The relationship between elbow flexor volume and angular stiffness at the elbow. Clin Biomech 1997;12:383-392.

57. Magnusson SP, Simonsen EB, Aagaard P, Boesen J, Johannsen F, Kjaer M. Determinants of musculoskeletal flexibility: viscoelastic properties, cross-sectional area, EMG and stretch tolerance. Scand J Med Sci Sports 1997;7:195-202.

58. Ryan ED, Herda TJ, Costa PB, et al. Passive properties of the muscle-tendon unit: The influence of muscle cross-sectional area. Muscle Nerve 2009;39:227-229.

59. Blackburn JT, Riemann BL, Padua DA, Guskiewicz KM. Sex comparison of extensibility, passive, and active stiffness of the knee flexors. Clin Biomech 2004;19:36-43.

60. Weppler CH, Magnusson SP. Increasing muscle extensibility: a matter of increasing length or modifying sensation? Phys Ther 2010;90:438–449.

61. Gajdosik RL, Vander Linden DW, McNair PJ, et al. Viscoelastic properties of short calf muscle-tendon units of older women: effects of slow and fast passive dorsiflexion stretches in vivo. Eur J Appl Physiol 2005;95:131-139.

62. Gajdosik RL, Vander Linden DW, McNair PJ, et al. Slow passive stretch and release characteristics of the calf muscles of older women with limited dorsiflexion range of motion. Clin Biomech 2004;19:398-406.

63. Gajdosik RL, Vander Linden DW, Williams AK. Influence of age on length and passive elastic stiffness characteristics of the calf muscle-tendon unit of women. Phys Ther 1999;79:827-838.

64. McHugh MP, Kremenic I, Fox MB, Gleim GW. The role of mechanical and neural restraints to joint range of motion during passive stretch. Med Sci Sports Exerc 1998;30:928-932.

65. Magusson SP, Simonsen EB, Aagaard P, Sorensen H, Kjaer M. A mechanism for altered flexibility in human skeletal muscle. J Physiol 1996;497:291-298.

66. Halbertsma JPK, van Bolhuis AI, Göeken LNH. Sport stretching: Effect on passive muscle stiffness of short hamstrings. Arch Phys Med Rehabil 1996;77:688-692.

67. Magnusson SP, Simonsen EB, Aagaard P, Dyhre-Poulsen P, McHugh MP, Kjaer M. Mechanical and physiological responses to stretching with and without preisometric contraction in human skeletal muscle. Arch Phys Med Rehabil 1996;77:373-378.

68. Magnusson SP, Aagaard P, Simonsen E, Bojsen-Moller F. A biomechanical evaluation of cyclic and static stretch in human skeletal muscle. Int J Sports Med 1998;19:310-316.

69. Chesworth BM, Vandervoort AA. Age and passive ankle stiffness in healthy women. Phys Ther 1989;69:217-224.

70. Palmer TB, Hawkey MJ, Thiele RM, et al. The influence of athletic status on maximal and rapid isometric torque characteristics and postural balance performance in Division I female soccer athletes and non-athlete controls. Clin Physiol Funct Imaging 2014[Epub: ahead of print].

71. Pillen S, Tak RO, Zwarts MJ, et al. Skeletal muscle ultrasound: correlation between fibrous tissue and echo intensity. Ultrasound Med Biol 2009;35:443-446.

72. Rosenberg JG, Ryan ED, Sobolewski EJ, Scharville MJ, Thompson BJ, King GE. Reliability of panoramic ultrasound imaging to simultaneously examine muscle size and quality of the medial gastrocnemius. Muscle Nerve 2014;49:736-740.

73. Fowles JR, Sale DG, MacDougall JD. Reduced strength after passive stretch of the human plantarflexors. J Appl Physiol 2000;89:1179-1188.

74. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol 2000;10:361-374.

75. Berg H, Tedner B, Tesch P. Changes in lower limb muscle cross-sectional area and tissue fluid volume after transition from standing to supine. Acta Physiol Scand 1993;148:379-385.

76. O'Sullivan K, Sainsbury D, O'Connor R. Measurement of thigh muscle size using tape or ultrasound is a poor indicator of thigh muscle strength. Isokinet Exerc Sci 2009;17:145-153.

77. Wilhelm EN, Rech A, Minozzo F, Radaelli R, Botton CE, Pinto RS. Relationship between quadriceps femoris echo intensity, muscle power, and functional capacity of older men. Age (Dordr) 20141-10.

78. Ahtiainen JP, Hoffren M, Hulmi JJ, et al. Panoramic ultrasonography is a valid method to measure changes in skeletal muscle cross-sectional area. Eur J Appl Physiol 2010;108:273-279.

79. Scanlon TC, Fragala MS, Stout JR, et al. Muscle architecture and strength: Adaptations to short term resistance training. Muscle Nerve 2014;49:584-592.

80. Nordez A, Cornu C, McNair P. Acute effects of static stretching on passive stiffness of the hamstring muscles calculated using different mathematical models. Clin Biomech 2006;21:755-760.

81. Duong B, Low M, Moseley AM, Lee RY, Herbert RD. Time course of stress relaxation and recovery in human ankles. Clin Biomech 2001;16:601-607.

82. Matsuo S, Suzuki S, Iwata M, Hatano G, Nosaka K. Changes in force and stiffness after static stretching of eccentrically-damaged hamstrings. Eur J Appl Physiol 2014[Epub: ahead of print].

83. Eby SF, Cloud BA, Brandenburg JE, et al. Shear wave elastography of passive skeletal muscle stiffness: Influences of sex and age throughout adulthood. Clin Biomech 2015;30:22-27.

84. Such C, Unsworth A, Wright V, Dowson D. Quantitative study of stiffness in the knee joint. Ann Rheum Dis 1975;34:286-291.

85. Vandervoort AA, Chesworth BM, Mick Jones NS. Passive ankle stiffness in young and elderly men. Can J Aging 1990;9:204-212.

86. Wiegner A, Watts R. Elastic properties of muscles measured at the elbow in man: I. Normal controls. J Neurol Neurosurg Psychiatry 1986;49:1171-1176.

87. Fouré, A, Nordez, A, McNair, P, Cornu, C. Effects of plyometric training on both active and passive parts of the plantarflexors series elastic component stiffness of muscle–tendon complex. Eur J Appl Physiol 2011;111:539-548.

88. Lee SS, Spear S, Rymer WZ. Quantifying changes in material properties of stroke-impaired muscle. Clin Biomech 2015[Epub: ahead of print].

89. Palmer TB, Akehi K, Thiele RM, Smith DB, Thompson BJ. Reliability of panoramic ultrasound imaging in simultaneously examining muscle size and quality of the hamstring muscles in young, healthy males and females. Ultrasound Med Biol 2015;41:675-684.

90. Picelli A, Tamburin S, Cavazza S, et al. Relationship between ultrasonographic, electromyographic, and clinical parameters in adult stroke patients with spastic equinus: an observational study. Arch Phys Med Rehabi 2014;95:1564-1570.

91. Vandervoort AA, Chesworth BM, Cunningham DA, Paterson DH, Rechnitzer PA, Koval JJ. Age and sex effects on mobility of the human ankle. J Gerontol 1992;47:M17-M21.

92. Mangine GT, Hoffman JR, Gonzalez AM, et al. Bilateral differences in muscle architecture and increased rate of injury in National Basketball Association players. J Athl Train 2014;49:794-799.

93. Csapo R, Malis V, Hodgson J, Sinha S. Age-related greater Achilles tendon compliance is not associated with larger plantar flexor muscle fascicle strains in senior women. J Appl Physiol 2014;116:961-969.

94. Stenroth L, Peltonen J, Cronin NJ, Sipilä S, Finni T. Age-related differences in Achilles tendon properties and triceps surae muscle architecture in vivo. J Appl Physiol 2012;113:1537-1544.

95. Fukuchi RK, Stefanyshyn DJ, Stirling L, Duarte M, Ferber R. Flexibility, muscle strength and running biomechanical adaptations in older runners. Clin Biomech 2014;29:304-310.

96. Stathokostas L, McDonald MW, Little R, Paterson DH. Flexibility of older adults aged 55–86 years and the influence of physical activity. J Aging Res 2013;Article ID 743843:1-8.

97. Nonaka H, Mita K, Watakabe M, et al. Age-related changes in the interactive mobility of the hip and knee joints: a geometrical analysis. Gait Posture 2002;15:236-243.

98. Chakravarty K, Webley M. Shoulder joint movement and its relationship to disability in the elderly. J Rheumatol 1993;20:1359-1361.

99. Lan C, Chen S-Y, Lai J-S. Changes of aerobic capacity, fat ratio and flexibility in older TCC practitioners: a five-year follow-up. Am J Chin Med 2008;36:1041-1050.

100. Mizuno T, Matsumoto M, Umemura Y. Decrements in stiffness are restored within 10 min. Int J Sports Med 2013;34:484-490.

101. Taniguchi K, Shinohara M, Nozaki S, Katayose M. Acute decrease in the stiffness of resting muscle belly due to static stretching. Scand J Med Sci Sports 2015;25:32-40.

102. Morse CI, Degens H, Seynnes OR, Maganaris CN, Jones DA. The acute effect of stretching on the passive stiffness of the human gastrocnemius muscle tendon unit. J Physiol 2008;586:97-106.

103. Mizuno T, Matsumoto M, Umemura Y. Viscoelasticity of the muscle–tendon unit is returned more rapidly than range of motion after stretching. Scand J Med Sci Sports 2013;23:23-30.

104. Matsuo S, Suzuki S, Iwata M, et al. Acute effects of different stretching durations on passive torque, mobility, and isometric muscle force. J Strength Cond Res 2013;27:3367-3376.

105. Sobolewski, EJ, Ryan, ED, Thompson, BJ. The influence of maximum range of motion and stiffness on the viscoelastic stretch response. Muscle Nerve 2013;48:571-577.

106. Magnusson SP, Aagaard P, Nielson JJ. Passive energy return after repeated stretches of the hamstring muscle-tendon unit. Med Sci Sports Exerc 2000;32:1160-1164.

107. McNair P, Dombroski E, Hewson D, Stanley S. Stretching at the ankle joint: viscoelastic responses to holds and continuous passive motion. Med Sci Sports Exerc 2001;33:354-358.

108. Muir I, Chesworth B, Vandervoort A. Effect of a static calf-stretching exercise on the resistive torque during passive ankle dorsiflexion in healthy subjects. J Orthop Sports Phys Ther 1999;29:106-115.

109. Power K, Behm D, Cahill F, Carroll M, Young W. An acute bout of static stretching: effects on force and jumping performance. Med Sci Sports Exerc 2004;36:1389-1396.

110. Garrett W, Califf J, Bassett F. Histochemical correlates of hamstring injuries. Am J Sports Med 1984;12:98-103.

111. Johnson M, Polgar J, Weightman D, Appleton D. Data on the distribution of fibre types in thirty-six human muscles: an autopsy study. J Neurol Sci 1973;18:111-129.

112. Wilson T, Zafuta M, Zobitz M. A biomechanical analysis of matched bone-patellar tendon-bone and double-looped semitendinosus and gracilis tendon grafts. Am J Sports Med 1999;27:202-207.

113. Garrett W. Muscle strain injuries. Am J Sports Med 1996;24:S2-S8.

114. Small K, Mc Naughton L, Matthews M. A systematic review into the efficacy of static stretching as part of a warm-up for the prevention of exercise-related injury. Res Sports Med 2008;16:213-231.

115. Behm D, Bambury A, Cahill F, Power K. Effect of acute static stretching on force, balance, reaction time, and movement time. Med Sci Sports Exerc 2004;36:1397-1402.

116. Behm D, Button D, Butt J. Factors affecting force loss with prolonged stretching. Can J Appl Physiol 2001;26:262-272.

117. Cramer JT, Beck TW, Housh TJ, et al. Acute effects of static stretching on characteristics of the isokinetic angle–torque relationship, surface electromyography, and mechanomyography. J Sports Sci 2007;25:687-698.

118. Cramer JT, Housh TJ, Johnson GO, Miller JM, Coburn JW, Beck TW. Acute effects of static stretching on peak torque in women. J Strength cond Res 2004;18:236-241.

119. Cramer JT, Housh TJ, Weir JP, Johnson GO, Coburn JW, Beck TW. The acute effects of static stretching on peak torque, mean power output, electromyography, and mechanomyography. Eur J Appl Physiol 2005;93:530-539.

120. Evetovich TK, Nauman N, Conley DS, Todd JB. Effect of static stretching of the biceps brachii on torque, electromyography, and mechanomyography during concentric isokinetic muscle actions. J Strength Cond Res 2003;17:484-488.

121. Franco BL, Signorelli GR, Trajano GS, de Oliveira CG. Acute effects of different stretching exercises on muscular endurance. J Strength Cond Res 2008;22:1832-1837.

122. Herda T, Ryan E, Smith A, et al. Acute effects of passive stretching vs vibration on the neuromuscular function of the plantar flexors. Scand J Med Sci Sports 2009;19:703-713.

123. Herda TJ, Cramer JT, Ryan ED, McHugh MP, Stout JR. Acute effects of static versus dynamic stretching on isometric peak torque, electromyography, and mechanomyography of the biceps femoris muscle. J Strength Cond Res 2008;22:809-817.

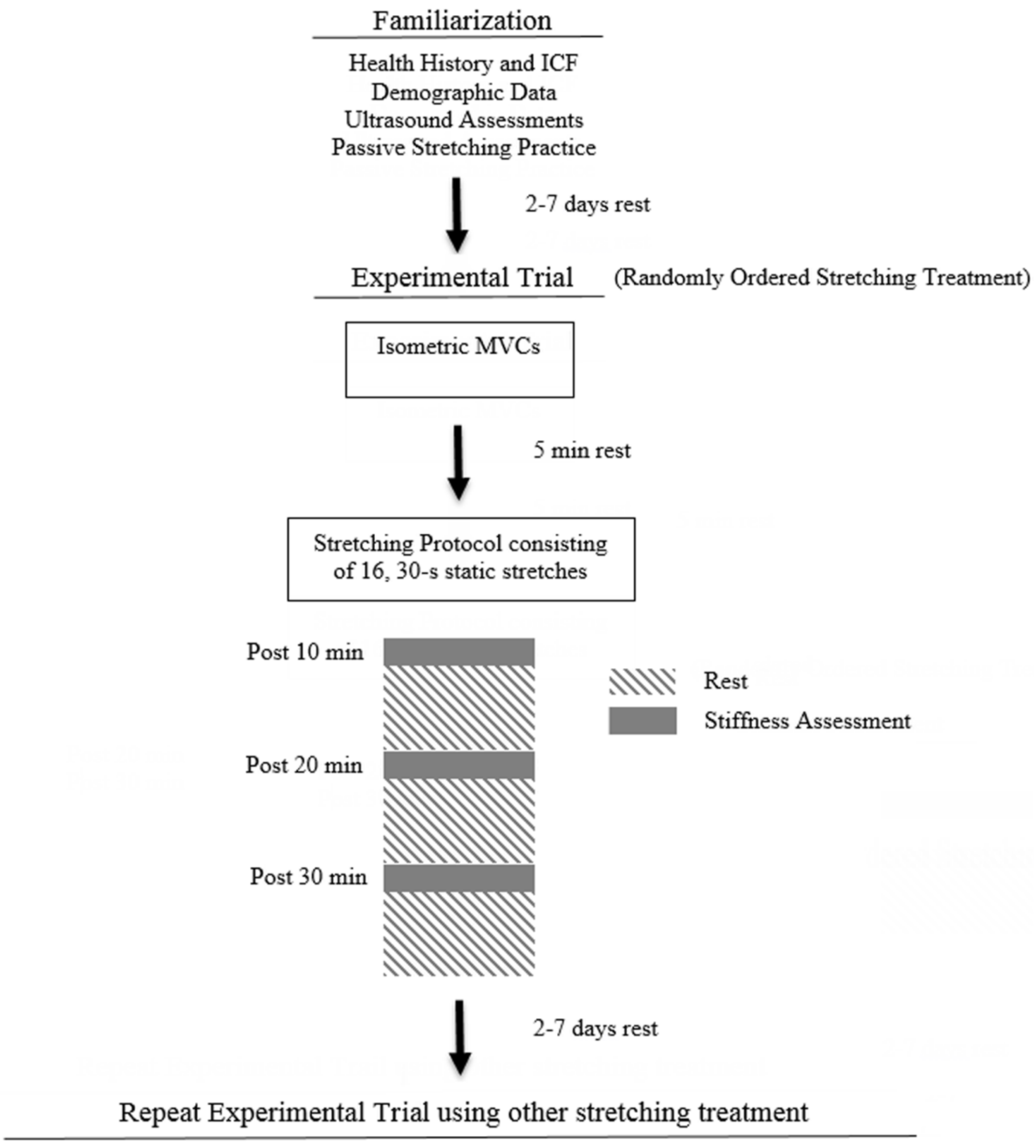
124. Nelson AG, Kokkonen J, Arnall D. Acute muscle stretching inhibits muscle strength endurance performance. J Strength Cond Res 2005;19:338-343.

125. Young W, Elliott S. Acute effects of static stretching, proprioceptive neuromuscular facilitation stretching, and maximum voluntary contractions on explosive force production and jumping performance. Res Q Exerc Sport 2001;72:273-279.

APPENDICES

APPENDIX A

RESEARCH DESIGN



APPENDIX B

INSTRUMENTED STRAIGHT-LEG RAISE TESTING SETUP

APPENDIX C

HEALTH HISTORY QUESTIONNAIRE

RECRUITMENT NO.____________

PRE-EXERCISE TESTING HEALTH & EXERCISE STATUS QUESTIONNAIRE

OKLAHOMA STATE UNIVERSITY
DEPARTMENT OF HEALTH AND HUMAN PERFORMANCE

Name ____ Date______________

Cell/Work Phone ______________________

E-mail address ______________________

Person to contact in case of emergency ____

Emergency Contact Phone ______________________

Gender ________ Age ______(yrs) Height ______(ft)______(in) Weight______(lbs)

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

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

Muscle Areas
( ) Upper Back & Neck
( ) Abdominal Regions
( ) Lower Back
( ) Buttocks
( ) Thighs
( ) Lower Leg
( ) Feet
( ) Other____________________

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

( ) High Blood Pressure
( ) Heart Disease or Dysfunction
( ) Peripheral Circulatory Disorder
( ) Lung Disease or Dysfunction
( ) Arthritis or Gout
( ) Edema
( ) Epilepsy
( ) Multiple Sclerosis
( ) High Blood Cholesterol or Triglyceride Levels
( ) Allergic reactions to rubbing alcohol

( ) Acute Infection
( ) Diabetes or Blood Sugar Level Abnormality
( ) Anemia
( ) Hernias
( ) Thyroid Dysfunction
( ) Pancreas Dysfunction
( ) Liver Dysfunction
( ) Kidney Dysfunction
( ) Phenylketonuria (PKU)
( ) Loss of Consciousness
( ) Visual Dysfunction

C. **FALL HISTORY** (✓Check the area that best describes the number of falls that you have experienced in the last 12 months)

( ) 0 falls
( ) 1 fall
( ) 2 or more falls

D. **PHYSICAL EXAMINATION HISTORY**

Approximate date of your last physical examination________________________________

Physical problems noted at that time____

Has a physician ever made any recommendations relative to limiting your level of physical exertion? __________YES ___________NO

If YES, what limitations were recommended?______________________________________

____

E. **CURRENT MEDICATION USAGE** (List the drug name and the condition being managed)

MEDICATION	CONDITION
____________________________	______________________________________
____________________________	______________________________________
____________________________	______________________________________

F. **EXERCISE STATUS**

Do you regularly engage in aerobic forms of exercise (i.e., jogging, cycling, walking, etc.)? **YES** **NO**

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

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

Do you regularly lift weights? **YES** **NO**

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

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

Do you regularly play recreational sports (i.e., basketball, racquetball, volleyball, etc.)? **YES** **NO**

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

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

PRE-EXERCISE TESTING HEALTH & EXERCISE STATUS QUESTIONNAIRE

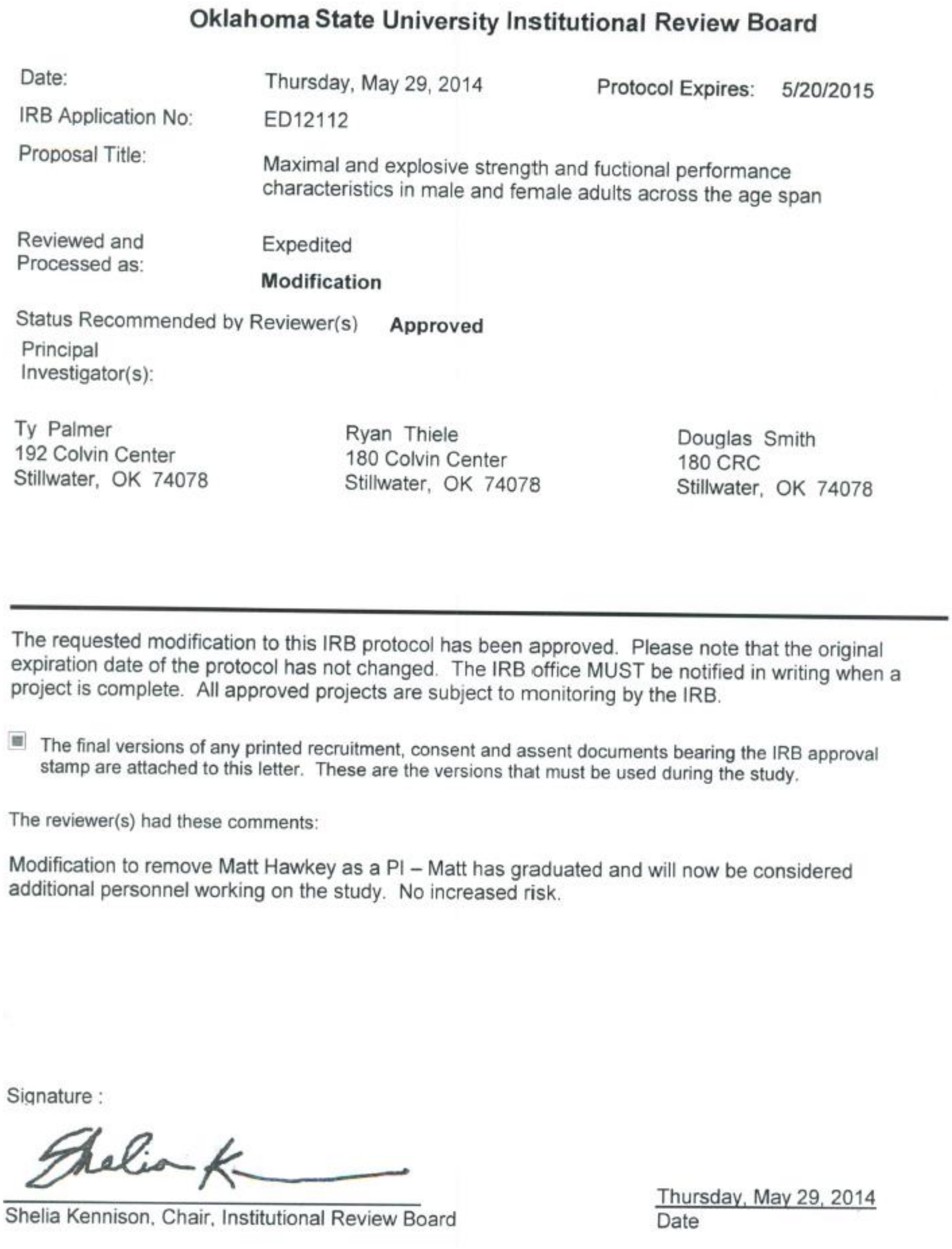
OKLAHOMA STATE UNIVERSITY
DEPARTMENT OF HEALTH AND HUMAN PERFORMANCE

Subject ID ____________________________ Date________________

EXCLUSION CRITERIA:

1. Participants have indicated they have current (within past 6 months) joint-muscle problems with their hips, legs, or knees that would prevent them from satisfactorily completing the testing.
2. If they have any specified condition or a physician has specified they are not able to complete the stretching treatments in which case they would not be allowed to complete the testing.

APPENDIX D: IRB APPROVAL



Oklahoma State University Institutional Review Board

Date: Thursday, May 29, 2014 **Protocol Expires:** 5/20/2015

IRB Application No: ED12112

Proposal Title: Maximal and explosive strength and fuctional performance characteristics in male and female adults across the age span

Reviewed and Processed as: Expedited

Modification

Status Recommended by Reviewer(s) **Approved**

Principal Investigator(s):

Ty Palmer
192 Colvin Center
Stillwater, OK 74078

Ryan Thiele
180 Colvin Center
Stillwater, OK 74078

Douglas Smith
180 CRC
Stillwater, OK 74078

The requested modification to this IRB protocol has been approved. Please note that the original expiration date of the protocol has not changed. The IRB office MUST be notified in writing when a project is complete. All approved projects are subject to monitoring by the IRB.

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

The reviewer(s) had these comments:

Modification to remove Matt Hawkey as a PI – Matt has graduated and will now be considered additional personnel working on the study. No increased risk.

Signature :

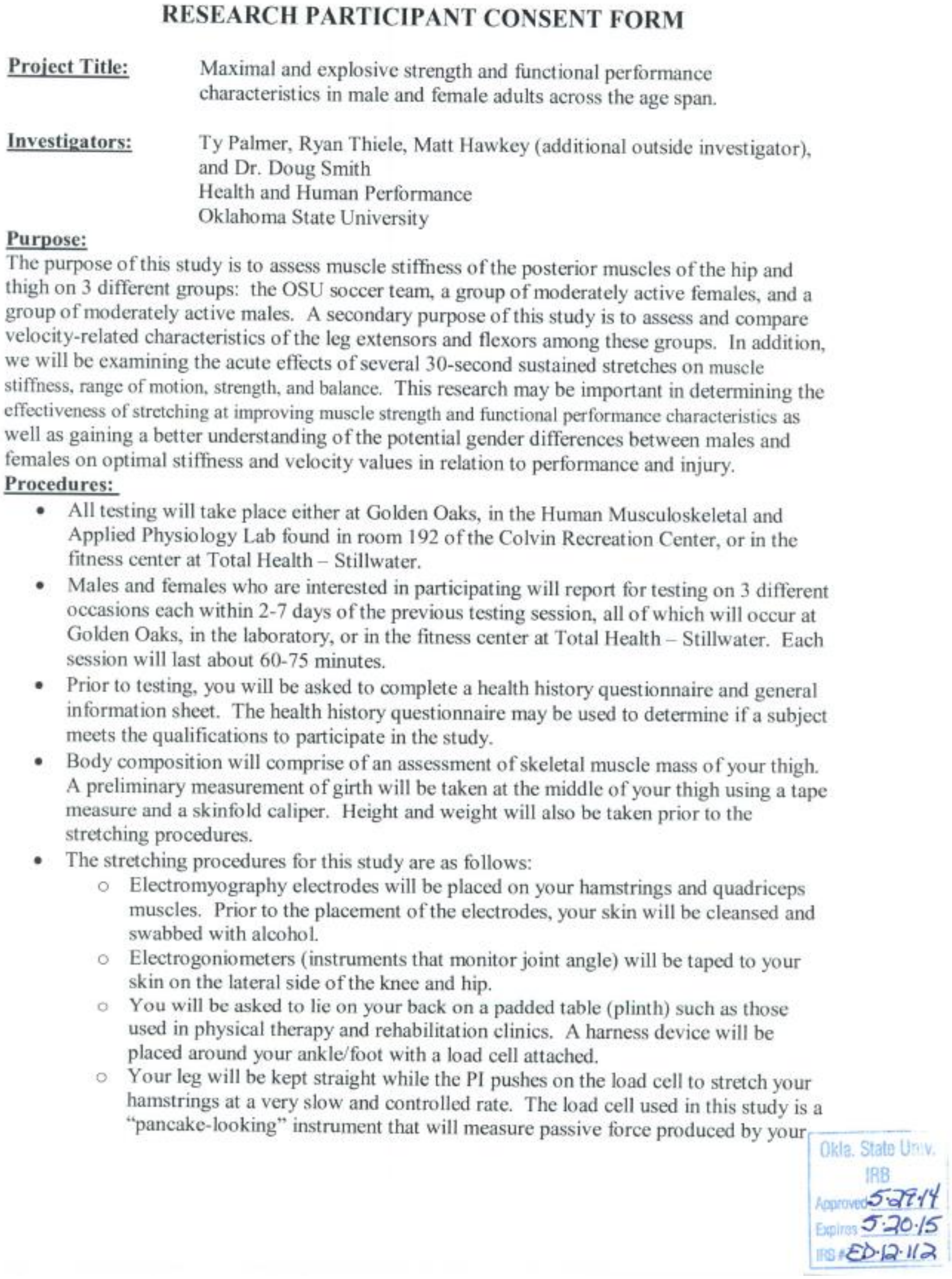
Shelia K

Shelia Kennison, Chair, Institutional Review Board

Thursday, May 29, 2014
Date

APPENDIX E

INFORMED CONSENT FORM



RESEARCH PARTICIPANT CONSENT FORM

Project Title: Maximal and explosive strength and functional performance characteristics in male and female adults across the age span.

Investigators: Ty Palmer, Ryan Thiele, Matt Hawkey (additional outside investigator), and Dr. Doug Smith
Health and Human Performance
Oklahoma State University

Purpose:

The purpose of this study is to assess muscle stiffness of the posterior muscles of the hip and thigh on 3 different groups: the OSU soccer team, a group of moderately active females, and a group of moderately active males. A secondary purpose of this study is to assess and compare velocity-related characteristics of the leg extensors and flexors among these groups. In addition, we will be examining the acute effects of several 30-second sustained stretches on muscle stiffness, range of motion, strength, and balance. This research may be important in determining the effectiveness of stretching at improving muscle strength and functional performance characteristics as well as gaining a better understanding of the potential gender differences between males and females on optimal stiffness and velocity values in relation to performance and injury.

Procedures:

- All testing will take place either at Golden Oaks, in the Human Musculoskeletal and Applied Physiology Lab found in room 192 of the Colvin Recreation Center, or in the fitness center at Total Health – Stillwater.
- Males and females who are interested in participating will report for testing on 3 different occasions each within 2-7 days of the previous testing session, all of which will occur at Golden Oaks, in the laboratory, or in the fitness center at Total Health – Stillwater. Each session will last about 60-75 minutes.
- Prior to testing, you will be asked to complete a health history questionnaire and general information sheet. The health history questionnaire may be used to determine if a subject meets the qualifications to participate in the study.
- Body composition will comprise of an assessment of skeletal muscle mass of your thigh. A preliminary measurement of girth will be taken at the middle of your thigh using a tape measure and a skinfold caliper. Height and weight will also be taken prior to the stretching procedures.
- The stretching procedures for this study are as follows:
  - Electromyography electrodes will be placed on your hamstrings and quadriceps muscles. Prior to the placement of the electrodes, your skin will be cleansed and swabbed with alcohol.
  - Electrogoniometers (instruments that monitor joint angle) will be taped to your skin on the lateral side of the knee and hip.
  - You will be asked to lie on your back on a padded table (plinth) such as those used in physical therapy and rehabilitation clinics. A harness device will be placed around your ankle/foot with a load cell attached.
  - Your leg will be kept straight while the PI pushes on the load cell to stretch your hamstrings at a very slow and controlled rate. The load cell used in this study is a "pancake-looking" instrument that will measure passive force produced by your

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    leg during the stretch. The stretch will be taken to your hip's maximum tolerated range of motion (ROM) and held for a count of 30 seconds before returning to a resting position. This entire movement will encompass a 30 – 45 second period. Approximately 16 stretches will be performed during each laboratory and/or community/fitness center visit and muscle stiffness, range of motion, strength, and balance will be assessed before and at 0, 10, 20, and 30 min after to examine the influence of stretching on these variables.
    - An isokinetic dynamometer will also be used to assess muscle stiffness. The procedures for this method will be similar to the manual stiffness assessment previously described. Unlike the manual assessment; however, the dynamometer will stretch your posterior leg muscles at a very slow rate that is controlled by a computer.
- In order to assess velocity, you will perform several knee extension and knee flexion movements as fast as possible against various resistances on an isokinetic dynamometer. You will be secured to the dynamometer chair with straps placed over your waist and thigh. For the knee extension assessments, you will be sitting in an upright position. For the knee flexion assessments, you will be lying in a prone position. All assessments will be conducted on the right leg. Velocity will be assessed by either the dynamometer or a goniometer. The goniometer will be taped to the lateral side of your knee.
- In addition, you will also complete two or three vertical jump, ultrasound, and balance tests during each session in order to determine the reliability of these assessments as well as their relationships among measures of muscle stiffness and velocity.
    - Balance will be assessed using a commercially designed balance test unit. For each assessment, you will stand on the platform of the balance unit with feet shoulder width apart and hands positioned on the hips. You will maintain a steady-upright posture by standing "as still as possible" throughout the duration of each assessment. Assessments will last between 20 and 30 seconds each, and will consist of both static and dynamic conditions. For the static condition, the balance unit platform will be locked in a horizontal, non-moving position. For the dynamic condition, the balance unit platform will be unlocked to allow for movement to occur about the platform in all directions (i.e. 360° range of motion).
    - Muscle architecture of the anterior and posterior muscles of your right thigh (i.e. hamstrings and quadriceps) will be assessed using a diagnostic ultrasound device. For each assessment, you will lie in either a supine (i.e. for assessment of the quadriceps) or prone (i.e. for assessment of the hamstrings) position on a cushioned plinth. Water-soluble gel will be placed on the surface of your skin at the site of each muscle prior to assessment in order to avoid compression or depression of the muscle. During assessment, a probe connected to the ultrasound device will be placed on your skin at the site of each muscle to view and capture images in both transverse and longitudinal planes.

Risks of Participation:

Risks associated with the study are minimal and with no greater physical demands than the current training regimen and/or fitness classes that you take part in during the semester. As a conditioned participant, it is unlikely that you will experience muscle soreness resulting from the trials. In case of injury or illness resulting from this study, emergency medical treatment will be available; researchers are CPR- 1st corresponder certified along with the access to 911 will be available. No funds have been set aside by Oklahoma State University to compensate you in the event of illness or injury.

Benefits:

You will be helping to advance the understanding of testing procedures used to commonly assess muscle stiffness in the exercise physiology field. You may also gain an understanding of these testing results and procedures for your own benefit.

Confidentiality:

You will be assigned an ID number. We are only interested in reporting data reflecting muscle stiffness of the group as a whole (i.e., moderately active male group). No individual data will be shared. Research records will be stored securely for 3 years in our advisor's office and only researchers and individuals responsible for research oversight will have access to the records. It is possible that the consent process and data collection will be observed by research oversight staff responsible for safeguarding the rights and wellbeing of people who participate in research. Medical clearance forms will only contain the subjects ID number and consent forms will contain names but no ID numbers. These forms will be kept in a locked file cabinet in our advisor's office which only the researchers will have access to. The signed consent forms will be kept in our advisor's office for 3 years after the research is complete per federal guidelines.

Compensation:

No additional incentive is being offered; however results of the study can be assessed by all participants following analysis.

Contacts:

If you need any additional information concerning the study contact Doug Smith 197 CRC, Oklahoma State University, Stillwater, OK 74078, 405-744-5500, doug.smith@okstate.edu, Ty Palmer, 192 CRC, Oklahoma State University, Stillwater, OK 74078, 405-744-9373, tybp@okstate.edu, or Ryan Thiele, 192 CRC, Oklahoma State University, Stillwater, OK 74078, ryan.thiele@okstate.edu.

If you should have questions about your rights as a research volunteer, you may contact Dr. Shelia Kennison, IRB Chair, 219 Cordell North, Oklahoma State University, Stillwater, OK 74078, 405-744-3377or irb@okstate.edu.

Participant Rights:

Participation in this research is voluntary and there is no penalty for refusal to participate. You are free to withdraw from the study at any time and revoke your consent to participate at any time without penalty

Signatures:

I have read and fully understand the consent form. I sign it freely and voluntarily. A copy of this form has been given to me.

Signature of Participant ____________ Date ____________

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

Signature of Researcher ____________ Date ____________

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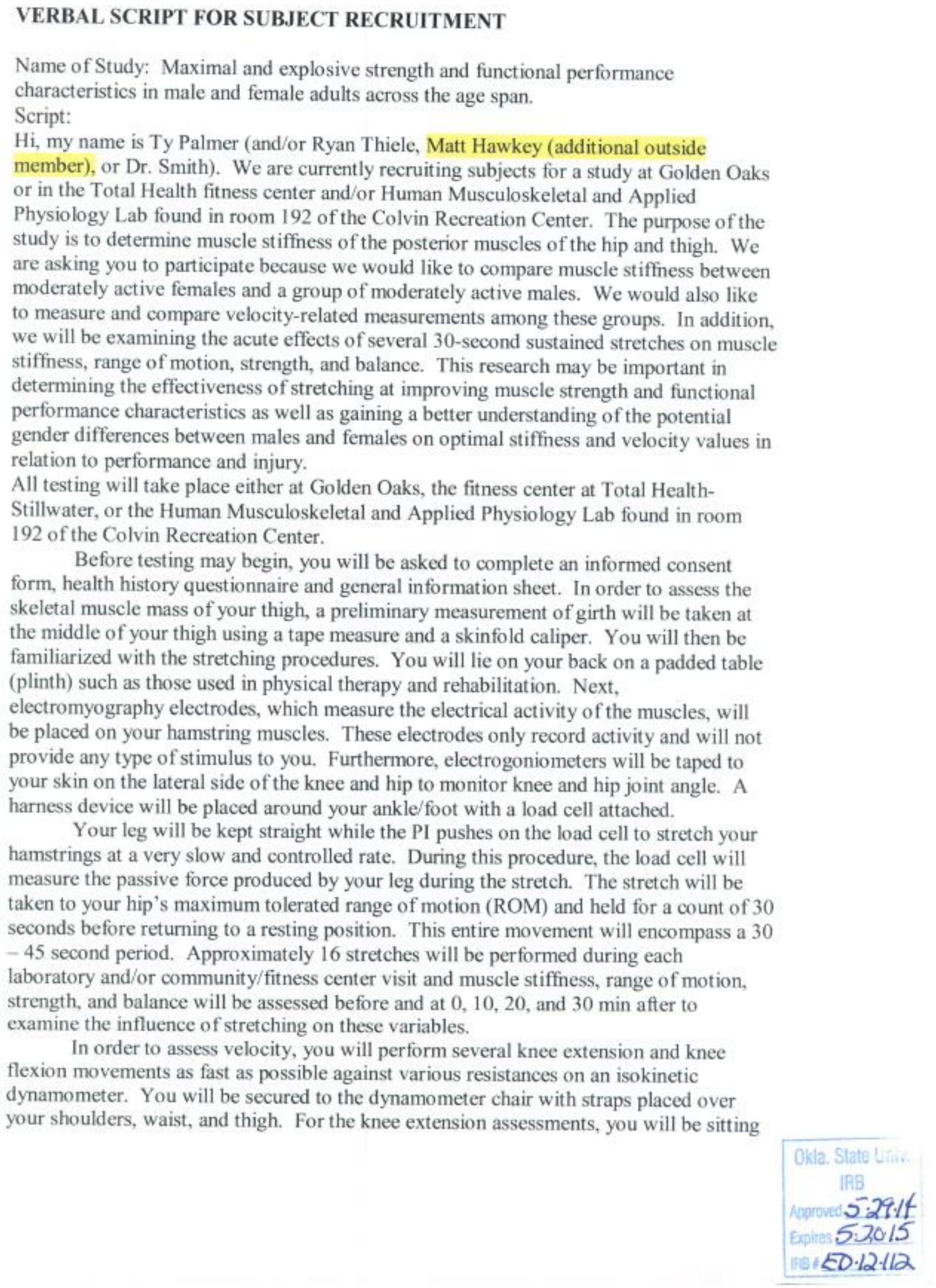
APPENDIX F

RECRUITMENT SCRIPT



VERBAL SCRIPT FOR SUBJECT RECRUITMENT

Name of Study: Maximal and explosive strength and functional performance characteristics in male and female adults across the age span.

Script:

Hi, my name is Ty Palmer (and/or Ryan Thiele, Matt Hawkey (additional outside member), or Dr. Smith). We are currently recruiting subjects for a study at Golden Oaks or in the Total Health fitness center and/or Human Musculoskeletal and Applied Physiology Lab found in room 192 of the Colvin Recreation Center. The purpose of the study is to determine muscle stiffness of the posterior muscles of the hip and thigh. We are asking you to participate because we would like to compare muscle stiffness between moderately active females and a group of moderately active males. We would also like to measure and compare velocity-related measurements among these groups. In addition, we will be examining the acute effects of several 30-second sustained stretches on muscle stiffness, range of motion, strength, and balance. This research may be important in determining the effectiveness of stretching at improving muscle strength and functional performance characteristics as well as gaining a better understanding of the potential gender differences between males and females on optimal stiffness and velocity values in relation to performance and injury.

All testing will take place either at Golden Oaks, the fitness center at Total Health-Stillwater, or the Human Musculoskeletal and Applied Physiology Lab found in room 192 of the Colvin Recreation Center.

Before testing may begin, you will be asked to complete an informed consent form, health history questionnaire and general information sheet. In order to assess the skeletal muscle mass of your thigh, a preliminary measurement of girth will be taken at the middle of your thigh using a tape measure and a skinfold caliper. You will then be familiarized with the stretching procedures. You will lie on your back on a padded table (plinth) such as those used in physical therapy and rehabilitation. Next, electromyography electrodes, which measure the electrical activity of the muscles, will be placed on your hamstring muscles. These electrodes only record activity and will not provide any type of stimulus to you. Furthermore, electrogoniometers will be taped to your skin on the lateral side of the knee and hip to monitor knee and hip joint angle. A harness device will be placed around your ankle/foot with a load cell attached.

Your leg will be kept straight while the PI pushes on the load cell to stretch your hamstrings at a very slow and controlled rate. During this procedure, the load cell will measure the passive force produced by your leg during the stretch. The stretch will be taken to your hip's maximum tolerated range of motion (ROM) and held for a count of 30 seconds before returning to a resting position. This entire movement will encompass a 30 – 45 second period. Approximately 16 stretches will be performed during each laboratory and/or community/fitness center visit and muscle stiffness, range of motion, strength, and balance will be assessed before and at 0, 10, 20, and 30 min after to examine the influence of stretching on these variables.

In order to assess velocity, you will perform several knee extension and knee flexion movements as fast as possible against various resistances on an isokinetic dynamometer. You will be secured to the dynamometer chair with straps placed over your shoulders, waist, and thigh. For the knee extension assessments, you will be sitting

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in an upright position. For the knee flexion assessments, you will be lying in a prone position. All assessments will be conducted on the right leg. Velocity will be assessed by either the dynamometer or a goniometer. The goniometer will be taped to the lateral side of your knee.

In addition, you will also complete two or three vertical jump, ultrasound, and balance tests during each session in order to determine the reliability of these assessments as well as their relationships among measures of muscle stiffness and velocity.

Extra credit will not be offered or advocated by the investigators for any subject who decides to participate in this study, nor will any other incentives for participation be offered.

All risks and benefits of participation in this study and your rights as a research subject will be described in the consent form provided at the first session before testing begins. You will be required to sign this in order to show that you understand all that is contained in this form. To reiterate, as a participant, you will be contributing to the understanding of muscle stiffness values for the posterior muscles of the hip and thigh. If you decide you do not want to participate at any time, you may drop out with no undue consequence. If you are interested and would like to set up times for participation or have any questions, you may contact Ty Palmer at (405) 744-9373, or at tybp@okstate.edu or Ryan Thiele at (405) 744-9373 or at ryan.thiele@osktate.edu. You may also choose to contact our faculty mentor/advisor, Dr. Doug Smith at (405) 744-9373, or at doug.smith@okstate.edu.

VITA

Ty B. Palmer

Candidate for the Degree of Doctor of Philosophy

Dissertation: AGE-RELATED TIME COURSE EFFECTS OF CONSTANT-ANGLE AND CONSTANT-TORQUE STRETCHING ON THE PASSIVE RESISTIVE PROPERTIES OF THE POSTERIOR HIP AND THIGH MUSCLES IN YOUNG AND OLD MEN

Major Field: Health, Leisure, & Human Performance

Biographical:

I was born and raised in Kerrville, TX. I enjoy lifting weights and watching movies as well as spending time with my finance. I look forward to what my future in higher education will bring.

Education:

Completed the requirements for the Doctor of Philosophy in Health & Human Performance at Oklahoma State University, Stillwater, Oklahoma in May 2015.

Completed the requirements for the Master of Education in Exercise Science at Texas State University, San Marcos, Texas in May 2011.

Completed the requirements for the Bachelor of Arts in Kinesiology at Texas Lutheran University, Seguin, Texas in May 2009.

Experience:
Graduate Assistant, Oklahoma State University
August 2011-May 2015
Graduate Assistant, Texas State University
August 2009-May 2011

Professional Memberships:
National Strength and Conditioning Association (2009 – Present)
American College of Sports Medicine (2011 – Present)