A GENDER COMPARISON OF REACTIVE KNEE STIFFNESS REGULATION STRATEGIES UNDER COGNITIVE LOADS

by

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ABSTRACT

<u>Context</u>: Unintentional injuries can occur due to errors in coordination and failure to anticipate or react to sudden joint forces. Neuromuscular control strategies facilitate joint stabilization by regulating knee stiffness, referred to as dynamic restraint; however, a concurrent cognitive load may disrupt or alter reflexes and the execution of routine motor programs. Furthermore, it is suggested that gender differences exist in cognitive faculties such as visual spatial and language skills, as well as lower extremity muscle activation strategies. **<u>Purpose</u>:** The purpose of this study was to assess whether preparatory and reactive knee stiffening strategies are affected differently in males and females exposed to gender biased cognitive loads. **<u>Participants</u>:** Twenty males (20.450±1.572 yrs; 88.153±17.866 kg; 179.395±6.235 cm) and 20 females (20.050±1.234 yrs; 58.768±6.970 kg; 163.887±6.392 cm) healthy volunteers with no current injury or previous surgery to their dominant lower extremity participated in the study. **<u>Interventions</u>:** The independent variables were the type of cognitive tasks administered, which included the Benton Judgment of Line Orientation (JOLO), Symbol Digit Modalities Test (SDMT), Serial 7's, and a control condition. A custom Stiffness and Proprioception Assessment Device (SPAD) was used to measure reactive knee stiffness. Participants were seated in the SPAD with the testing leg in 30° of knee flexion. They were then instructed to perform one of the three cognitive tasks or the control condition. During this period (approximately 10 seconds) they were instructed to react to a randomly timed knee flexion perturbation (excursion = 40°, velocity = 100°/sec, acceleration = 1000°/sec^2). Reactive stiffness was measured from the starting position of 30° knee flexion to the end of the 40° perturbation. Surface electromyography (EMG) was used to measure muscle activation at the medial and lateral quadriceps and hamstrings muscles. Data was processed using customized LabVIEW software (National Instruments, Austin, Tx). An analysis of variance with repeated measures was used to analyze the differences in reactive knee stiffness and muscle activation strategies between the cognitive tasks and a control condition. **<u>Main Outcome Measures</u>:** Stiffness, normalized to body weight, was calculated as Δ torque (Nm) / Δ position (degrees) and neuromuscular control was assessed through the amplitude and timing of quadriceps and hamstring EMG data. **<u>Results</u>:** Reactive knee stiffness values were significantly less during the cognitive tasks compared to the control condition (JOLO = 0.034 ± 0.014 Nm/deg/kg, SDMT = 0.037 ± 0.013 Nm/deg/kg, Serial 7's = 0.037 ± 0.012 Nm/deg/kg, control = 0.048 ± 0.011 Nm/deg/kg). Females had greater overall stiffness than males. The quadriceps muscles had faster and greater activation than the hamstring muscles; however, no gender differences were observed. No overall differences were found among the cognitive loading tasks. **<u>Conclusion</u>:** Optimum muscle activation and stiffness strategies are necessary to properly stabilize joints during movements. Cognitive tasks may decrease the ability of healthy individuals to reactively stiffen their knee joint in response to sudden external perturbations. These data support the significant role neurocognitive processes may have on unintentional musculoskeletal injury because cognitive loading appears to interfere with the normal force attenuating properties of eccentric muscle contractions. This also suggests caution should be used when implementing cognitive

loading as a modality to increase the level of difficulty during prevention and rehabilitation programs as it may expose individuals to greater risk of unintentional injury.

CHAPTER 1

INTRODUCTION

Unintentional injuries to the anterior cruciate ligament (ACL) are common during physical activity (Griffin, et al., 2000; Griffin, et al., 2006) and females have a higher incidence than males. The ACL primarily resists anterior translation of the tibia, in relation to the femur. More than 70% of ACL injuries occur through non-contact mechanisms while decelerating, pivoting, or landing where ground-reaction forces can exceed five times a person's body weight (McNair & Prapavessis, 1999; Swanik, et al., 2007). Disruption of the ACL can result in excessive anterior tibial translation and diminished joint sensation (Demont, et al., 1999; Fonseca, et al., 2004; Johansson, et al., 1991; Rack & Westbury, 1974; Skinner, et al., 1984; Swanik, et al., 1997). This can reduce a joints mechanical stability, alter neuromuscular control, and impair dynamic restraint by often causing the knee to become functionally unstable (Johansson, et al., 1991; Rack & Westbury, 1974; Swanik, et al., 1997). Thus, previous studies on unintentional, non-contact ACL knee injury have focused on the biomechanical risk factors (Bjordal, et al., 1997; Griffin, et al., 2000; Swanik, et al., 2004); however, until recently, the cognitive factors mediating neuromuscular control and their potential interaction with known gender differences in the brain have been overlooked. Additional research focusing on these variables may partially explain the noncontact nature of these injuries and increased risk among females.

Joint stability relies on static and dynamic restraints as the knee is subjected to various loads during functional movement. However, the static restraints (ligaments, menisci, bones, capsules) alone offer inadequate stability to the knee during physiologic loading (Colby, et al., 2000). Therefore, dynamic restraints (muscles) act as the primary stabilizers of the knee during functional tasks. Muscle stiffness is defined as the degree to which a muscle resists changes in length (Swanik, et al., 1997), and the level of muscle activation during movement largely determines optimum joint stiffness. Because stiff muscles resist stretching episodes more effectively, they are able to provide more effective dynamic restraint by opposing excessive joint displacement (Swanik, et al., 1997). During functional tasks, excessive energy may be rapidly absorbed in muscles and tendons, thus reducing transmission of deleteriously high forces into ligaments such as the ACL (Arampatzis, et al., 2001; Wilson, et al., 1991). For this reason, the capacity to optimally regulate joint stiffness through preparatory and reactive muscle contractions is a critical component of joint stabilization.

Neuromuscular control is defined as the transformation of neural information or motor commands into physical energy via muscle activation (Swanik, et al., 1997). It is one of the critical factors that affect knee joint stability. During high speed and load conditions, it is an important determinant guiding motor behavior for performance and prevention of injuries, such as ACL injury**.** Both feed-forward and feedback motor control strategies govern the instantaneous, and continuously changing level of dynamic restraint, which must protect capsuloligamentous structures from excessive joint loads. Feed-forward control is responsible for planning and/or preprogramming muscle(s) activation levels in anticipation of joint loading, and is based on learned experiences from past. This preparatory muscle activation increases joint stiffness and has been shown to promote knee stability (Bryant, et al., 2008; Demont, et al., 1999; McNair & Marshall, 1994; Swanik, et al., 2004). Feedback control continuously regulates motor control through reflex pathways (Swanik, et al., 1997) . An imbalance or delay in neuromuscular activation can lead to improper limb position and may place an increased stress or strain on the knee, resulting in ACL injury.

Both feed-forward and feedback neuromuscular strategies are controlled from within the central nervous system, and there is growing evidence that neurocognitive factors may have a critical role in determining injury risk and the subsequent recovery during rehabilitation (Johansson, 1991; Nideffer, 1983; Swanik, et al., 2007; Swanik, et al., 1997; Taylor & Thoroughman, 2008). Recent studies show that neurocognitive characteristics, such as reaction time, processing speed, and visual spatial skills may have a role in non-contact injuries, by affecting both movement planning and reaction to unanticipated events (Beauchet, et al., 2005; Blackburn, et al., 2004; Ebersbach, et al., 1995; Getchell & Whitall, 2003; Hewett, et al., 2004; Swanik, et al., 2007). It has been demonstrated that increasing a person's cognitive load (increased amount and speed of neural processing) can narrow one's visual field, slow reaction time, and alter muscle activity resulting in poor coordination (Dault, et al., 2001; Desimone & Duncan, 1995; Ebersbach, et al., 1995; Swanik, et al., 2007; Taimela, 1990). Therefore, the presence and the type of cognitive loading interferes with an individual's ability to adequately conduct motor planning and then also react appropriately to unanticipated events. This momentary lapse in cognitive performance can disrupt or alter what would be routine motor programs, or reflexive muscle activity. This scenario may lead to errors in judgment or coordination where the individual fails to properly negotiate the timing and amplitude of muscle contractions with impending joint loads, which could diminish dynamic restraint capabilities and expose the knee to injury (Swanik, et al., 2007).

Because gender differences have also been identified in cognitive performance, muscle activation strategies and knee stiffness, research should be conducted to explore a potential interaction related to the high incidence of unintentional, noncontact ACL injuries, especially in females. Males tend to excel in cognitive performance tests related to visual and spatial tasks, while females demonstrate advantages in verbal or language tasks (Adam, et al., 1999; Jones & Gallo, 2002; Vaquero, et al., 2004). Females also tend to use the quadriceps muscle more than males, which may increase the anterior tibiofemoral shear load that predisposes an ACL to injury. Previous studies also suggest that stiffness regulation has a pivotal role in describing the difference in ACL injury rates between genders (Blackburn, et al., 2004; Cammarata & Dhaher, 2008; Granata, et al., 2002). Several studies have suggested that females have greater knee joint laxity and less joint stiffness than males, due to hormonal influences (Cammarata & Dhaher, 2008; Deie, et al., 2002; Rau, et al., 2005; Shultz, et al., 2005). However, earlier stiffness studies mainly relied on indirect measurements, sub-physiologic loads, or non-normalized data to account for gender differences in body size. Studies demonstrating gender differences on the effect of cognitive loads on ACL injury and knee stability are also quite limited (Henry & Kaeding, 2001). These joint stiffness, neuromuscular, and neurocognitive characteristics appear to be sexually dimorphic; but very little is known with regard their combined influence on knee stability.

The purpose of this study was to determine knee stiffness in both males and females while performing a cognitive task. This study is the first to simultaneously measure the neuromuscular recruitment and stiffness regulation strategies of participants while they volitionally stiffen their knee joints and respond to unanticipated joint perturbations during different cognitive loading conditions. In this study, we tested the hypotheses that (1) females have lower scores during the visual spatial task than males while males have lower scores during the language task than females, (2) females have faster muscle activation strategies and less reactive knee stiffness values than males, (3a) males and females have slower muscle activation strategies and reactive knee stiffness while performing different cognitive loading tasks, and (3b) females exhibit greater muscle activation changes and knee stiffness reduction during visual-spatial cognitive loads while males exhibit greater muscle activation changes and knee stiffness reduction during verbal cognitive loads.

CHAPTER 2

METHODS

Experimental Design

This is a repeated measures posttest only group design consisting of 20 male and 20 female volunteers. The number of participants was determined through an a priori power analysis using G*Power v3.0.1 (Heinrich-Heine-Universität, Düsseldorf) with power parameters set as follows: $\alpha = 0.05$, $1 - \beta = 0.80$, and effect size was determined using the preliminary means and standard deviations (Faul, et al., 2009). The independent variables are gender (male or female) and the type of cognitive tasks administered, which included the Benton Judgment of Line Orientation (JOLO), Symbol Digit Modalities Test (SDMT), Serial 7's, and a control condition. The dependent variables are measurements of knee stiffness and muscle activity (amplitude and timing) quantified with electromyographic recordings during joint perturbation.

Participants

Twenty male and twenty female volunteers within the 18-25 years (Males: 20.450±1.572 yrs, Females: 20.050±1.234 yrs) age range were recruited from the University of Delaware population. Before testing, each participant completed the informed consent process (UDIRB #HS 09-699) (Appendix A) approved by the University of Delaware Internal Review Board. Participants were asked to complete the Physical Activity Readiness Questionnaire (PAR-Q) (Appendix B) to determine potential eligibility. If the participant answered, "Yes" to questions pertaining to pains in the heart or chest, faintness or dizziness, bone or joint problems, or low back problems, he/she was not included in the study. Female participants were included if they were within Day 0 to 12 of their menstrual cycle, to minimize the potential influence of hormone fluctuation on ligament laxity. The menstrual cycle was determined through self-reporting, by having the female participants answer the question: "When was your last menstruation?" Participants were tested on their dominant leg, which is operationally defined as the leg that would be used to single-leg jump for distance (Croce, et al., 2004; Russell, et al., 2007).

Participants were excluded from the study if they have had (1) any fractures to test leg within the last 1 year, (2) other knee injuries requiring surgery, (3) any current bone, muscular, joint injuries to the hip, knee, and ankle, and (4) any cardiovascular, metabolic or neurological abnormalities that limits moderate physical activity.

Instrumentation

Stiffness and Proprioception Assessment Device (SPAD)

Testing was performed using the custom-built stiffness and proprioception assessment device (SPAD) (Figure 1). The SPAD is a brushless servomotor (B-404-B-B4, Danaher/Kollmorgen, Radford, Va.) that is fitted into a gearbox (UT018-050, 50:1, Danaher Motion, Radford, Va.) that is connected to an amplifier/controller (Xenus driver XSL-12-36-R, Copley Controls, Canton, Ma.). The amplifier (input: 230 VAC, 3PH, output: 18 FLA, 50/60 Hz) is mounted ~4-ft above the ground and connected to the motor with a 12-foot long feedback cable (Model # CEF-RO- 006-900, Pacific Scientific, Rockford, IL) and also connected to a personal computer through a Kvasar CAN cable. The controller receives a three-phase, 240-volt, 30-amp enclosed I-T-E switch power supply through a power cable (Model # CEP-A6-006-904, Pacific Scientific, Rockford, IL). The mated servomotor and gearbox are mounted in a cast aluminum pedestal that is offset from the subject's chair. An adaptor arm and torque reaction sensor (Model # T5400, Futek Advanced Sensor Technology, Irvine, CA) with a 565 N capacity and 1.43 X 10^5 ft-lb/rad torsional stiffness is coupled to the gearbox. Signals from the torque reaction sensor pass through a conditioner (Model # D502, Futek Advanced Sensor Technology, Irvine, CA) at 60 Hz and have a 0 to 10 Vdc analog output range. The signal conditioner digitally displays torque values and also sends an analog torque signal through a BNC box so that is can be recorded and displayed in LabVIEW software. (National Instruments, Austin, Tx)

For safety purposes, internal motor settings cannot exceed preset speeds and there are three emergency stop switches that can disable the motor during testing. The operator and test participant each hold an emergency stop button that when depressed, it will disable the motor. Also, if the adaptor arm travels beyond the test parameter range of motion, a proximity sensor (#S4602896, Turck Inc. USA, Minneapolis, MN) disables the motor. When the motor is disabled, the operator must re-start the power supply to continue tests. The LabVIEW motor control software also has "soft limits" which disables the motor amplifier if motion exceeds individualized motion limits. The SPAD is also fitted mechanical stops to limit motion through an adjustable range and brass screws in the adapter arm flange connected to the gear box, which will fail under excessive torque, disengaging the drive shaft from the adapter arm. The SPAD device is operated using a personal computer with a customized LabVIEW virtual instrument and motor control software program (Figure 2).

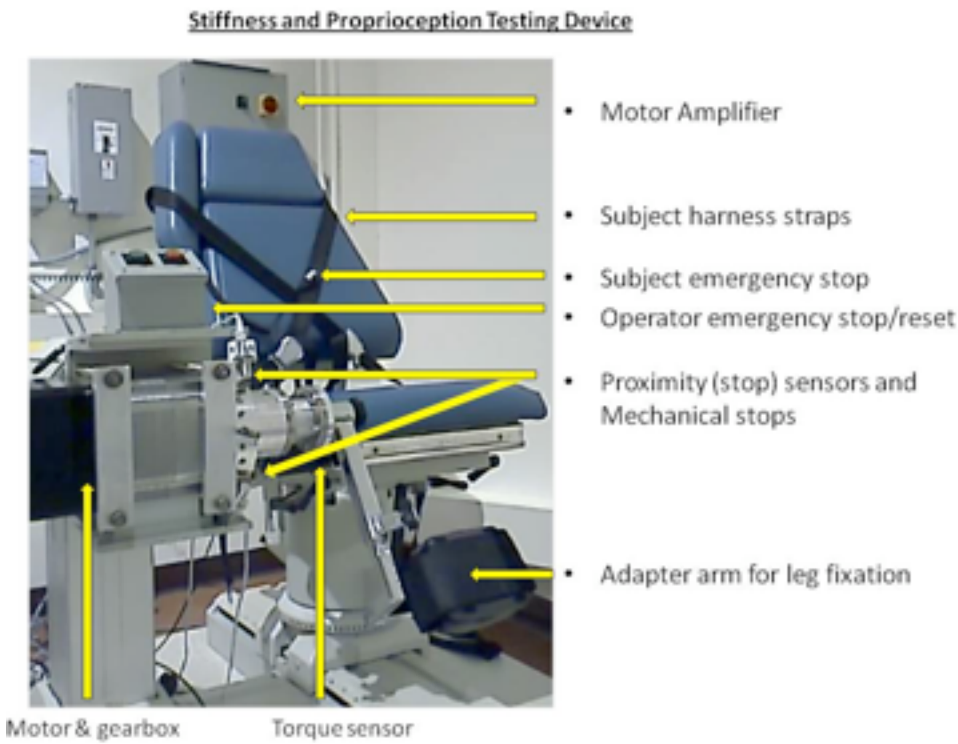

Figure 1. Stiffness and Proprioception Assessment Device (SPAD)

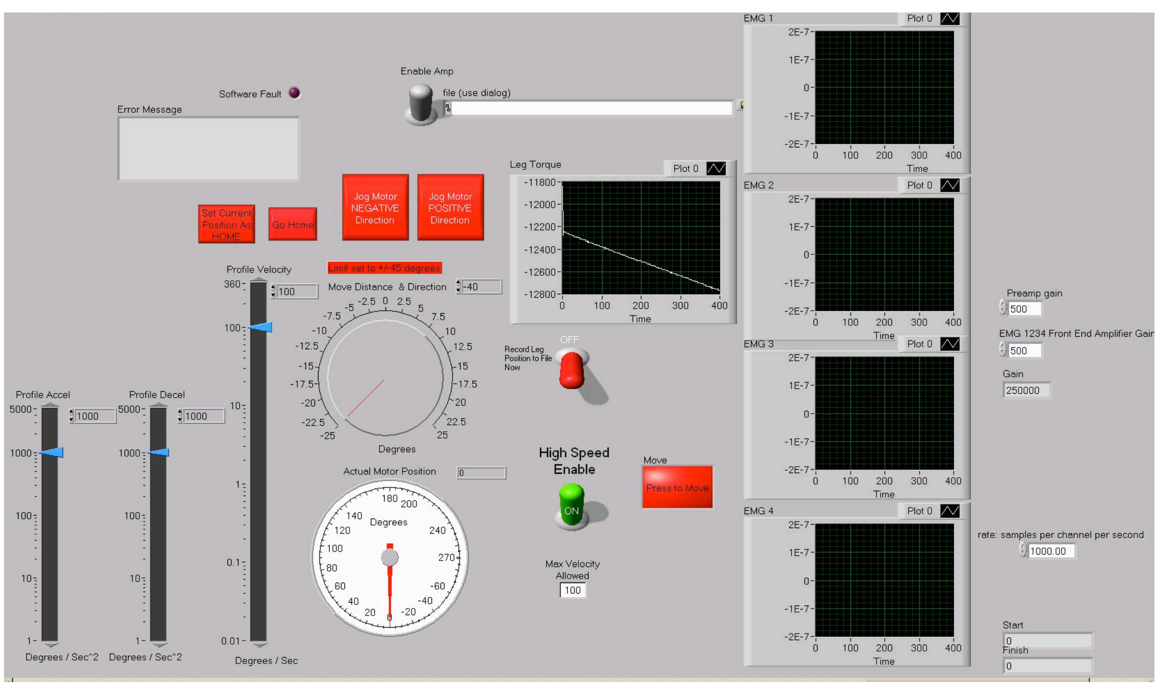

Figure 2. The custom LabVIEW virtual instrument and motor control software program.

Electromyography (EMG)

Surface electromyography (EMG) was collected from the vastus medialis, vastus lateralis, medial hamstrings, and lateral hamstrings to determine stiffness regulation strategies by analyzing the amplitude and timing of the muscular contractions. MBS self-adhesive Ag/AgCl bipolar surface electrodes (Multi Bio Sensors Inc., El Paso, Texas) were used to collect EMG data, and a telemetered EMG unit (Konigsberg Instruments, Inc., Pasadena, CA) was used to record EMG with a real-time visual display. Electrode placement was identified by bony landmarks and through palpation of the mid-belly of the contractile component of the muscle during an isometric contraction (Basmajian & DeLuca, 1985). The reference electrode was placed on the patella. Each electrode is 10mm in diameter and was placed 25mm apart. The electrode placement sites were shaven, abraded, and cleansed with an alcohol swab (70% ethanol solution) to decrease the impedance from the skin. The signal was converted from analog to digital data with an A/D card, and then passed to a computer where the raw EMG data were sampled at 2,400 Hz and further analyzed with LABVIEW software (National Instruments, Austin, Tx). The EMG signal was filtered at a band-pass of 20-400Hz. The EMG was then rectified and low-pass filtered at 5Hz to create a linear envelope. EMG was normalized to the maximum voluntary isometric contraction (MVICs) of the quadriceps and hamstrings (Basmajian & DeLuca, 1985; Huxel, et al., 2008).

Cognitive Loads

Participants performed 3 different cognitive tasks during the stiffness testing: the "Judgment of Line Orientation" test (JOLO), "Symbol Digit Modalities Test" (SDMT), and Serial 7's. Participants performed the JOLO and SDMT prior to the control condition to obtain raw scores and again during the stiffness testing. In a "Judgment of Line Orientation" task, participants view two line segments at various angles and must match the segments to an array of numbered lines (Figure 3). This task is generally more difficult for females (Caparelli-Daquer, et al., 2009; Rahman & Wilson, 2003). The "Symbol Digit Modalities Test" is considered more difficult for males (Jorm, et al., 2004; Sheridan, et al., 2006). For this test participants are given a key and asked to match symbols with numbers. On the bottom of the page are a series of symbols without the number, and participants must say, in order, what number goes with each symbol (Figure 3). During the Serial 7's task, the participant counted down by 7's from 100. After each trial, the subject began counting down from the last number stated from the previous trial. This task is generally considered gender-neutral (Líndal & Stefansson, 1993).

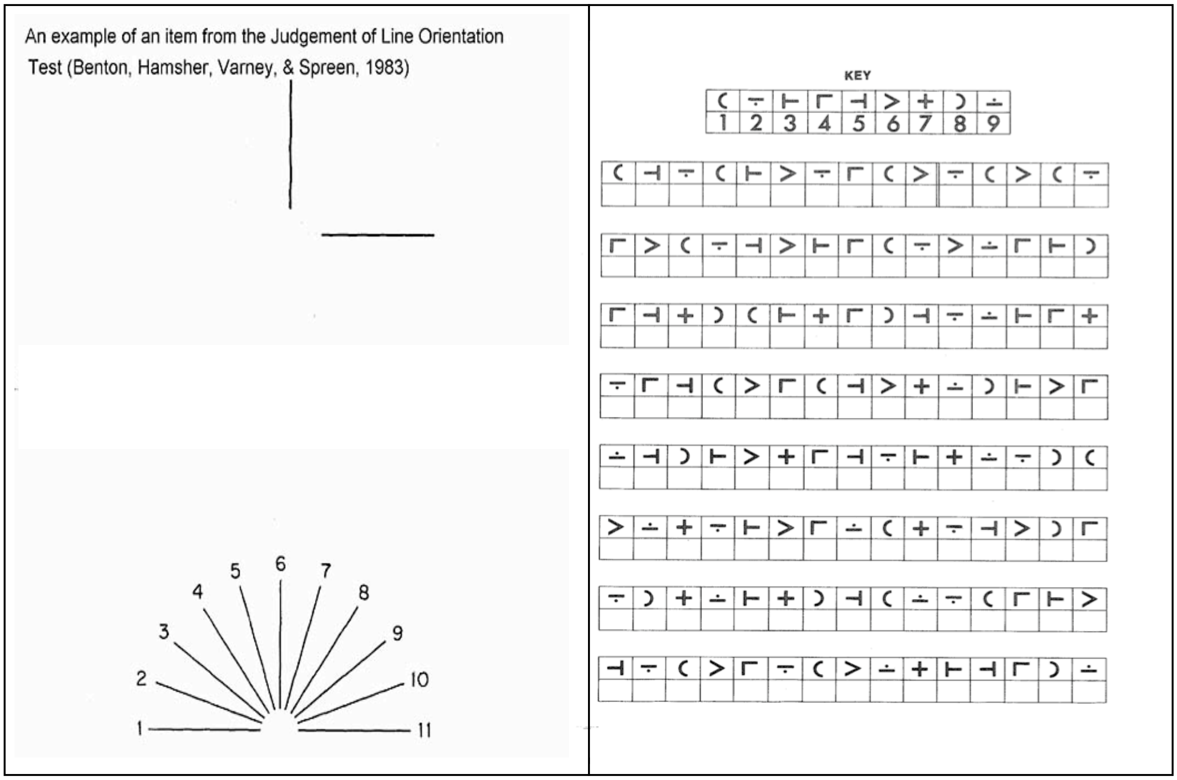

Figure 3. Judgment of Line Orientation (JOLO) on left and Symbol Digit Modalities Test (SDMT) on right.

Procedures

Participants were asked to report to the Human Performance Lab for one testing session lasting approximately 90 minutes. Upon arrival, participants completed the informed consent document and PAR-Q as described earlier. Age, mass, and height of each participant were also recorded. The participant was then asked to perform a 5-minute stationary bike warm-up followed by 5 minutes of stretching of their quadriceps and hamstrings, which is provided with a handout and verbal instructions (Appendix C).

The SPAD was configured to test the dominant leg. The participant was positioned on the SPAD with his or her leg bent to 30 degrees with the trunk positioned at 90 degrees of flexion. The axis of rotation of the adapter arm was in line with the axis of rotation of the lateral knee joint. A vacuum splint was used to help mechanically ground the limb and adaptor arm, which ensures that torque responses result from movement at the knee and minimize lower leg soft tissue artifact. A thigh pad was also used for stability of the femur and hip.

The parameters for knee stiffness testing remained the same for each perturbation with a quick acceleration of a 1000 deg/sec^2 to a velocity of 100°/s and a flexion arc of

40° on the dominant leg. Various testing conditions of reactive stiffening included a control and 3 cognitive loading tasks. The cognitive tasks included the "Judgment of Line Orientation test, "Symbol Digit Modalities Test," and Serial 7's. During the reactive stiffening trials, the participant was relaxed and instructed to contract as hard and as fast as he/she could once he/she began to detect movement of the adapter arm. The participants performed the control condition first. Next, in a random order, the participants were asked to perform the cognitive loading tasks. Throughout all conditions, the perturbation was randomly applied within a 10-second time span once the participants were notified that the perturbation would occur shortly while performing a cognitive loading task. Also, the participant wore headphones for all conditions to mute potentially auditory distractions. Resistance to the perturbation was detected by the torque sensor and recorded by the computer. Joint stiffness was calculated as the Δ force (Newton · meter) / Δ displacement (degrees). Five trials were collected for each condition, with short rest periods between repetitions and conditions.

Data Analysis

Analog signals for torque, position, and EMG were collected using Cortex 1.0 software (Motion Analysis Corp., Santa Rosa, CA). A custom software program using LabView 8.5 (National Instruments, Austin, TX) was used to analyze position and torque data, calculate stiffness, and analyze all EMG signals. Stiffness values were calculated according to the position data at 4^o, 20^o, and 40^o of the flexion perturbation. EMG was averaged over the five trials for each of the four conditions (control, JOLO, SDMT, and SEVEN). Normalized stiffness values were obtained by dividing each participant's stiffness values by their body mass (kg). EMG was analyzed for a window of 150-ms prior to the perturbation and 600-ms after the initiation of the perturbation.

Statistical Analysis

For all statistical analyses, significance was set at $p<0.05$. Demographic and raw cognitive test scores were assessed using one-way analysis of variance (ANOVA). Repeated measures two-way ANOVA was used as the primary statistical analysis to determine differences in gender and knee stiffness while performing a cognitive task. A pairwise comparison was used to determine mean statistical differences in knee stiffness while performing a cognitive task between males and females, as well as differences in muscle activation strategies.

CHAPTER 3

RESULTS

Demographics and Cognitive Test Scores

Statistics for demographics and cognitive scores (scores recorded before stiffness testing protocol) are provided in Table 1. Ages of male and female participants ranged from 18 to 25, and were not significantly different ($p=0.38$). However, weight, height, and leg lengths were significantly greater in male than female participants ($p<0.001$). Males produced greater quadriceps (QMVIC) and hamstring (HMVIC) maximal voluntary isometric contractions than females ($p<0.05$). Overall, HMVIC values were significantly greater than QMVIC values in both genders ($p<0.05$). No differences were found between males and females in the JOLO and SDMT tests (Figure 4).

Table 1. Demographic and Test Score Statistics

	Female N=20	Male N=20	p-value
Age (yrs)	20.050±1.234	20.450±1.572	0.376
Weight (kg)	58.768±6.970	88.153±17.866	<0.001†
Height (cm)	163.887±6.392	179.395±6.235	<0.001†
Leg Length (cm)	40.125±2.650	43.475±2.274	<0.001†
QMVIC (Nm)	484.600±156.482	761.800±180.465	0.018*
HMVIC (Nm)	636.000±190.177	1001.750±254.576	0.014*
JOLO	24.700±3.701	26.400±2.761	0.108
SDMT	65.55±8.00	65.25±7.873	0.906

*Significant at the p-value <0.05
†Significant at the p-value <0.001

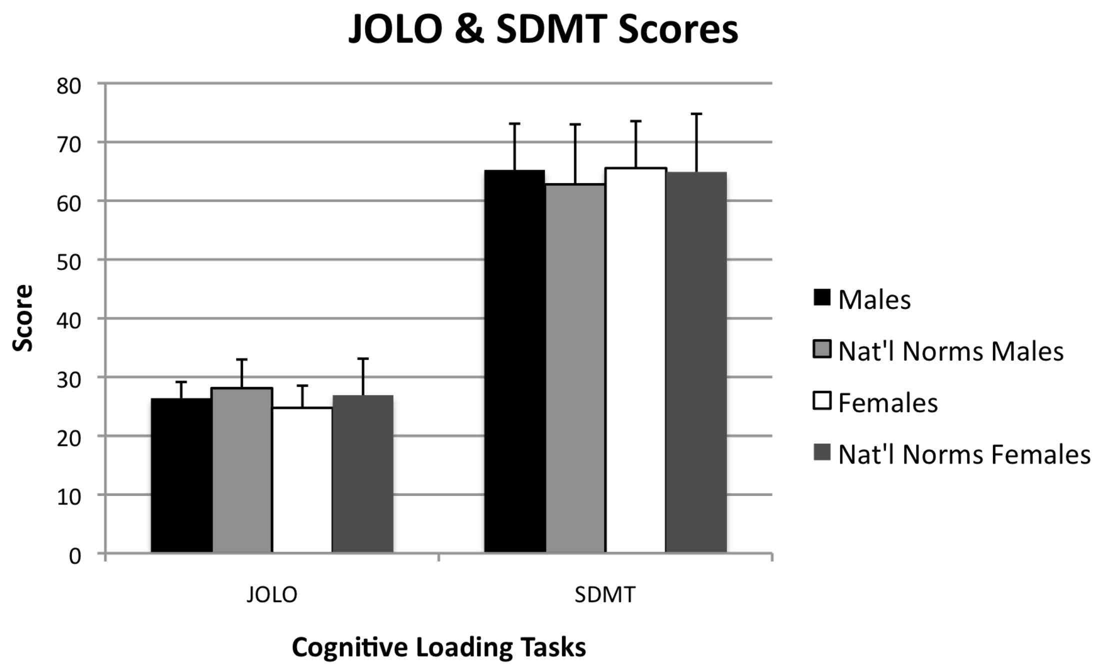

Figure 4. Judgment Line of Orientation (JOLO) and Symbol Digit Modalities Test (SDMT) scores between males and females, with national normative scores.

Reactive Knee Stiffness

Non-Normalized Stiffness Values

The following results pertain to the 4° (Table 2) and total (40°) non-normalized stiffness values (Table 3), categorized by the following independent variables: gender, control, JOLO, SDMT, and Serial 7's. The results are not normalized to each individual's body mass.

4° Non-Normalized Stiffness

Males had greater knee stiffness than females during the first 4° of the perturbation (3.926±0.632 Nm/deg and 2.746±0.397 Nm/deg, respectively; $p<0.001$). Cognitive loading conditions did not affect the 4° stiffness values when compared to control, and no differences were found among the cognitive loading conditions ($p=0.357$). A gender interaction was found during cognitive loading tasks ($p=0.019$). Thus, for each condition, males had greater stiffness than females regardless of the gender-biased cognitive task (Table 2; Figure 5).

Table 2. 4° Non-Normalized Stiffness Values

Independent Variable		Mean ± SD (Nm/Deg)		p-value	Interactive p-value
†Gender		Males	3.926±0.632	<0.001	-
		Females	2.746±0.397		
Cognitive Loading Tasks		Control	3.203±0.801	0.357	-
		JOLO	3.188±0.717		
		SDMT	3.218±0.792		
		Serial 7's	3.248±0.780		
#Gender, Cognitive Loading Tasks	Control	Males	3.770±0.695	-	0.019
		Females	2.636±0.396		
	JOLO	Males	3.672±0.647	-	
		Females	2.702±0.376		
	SDMT	Males	3.819±0.576	-	
		Females	2.617±0.414		
	Serial 7's	Males	3.833±0.608	-	
		Females	2.664±0.400		

JOLO: Judgment Line of Orientation; SDMT: Symbol Digit Modalities Test
#Significant at the p-value <0.01
†Significant at the p-value <0.001

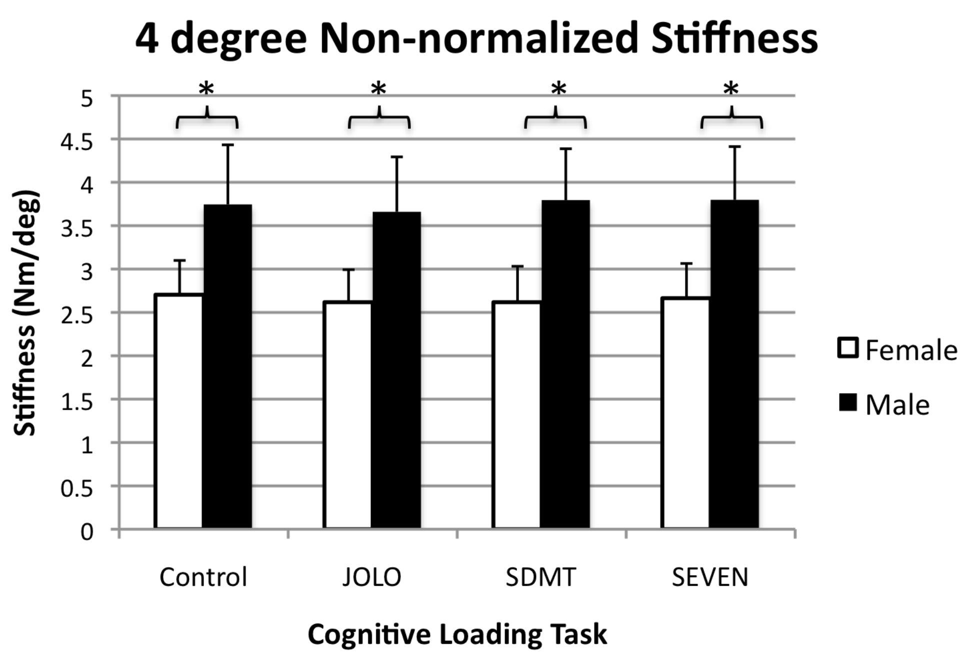

Figure 5. Cognitive loading tasks and gender for the 4° non-normalized stiffness values. JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; SEVEN: Serial 7's

Total (40°) Non-Normalized Stiffness

Table 3 shows non-normalized total (40°) stiffness. No gender differences were found with the total (40°) perturbation (Males: 3.003±1.494 Nm/deg, Females: 2.532±0.640 Nm/deg; p=0.82). Among the conditions, significant differences were present between the control and each of the cognitive loading tasks, where stiffness decreased with the JOLO, SDMT, and Serial 7's (p<0.001) (Figure 6). There were no significant differences among the cognitive loading tasks (p>0.05). In contrast to the 4° stiffness, no interaction was found between gender and cognitive loading tasks for the total perturbation (p=0.202).

Table 3. Total (40°) Non-Normalized Stiffness Values

Independent Variable		Mean ± SD (Nm/Deg)		p-value	Interactive p-value
Gender		Males	3.003±1.494	0.082	-
		Females	2.532±0.640		
†Cognitive Loading Tasks		Control	3.427±0.940	<0.001	-
		JOLO	2.421±1.025		
		SDMT	2.574±0.858		
		Serial 7's	2.649±0.888		
Gender, Cognitive Loading Tasks	Control	Males	3.748±1.164		0.202
		Females	3.106±0.492		
	JOLO	Males	2.627±1.231		
		Females	2.205±0.736		
	SDMT	Males	2.705±2.574		
		Females	2.444±0.659		
	Serial 7's	Males	2.649±0.888		
		Females	2.374±0.671		

JOLO: Judgment Line of Orientation; SDMT: Symbol Digit Modalities Test
†Significant at the p-value <0.001

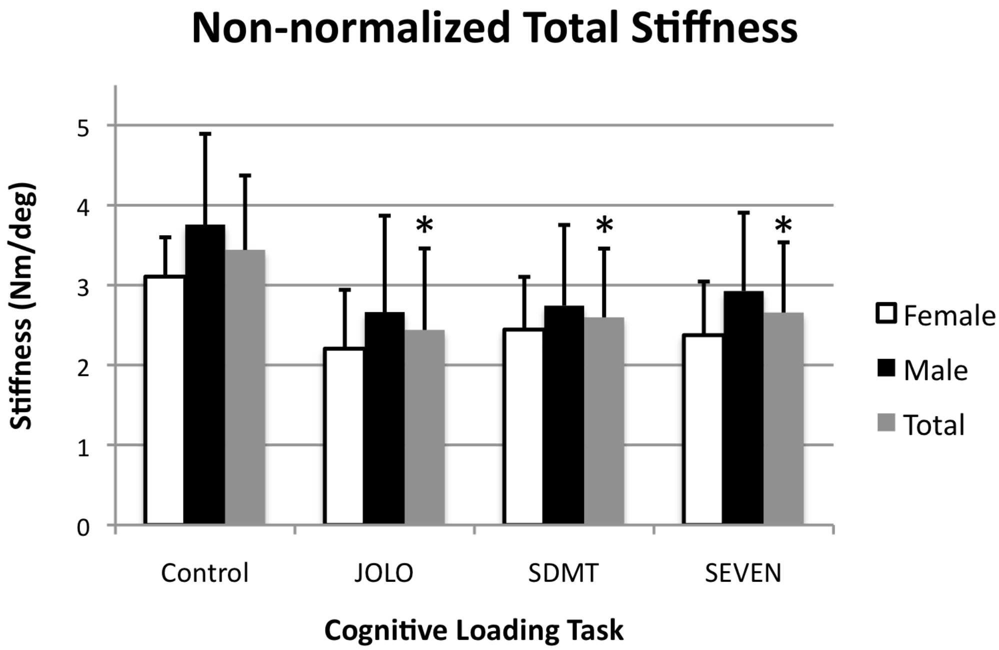

Figure 6. Cognitive loading tasks and gender for the total (40°) non-normalized stiffness values. * indicates significance at $p<0.05$ in each cognitive loading task compared to the control condition. JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; SEVEN: Serial 7's

Normalized Stiffness Values

The following results pertain to 4° (Table 4) and total (40°) normalized stiffness values (Table 5).

4° Normalized Stiffness

Figure 7 shows stiffness values after 4° of movement in each condition for each gender. No gender differences were present in the first 4° of the perturbation (Males: 0.044±0.008 Nm/deg/kg, Females: 0.045±0.006 Nm/deg/kg; $p=0.451$). Stiffness during the control condition was greater than the stiffness during the cognitive loading conditions ($p<0.001$); however, no differences were found among the JOLO, SDMT, and Serial 7's. Similar to that observed with non-normalized values, an interaction was found between cognitive loading tasks and gender ($p=0.008$). Females had more stiffness during the JOLO (0.046±0.007 Nm/deg/kg) than the SDMT (0.045±0.006 Nm/deg/kg), whereas males had more stiffness during the SDMT (0.044±0.008 Nm/deg/kg) than the JOLO (0.043±0.008 Nm/deg/kg) ($p<0.05$).

Table 4. 4° Normalized Stiffness Values

Independent Variable			Mean ± SD (Nm/Deg/kg)	p-value	Interactive p-value
Gender		Males	0.044±0.008	0.451	-
		Females	0.045±0.006		
†Cognitive Loading Tasks		Control	0.048±0.011	<0.001	-
		JOLO	0.034±0.014		
		SDMT	0.037±0.013		
		Serial 7's	0.037±0.012		
Gender, #Cognitive Loading Tasks	Control	Males	0.044±0.008	-	0.008
		Females	0.045±0.006		
	JOLO	Males	0.043±0.008	-	
		Females	0.046±0.007		
	SDMT	Males	0.044±0.008	-	
		Females	0.045±0.006		
	Serial 7's	Males	0.045±0.008	-	
		Females	0.045±0.006		

JOLO: Judgment Line of Orientation; SDMT: Symbol Digit Modalities Test
*Significant p<0.05
#Significant p<0.01

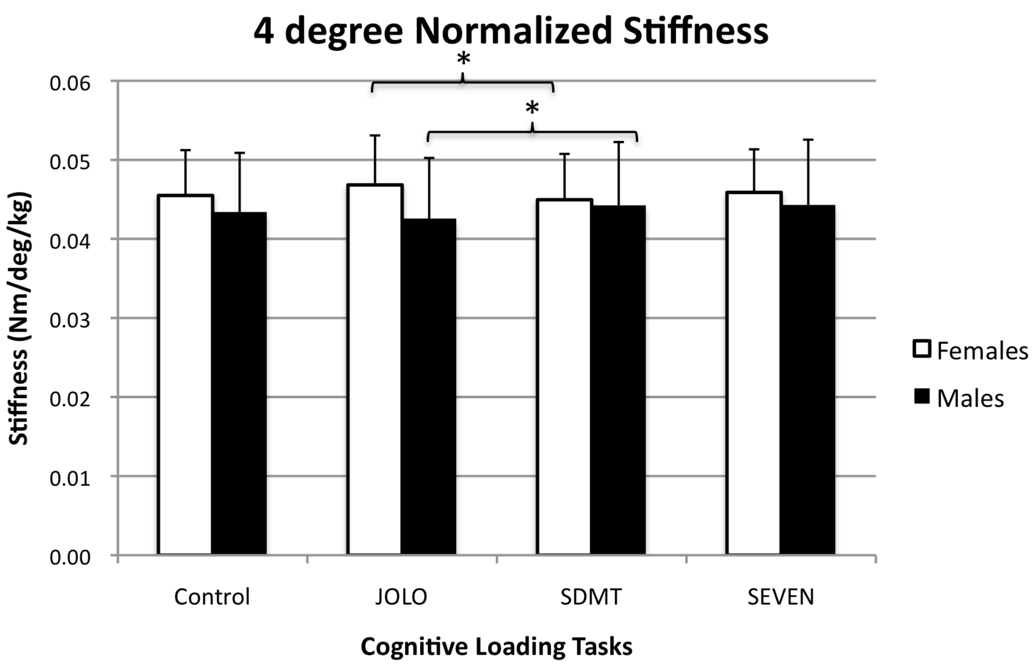

Figure 7. Cognitive loading tasks and gender for the 4° normalized stiffness values. JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; SEVEN: Serial 7's

Total (40°) Normalized Stiffness

During the 40° perturbation, females had greater stiffness values than males when normalized to body mass (0.043±0.010 Nm/deg/kg and 0.035±0.014 Nm/deg/kg, respectively; p=0.020) (Figure 8). Similar to 4° stiffness results, differences were found between the control condition and each of the cognitive loading conditions (p<0.001), where there was a decrease in stiffness with all cognitive loading tasks; however, no differences were found among the JOLO, SDMT, and Serial 7's tasks (p>0.05) (Figure 9). No interaction between gender and the cognitive loading tasks was found (p=0.288).

Table 5. Total (40°) Normalized Stiffness Values

Independent Variable		Mean ± SD (Nm/Deg/kg)		p-value	Interactive p-value
*Gender		Males	0.035±0.014	0.020	-
		Females	0.043±0.010		
†Cognitive Loading Tasks		Control	0.048±0.011	<0.001	-
		JOLO	0.034±0.014		
		SDMT	0.037±0.013		
		Serial 7's	0.037±0.012		
Gender, Cognitive Loading Tasks	Control	Males	0.044±0.014		0.288
		Females	0.053±0.006		
	JOLO	Males	0.031±0.015		
		Females	0.038±0.012		
	SDMT	Males	0.031±0.013		
		Females	0.042±0.010		
	Serial 7's	Males	0.034±0.012		
		Females	0.040±0.011		

JOLO: Judgment Line of Orientation; SDMT: Symbol Digit Modalities Test
†Significant at the p-value<0.001

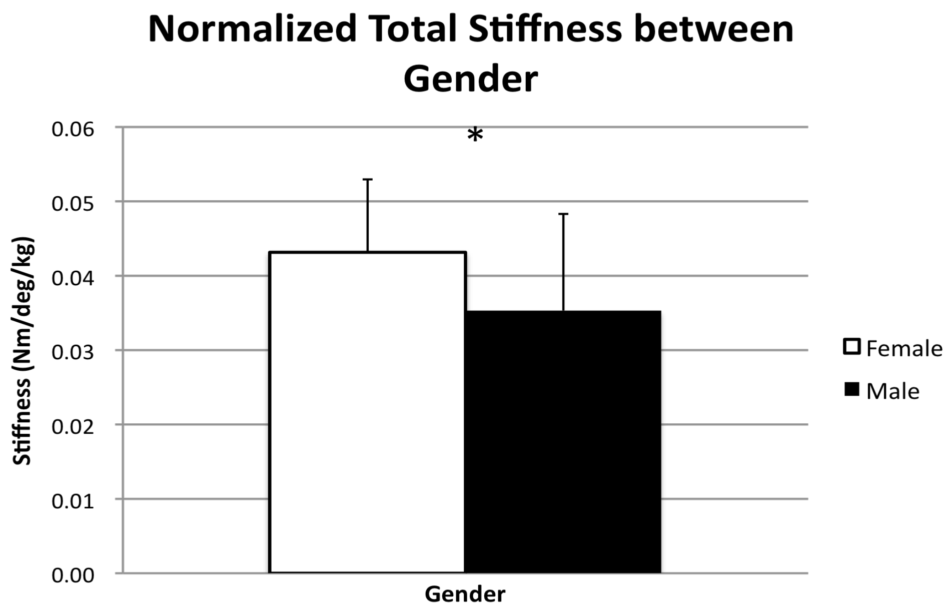

Figure 8. Normalized total (40°) stiffness between males and females. * indicates significance at p<0.05.

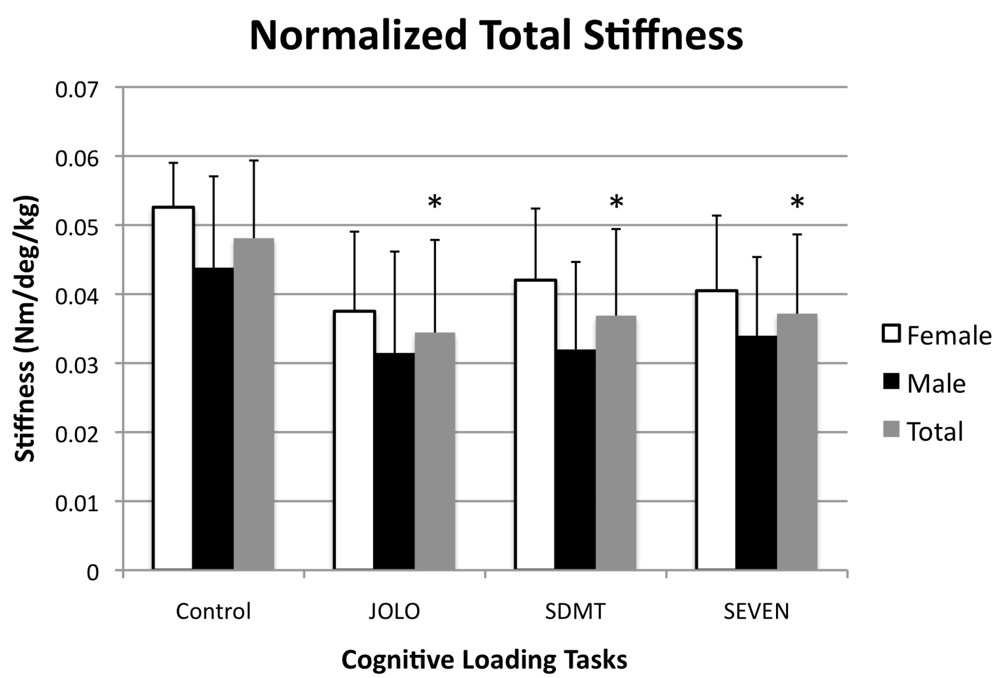

Figure 9. Cognitive loading tasks and gender for the total (40°) normalized stiffness values. * indicates significance at p<0.05 in each cognitive loading task compared to the control condition. JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; SEVEN: Serial 7's

Electromyography (EMG)

EMG was obtained in order to assess the muscle activation strategies used to regulate stiffness. Data were collected from the vastus medialis (VM), vastus lateralis (VL), medial hamstring (MH), and lateral hamstring (LH) throughout all stiffness measurement trials and conditions. The following independent variables are categorized as gender, cognitive loading tasks (control, JOLO, SDMT, and Serial 7's), and muscle (VM, VL, MH, and LH).

Electromechanical Delay (EMD)

The following data represent the time lag between muscle activation and muscle force production. No differences were found between gender, among cognitive loading tasks, and among muscles ($p=0.512$, $p=0.689$, $p=0.133$, respectively). Also, no interaction was found among the independent variables ($p>0.05$) (Table 6).

Table 6. Electromechanical Delay (EMD) Values

Independent Variable		Mean ± SD (ms)		p-value	Interactive p-value
Gender		Males	92.671±44.047	0.512	-
		Females	94.960±34.090		
Cognitive Loading Tasks		Control	92.885±39.322	0.689	-
		JOLO	94.453±41.873		
		SDMT	93.083±37.208		
		Serial 7's	94.825±40.120		
Muscles		VM	91.262±40.012	0.133	-
		VL	87.670±44.440		
		MH	103.808±34.398		
		LH	92.497±39.674		
Gender, Cognitive Loading Tasks	Control	Males	91.676±43.479	-	0.192
		Females	94.094±34.002		
	JOLO	Males	94.188±45.679	-	
		Females	94.719±36.601		
	SDMT	Males	92.264±43.220	-	
		Females	93.920±30.425		
	Serial 7's	Males	92.555±43.810	-	
		Females	97.106±35.332		
Cognitive Loading Tasks, Muscle	Control	VM	91.479±41.001	-	0.306
		VL	87.100±42.997		
		MH	103.236±34.220		
		LH	89.727±39.071		
	JOLO	VM	93.025±42.667	-	
		VL	87.964±44.849		
		MH	101.744±36.225		
		LH	95.082±43.750		
	SDMT	VM	87.914±33.113	-	
		VL	87.929±44.581		
		MH	104.414±34.112		
		LH	92.073±37.026		
	Serial 7's	VM	92.629±43.267	-	
		VL	87.724±45.334		
		MH	105.840±33.034		
		LH	93.106±38.847		
Gender, Muscle	VM	Males	86.798±36.162	-	0.752
		Females	95.744±43.672		
	VL	Males	84.303±48.961	-	
		Females	91.055±40.391		
	MH	Males	105.800±38.808	-	
		Females	101.828±30.173		
	LH	Males	93.782±52.258	-	
		Females	91.212±22.125		

Table 6. EMD values cont.

Gender, Cognitive Loading Task, Muscle	Male	Control	VM	86.460±35.988	-	0.474
			VL	84.468±48.422		
			MH	105.474±37.627		
			LH	90.303±51.879		
		JOLO	VM	88.163±37.485	-	
			VL	84.177±48.764		
			MH	105.284±38.234		
			LH	99.128±58.234		
		SDMT	VM	86.494±35.565	-	
			VL	84.446±49.035		
			MH	105.699±39.837		
			LH	92.416±48.443		
		Serial 7's	VM	86.075±35.611	-	
			VL	84.121±49.621		
			MH	106.742±39.034		
			LH	93.280±50.475		
	Female	Control	VM	96.499±45.852	-	
			VL	89.732±37.888		
			MH	100.997±31.262		
			LH	89.151±21.007		
		JOLO	VM	97.887±47.770	-	
			VL	91.751±41.481		
			MH	98.203±34.719		
			LH	91.035±22.433		
		SDMT	VM	89.409±31.226	-	
			VL	91.411±40.615		
			MH	103.129±28.249		
			LH	91.731±21.611		
		Serial 7's	VM	99.184±49.839	-	
			VL	91.326±41.579		
			MH	104.983±26.462		
			LH	92.933±23.446		

JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; VM: vastus medialis; VL: vastus lateralis; MH: medial hamstring; LH: lateral hamstring

Peak EMG

The following data pertain to the peak EMG reached during the perturbation. Table 7 presents differences and interactions for peak EMG. No gender differences were found in attaining peak EMG (Males: 42.927±57.167 %, Females: 53.277±57.167 %; $p=0.362$). Significantly higher peak EMG was reached when reacting to the control condition compared to the cognitive loading tasks ($p<0.001$), but no differences existed among the JOLO, SDMT, and Serial 7's ($p>0.05$). When performing a cognitive loading task, there was approximately a 30% decrease in peak EMG compared to the control condition. The magnitude of peak EMG was significantly different among the muscles where the VM had the greatest EMG (83.812±91.232 %), while the MH had the least (8.787±7.148 %). Also within each testing condition, all muscles showed differences, except for the quadriceps ($p<0.05$).

Table 7. Peak EMG Values

Independent Variable			Mean ± SD (%)	p-value	Interactive p-value
Gender		Males	42.927±57.167	0.362	-
		Females	53.277±57.167		
†Cognitive Loading Tasks		Control	61.348±52.307	<0.001	-
		JOLO	41.817±31.692		
		SDMT	43.744±43.148		
		Serial 7's	45.460±53.905		
#Muscles		VM	83.812±91.232	0.005	-
		VL	72.846±57.437		
		MH	8.787±7.148		
		LH	26.925±25.234		
Gender, Cognitive Loading Tasks	Control	Males	58.286±32.217	-	0.258
		Females	64.505±66.066		
	JOLO	Males	38.146±24.631	-	
		Females	45.445±37.082		
	SDMT	Males	37.678±26.937	-	
		Females	49.882±53.975		
	Serial 7's	Males	37.598±25.018	-	
		Females	53.274±71.546		
*Cognitive Loading Tasks, *Muscle	Control	VM	106.213±106.874	<0.05	<0.001
		VL	91.399±62.026		
		MH	11.432±6.286		
		LH	26.925±25.234		
	JOLO	VM	69.318±57.469	<0.05	
		VL	65.489±43.244		
		MH	8.876±5.708		
		LH	23.587±20.347		
	SDMT	VM	79.651±89.330	<0.05	
		VL	63.147±51.116		
		MH	7.990±11.318		
		LH	24.188±20.828		
	Serial 7's	VM	80.066±111.254	<0.05	
		VL	71.349±73.364		
		MH	6.850±5.279		
		LH	23.577±25.722		
Gender, Muscle	VM	Males	72.922±39.509	-	0.595
		Females	94.759±123.466		
	VL	Males	67.502±39.412	-	
		Females	78.409±72.130		
	MH	Males	7.067±4.784	-	
		Females	10.484±8.415		
	LH	Males	24.217±25.098	-	
		Females	29.454±24.658		

Table 7. Peak EMG values cont.

Gender, Cognitive Loading Task, Muscle	Male	Control	VM	101.876±45.15	-	0.284
			VL	86,288±40.332		
			MH	9.277±4.504		
			LH	35.703±38.879		
		JOLO	VM	62.802±33.276	-	
			VL	60.799±38.278		
			MH	7.989±6.208		
			LH	20.994±20.761		
		SDMT	VM	94.097±117.536	-	
			VL	57.650±33.538		
			MH	5.438±4.398		
			LH	22.420±23.709		
		Serial 7's	VM	61.805±33.504	-	
			VL	65.270±45.499		
			MH	5.566±4.028		
			LH	17.752±17.042		
	Female	Control	VM	110.779±148.047	-	
			VL	96.778±79.657		
			MH	13.473±7.130		
			LH	36. 991±29.430		
		JOLO	VM	75.833±74.716	-	
			VL	70.178±48.240		
			MH	9.719±5.208		
			LH	26.050±20.163		
		SDMT	VM	94.097±117.536	-	
			VL	68.933±65.266		
			MH	10.543±15.161		
			LH	25.956±17.937		
		Serial 7's	VM	98.327±153.564	-	
			VL	77.747±95.358		
			MH	8.201±6.160		
			LH	28.818±31.104		

JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; VM: vastus medialis; VL: vastus lateralis; MH: medial hamstring; LH: lateral hamstring
*Significant at the p-value $p<0.05$
†Significant at the p-value<0.001

Time to Peak (TTP)

The following data represent the time to reach peak torque during the perturbation (Table 8). Males were significantly faster to reach peak torque than females (338.060±57.090 ms and 362.451±48.158 ms, respectively; p=0.039). Also while performing the JOLO, SDMT, or Serial 7's, the participants were approximately 9% slower to reach peak torque compared to the control condition (p<0.001) (Figure 10). No differences among the muscles and interactions were found (p>0.05).

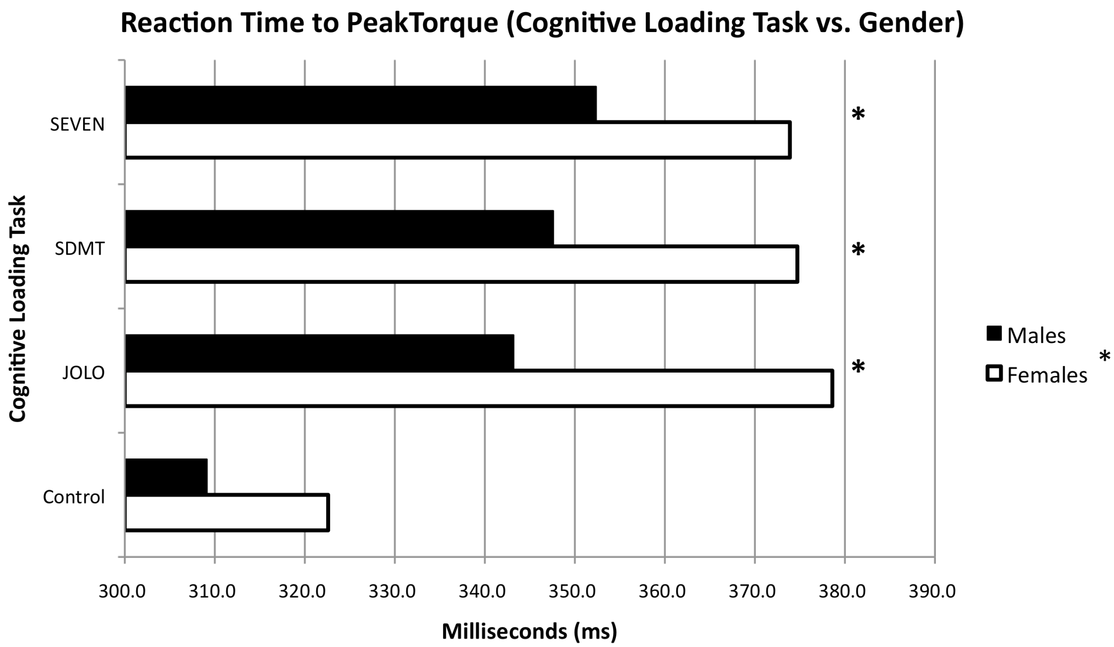

Figure 10. Reaction time to peak torque (ms) between cognitive loading tasks and gender. * indicates significance at p<0.05 between control and each cognitive loading task condition. JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; SEVEN: Serial 7's

Table 8. Time to Peak (TTP) Values

Independent Variable			Mean ± SD (ms)	p-value	Interactive p-value
*Gender		Males	338.060±57.090	0.039	-
		Females	362.451±48.158		
†Cognitive Loading Tasks		Control	315.857±62.798	<0.001	-
		JOLO	360.620±53.934		
		SDMT	361.155±48.226		
		Serial 7's	363.141±52.942		
Muscles		VM	357.793±51.630	0.077	-
		VL	346.842±56.145		
		MH	343.466±58.881		
		LH	352.672±51.244		
Gender, Cognitive Loading Tasks	Control	Males	309.118±67.236	-	0.447
		Females	322.597±58.257		
	JOLO	Males	342.183±54.834	-	
		Females	378.602±46.345		
	SDMT	Males	347.591±49.262	-	
		Females	374.719±43.081		
	Serial 7's	Males	352.350±57.028	-	
		Females	373.887±44.947		
Cognitive Loading Tasks, Muscle	Control	VM	329.071±61.532	-	0.295
		VL	302.805±63.411		
		MH	316.337±67.042		
		LH	315.217±59.207		
	JOLO	VM	365.145±47.164	-	
		VL	368.399±57.878		
		MH	346.281±66.381		
		LH	362.656±44.312		
	SDMT	VM	370.622±49.546	-	
		VL	359.075±52.412		
		MH	351.892±42.557		
		LH	363.030±48.391		
	Serial 7's	VM	366.334±48.279	-	
		VL	357.089±50.879		
		MH	359.353±59.545		
		LH	369.786±53.066		
Gender, Muscle	VM	Males	345.008±52.597	-	0.116
		Females	370.816±46.739		
	VL	Males	327.620±53.534	-	
		Females	366.064±51.912		
	MH	Males	332.914±62.097	-	
		Females	354.190±53.033		
	LH	Males	346.700±60.133	-	
		Females	358.734±40.946		

Table 8.Peak EMG values cont.

Gender, Cognitive Loading Task, Muscle	Male	Control	VM	325.120±66.386	-	0.912
			VL	290.517±58.222		
			MH	310.168±76.373		
			LH	310.668±67.964		
		JOLO	VM	347.028±40.976	-	
			VL	340.057±55.260		
			MH	329.833±72.730		
			LH	355.814±50.370		
		SDMT	VM	355.217±45.523	-	
			VL	342.466±48.021		
			MH	335.868±45.762		
			LH	356.813±57.744		
		Serial 7's	VM	352.666±57.504	-	
			VL	337.440±52.633		
			MH	355.786±53.524		
			LH	363.507±64.452		
	Female	Control	VM	333.022±57.720	-	
			VL	315.093±67.424		
			MH	322.506±57.558		
			LH	319.766±50.328		
		JOLO	VM	384.215±46.638	-	
			VL	396.741±46.166		
			MH	363.594±55.695		
			LH	369.857±36.882		
		SDMT	VM	386.027±49.666	-	
			VL	375.685±52.459		
			MH	367.917±32.906		
			LH	369.248±37.293		
		Serial 7's	VM	380.002±32.932	-	
			VL	376.738±41.600		
			MH	362.742±65.973		
			LH	376.066±39.282		

JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; VM: vastus medialis; VL: vastus lateralis; MH: medial hamstring; LH: lateral hamstring
*Significant at the p-value p<0.05
†Significant at the p-value<0.001

Onset

The following results pertain to the time the muscles begin to activate in response to the perturbation. Table 9 shows data for gender, cognitive loading tasks, muscles, and their interactions. No differences were found between males and females (90.683±43.256 ms and 85.215±43.834 ms, respectively; $p=0.622$). The onset of muscle activation during the control condition was faster than during the cognitive loading conditions ($p<0.001$). When performing a cognitive loading task, participants had 25% slower onset times compared to the control condition values. No differences were found among the JOLO, SDMT, and Serial 7's ($p>0.05$). In all conditions, the onset response times in all muscles were significantly different from one another ($p<0.001$), except for the quadriceps. The VM was the fastest to activate (69.962±33.807 ms), while the MH was slowest (115.149±59.517 ms). No interaction was found between the cognitive loading tasks and muscles ($p=0.123$).

Table 9. Onset Values

Independent Variable			Mean ± SD (ms)	p-value	Interactive p-value
Gender		Males	90.683±43.256	0.622	-
		Females	85.215±43.834		
†Cognitive Loading Tasks		Control	71.873±30.726	<0.001	-
		JOLO	95.490±47.867		
		SDMT	90.913±44.570		
		Serial 7's	93.610±51.141		
†Muscles		VM	69.962±33.807	<0.001	-
		VL	75.931±35.782		
		MH	115.149±59.517		
		LH	90.844±35.199		
Gender, Cognitive Loading Tasks	Control	Males	74.427±31.255	-	0.080
		Females	69.337±29.851		
	JOLO	Males	92.206±44.958	-	
		Females	98.774±51.306		
	SDMT	Males	96.626±44.906	-	
		Females	85.099±43.895		
	Serial 7's	Males	99.473±51.906	-	
		Females	87.652±50.284		
Cognitive Loading Tasks, Muscle	Control	VM	58.035±26.391	-	0.123
		VL	88.129±36.878		
		MH	88.129±36.878		
		LH	80.997±38.373		
	JOLO	VM	77.887±31.555	-	
		VL	120.781±62.387		
		MH	120.781±62.387		
		LH	98.31250.681		
	SDMT	VM	75.381±33.119	-	
		VL	122.094±63.779		
		MH	122.094±63.779		
		LH	89.473±45.611		
	Serial 7's	VM	68.543±44.161	-	
		VL	129.594±75.025		
		MH	129.59475.025		
		LH	94.595±46.131		
Gender, Muscle	VM	Males	73.432±37.147	-	0.803
		Females	66.389±29.955		
	VL	Males	76.447±32.382	-	
		Females	75.432±39.519		
	MH	Males	119.308±58.852	-	
		Females	110.896±59.754		
	LH	Males	93.544±44.643	-	
		Females	88.145±46.108		

Table 9. Onset values cont.

Gender, Cognitive Loading Task, Muscle	Male	Control	VM	50.069±27.528	-	0.406
			VL	61.687±19.679		
			MH	97.744±41.998		
			LH	82.207±35.814		
		JOLO	VM	79.281±33.396	-	
			VL	81.758±42.088		
			MH	113.259±56.932		
			LH	94.526±47.415		
		SDMT	VM	83.147±37.516	-	
			VL	79.243±35.040		
			MH	129.442±57.294		
			LH	94.670±49.773		
		Serial 7's	VM	75.233±50.147	-	
			VL	83.100±32.720		
			MH	136.788±79.184		
			LH	102.772±45.572		
	Female	Control	VM	60.001±25.763	-	
			VL	59.045±23.106		
			MH	78.513±28.862		
			LH	79.787±41.674		
		JOLO	VM	76.494±30.404	-	
			VL	88.200±52.067		
			MH	128.303±68.034		
			LH	102.099±54.718		
		SDMT	VM	67.207±26.316	-	
			VL	74.165±37.218		
			MH	114.746±79.381		
			LH	84.276±41.664		
		Serial 7's	VM	61.853±37.338	-	
			VL	80.318±45.684		
			MH	122.021±71.738		
			LH	86.418±46.375		

JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; VM: vastus medialis; VL: vastus lateralis; MH: medial hamstring; LH: lateral hamstring
†Significant at the p-value<0.001

Pre-Perturbation Area

The following results represent the EMG areas 150 ms prior to the perturbation (Table 10). No differences were found in gender, cognitive loading tasks, and muscles ($p=0.080$, $p=0.372$, p=0247. respectively). Also, no interaction was found among the independent variables ($p>0.05$).

Table 10. Pre-Perturbation Area Values

Independent Variable			Mean ± SD (%)	p-value	Interactive p-value
Gender		Males	0.132±0.112	0.080	-
		Females	0.249±0.378		
Cognitive Loading Tasks		Control	0.174±0.211	0.372	-
		JOLO	0.218±0.283		
		SDMT	0.176±0.254		
		Serial 7's	0.198±0.396		
Muscles		VM	0.186±0.272	0.247	-
		VL	0.269±0.544		
		MH	0.143±0.174		
		LH	0.168±0.154		
Gender, Cognitive Loading Tasks	Control	Males	0.118±0.098	-	0.479
		Females	0.227±0.268		
	JOLO	Males	0.158±0.148	-	
		Females	0.279±0.364		
	SDMT	Males	0.126±0.097	-	
		Females	0.224±0.338		
	Serial 7's	Males	0.127±0.103	-	
		Females	0.267±0.542		
Cognitive Loading Tasks, Muscle	Control	VM	0.117±0.193	-	0.341
		VL	0.221±0.353		
		MH	0.133±0.162		
		LH	0.165±0.137		
	JOLO	VM	0.192±0.197	-	
		VL	0.343±0.559		
		MH	0.153±0.201		
		LH	0.185±0.173		
	SDMT	VM	0.176±0.273	-	
		VL	0.226±0.459		
		MH	0.143±0.157		
		LH	0.158±0.128		
	Serial 7's	VM	0.200±0.426	-	
		VL	0.285±0.805		
		MH	0.143±0.175		
		LH	0.162±0.179		
Gender, Muscle	VM	Males	0.124±0.088	-	0.401
		Females	0.246±0.361		
	VL	Males	0.162±0.163	-	
		Females	0.370±0.736		
	MH	Males	0.112±0.086	-	
		Females	0.175±0.231		
	LH	Males	0.131±0.109	-	
		Females	0.205±0.185		

Table 10. Pre-Perturbation Area values cont.

Gender, Cognitive Loading Task, Muscle	Male	Control	VM	0.117±0.085	-	0.423
			VL	0.120±0.116		
			MH	0.103±0.082		
			LH	0.130±0.111		
		JOLO	VM	0.141±0.128	-	
			VL	0.226±0.236		
			MH	0.115±0.093		
			LH	0.147±0.135		
		SDMT	VM	0.112±0.057	-	
			VL	0.148±0.148		
			MH	0.119±0.089		
			LH	0.127±0.092		
		Serial 7's	VM	0.125±0.083	-	
			VL	0.154±0.150		
			MH	0.109±0.080		
			LH	0.121±0.099		
	Female	Control	VM	0.234±0.245	-	
			VL	0.311±0.461		
			MH	0.164±0.212		
			LH	0.198±0.153		
		JOLO	VM	0.241±0.239	-	
			VL	0.460±0.746		
			MH	0.192±0.271		
			LH	0.222±0.201		
		SDMT	VM	0.238±0.371	-	
			VL	0.301±0.623		
			MH	0.168±0.206		
			LH	0.190±0.151		
		Serial 7's	VM	0.271±0.588	-	
			VL	0.410±1.114		
			MH	0.117±0.233		
			LH	0.208±0.235		

JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; VM: vastus medialis; VL: vastus lateralis; MH: medial hamstring; LH: lateral hamstring

Reflexive Area (0-250ms Post-Perturbation)

The following results represent the areas for 250-ms time period after the initiation of the perturbation (Table 11). No gender differences were found 0-250 ms post-perturbation (Males: 1.637±1.210%, Females: 2.618±2.259%; $p=0.306$). There was a significant decrease of approximately 60% in muscle activation when performing the cognitive tasks (JOLO, SDMT, and Serial 7's) compared to the control condition ($p<0.001$). Differences were found between the quadriceps and hamstrings muscles, as well as in the medial and lateral hamstrings ($p<0.001$). Medial and lateral quadriceps had no differences (VM: 3.009±3.176%, VL: 2.906±2.905%; $p>0.05$). The VM had the most muscle activation (3.009±3.176%), while the MH had the least activation (0.535±0.403%).

Table 11. Reflexive Area (0-250ms Post-Perturbation) Values

Independent Variable			Mean ± SD (%)	p-value	Interactive p-value
Gender		Males	1.637±1.210	0.306	-
		Females	2.618±2.259		
†Cognitive Loading Tasks		Control	3.378±3.263	<0.001	-
		JOLO	1.213±1.021		
		SDMT	1.498±1.740		
		Serial 7's	1.411±1.292		
†Muscles		VM	3.009±3.176	<0.001	-
		VL	2.906±2.905		
		MH	0.535±0.403		
		LH	1.050±0.831		
Gender, Cognitive Loading Tasks	Control	Males	2.950±1.769	-	0.506
		Females	3.817±4.282		
	JOLO	Males	1.105±0.885	-	
		Females	1.312±1.070		
	SDMT	Males	1.227±1.169	-	
		Females	1.770±2.169		
	Serial 7's	Males	1.266±1.017	-	
		Females	1.553±1.516		
#Cognitive Loading Tasks, #Muscle	Control	VM	5.473±6.210	<0.01	<0.001
		VL	5.427±4.970		
		MH	0.756±0.471		
		LH	1.855±0.1401		
	JOLO	VM	1.755±1.306	<0.01	
		VL	1.787±1.579		
		MH	0.496±0.459		
		LH	0.815±0.741		
	SDMT	VM	2.676±3.337	<0.01	
		VL	2.132±2.702		
		MH	0.433±0.316		
		LH	0.751±0.604		
	Serial 7's	VM	2.132±1.853	<0.01	
		VL	2.278±2.371		
		MH	0.456±0.365		
		LH	0.781±0.578		
Gender, Muscle	VM	Males	2.639±1.925	-	0.716
		Females	3.387±4.033		
	VL	Males	2.609±1.911	-	
		Females	23.203±3.684		
	MH	Males	0.416±0.244	-	
		Females	0.653±0.490		
	LH	Males	0.884±0.760	-	
		Females	1.208±0.830		

Table 11. Reflexive Area (0-250ms Post-Perturbation) values cont.

Gender, Cognitive Loading Task, Muscle	Male	Control	VM	4.824±2.554	-	0.662
			VL	4.915±3.114		
			MH	0.577±0.308		
			LH	1.483±1.100		
		JOLO	VM	1.761±1.360	-	
			VL	1.450±0.930		
			MH	0.395±0.266		
			LH	0.813±0.986		
		SDMT	VM	2.031±2.322	-	
			VL	1.996±1.820		
			MH	0.329±0.176		
			LH	0.552±0.357		
		Serial 7's	VM	1.941±1.463	-	
			VL	2.074±1.781		
			MH	0.362±0.224		
			LH	0.687±0.599		
	Female	Control	VM	6.157±8.577	-	
			VL	5.965±6.427		
			MH	0.935±0.542		
			LH	2.209±1.583		
		JOLO	VM	1.749±1.285	-	
			VL	2.091±1.969		
			MH	0.592±0.578		
			LH	0.817±0.448		
		SDMT	VM	3.321±4.073	-	
			VL	2.284±3.485		
			MH	0.536±0.388		
			LH	0.938±0.730		
		Serial 7's	VM	2.322±2.197	-	
			VL	2.472±2.855		
			MH	0.550±0.453		
			LH	0.869±0.557		

JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; VM: vastus medialis; VL: vastus lateralis; MH: medial hamstring; LH: lateral hamstring
†Significant at the p-value<0.001

Reflexive Area (250-500ms Post-Perturbation)

The following results pertain to the areas from 250ms to 500ms time period of the perturbation (Table 12). Similar to the first 250ms after the perturbation, no differences between males and females were found (5.439±3.536%/ms and 7.978±8.092%/ms, respectively; p=0.137). When performing a cognitive loading task, there was 25% less muscle activation than the control condition (p<0.001). No differences were found among the JOLO, SDMT, and Serial 7's (p>0.05). Similar individual muscle results that were found during the 0-250ms Post Perturbation period were also observed during the 250-500 ms period. The quadriceps had greater activation than the hamstrings (p<0.001). The lateral hamstrings also had greater activation than the medial hamstrings (LH: 3.783±3.362%/ms, MH: 1.261±0.964%./ms; p<0.001), but no differences were found between medial and lateral quadriceps (VM: 11.741±12.812%/ms, VL: 10.028±8.342%/ms; p>0.05). The VM had the most muscle activation (11.741±12.812%/ms); the MH had the least muscle activation (1.261±0.964%/ms). Figure 11 summarizes the muscle activation areas from perturbation to 500ms post-perturbation. Within each muscle, there was 20-30% decrease in muscle activation when performing the JOLO, SDMT, and Serial 7's compared to the control condition (p<0.01). Within each testing condition, the VM had the most muscle activation, while the MH had the least activation (p<0.01).

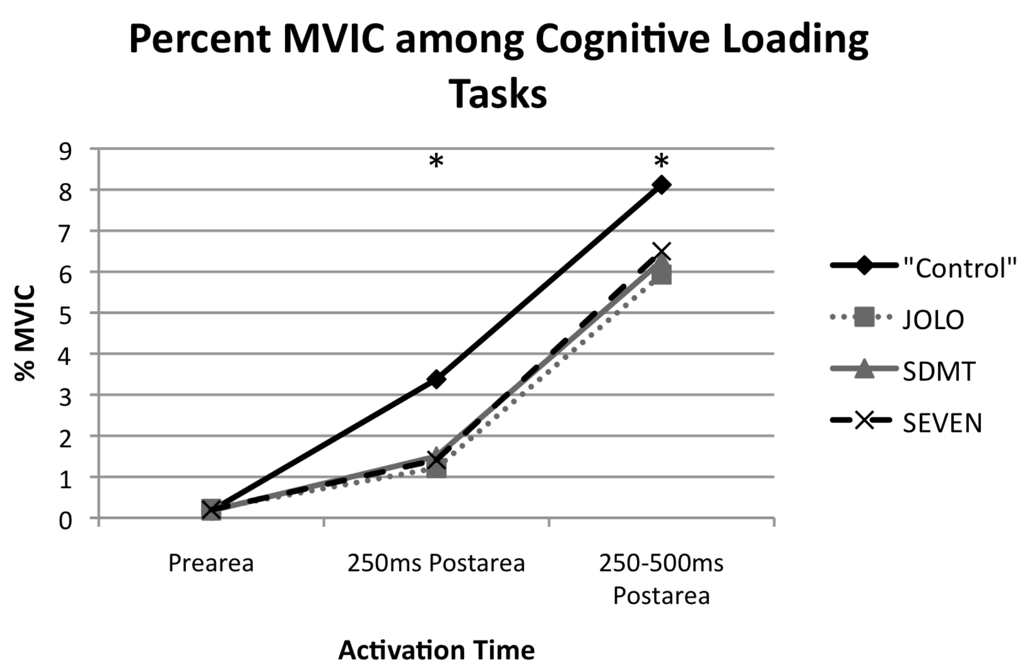

Figure 11. Muscle activation activity among cognitive loading tasks at different activation times. * indicates significance at p<0.05 between the control and each cognitive loading task condition. JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; SEVEN: Serial 7's

Table 12. Reflexive Area (250-500ms Post-Perturbation) values

Independent Variable			Mean ± SD (%/ms)	p-value	Interactive p-value
Gender		Males	5.439±3.536	0.137	-
		Females	7.978±8.092		
†Cognitive Loading Tasks		Control	8.120±7.021	<0.001	-
		JOLO	5.930±4.722		
		SDMT	6.265±6.329		
		Serial 7's	6.499±7.407		
†Muscles		VM	11.741±12.812	<0.001	-
		VL	10.028±8.342		
		MH	1.261±0.964		
		LH	3.783±3.362		
Gender, Cognitive Loading Tasks	Control	Males	6.941±3.978	-	0.302
		Females	9.335±9.033		
	JOLO	Males	5.082±3.606	-	
		Females	6.774±5.477		
	SDMT	Males	4.844±3.346	-	
		Females	7.697±8.087		
	Serial 7's	Males	4.890±3.213	-	
		Females	8.108±9.771		
#Cognitive Loading Tasks, #Muscle	Control	VM	14.140±13.676	<0.01	0.003
		VL	11.897±9.115		
		MH	1.606±10.69		
		LH	4.837±4.225		
	JOLO	VM	9.866±8.466	<0.01	
		VL	9.142±6.647		
		MH	1.260±0.876		
		LH	3.454±2.901		
	SDMT	VM	11.257±13.012	<0.01	
		VL	9.263±8.165		
		MH	1.122±1.175		
		LH	3.415±2.965		
	Serial 7's	VM	11.702±16.095	<0.01	
		VL	9.811±9.440		
		MH	1.057±0.735		
		LH	3.425±3.360		
Gender, Muscle	VM	Males	9.270±5.180	-	0.351
		Females	14.326±17.229		
	VL	Males	8.459±5.195	-	
		Females	11.883±10.575		
	MH	Males	0.942±0.653	-	
		Females	1.581±1.098		
	LH	Males	3.087±3.115	-	
		Females	4.432±3.466		

Table 12. Reflexive Area (250-500ms Post-Perturbation) values cont.

Gender, Cognitive Loading Task, Muscle	Male	Control	VM	12.319±5.909	-	0.238
			VL	10.191±5.273		
			MH	1.207±0.709		
			LH	4.049±4.021		
		JOLO	VM	8.359±5.023	-	
			VL	7.856±5.236		
			MH	1.044±0.886		
			LH	3.071±3.278		
		SDMT	VM	8.197±5.062	-	
			VL	7.731±4.990		
			MH	0.745±0.516		
			LH	2.702±2.816		
		Serial 7's	VM	8.206±4.726	-	
			VL	8.057±5.281		
			MH	0.771±0.501		
			LH	2.527±2.345		
	Female	Control	VM	16.056±18.719	-	
			VL	13.693±11.807		
			MH	2.006±1.227		
			LH	5.585±4.378		
		JOLO	VM	11.373±10.822	-	
			VL	10.427±7.733		
			MH	1.476±0.831		
			LH	3.819±2.522		
		SDMT	VM	14.318±17.383	-	
			VL	10.876±10.445		
			MH	1.500±1.507		
			LH	4.093±3.013		
		Serial 7's	VM	15.199±21.992	-	
			VL	11.656±12.316		
			MH	1.343±0.827		
			LH	4.233±3.951		

JOLO: Judgment of Line Orientation; SDMT: Symbol Digit Modalities Test; VM: vastus medialis; VL: vastus lateralis; MH: medial hamstring; LH: lateral hamstring
#Significant at the p-value <0.01
†Significant at the p-value <0.001

CHAPTER 4

DISCUSSION

The goals of this study were to determine the gender effects of cognitive loading tasks on knee stiffness and reactive muscle activation strategies. Previous research has identified that cognitive factors such as visual-spatial skills, processing speed, reaction time and memory may predispose individuals to noncontact knee injuries; and that these injuries occur as a result of disrupted muscle activation patterns and a failure to regulate joint stiffness. Moreover, gender differences may exist with some of these neurocognitive, neuromuscular, and stiffness characteristics as well, which may predispose females to a greater risk of knee injury (Adam, et al., 1999; Caplan, et al., 1985; Carcia, et al., 2005; Granata, et al., 2002; Hinsey, et al., 2010; Krishnan, et al., 2008; Krishnan & Williams, 2009; Líndal & Stefansson, 1993; Shultz, et al., 2001; Stumpf, 1993). However, current theories do not provide an adequate explanation for these potential differences. The primary findings of our study are that all cognitive loading conditions (JOLO, SDMT, and Serial 7's) slowed the muscle activation responses and reduced the amplitude of muscle activity, in both males and females. This resulted in diminished dynamic restraint capabilities, as evidenced by decreased joint stiffness after an unanticipated knee joint perturbation. While males presented with greater short-range stiffness, females generated greater overall knee stiffness when body size was considered. Females also demonstrated slower activation rates compared to males, regardless of the gender-biased cognitive loading task performed. These differences in muscle activation and the propensity for females to generate greater knee stiffness have also been observed during functional tasks and may reflect different motor strategies in response to sudden knee loading. Additional studies are warranted to determine how cognitive loads may be contributing to all non-contact knee injuries and the disproportionate incidence experienced among females.

Cognitive Loading Tasks

Changes in attentional demands within the central nervous system (CNS) can increase the risk of injury. Structures within the brain, such as the frontal, parietal, and occipital lobes, as well as the cerebellum, have important functional roles in this capacity. The parietal lobe receives and processes information, where the frontal lobe plans skilled muscle movements (Lehr, 2009). The occipital lobe assists with assimilating and processing visual information (Lehr, 2009), and the cerebellum integrates sensory information and the parietal lobe's coordination of voluntary movements. During non-stressful conditions, individuals can adjust their attention to incoming sensory signals and respond appropriately to situational demands (Nideffer, 1983). It is clear from our studies that the cognitive loading tasks significantly reduce knee stiffness and muscle activation. Increased cognitive loading can alter the ability to process information and narrow attention, leaving less mental capacity for a concurrent task. Salmon and Thompson (2007) found that performance decreased when performing a dual task of isometric maximal voluntary contractions (IMVC) of elbow flexors and a memory recall task of words. As the sensory complexity increases or a situation becomes more stressful, attention narrows and the ability to process information decreases (Nideffer, 1983).

With regard to gender differences, earlier studies have suggested that males perform better during visual spatial and mathematic tasks, while females excel on verbal and memory tasks (Adam, et al., 1999; Jones & Gallo, 2002; Klinteberg, et al., 1987; Vaquero, et al., 2004). In our study, we administered the JOLO (visual-spatial) and SDMT (verbal) before testing, and found that the scores followed previously established national norms, but did not reach alpha levels that would indicate significant gender differences. There is debate whether these potential cognitive differences are meaningful. For the JOLO, the national norm is 25.6 for males and 25.3 for females (Benton, et al., 1994); the SDMT national norm ranges from 61.93 ± 10.15 to 69.91 ± 12.64 (A. Smith, 1982). This is in contrast to the findings of Caparelli-Dáquer et al. (2009) and Jorm et al. (2004) who reported scores from the JOLO and SDMT that showed significant gender differences. Both studies used a sample size over 100 subjects per gender, compared to the sample size of 40 subjects in our study. It is difficult to know whether the lack of a significant difference in our study was due to the smaller sample size or to other factors. It is possible that the type and amount of mental practice or learning from past experiences could explain the difference in results. For example, it has been reported that females can closely match males' performance through training (Cherney, 2008; Gagnon, 1985; Subrahmanyam & Greenfield, 1994). Spence et al. (2009) found no gender differences ($p>0.05$) during a spatial selective attention skill, suggesting that females can perform as well as males given the same starting level and same training. Females can also learn at a higher rate and can eventually equal males, even if starting from different levels (Spence, et al., 2009). Kass et al. (1998) also found that females can increase their visual spatial abilities to the level of males with proper instruction and training. It is possible that females included in our study have unconsciously practiced visual spatial skills, especially those who have participated in sports such as soccer and basketball that may selectively promote visual-spatial skills. With descriptive analysis of the groups and individual results, one could expect to identify females from our study who performed as well as males, and vice versa at the cognitive tasks that are supposed to be gender biased. It is likely that through unspecified training histories, cognitive task performances between males and females could be similar, and that individual variability in cognition supersedes overall gender differences.

It has been hypothesized that hormones can influence the development of spatial abilities differently in males and females (Kimura, 1992; McGee, 1978). In particular, neurobiological studies suggest that higher levels of prenatal testosterone may be linked to brain development favoring spatial abilities and physical attributes beneficial to athletic performance. Kimura (1992) also found that females with high levels of testosterone scored better on a spatial task than did females with low levels of testosterone. The opposite pattern was found in men, where those with high levels of testosterone scored worse than men with low levels. This suggests that an optimal level of testosterone is necessary to excel at spatial tasks. The rise and fall of spatial abilities tend to parallel the development of sex hormones (McGee, 1978). Gender differences become apparent around adolescence, but as education and experiences of males and females are more shared, differences in spatial ability may be less pronounced (Linn & Petersen, 1985; Stumpf & Klieme, 1989). Although attempts were made to eliminate testing errors related to the menstrual cycle in our female subjects, hormone levels were not measured in our study and our results could be due to higher levels. Schmidt et al. (2009) also found similar patterns of brain activation using functional magnetic resonance imaging data (fMRI) between males and females during a verbal task that increased the demand on working memory. Males and females performed equally well in terms of accuracy and response times during the cognitive task, and also used similar activation patterns in the brain (Schmidt, et al., 2009). The influence of hormones may explain gender similarities in cognition; however, physiologically hormone fluctuation can cause an increase or decrease in joint laxity, affecting the level of stiffness and joint stability.

Stiffness

Stiffness is an important factor and a fundamental measure of joint stability in response to a load (McNair, et al., 1992; Swanik, et al., 2005). An increase in stiffness can help stabilize the joint; however, factors such as joint position and laxity can influence the appropriate level of stiffness regulation needed to optimally stabilize the joint (Huxel, et al., 2008). Several previous studies suggest that females have less stiffness than males due to factors such as reflexes and hormonal differences. Shultz et al. (2005) reported that females had increased laxity and decreased joint stiffness at the knee compared to males due to hormonal differences. Females had an increase in joint laxity that coincided with days of the menstrual cycle when estradiol and progesterone levels were elevated (Shultz, et al., 2005). Wojtys et al. (1998) found similar results and also reported that more ACL injuries occurred during the ovulatory phase of the menstrual cycle and less during the follicular phase. However, these studies tested knee stiffness passively with little contribution by muscle to dynamically stabilize the knee, and recent research suggests these laxity tests do not correlate with functional joint stability (Eastlack, et al., 1999; Queale, et al., 1994; Snyder-Mackler, et al., 1997). We did observe that males had a greater short-range stiffness during the first 4° of the movement. Short-range stiffness is usually higher and attributed to passive connective tissue properties as well as the reverse-pivoting of existing actin-myosin cross-bridges. Sinkjaer et al. (1988) found short-range stiffness at the ankle. Between 2° to 7°, they found ankle stiffness to range from 2-4 Nm/deg with a standard deviation of <0.65 Nm/deg (Sinkjaer, et al., 1988). Although the stiffness values were found at the ankle, they are similar to our non-normalized results at the knee. It is plausible that hormones may influence the elasticity of connective tissue in females, or that greater muscle mass in males would result in a greater number of cross-bridges. This may explain, why short-range stiffness did not differ between genders when our data was normalized to body mass. Hinsey et al. (2010) found that when relaxed and reacting to the 40° perturbation, females had more stiffness than males when relaxed.

In our study, females had greater reactive knee stiffness than males for the total 40° movement when normalized to body mass (kg). In contrast to our findings, Granata et al. (2002) found that males had greater stiffness than females at three hopping frequencies (3.0 Hz, 2.5 Hz, and a preferred hopping rate) and this was suggested as a factor to help prevent knee injuries in males. However, they did not normalize stiffness to body mass, which may alter these interpretations. Several other studies have normalized stiffness to body mass, and found the opposite gender results. Most studies that normalized stiffness to body weight used protocols involving hopping/vertical loading, whereas our protocol was taken place in a constrained, seated position with minimal axial loading. Cammarata et al. (2008) found that males had greater frontal plane stiffness than females during valgus loads and that stiffness increased with greater external loads. They also found that valgus stiffness was roughly 20% higher than varus stiffness. Padua et al. (2006) found that males had 0.49±0.14 kN/m stiffness values and females had 0.50±0.20 kN/m stiffness values during a 2-legged hopping protocol at 2 different frequencies (3.0 Hz and self selected rate). But, again no differences existed between gender when stiffness was normalized to body mass.

This is the first study that directly links increased cognitive load to alterations in or decreased dynamic restraint. Although it has been suggested that males and females have a better performance on certain cognitive loading tasks compared to the opposite sex, we found that there was no difference among the cognitive loading conditions. However, all 3 cognitive loading tasks decreased the capacity of subjects to reactively stiffen their knees. These types of conditions may interact leaving individuals vulnerable to failures in neuromuscular control and the dynamic restraint mechanism when one is exposed to unforeseen cognitive and physical loading outside of a controlled laboratory setting. Additional research must be completed to appreciate what is the optimum level of stiffness because while high levels of stiffness may intuitively appear to provide greater stability, it may simultaneously limit functional performance. Conversely, lower stiffness levels would permit the unconstrained joint motion needed for high-speed physical activities, but exposed ligamentous structures to excessive stress and/or strain.

Electromyography

Stiffness is regulated through preparatory and reactive muscle recruitment strategies based on functional demands of a task, but these must be balanced with the needs to maintain joint stability (Huxel, et al., 2008). Co-contraction of the quadriceps and hamstrings can further stiffen the knee joint, promote stability, and protect the knee from joint injury, but could also reduce joint excursions and velocities needed to perform functional tasks during physical activity (Louie & Mote, 1987; Markolf, et al., 1978; Swanik, et al., 2005).

Neuromuscular control has been implicated as a primary contributor to a higher incidence in non-contact knee injuries in females than males. We found that males had greater MVIC's (maximum voluntary isometric contractions) in both hamstrings and quadriceps than females. A balance of force between both muscles is important for normal knee function. Andersen et al. (2001) found that the ratio of hamstring-to-quadriceps strength was significantly less in females than male athletes and greater hamstring strength is necessary to prevent excessive anterior shear loads on the tibia. Malinzak et al. (2001) found that female athletes had increased quadriceps and decreased hamstring muscle activation compared to males when running, side-cutting, and cross-cutting. On average, females weighed less than males; it is possible that mass and moment of inertia account in part for muscle differences and whether peak torque was normalized to body mass (Malinzak, et al., 2001).

The importance of a balanced or well-coordinated recruitment of the thigh muscles acting on the knee is further understood by considering the timing of activation. No differences between genders were found in electromechanical delay (EMD) and pre-movement area of muscle activation. Both males and females had similar activation strategies at the beginning of the movement. No observation was made that may indicate heightened arousal levels such as increased resting tone (EMG) or torque prior to the perturbation and would bias reflexive activation. This agrees with a study by Carcia et al. (2005) who also found that there were no gender differences in muscle responses at different knee flexion angles and suggests that neuromuscular recruitment patterns were similar between males and females. However, we found that females were slower to reach peak EMG than males. Nagano et al. (2007) also found that females took longer time to reach peak ground reaction force than males after the time of foot contact during a single limb drop landing. An increase in internal tibial rotation combined with greater quadriceps activity and lower hamstring activity may be a cause for the higher incidence of noncontact ACL injuries (Nagano, et al., 2007). An instantaneous compensatory and protective response would be necessary to maintain and prevent injury, otherwise it could make females more susceptible to knee injuries.

We also found that the quadriceps and hamstrings follow a recruitment order starting with VM followed by VL, LH, and MH. While it maybe suggested this is a "quadriceps dominant" strategy, our methods used a sudden knee flexion move, which would most likely excite muscle spindle reflexes in these muscles first. Quadriceps strength can account for functional outcomes after surgeries (Chmielewski, et al., 2002). Clinicians and practitioners concentrate primarily on strengthening the quadriceps, especially VM, after an ACL injury because of frequent atrophy; however, there is little evidence to support the belief that performance of specific quadriceps exercises during the initial postoperative weeks results in improved outcomes following an ACL reconstruction. Shaw et al. (2005) found that acute postoperative quadriceps exercises resulted in improvements in muscle strength and lower limb function, faster recovery in range of motion, and a lower incidence of abnormal knee laxity (Shaw, et al., 2005). Our findings that males recruited their muscles faster than females are in contrast with those reported by Carcia et al. (2005), who found that females recruited their quadriceps faster than males, and hamstrings were recruited before the quadriceps. Shultz et al. (2001) also found that females had faster quadriceps response than males during internal and external perturbation conditions. Methodological differences performing a rotary perturbation in a single leg stance may in part explain the contrasting findings. High quadriceps activation increases anterior translation of the femur on the tibia. The VM activated the fastest, which can cause more internal tibial rotation. In our study, the hamstrings were slower to activate and had lower activation rates. This can cause a relatively weak co-contraction ratio needed to protect the knee joint from excessive anterior tibial strain. Also, the MH was the slowest and weakest to activate, which makes it difficult to counteract the VM during anterior tibial translation.

No significant gender differences were found among the muscles during the perturbation; however, our results showed a trend in which females produced greater peak EMG, had faster muscle activation onsets, and greater muscle activity than males. Croce et al. (2004) determined differences between pre- and post- pubescent males and females in their quadriceps and hamstrings muscle activation patterns for pre- and post-landing stages. They found no differences between genders, but found significant developmental level differences ($p<0.05$). Post-pubescent subjects (19-29 years old) displayed a greater level of hamstring co-contraction prior to landing than pre-pubescent subjects (7-11 years old). This suggests that older individuals used a strategy of pre-tuning the hamstrings by using more central nervous system feed-forward activation prior to landing to control the ground reaction forces and anterior tibial displacement experienced by the knee (Croce, et al., 2004). However, Huston and Wojtys (1996) found that the timing and pattern of muscle activation in response to an anterior-directed force on the proximal tibia was different between male and female athletes were males required less time to generate peak torque in their hamstrings compared to females.

An increase in general muscle tension or a decrease in concentration due to attentional demands can reduce an individual's control over muscle coordination and timing (Andersen & Williams, 1988; R. E. Smith, 1980). Our study shows that all three cognitive loads (JOLO, SDMT, Serial 7's) decreased muscle performances to a similar extent. Performing only one cognitive loading task significantly slowed the onset of muscle activation and time to reach peak torque. The amount of muscle generated at peak torque also decreased with cognitive loading tasks. Also, individual muscles were negatively affected by cognitive loading tasks. In the first 250 ms of the movement, muscle activity was reduced by approximately 60% while performing a cognitive loading task compared to the control condition. In addition, from 250-500ms after the movement, muscle activity was still 20% lower than the control condition. Having more quadriceps activity is considered by some to negatively effect knee stability by placing an individual at an increased risk of ACL injury, particularly near the end range of extension, where the hamstrings have limited ability to restrain anterior tibial translation (Carcia, et al., 2005). However, this data suggests that more research is needed because during physical activity, when sudden knee flexion loads are common, the quadriceps are also the primary antigravity muscles needed to absorb, store or dissipate ground reaction forces, in effect, stress shielding ligaments such as the ACL in the process.

Limitations

One factor that may have affected our results is that we used standard body weight (kg) instead of lean body mass. Although physically active participants were recruited, all had different body compositions. Another limitation may be that we used subjective questionnaire for females with regard to their menstrual cycle. Females were asked to participate if they were in days 0 to 12 of their menstrual cycle and to answer if they were currently taking any medication (including contraceptives) during the PAR-Q. It was difficult to assess whether the answers were truthful or accurate. Additionally, during testing, the control condition was performed first to ameliorate safety concerns and risk of injury during the knee perturbations. To speed data collection, the conditions were administered in the following order: JOLO, SDMT, and Serial 7's, which could create an order effect. However, the brief testing period, examination of pilot data and statistical analyses make this limitation unlikely.

Conclusion

The results of this investigation indicate that females demonstrate greater total stiffness than males, but had similar muscle activation amplitudes. Also, regardless of the purposeful inclusion of gender-biased cognitive tasks, the three types of cognitive loads all decreases stiffness and slowed neuromuscular performance. Different kinds of cognitive tasks may all decrease the ability of healthy individuals to reactively stiffen their knee joint regardless of gender. Cognitive loading appears to interfere with the normal force attenuating properties of eccentric muscle contractions, which impairs the dynamic restraint mechanism and may expose individuals to joint injury. This suggests that while cognitive loading may be use to enhance the level of difficulty during conditioning and rehabilitation tasks, caution should be used as they significantly impair an individual capacity to reactively stiffen their joint should unanticipated events occur.

CHAPTER 5

LITERATURE REVIEW

Unintentional injuries to the anterior cruciate ligament (ACL) are very common within the knee joint. About 80,000 up to 250,00 ACL injuries occur annually in the United States with the highest incidence in individuals between ages 15 to 25 years old (Griffin, et al., 2000; Griffin, et al., 2006). More than 70% of ACL injuries occur through noncontact mechanisms such as decelerating or landing. During these mechanisms the lower extremity anti-gravity muscles must absorb large ground-reaction forces that are five times greater than the average body weight (Griffin, et al., 2000; P. J. McNair & Prapavessis, 1999; Swanik, et al., 2007). Neuromuscular control determines the timing and level of muscle activation needed to stiffen the knee in response to these external forces. The stiffness regulation strategies can help enhance dynamic knee joint stability and protect ligaments from excessive stress by absorbing loads through eccentric lengthening of muscles (Demont, et al., 1999; Fonseca, et al., 2004; Lephart, et al., 1992). However, a brief disruption in the cognitive processes can cause the control of muscle activation to disrupt motor programs placing the individual at an increased risk of injury (Swanik, et al., 2007). Attention to different cognitive loads, such as visual spatial awareness or verbal/communication, is often required during physical activity and may interact with stiffness regulation strategies to predispose certain individuals to coordination errors. Moreover, sex differences have been found related to neurocognition and stiffness regulation. It has been suggested that females have less joint stiffness compared to males due to factors such as slow muscle responses and ineffective neuromuscular activation (Henry & Kaeding, 2001). Females also show deficits in visual spatial tasks, whereas males show deficits in verbal tasks (Jones & Gallo, 2002; Klinteberg, et al., 1987). Studying these variables may identify additional, underlying risk factors for noncontact knee injuries and allow for the development of appropriate strategies for injury screening and prevention.

Joint Stability

The maintenance of functional joint stability encompasses two primary aspects. The first, static restraint, is provided by ligaments and other non-contractile joint tissue that guide normal arthrokinematics (Colby, et al., 2000; Woo, et al., 1991). The second is provided by the muscles acting to absorb loads and promote joint compression, referred to as dynamic restraint (Johansson, 1991). To prevent injuries, static and dynamic restraints act in synergy, by accommodating the rapidly changing, high joint loads experienced functionally during movements (Colby, et al., 2000).

Static restraints (ligaments, bones, capsules) alone offer inadequate stability to the knee during physiologic loading (Colby, et al., 2000) The primary role of static restraints is mechanical, guiding normal joint kinematics; however, capsuloligamentous tissue also has a sensory role in detecting joint motion and position, and mediating control for dynamic stability (Swanik, et al., 1997). Dynamic restraints (muscles) act as the primary stabilizers of the knee during functional tasks. The dynamic restraint system is influenced by mechanoreceptors, which detect deformation of capsuloligamentous and musculotendinous tissues, and encode sensory signals that provide information on joint forces, positions, and motions. There are two types of mechanoreceptors identified in muscle: muscle spindles and Golgi tendon organs (GTO's) (Arnold & Docherty, 2006). Muscle spindles detect changes in muscle length and the rate of length change (Barker, 1974; Clark, et al., 1985; Guyton, 1981). Each spindle contains intrafusal and extrafusal muscle fibers. Intrafusal fibers are innervated by afferent nerves; extrafusal fibers have contractile properties and are innervated by gamma motor (efferent) nerves (Barker, 1974; Leksell, 1945; Swanik, et al., 2005; Swanik, et al., 1997). The gamma motor nerves then regulate the sensitivity of muscle spindles to length and velocity changes, thus accommodating for muscle shortening while continuously transmitting afferent signals (Barker, 1974; Swanik, et al., 2005). Gamma efferents are also directly influenced by descending signals from the cerebral cortex and reflexively by afferent signals from other cutaneous, muscular, and articular receptors, which therefore help control muscle spindle sensitivity. When a muscle is stretched, muscle spindles detect the length change and send signals to the spinal cord, which will trigger the stretch reflex to resist changes in length by contracting the muscle. These signals are also transmitted along ascending tracts to supraspinal centers to assist with the perception of joint motion and position and formulation and modification of motor control strategies (Freeman & Wyke, 1966; Gardner, et al., 1949; Swanik, et al., 2005; Warren, et al., 1993).

Golgi tendon organs detect changes in muscle tension and protect muscles from excessive loads by reflexively inhibiting the agonist and activating the antagonist muscles (Guyton, 1981; Hutton & Atwater, 1992; Swanik, et al., 2005). Golgi tendon organs can detect a large range in change and rate in tension, but can also facilitate muscle contractions under certain functional conditions, referred to as reflex reversal (Kandell, et al., 1996). If the muscle tension exceeds a certain threshold, the GTO's overcome muscle spindle signaling for muscle excitation and conversely send strong inhibitory signals to the spinal cord causing agonist and synergistic muscles to relax. Therefore the cumulative, reflexive influence of muscle spindles and GTO's is combined with descending motor commands to mediate muscle timing and activation levels.

The capacity of muscle tension to assist with joint stabilization is dictated by its stiffness properties (Lieber & Fridén, 1993). Stiffness refers to the degree to which a muscle resists changes in length (change in force/ change in length). The mechanical property of stiffness is characterized by objects that deform under the influence of an external force, generate force to oppose an external force, and can store elastic energy (Latash & Zatsiorsky, 1993). The level of muscle activation during a certain movement largely determines muscle stiffness and hence optimum joint stiffness. For instance, increasing muscle activation causes an increase in stiffness, which has been shown to contribute to joint stability (Henry & Kaeding, 2001; Lieber & Fridén, 1993). Muscle contractions can increase knee joint stiffness 10-fold (Kochner, et al., 1994; Markoff, et al., 1990; P.J. McNair, et al., 1992; Swanik, et al., 1997). The muscle forces generated to stabilize a joint ultimately results from actin-myosin interactions within the sarcomere (Lieber & Fridén, 1993). Muscle fibers also have intrinsic properties that contribute to the length-tension and force-velocity relationships. Length-tension relationships demonstrate that muscles are most effective in joint stabilization when they are at an optimal sarcomere length (Lieber & Fridén, 1993). When muscles are at a shorter or longer sarcomere length, force tends to decrease. Dynamic joint stabilization is also affected by the force-velocity relationship. Muscle contractile velocity is a direct function of the load imposed on it (Lieber & Fridén, 1993). At high shortening velocities, small forces are generated, while at low velocities, muscle forces are high. Stiff muscles resist stretching episodes more effectively, have greater tone, and provide more effective dynamic restraint to joint displacement (Johansson, 1991). Muscle stiffness is also partially determined by the intrinsic properties of the muscle and feedback control provided by the nervous system to stabilize muscle force and regulate muscle fiber recruitment (Lieber & Fridén, 1993). It is suggested that a fast motor response of 30-70 milliseconds (ms) is necessary to reactively stiffen the joint and be effective in protecting joint structures (Swanik, et al., 2004). Compared to this, individuals with knee injuries have slightly longer delays in their motor response (~99 ms) compared to a healthy uninjured group (Swanik, et al., 2004). Having a delayed motor response presents inadequate muscle activation and stiffness, which may increase the risk of knee injury.

During physical activity, the energy exchange that occurs between muscles, tendons, and ligaments is important for movement efficiency, and can be influenced by muscle stiffness to increase performance or prevent injury. Sinkjaer et al. (1988) evaluated the mechanical response to a stretch in the ankle dorsiflexors at different levels of voluntary contraction. The total mechanical response of an active muscle was defined as the sum of intrinsic responses (contractile apparatus plus mechanical behavior of passive tissues), and the reflex mediated response (Sinkjaer, et al., 1988). The reflex component appeared strong enough to increase muscle stiffness beyond that which was produced by the intrinsic properties and modify the joint's mechanical responses to external perturbations. It was found that at 30% of a maximal voluntary contraction (MVC), the reflex increased overall stiffness beyond the intrinsic stiffness by 75% (Sinkjaer, et al., 1988). This demonstrates that when all motor units in the muscle are recruited, the muscle becomes less responsive to brief fluctuations (Sinkjaer, et al., 1988).

In a study by Arampatizis et al. (2001), stiffness was measured by examining muscle activation during a drop jump. They found that leg and ankle stiffness increased with shorter ground contact times during a jump. The study showed that muscle stiffness influenced the vertical take-off velocity during the positive phase of a drop jump (Arampatzis, et al., 2001). An optimum stiffness value was observed to maximize mechanical power (Arampatzis, et al., 2001). This observation is consistent with the theory that stiffness, to some extent, determines how effectively and rapidly internal forces are transmitted through to the skeletal system, and enhance force production (Wilson, et al., 1994). This also supports the role of muscle stiffness as a critical component of joint stabilization. As muscle stiffness increases, joint stability is enhanced and aids in resisting sudden joint movements.

Neuromuscular Control

Neuromuscular control is an important determinant in guiding motor behavior for functional performance and injury prevention. Neuromuscular control is defined as the transformation of neural information or motor commands into physical energy via muscle activation (Swanik, et al., 1997). Neuromuscular control regulates muscle tension to control specific joint movements, and contributes to dynamic restraints to maintain the integrity of capsuloligamentous structures from extraneous movements thereby maintaining stability throughout a normal range of motion. The dynamic restraint mechanism protects capsuloligamentous structures from excessive joint loads through muscle stiffness and is influenced by neuromuscular characteristics such as preparatory and reactive muscle activation, (Swanik, et al., 2004). A decrease in neuromuscular control can allow abnormal stress to be placed on ligament structures that may surpass the ultimate failure strength of that ligament and cause significant injury.

Neuromuscular coordination of the knee joint includes feed forward and feedback motor control loops. Feed-forward neuromuscular control involves planning movements and preprogramming muscle activation based on past experiences (Dunn, et al., 1986; Leksell, 1945; Swanik, et al., 2005). Feed-forward control activates muscles around the joint before excessive loading occurs, which will aid in absorbing large forces at initial ground contact, and in turn decrease stress on the ligaments. Feedback neuromuscular control continuously modifies muscle activity primarily through vision and mechanoreceptive signals, to maintain stability and maximize performance. Feedback strategies may alter the pre-programmed strategies of muscle activation in response to unanticipated external stimuli within the individuals' environment (Hewett, et al., 2005). Imbalanced or delayed neuromuscular firing can lead to improper limb positioning and place an increase strain or load on the knee via suboptimal stiffness regulation (Hewett, et al., 2005).

Swanik et al. (2004) identified neuromuscular characteristics related to dynamic restraint of the knee in females. The females who had an ACL injury showed greater preparatory activity in the lateral hamstring muscles compared to uninjured females. Contraction of the hamstring muscle produces a posterior-directed protective force, decreasing shearing at the knee and thus acts as an ACL agonist (Henry & Kaeding, 2001; Lephart, et al., 1992; Wojtys & Huston, 1994). The quadriceps are considered antagonistic (increasing stress) to the ACL and during forceful knee extensor activities, causes anterior tibial translation. An increase in anterior tibial translation can pre-load the ACL and increase the risk of knee injury. This research suggests that individuals may develop feed-forward strategies to compensate for mechanical instability through dynamic restraint (Dhaher, et al., 2005; Swanik, et al., 2004). Ultimately, co-activation of both quadriceps and hamstring muscles can help reduce laxity and strain on the ACL by increasing joint compressive loads and decreasing tensile forces experienced by the cruciate ligaments (Markolf, et al., 1981; Rudolph, et al., 2000; Shimokochi & Shultz, 2008). Events that disrupt feed-forward and feedback neuromuscular control processes may alter muscle stiffness regulation and dynamic restraint capabilities, exposing the individual to aberrant joint biomechanics and increasing the risk of injury.

Cognitive Loading

Several neurocognitive phenomena have been identified that have the potential to disrupt the formulation and execution of preparatory and reflexive muscle activation strategies. A change in attentional demands or lack of concentration within the central nervous system (CNS) is a major cause of stress-related injuries (Andersen & Williams, 1988). Several structures within the brain, including the frontal, parietal, and occipital lobes, as well as the cerebellum all have important functional roles in this capacity. The parietal and frontal lobes receive and process information, and help control and plan skilled muscle movements, respectively (Lehr, 2009). The occipital lobe assists with the assimilation and processing visual information (Lehr, 2009), and the cerebellum integrates sensory information and the parietal lobe's coordination of voluntary movements. Changes in such brain functions can cause neurocognitive deficits. During non-stressful conditions, individuals can adjust their attention to incoming sensory signals and respond appropriately to situational demands (Nideffer, 1983). Stressful situations require a broadened attention and external focus. This helps individuals react to complex, rapidly changing environments similar to many sports and physical activities. As the sensory complexity increases or a situation becomes more stressful, attention narrows and the ability to process information decreases (Nideffer, 1983). An individual can excessively filter sensory information when attention becomes more internally focused and control of the feedback loop within the neuromuscular system becomes more difficult (Nideffer, 1983; Swanik, et al., 1997). Loss of sensory information may cause an increase in the number of errors during a movement execution because attention is diverted from the joint/muscle receptors feedback, to the stressful situation making the individual overly-analytical (Nideffer, 1983). Under a stressful situation, an individual may not be able to react to the external stimuli or may attend to stimuli irrelevant to the present task and fail to detect vital cues (Andersen & Williams, 1988). During these situations, the visual field can also narrow, diminishing the ability to properly pick up visual cues in the periphery, which can increase the risk of injury (Andersen & Williams, 1988).

Recent clinical data support this theory when it was revealed that neurocognitive characteristics, such as reaction time, processing speed, and visual spatial skills may have a role in noncontact knee injuries by affecting both movement planning and reaction to unanticipated events. Swanik et al. (2007) examined the relationship between decreased neurocognitive performance and noncontact ACL (NCACL) injuries in athletes. The athletes with and without NCACL injuries were tested using the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) software (Swanik, et al., 2007). This test examined deficits in reaction time, processing speed, working memory and attention, and concentration. The results showed that athletes with NCACL injuries had lower ImPACT scores before sustaining their injuries than the athletes who did not have NCACL injuries (Swanik, et al., 2007). Swanik et al. (2007) concluded that situational awareness is a prerequisite to executing complex motor programs during physical activity. Increases in a person's cognitive load (amount and speed of neural processing) may slow reaction time and alter the timely formation or execution of muscle activity, which is associated with poor coordination (Blackburn, et al., 2004; Hewett, et al., 2004; Swanik, et al., 2007). Therefore the deficits in reaction time, processing speed, and visual and verbal memory could cause errors in judgment or a loss of coordination by disrupting neuromuscular control, which may compromise dynamic restraint and increase the risk of injury (Swanik, et al., 2007).

Salmon et al. (2007) also studied the decrement in performance of a physical task with a concurrent cognitive load. There seem to be cognitive limits in ones' ability to divide attention between two or more actions at the same time. The high demands of executing a motor task may leave less mental capacity for a concurrent cognitive load and vice versa (Salmon & Thomson, 2007). In the study, the subjects performed a dual task of isometric maximal voluntary contractions (IMVC) of elbow flexors and a memory recall task of words. The results showed that both the mean force production of the IMVC's and memory recall were reduced while performing a dual task. The average of decrement in force and number of words recalled was approximately 16% (Salmon & Thomson, 2007). This may occur because central processing of dual tasks prioritizes the cognitive task first and the motor task cannot occur until the cognitive task is complete. This brings about measurable impairments of the motor task and decreases force production (Salmon & Thomson, 2007). However, there is still limited research regarding reactive muscle stiffness when performing a cognitive task concurrently, and the interaction of sex differences in both neurocognition and stiffness regulation has not been investigated.

Gender Differences

Females are six times more likely to suffer a noncontact knee injury than males and it is suggested that neuromuscular factors are the primary contributor (Beck & Wildermuth, 1985; Bjordal, et al., 1997; Griffin, et al., 2000). While these numbers are discouraging, previous studies also do not address any potential mechanisms explaining why a large number of males also sustain unintentional knee injuries (Beck & Wildermuth, 1985; Bjordal, et al., 1997; Griffin, et al., 2000). Gender differences have been identified with knee laxity, as well as cognitive performances (Adam, et al., 1999; Cammarata & Dhaher, 2008; Henry & Kaeding, 2001). Evidence suggests that females have an increased laxity and a decrease in joint stiffness at the knee compared to males due to hormonal differences (Cammarata & Dhaher, 2008; Deie, et al., 2002; Rau, et al., 2005; Shultz, et al., 2005; Wojtys, et al., 1998). These factors may place the female knee joint at a higher risk of injury. Schultz et al. (2005) studied the differences in knee joint laxity between genders across the female menstrual cycle. They found that females had an increase in knee joint laxity that coincided with days of the menstrual cycle when estradiol and progesterone levels were elevated (Shultz, et al., 2005). It has been reported that estrogen is known to cause decreased ligament stiffness (Henry & Kaeding, 2001). Gender differences were cycle dependent, as well as dependent on the concentration of hormones (Rau, et al., 2005). It is suggested that differences in knee laxity between males and females were greatest when females were in the early luteal phase of their menstrual cycle (Deie, et al., 2002; Shultz, et al., 2005). However, Abt et al. (2007)

found conflicting results stating that neuromuscular and biomechanical characteristics are not influenced by estradiol and progesterone fluctuations. Although the consensus is lacking regarding the relationship of menstrual cycle phase to knee laxity in females, hormonal factors are controlled by being tested within days 0-12 of their menstrual cycle.

Another study reported that sex differences existed in quadriceps and hamstring neuromuscular control. Poor neuromuscular control can affect the ability to minimize dangerous loads to the knee (Krishnan, et al., 2008). Granata et al. (2002) evaluated whether females demonstrate less leg stiffness during a two-legged hopping task compared to males. They found that leg stiffness in females was about 77% of the leg stiffness in males (Granata, et al., 2002). Granata (2002) suggested that there are neuromuscular and biomechanical differences between males and females when performing a two-legged hopping task. Females tend to contract their quadriceps faster and use a higher magnitude of muscle activity compared to males, indicating that females may use different motor strategies to complete functional tasks (Carcia, et al., 2005; Krishnan, et al., 2008). The higher level of quadriceps activity in females can lead to greater anterior tibiofemoral shear loads, predisposing them to a knee injury (Krishnan, et al., 2008).

Gender differences in cognitive performance have not been examined with respect to dynamic stabilization and injury proneness. Males tend to excel on visual spatial and mathematic tasks, while females demonstrate advantages on verbal tasks (Adam, et al., 1999; Jones & Gallo, 2002; Klinteberg, et al., 1987; Vaquero, et al., 2004). Adam et al. (1999) studied gender differences in information processing strategies of choice reaction time tasks that required a verbal response to a spatial location target stimulus. They found that males had faster reaction times in spatial choice reaction time tasks compared to females, suggesting that there were differences in processing strategies. Klinteberg et al. (1987) assessed cognitive approaches of males and females in a reaction time task and a visual spatial perceptual maze task. Solving mazes involved visual spatial abilities like forming a visual representation of the target pattern of the maze. Males were consistently faster than females during the tasks; however, females were more accurate than males, and used a more cautious strategy (Klinteberg, et al., 1987). Another study found similar cognitive sex differences using the Mini-Mental State Examination (MMSE) (Jones & Gallo, 2002). The MMSE is a short assessment instrument that assesses orientation to time and place, attention, memory, and ability to follow commands. The most difficult items on the test were serial subtraction and spelling “w-o-r-l-d” backwards. It was shown that males were more likely than females to make mistakes on spelling backwards, whereas females erred on serial subtractions (Jones & Gallo, 2002). Neurocognitive abilities appear to be sexually dimorphic; but no research exists studying their interaction with regard to knee stability and it is unclear whether the impairment of neuromuscular control and joint stability depends on the type of cognitive task performed.

Summary

Neuromuscular control, stiffness regulation, cognitive loads, and gender differences are factors that may all be associated with knee injuries. There are still a limited number of studies that support the relationship between neurocognitive function and the cause of knee injuries. An investigation of knee stiffness measured under different cognitive tasks could be insightful and increase the importance of neuromuscular control in regard to injury prevention and rehabilitation, and further our understanding of the disparity between sexes related to unintentional knee injuries.

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APPENDIX A. INFORMED CONSENT FORM

Research Study: A Gender Comparison of Reactive Knee Stiffness Regulation Strategies Under Cognitive Loads

Investigators: Allison Kim B.S. (Graduate Assistant) and
Charles Buz Swanik, PhD, Associate Professor
(Department of Health, Nutrition and Exercise Sciences)

1. PURPOSE/DESCRIPTION OF THE RESEARCH

Introduction

You are invited to take part in a research study to compare knee stiffness differences between males and females while distracted. The distraction consists of different mental tasks such as counting backwards and matching symbols to numbers. Your participation is voluntary and you are no way obligated to take part in this testing. You may withdraw your participation in this study at anytime without penalty.

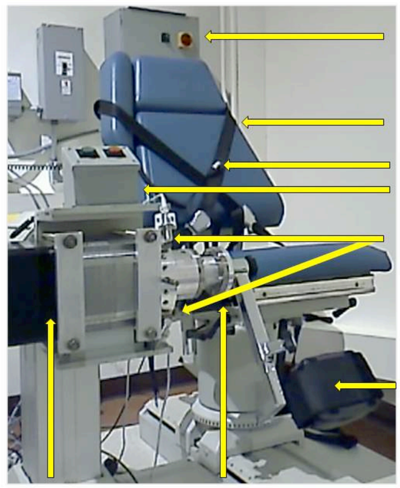
Purpose

The purpose of this research is to determine if males and females have different strategies to resist knee bending in response to mental tasks that distract a person's concentration. Also, it will help determine whether mental distraction during physical activity can lead to injury. The findings will help provide more evidence on the role of mental tasks and muscle contraction strategies in protecting the knee between males and females.

Eligibility

Approximately 40 people will participate in this study (20 men and 20 women. If you agree to participate, you will be scheduled for one testing session that will last approximately 1 1/2 hours. This testing will occur in the Human Performance Laboratory in the Fred Rust Arena at the University of Delaware, Newark DE 19716. You will be asked to wear active shorts during testing.

Stiffness and Proprioception Testing Device



Procedures

We will test the stiffness of your knee joint when your thigh muscles contract and relax. Testing will be performed using the custom-built stiffness device (SPAD—shown above) that will measure your muscle contractions and how your knee resists bending. This is a seated device that will measure the strength (force) of your thigh muscles during the test.

Before testing, you will fill out a Physical Activity Readiness Questionnaire (PAR-Q) to look at your activity level. You will then warm-up on the bike for 5 minutes and stretch your muscles. In order to determine when your muscles turn on and off, we will tape small sensors over the muscles in the front and back of your thigh with adhesive skin tape after the skin over the muscles has been shaven, abraded, and cleansed with an alcohol swab. Hypoallergenic tape or non-tape methods of attaching the equipment will be available if you are allergic to adhesive skin tape. Cables from the sensors will be attached to a small box near you during the tests. The box sends information about your muscles to a computer.

To test knee stiffness, you will be seated securely in a chair with the knee (of the leg to be tested) placed in a splint, so extra movements will not occur during testing. Once your body and leg are stabilized, your leg will be in a slightly bent position. From this position you will be asked to push or pull against the device as hard as you can for a few seconds; this will be performed three times. You will then be asked to relax your muscles before the test begins. You will also be asked to complete tasks such as counting backwards, memorizing numbers, or matching lines. Each condition will be tested 5 times. Sometime within 10 seconds of starting each test, your leg will be moved a short degree in backward rotation (knee flexion) by the device. When you feel the motion you will react and try to stop knee flexion by contracting your muscles.

You will hold an emergency stop switch in your hand so that you can turn the device off at any point during the testing procedure. The tester will also hold an emergency stop switch. Emergency stop sensors are also located in the device motor and on the attachment arm, so that your leg will not be moved beyond your normal limits.

2. CONDITIONS OF SUBJECT PARTICIPATION

You should not participate in this research study if you have a history of:

1. Previous injuries to the lower back, hips, knees, or ankles;
2. Any injuries to the test leg within the last 1 year;
3. Any hearing impairments or complications;
4. If you are pregnant; or
5. Neurological or cardiovascular problems that limit moderate physical activity

Your participation in this research is completely voluntary and you may withdraw from this study at any time without penalty.

If you are physically injured during laboratory testing procedures, you will receive immediate first aid care. If you require additional medical treatment, you will be responsible for the cost.

3. RISKS AND BENEFITS

You may experience some muscle or joint soreness within the next few days following the testing session. The soreness is similar to what you may feel following a vigorous weight lifting routine. There is minimal risk of muscle and/or joint injury (i.e. pulled muscle, joint sprain) as a result of testing Close supervision, use of rest periods, and use of emergency stop switches during testing will minimize risks involved with this protocol.

4. CONFIDENTIALITY

Each subject will be identified by a case number and the investigators will have access to the data. Information and data will be stored on a computer until the study is completed and published. Neither your name nor any identifying information will be used in any publication or presentation resulting from this study. Following completion of the study, the data will be copied, removed from the computer, and stored in a locked cabinet indefinitely. The data may be used in the future for comparisons with data from other research studies.

4. FINCANCIAL CONSIDERATIONS

There will be no compensation for your participation.

5. CONTACTS

Any questions or concerns regarding this research study should be directed to:

Charles "Buz" Swanik, PhD, ATC
151 Human Performance Laboratory
c/o Fred Rust Ice Arena
541 South College Avenue
University of Delaware
Newark, Delaware 19716
Phone: (302) 831-2306

Any further questions regarding your rights as a participant in a research study should be directed to

Chair of the Human Subjects Review Board
Office of the Vice Provost for Research
210 Hullihen Hall
University of Delaware
Newark, Delaware 19716
Phone: (302) 831-2137

6. SUBJECT'S ASSURANCE

I have read the above informed consent document. The nature, demands, and risks and benefits of the study described above have been discussed with the investigators. I have been given the opportunity to ask questions regarding this study and they have been answered to my satisfaction. I understand that participation in this study is voluntary and that I may withdraw at any time without consequence. A copy of this consent form has been given to me.

7. CONSENT SIGNATURES

Participant's Signature:____________________________________ Date:_______

Participant's Name (please print):___________________________

Investigator Signature:_____________________________________ Date:_______

APPENDIX B. PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)

Physical Activity Readiness Questionnaire (PAR-Q)

Common sense is your best guide in answering these few questions. Please read the carefully and check **YES** or **NO** opposite the question if it applies to you. If yes, please explain.

<u>YES</u>	<u>NO</u>	
____	____	1. Has your doctor ever said you have heart trouble? Yes, ____________________
____	____	2. Do you frequently have pains in your heart and chest? Yes, ____________________
____	____	3. Do you often feel faint or have spells of severe dizziness? Yes, ____________________
____	____	4. Has a doctor ever said your blood pressure was too high? Yes, ____________________
____	____	5. Has your doctor ever told you that you have a bone or joint problem(s), such as arthritis that has been aggravated by exercise, or might be made worse with exercise? Yes, ____________________
____	____	6. Is there a good physical reason, not mentioned here, why you should not follow an activity program even if you wanted to? Yes, ____________________
____	____	7. Are you over age 60 <u>**and**</u> not accustomed to vigorous exercise? Yes, ____________________
____	____	8. Do you suffer from any problems of the lower back, i.e., chronic pain, or numbness? Yes, ____________________
____	____	9. Are you currently taking any medications? If YES, please specify. Yes, ____________________
____	____	10. Do you currently have a disability or a communicable disease? If YES, Please specify, Yes, ____________________

____________________ ____________________ ____________________

Print Name Signature Date

APPENDIX C. STRETCHING PROTOCOL

Quadriceps and Hamstrings Stretching Techniques

Quadriceps:

Stand and touch the wall for support. Bend your heel towards your back and pull your ankle and forefoot to your rear end. Hold for 30 seconds. Repeat 3 times.

Hamstrings:

Stand and slightly bend your knees. Bend at the waist and reach toward your toes or floor and hold for 30 seconds. Repeat 3 times.