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A sex comparison of reactive knee stiffness regulation strategies under cognitive loads☆

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ABSTRACT

Background: Sex differences may exist in cognitive faculties and neuromuscular strategies for maintaining joint stability. The purpose of this study was to assess whether preparatory and reactive knee stiffening strategies are affected differently in males and females exposed to sex-biased cognitive loads.
Methods: 20 male and 20 female volunteers were tested for knee joint stiffness and quadriceps and hamstring muscle activation patterns throughout a rapid eccentric knee extension perturbation. Participants were tested under 3 cognitive loads (Benton's Judgment of Line Orientation; Symbol Digit modalities Test; and Serial 7's) and a control condition. Apparent knee joint stiffness and muscle activation amplitude and timing were quantified throughout the perturbation across the 4 conditions.
Findings: Reactive knee stiffness values were significantly less during the cognitive tasks compared to the control condition (Judgment of Line Orientation = 0.034 Nm/deg/kg, Symbol Digit Modalities Test = 0.037 Nm/deg/kg, Serial 7's = 0.037 Nm/deg/kg, control = 0.048 Nm/deg/kg). Females had greater normalized total apparent stiffness than males. The quadriceps muscles had faster and greater activation than the hamstring muscles; however, no group differences were observed. No overall differences in muscle activation (magnitude and timing) were found between the cognitive loading tasks.
Interpretation: Cognitive loading may decrease the ability of healthy individuals to reactively stiffen their knee joint and appears to interfere with the normal stiffness regulation strategies. This may elucidate an extrinsic risk factor for non-contact knee ligament injury.

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1. Introduction

Unintentional injuries to the anterior cruciate ligament (ACL) are common during physical activity, with females reporting a higher incidence than males (Boden et al., 2010). More than 70% of these injuries occur during non-contact mechanisms while decelerating, pivoting, or landing (Boden et al., 2009; Colby et al., 2000). Previous studies have focused on biomechanical risk factors; however, until recently, the cognitive factors mediating neuromuscular control and their potential interaction with known sex differences have been largely untested (Shultz et al., 2012; Swanik et al., 2007). These variables have the potential to partially explain the non-contact nature of these injuries and increased risk among females.

Joint stability relies on the integration of static and dynamic restraints to provide an appropriate level of stiffness capable of protecting the joint from unanticipated loading (Needle et al., 2014). Descriptions of static restraints include the capsuloligamentous structures that offer innate stiffness that is inadequate to protect the joint from injury in isolation. Therefore, injury prevention is dependent on precise neuromuscular activation of dynamic restraints, comprising the musculotendinous unit, to optimize task-dependent joint stiffness. Levels of muscle activation may subsequently serve to modify short-range stiffness, comprising the resistance from static restraints and reverse actin-myosin cross bridge cycling; and total stiffness, regulated further from reflexive and volitional muscle activation (Rack and Westbury, 1974; Sinkjaer et al., 1988). 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 (Wilson et al., 1991a). Both preparatory (feed-forward) and reactive (feedback) neuromuscular control strategies govern the instantaneous and continuously changing level of dynamic restraint. An imbalance or delay in

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neuromuscular activation can lead to improper limb position and may place an increased stress or strain on the knee, resulting in ACL injury (Colby et al., 2000). Understanding the preparatory and reactive neuromuscular activation patterns in response to a rapid perturbation of the joint has the potential to provide valuable insight into factors capable of modifying the dynamic restraint mechanism and subsequently joint stiffness.

Growing evidence has implicated neurocognitive factors, originating in the central nervous system, as having a critical role in modifying preparatory and reactive muscular control and subsequently moderating injury risk and recovery (Everhart et al., 2015; Kapreli et al., 2009; Swanik et al., 2007). Factors 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 (Swanik et al., 2007). It has been demonstrated that increasing an individual's cognitive load (increased amount and subsequent decreased speed of neural processing) can narrow one's visual field, slow reaction time, and alter muscle activity resulting in poor coordination (Burcal et al., 2014; Dault et al., 2001; Desimone and Duncan, 1995; Ebersbach et al., 1995). Therefore, the presence and type of cognitive loading interferes with an individual's ability to adequately conduct motor planning, and then also react appropriately to unanticipated events. This scenario may lead to errors in judgment where the individual fails to properly negotiate timing and amplitude of muscle contractions with impending joint loads, potentially diminishing dynamic restraint capabilities (Baumeister et al., 2008, 2011).

Because sex differences have 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, non-contact ACL injuries in females. Previous studies suggest that stiffness regulation has a pivotal role in describing the difference in ACL injury rates between sexes, as females tend to use more quadriceps activity, or less hamstring co-activation than males, potentially increasing anterior tibiofemoral shear (Blackburn et al., 2004; DeAngelis et al., 2015; Granata et al., 2002). Additionally, hormonal influences have been tied to increased knee laxity and subsequently decreased stiffness among females (Shultz et al., 2005). Despite these data, sex differences in cognitive processing may offer further rationale for differences in injury rates. Males tend to excel in cognitive performance tests related to visual and spatial tasks, while females demonstrate advantages in verbal or language tasks, with this improved performance typically associated with decreased cognitive demand (Adam et al., 1999; Jones & Gallo, 2002; Vaquero et al., 2004). As preparing for and reacting to potentially injurious loads would require strong visuospatial abilities, these factors may provide insight to why risk factors become expressed and therefore result in injury.

These joint stiffness, neuromuscular, and neurocognitive characteristics appear to be sexually dimorphic, but very little is known with regard to their combined influence on knee stability. Therefore, the purpose of this study was to determine the interaction between sex and cognitive tasks on knee stiffness regulation and thigh muscle activation following a dynamic knee perturbation. We hypothesized decreased knee stiffness and delayed and diminished recruitment patterns in females, with further decreases while individuals undergo cognitive tasks. Furthermore, we hypothesized greater deficits in knee stiffness regulation in females during a spatial cognitive task, while males would express greater changes during verbal cognitive task.

2. Methods

2.1. Experimental design

This study implemented a repeated-measures post-test only group design. An *a priori* power analysis with parameters of $\alpha = 0.05$, $1 - \beta = 0.8$, and $f = 0.25$ with preliminary data was used to determine a minimum sample size of 12 subjects per group (GPower, Heinrich-Heine-Universitat, Dusseldorf). Independent variables included sex (male or female) and the type of cognitive task, which included the Benton Judgment of Line Orientation (JOLO, Forms H & V), Symbol Digit Modalities Test (SDMT), Serial 7's, and a control condition. The dependent variables included calculation of apparent knee joint stiffness from recorded joint position and torque, and muscle activity (amplitude and timing) quantified with electromyographic (EMG) recordings during an eccentric knee extension joint perturbation.

2.2. Participants

Twenty male and 20 female volunteers between the ages of 18 and 25 were recruited from a university population. Before testing, participants provided institution-approved informed consent and completed the physical activity readiness questionnaire (Thomas et al., 1992) to determine eligibility. Participants were excluded if they answered “yes” to questions pertaining to pains in the heart or chest, faintness or dizziness, bone or joint problems, or low back problems. Additionally, participants were excluded if they reported a history of fractures or surgery to the leg, or had any current bone, muscular, or joint injuries to the leg. Female participants were included if they were within Day 0 to 12 of their menstrual cycle (determined via self-report), to minimize the potential influence of hormone fluctuation on ligament laxity (Shultz et al., 2005).

2.3. Instrumentation

Stiffness was tested using a custom-built Stiffness and Proprioceptive Assessment Device (SPAD) capable of providing precise joint perturbations while transmitting analog signals of position and torque (DeAngelis et al., 2015; Hamstra-Wright et al., 2005; Needle et al., 2015). Surface electromyography was collected from the vastus medialis (VM), vastus lateralis (VL), medial hamstrings (semitendinosis, MH), and lateral hamstrings (biceps femoris, LH) to determine stiffness regulation strategies. Each muscle was identified through palpation of the mid-belly, and the skin was prepared by removing hair, cleansing the skin with alcohol (70% ethanol solution), and abrading. Self-adhesive Ag/AgCl bipolar surface electrodes (Phillips Medical, Andover, MA) were placed over each muscle and connected to a wireless telemetered EMG unit (Konigsberg Instruments, Inc., Pasadena, CA). Signals of position, torque, and EMG activity were converted from analog to digital data and synchronized in customized LabVIEW software (National Instruments, Austin, TX) at 2400 Hz.

2.4. Cognitive loading tasks

Participants performed 3 different cognitive tasks: the JOLO, SDMT, and Serial 7's, as well as a fourth control condition. Immediately prior to stiffness testing procedures, the 3 cognitive tasks were explained to the participants in conjunction with practice materials provided with the tests. In the JOLO task, participants viewed 2 line segments at various angles and matched the segments to an array of similarly oriented numbered lines. This task is generally more difficult for females (Caparelli-Daquer et al., 2009; Rahman & Wilson, 2003). The SDMT required participants to match an array of symbols with numbers with a given key. This test is generally more difficult for males (Sheridan et al., 2006). During serial 7's, participants counted backwards from 100 by subtracting 7 from each number. After each trial, the subject began counting from the last number stated. This task is generally considered gender neutral (Lindal and Stefansson, 1993). All cognitive tasks required only verbal responses from individuals, which were recorded to determine accuracy. Scores for the standardized JOLO and SDMT were calculated to allow for calculation of baseline differences between sexes.

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