NEUROMECHANICAL CONTRIBUTIONS

TO HAMSTRING STIFFNESS

DYSREGULATION AND INJURY

by

Andrea Di Trani

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Biomechanics and Movement Science

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Andrea Di Trani

Approved: _____
Samuel Lee, Ph.D.
Director of Biomechanics and Movement Science Program

Approved: _____
Kathleen Matt, Ph.D.
Dean of the College of Health Sciences

Approved: _____
Ann L. Ardis, Ph.D.
Senior Vice Provost for Graduate and Professional Education

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: _____

Charles Buz Swanik, Ph.D.
Professor in charge of dissertation

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: _____

Thomas Buckley, Ph.D.
Member of dissertation committee

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: _____

Jeffrey Rosen, Ph.D.
Member of dissertation committee

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: _____

Karin Silbernagel, Ph.D.
Member of dissertation committee

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

x

xi

ABSTRACT

Hamstring strain injuries (HSI) remain one of the most commonly occurring
medical problems in sport and recreation and are associated with high rates of missed
playing time and re-injury. Despite increased research interest over recent decades, the
financial cost and incidence of HSI continue to rise. A number of risk factors and
mechanisms have been explored, but evidence remains inconclusive. The relationship
between the nervous system and hamstring muscle properties has not been thoroughly
examined. Evidence demonstrates deafferentation following other musculoskeletal
injuries with negative implications on proprioception and function. Additionally,
impaired muscle activation and stiffness regulation have also been linked to altered
neural input from afferent receptors. However, it is unclear if similar maladaptations
occur after HSI and if there is an association with the persistent symptoms, inability to
return to pre-injury levels, and likelihood for re-injury following return-to-play.
Further, it is unknown how common sports related experiences that are suspected to
predispose to HSI, such as fatigue and competitive anxiety, interact with the neural
and muscular properties of the hamstrings. Therefore, the purpose of this dissertation
was to examine how hamstring neuromechanics become instantaneously decoupled in
previously injured limbs and during fatigue and anxiety, as measured through patient
reported outcomes, proprioception, and stiffness regulation. The results of this study
demonstrate that: 1) sensory disconnect occurs following HSI between patient-
reported tightness and objective extensibility, which is also linked to decreased
proprioceptive acuity; 2) proprioceptive deficits exist following HSI with associated

stiffness dysregulation and poor functional outcomes scores; 3) fatigue and anxiety contribute to stiffness dysregulation, with certain alterations amplified by previous HSI. These findings suggest that neural maladaptations continue to linger after HSI, possibly representative of mechanoreceptor trauma or central processing errors resulting from straining mechanisms. These neural alterations could interfere with the hamstrings' ability to absorb and dissipate energy during rapid eccentric contractions, thereby increasing the risk of injury. This study indicates that examination of proprioceptive function and stiffness regulation can identify abnormal neuromechanical function in previously injured hamstrings. Based on the findings of this study, we provide new areas of hamstring prevention and assessment that have not been thoroughly considered and highlight that interventions may be needed to attenuate the neuromechanical consequences of fatigue and anxiety.

Chapter 1

NEUROMECHANICS OF HAMSTRING STRAIN INJURIES

Introduction

Hamstring strain injuries (HSI) are among the most commonly occurring soft tissue medical problems in sport and recreation that affect individuals at the high school, collegiate, professional, and masters levels. (J. H. M. Brooks, Fuller, Kemp Simon P. T., & Reddin, 2006; J. H. Brooks, Fuller, Kemp, & Reddin, 2005; Feeley et al., 2008; Orchard & Seward, 2002; Posner, Cameron, Wolf, Belmont, & Owens, 2011; Seward, Orchard, Hazard, & Collinson, 1993; Woods et al., 2004) Epidemiological studies across various sports leagues have indicated that HSI are one of the highest ranked causes of missed playing time in both practice and competition, with an average of up to 25 days lost per injury. (Alonso et al., 2012; J. H. Brooks et al., 2005; Feeley et al., 2008; Orchard & Seward, 2002; Posner et al., 2011; Seward et al., 1993) Even more alarming is the re-injury rate of 12 – 34% following return-to-play, which ranks as the highest of all sports-related injuries. (Malliaropoulos, Isinkaye, Tsitas, & Maffulli, 2011; Orchard & Seward, 2002) The sustained reoccurrence results in more severe symptoms and double the recovery time. (J. H. M. Brooks et al., 2006; Koulouris, Connell, Brukner, & Schneider-Kolsky, 2007) Current HSI management is ineffective as demonstrated by persistent symptoms following return to play, failure to achieve pre-injury competitive status, (Sole, Milosavljevic, Nicholson, & Sullivan, 2012; Verrall, Slavotinek, Barnes, Fon, & Spriggins, 2001) and high injury rates. (M. D. A. Opar, Williams, & Shield, 2012) Thus, management

of HSI proves to be a challenge to the patient and clinician, (Heiderscheit, Sherry, Silder, Chumanov, & Thelen, 2010) in addition to being a detriment to health related quality of life. (Engebretsen, Myklebust, Holme, Engebretsen, & Bahr, 2010; H. Liu, Garrett, Moorman, & Yu, 2012) Despite increased interest in recent decades, research in this area has remained largely inconclusive; (Freckleton & Pizzari, 2013) incidence rates and the financial cost of HSI have continued to rise, with an estimated yearly loss of $353,469 per NFL team. (Brukner, 2015; Hickey, Shield, Williams, & Opar, 2014) Research has attempted to explore a number of risk factors and potential deficits following injury, to alleviate the uncertainty regarding prevention and rehabilitation of HSI. Strength measures, flexibility, and muscle imbalances have all been previously explored; however, a recent meta-analysis concluded that age and previous history of HSI appear to be the only definitive risk factors for HSI, (Freckleton & Pizzari, 2013) highlighting the inconclusive results in the literature thus far. A particular area of research that has not been explored is the decoupling of the nervous system and hamstring muscle properties in a previously injured population. Muscle strain, along with other sports-related factors, such as fatigue and competitive anxiety, may cause functional alterations in proprioceptive acuity, muscle activation patterns, and stiffness regulation strategies through a neuromechanical decoupling. Therefore, a novel approach to closely inspect the momentary decoupling of neuromechanical factors that leads to near instantaneous and excessive muscle strain energy of the hamstrings in both healthy controls and a previously injured subjects is warranted. The purpose of this literature review is to explore passive tissue characteristics, sensorimotor function, and muscle stiffness regulation in an effort to determine the potential influence that injury, fatigue, and anxiety have on neuromechanical function of the hamstrings.

Passive Tissue Characteristics and Extensibility

Muscle injury results from active mechanical strain during regulation of load absorption, opposed to high peak forces during high-speed activities. (S. V. Brooks, Zerba, & Faulkner, 1995; Heiderscheit et al., 2005; Lieber & Friden, 1993; Schache, Wrigley, Baker, & Pandy, 2009) This mechanism of injury leads to structural myofibril damage consisting of sarcomere disruption, (J. Friden & Lieber, 1992; Lieber & Friden, 1993) most often occurring near or at the musculotendinous junction of the long head of the biceps femoris. (De Smet & Best, 2000; Koulouris & Connell, 2003; Slavotinek, Verrall, & Fon, 2002) Clinical presentation of acute muscle strain symptoms results and once subsided, long-term sequelae following injury may include altered passive tissue properties. (Silder, Reeder, & Thelen, 2010) Tissue changes may occur following injury with scar development, altering the mechanics of running gait, specifically during HS lengthening. (Silder et al., 2010) It is hypothesized that such maladaptations can be observed in laboratory testing, specifically methods that target the mechanical properties of passive tissues (i.e. short range muscle stiffness). *In-vivo* analysis of tissue displacement in healthy and previously injured subjects has revealed that injured HS muscles have significantly decreased motion along the musculotendinous junction, as well as significantly greater strain throughout the length of the entire muscle. (Silder et al., 2010) In healthy individuals, the surface area for transmission of forces to the tendon is increased by means of a vast folding of the sarcolemma in the muscle fibers in proximity to the musculotendinous junction. (Kääriäinen, Järvinen, Järvinen, Rantanen, & Kalimo, 2000) This allows for increased compliance in the musculotendinous tissues while the limb is exposed to tension; (Purslow, 2002) however, in those with a previous history of muscle strain injury, sarcolemma damage occurs with the eventual materialization of fibrous scar tissue.

(Best & Hunter, 2000; Purslow, 2002) Hence, changes at the cellular tissue level post-injury can alter a muscle's ability to achieve optimal extensibility during activity. Unrestricted extensibility allows for optimal biomechanical factors such as desirable length of tendon, overlap of actin/myosin, and thickness allowing for suitable production of passive and active tension for energy absorption. (Weppler & Magnusson, 2010)

Muscle Extensibility

While extensibility has been studied as a risk factor for HSI, the evidence remains weak due to inconsistent results. (Hennessey & Watson, 1993; Orchard, Marsden, Lord, & Garlick, 1997; Witvrouw, Mahieu, Danneels, & McNair, 2004; Worrell & Perrin, 1992) The use of varying terminology may also be prohibiting gains in understanding the role extensibility plays in strain injury risk. Extensibility refers to the furthest length that is achievable by a muscle. The individual's interpretation of a maximum extension is most often used, and is suspected that this consideration has been grossly disregarded in previous studies that have applied passive tension. (Weppler & Magnusson, 2010) A gold standard for measuring HS extensibility does not exist and a number of assessments have been previously utilized, including the sit and reach, straight-leg-raise, and the active and passive knee extension tests. The active knee extension (AKE) test is recognized as a reliable assessment tool for extensibility of the hamstrings since it limits error due to clinician delivered forces, as applied in passive tests. Using this test, decreased extensibility is typically defined as a difference of 20° between limbs. (D. S. Davis, Ashby, McCale, McQuain, & Wine, 2005) Decreased physical lengthening of tissue is due to contractile properties and the amount of force required to lengthen a muscle is related to alpha motor neuron

4

activity. This suggests that an active contraction directly increases stiffness and decreases extensibility, indicating the importance of neural components in muscle elongation. (Kuilart, Woollam, Barling, & Lucas, 2005; Mense, Simons, & Russell, 2001)

The Fusimotor System, Muscle Spindles, and Muscle Tone

The muscle spindle is an important sensory receptor that functions to detect change in length. Located within the muscle belly, the spindle plays an important role in providing proprioceptive information for the central nervous system (CNS), since muscle length is closely related with joint position. (Pearson & Gordon, 2000) Each encapsulated spindle consists of intrafusal fibers, afferent sensory endings (Type Ia & II), and efferent motor endings (static and dynamic gamma motor neurons). The muscle spindle contains two types of intrafusal fibers: nuclear bag fibers (static and dynamic) and nuclear chain fibers. (Pearson & Gordon, 2000) All intrafusal fibers have one large diameter (Ia) primary sensory ending wrapped around the fiber centers, known as annulospiral endings. Secondary receptors within the static bag and chain outer fiber regions are known as "flower spray endings," which are medium diameter (II) receptors. (Pearson & Gordon, 2000) Innervation of the intrafusal fibers is provided by gamma motor neurons. They modulate muscle spindle activity as their activation leads to intrafusal fiber shortening at their polar regions, which increases sensory ending firing rate. More specifically, innervation of the dynamic bag fibers is provided by dynamic gamma motor neurons, while the static counterparts supply the static bag fibers and chain fibers. (Pearson & Gordon, 2000) The series of events that allows gamma motor neurons to alter the sensitivity of muscle spindles through varying degrees of neuronal activity represents what is referred to as the *fusimotor*

system. (Pearson & Gordon, 2000) The intrafusal fibers increase in length as the entire muscle elongates due to the orientation of the muscle spindle in a parallel fashion with the extrafusal fibers within the muscle belly, which are innervated by alpha motor neurons. (Pearson & Gordon, 2000) Hence, any increase in the activity of the fusimotor system will result in increased sensory traffic, reflexive motor action potentials, and levels of muscle tone or contraction. (Pearson & Gordon, 2000)

The receptor endings are extremely sensitive; therefore the information they provide to the central nervous system, in quick response to unexpected length changes, can be utilized to produce corrective movements. (Pearson & Gordon, 2000) Information from peripheral afferents is gathered and organized by the muscle spindle, which is then modified and relayed to the CNS as a signal referred to as a "final common input." (Johansson, Sjölander, & Sojka, 1991) Through this process, muscle activity is constantly monitored and adjusted during movement by means of the stretch reflex arc. (Hoffer & Andreassen, 1981) According to Johansson et al. (Johansson et al., 1991), the coordinated transmission of motor commands through reflexive and descending pathways allows for a modification of muscle stiffness during activity. Activation of the alpha motor neurons alone results in a stoppage of Ia fiber firing, since a slackening of the spindle occurs, with muscle shortening during contraction. Nonetheless, a simultaneous stimulation of the gamma motor neurons allows for continued Ia firing, as tension remains applied to the spindle during intrafusal fiber contraction. (Johansson et al., 1991) This synchronized activity, referred to as *alpha-gamma co-activation*, is utilized in voluntary movement to maintain an optimal stabilization of muscle spindle sensitivity. (Johansson et al., 1991) Thus, it would be expected that deafferentation of the muscle spindle may be associated with a

neuromechanical decoupling resulting in altered fusimotor activity. This, in turn, could cause produce sensorimotor deficits and thereby increase the risk of HSI. (Johansson et al., 1991)

A "set point" of extensibility may be pre-determined by the neural system, suggesting a direct control of the length achieved by the muscle, in addition to its motion resistance and lengthening sensitivity. (Krabak, Laskowski, Smith, Stuart, & Wong, 2001; Lin & Rymer, 1993) The protective reflexes supplied by the muscle spindle and Golgi tendon organ (GTO) serve as key factors of length achieved by a muscle. (Hamill & Knutzen, 2006) The neurological stretch reflex is comprised of the peripheral and central contributions of the neural system. The impact of alpha and gamma motor neurons, along with other receptors including Renshaw cells, supraspinal pathways, and intra- and extrafusal fibers of muscle have also been suspected as determinant of the "set point." (R. S. Hutton & Atwater, 1992; R. Hutton, 1992; Lin & Rymer, 1993) Sherrington identified the presence of reflex control in animal studies, supporting this role of the nervous system in extensibility. (Sherrington, 1916) During muscle lengthening, the stretch reflex arc may control the balance between the agonist and antagonist muscles. (Krabak et al., 2001) At this time, it is unknown what muscle properties are truly indicative of an ideal muscle length, (Weppler & Magnusson, 2010) as it is a multidimensional muscle characteristic. (Özkaya, Nordin, Goldsheyder, & Leger, 2012)

Stretching and Extensibility

A number of mechanical theories have been developed to explain improvements in muscle extensibility with stretching. (Weppler & Magnusson, 2010) Viscoelastic deformation is believed to account for the immediate increase in

extensibility post-stretching. (Taylor, Dalton, Seaber, & Garrett, 1990) The viscoelastic properties of muscle allow for an increase in muscle length; however, research has shown this just to be a transient effect lasting less than one minute. (Magnusson, Simonsen, Aagaard, & Kjaer, 1996; Magnusson, Aagaard, & Nielson, 2000) A second theory indicates that stretching produces long-lasting length changes in connective tissue; (Warren, Lehmann, & Koblanski, 1971) however, research has failed to support this hypothesis. (Weppler & Magnusson, 2010) Animal experiments have led to the development of the theory that stretching will increase the number of sarcomeres in series, thereby allowing for greater extensibility. (Goldspink, Tabary, Tabary, Tardieu, & Tardieu, 1974) This theory also lacks empirical data due to imaging technology required to examine such effects. (Weppler & Magnusson, 2010) Additionally, it has been proposed that stretching induces stretch reflex alterations that allow for gains in extensibility. (Weppler & Magnusson, 2010) At this time, just one study has examined the effects of hamstring stretching in a population of previously injured patients. (O'Sullivan, Murray, & Sainsbury, 2009) Those with a previous history of HSI displayed a greater increase in extensibility following a warm-up and stretch; however, a small sample size yielded non-significant results. The significance of one's perceived extensibility limit has been recognized and has been underestimated in previous investigations. (Weppler & Magnusson, 2010) A more modern "sensory theory" purports that stretching-induced improvements in extensibility are the result of alterations to the individual's sensation experienced during stretching, without any impact of the length of the muscle. These changes in perception have yet to be fully understood but could be due to peripheral adaptations

or central processes, or possibly a mix of both mechanisms. (Weppler & Magnusson, 2010)

Specifically with respect to HSI, the perception of muscle tightness is a component of extensibility that should be considered, as symptoms of tightness are known to persist upon return to high-speed activity despite a lengthy recovery period with full return of strength. (Sole et al., 2012) The term "tight," while non-specific and not recognized medically as a formal diagnosis, has been associated with the subjective perception of decreased extensibility. (Kuilart et al., 2005) At this time, it is unknown if the subjective feelings of tightness are coupled with actual decreased hamstring extensibility. Sensitization of mechanoreceptors following HSI could be responsible for delivering aberrant sensory information or peripheral tethering of nerves to scar tissue may result in symptoms of tightness that might not be directly correlated with functional outcomes and objective measures of extensibility. (D. Butler & Gifford, 1989; McHugh, Tallent, & Johnson, 2013)

Extensibility was previously measured in subjects with "perceived" HS tightness using the AKE test, but compared their results to existing normative data of the passive knee extension test instead. (Kuilart et al., 2005) Perceived tightness was not significantly related to an actual decrease in HS extensibility, suggesting a neuromechanical source of subjective tightness; however, a subjective scale was not used to measure perceived tightness, and decreased extensibility was required for inclusion into the perceived tightness group. (Kuilart et al., 2005) This leaves the importance of perceived tightness as an unanswered problem. The simultaneous examination of objective extensibility and subjective tightness in healthy controls and subjects with a previous history of HSI would help to elucidate the relationship

between these measures. The influence of perception has also been examined in patients with patellofemoral syndrome, showing that increased perceived stiffness is not associated with biomechanical stiffness of a joint. (Hamstra-Wright, Swanik, Ennis, & Swanik, 2005) However, a significant correlation was found between perceived stiffness and pain, which suggests that injured patients might have been misinterpreting the sensation pain to be stiffness. (Hamstra-Wright et al., 2005) This may indicate that altered sensation might also be influencing other aspects of neuromechanical function following injury. It is suspected that a similar decoupling could be occurring with HSI, leading to prolonged feelings of tightness, which could be attributed to muscle spindle sensitization following injury.

It is proposed that a novel research design that includes variables of objective extensibility, perceived limits of extensibility, and measures to examine the resultant effect on muscle stiffness regulation could elucidate the involvement of the neural system following HSI. The simultaneous observation of changes in extensibility and subjective perception of tightness between a control and post-stretch measure would help to elucidate the uncertainty associated with this sensory theory and confirm the neural contribution to stretching. Therefore, future studies exploring the response of stretching are needed to determine how strain mechanisms affect extensibility and to identify the sensory contribution to muscle lengthening. Overall, further research in this area is warranted to study the influence that perception has on extensibility, especially how injury affects this process and the influence of altered perception on other aspects of sensorimotor function. At this time it is unknown how such measurements are associated with function during activity. (Weppler & Magnusson, 2010) Hamstring strain injury may result in passive tissue adaptations and alterations

to spindle function that interfere with normal neuromechanical processes. Furthermore, an interruption to motor commands may occur in the descending or reflex pathways from the muscle spindle system, as there is a primitive reflex motor reaction due to the presence of pain, which would alter proprioception accuracy. (C. Swanik, Rubash, Barrack, & Lephart, 2000)

Proprioception And Sensorimotor Function

During physical activity, the hamstrings are placed under intense sensorimotor demands as they operate to perform both eccentric deceleration and torque production. (Cameron, Adams, & Maher, 2003; Woods et al., 2004) Injury typically occurs in high-speed movements during the late swing phase of gait, as the muscles are eccentrically loaded to decelerate the limb. (Chumanov, Schache, Heiderscheit, & Thelen, 2012; Heiderscheit et al., 2005; Thelen, Chumanov, Best, Swanson, & Heiderscheit, 2005) At this point, the musculotendinous complex of the biceps femoris undergoes a stretch-shortening cycle, with maximum stretch occurring at approximately 90% of the gait cycle. Electromyography (EMG) analysis has shown that the HS are two to three times more active at this point compared to the stance and early swing phase, as they slow down the lower limb before heel strike. (Yu et al., 2008) The hamstrings must meet these functional requirements within a small timeframe (milliseconds) to avoid excessive strain resulting from insufficiencies in sensorimotor control or coordination. (Bennell, Tully, & Harvey, 1999; Cameron et al., 2003)

Freeman first proposed injury (ankle) results in deafferentation that decreases proprioceptive acuity. (M. A. Freeman, Dean, & Hanham, 1965) It is hypothesized that residual deficits following the acute injury phase induce a decoupling between the

nervous system and muscle properties as a result of muscle strain injury as well. The CNS receives information from the receptors located in peripheral muscles, joints, and skin in reference to mechanical changes to tissues. (Grigg, 2010) Proprioceptive receptor sensitization during the acute phase of HSI has been reported to lead to symptoms of heaviness and dullness in the limbs, which may further develop into persistent sensitization to mechanical stress. (Villarreal, Funez, de Queiroz Cunha, Parada, & Ferreira, 2013; Yamashita, Minaki, Takebayashi, Sakamoto, & Ishii, 1999) The role that the gate theory of pain management plays, with respect to the muscle spindle system and nociceptive information, has also been addressed. Based on this theory, the CNS is responsible for interpreting both somatosensory and nociceptive signals, with each one possessing the ability to cause an inhibition of the other, (Hall, 2010; Melzack & Wall, 1967) which could result in errors during activity as a result of superseding signals. It remains to be established how proprioceptive function is altered following HSI. Strain injury could damage mechanoreceptors embedded within the muscle belly (spindle) and GTOs at the musculotendinous junction, causing deafferentation of these sensory receptors and proprioceptive deficits. (Lephart, Pincivero, Giraldo, & Fu, 1997) Laboratory-induced inflammation has been shown to produce an excitation of the nociceptive and proprioceptive units, causing sensitization to mechanical pressure. (Yamashita et al., 1999) A much lower level of stress causes excitation of nociceptors, and their continuous discharge, even when exposed to a relatively harmless level of mechanical stress.

Proprioception has been defined as the sense of being able to detect movement of the joints (kinesthesia), joint position, and muscle force. (Riemann, Myers, & Lephart, 2002) All three of the proprioception submodalities (kinesthesia, joint

position sense, and force sense) have been examined to measure proprioception in various populations of human subjects. (Riemann, Myers, & Lephart, 2002) Typical proprioceptive assessment focuses on sensorimotor evaluation targeted at either afferent or efferent signals, or the resultant muscle contraction. (Riemann, Myers, & Lephart, 2002) *Kinesthesia* testing, more commonly referred to as threshold to detection of passive motion (TTDPM), involves the recognition of movement and thus partially relies on reaction time. (Riemann et al., 2002) The location of GTOs in the musculotendinous junction places them at increased risk for damage under excessive strain conditions. Impaired GTO function will influence the ability to accurately detect and estimate force production, which can be referred to as *force control*. (D. I. McCloskey, Gandevia, Potter, & Colebatch, 1983) The sub-modality of force sense is defined as one's capacity to detect a specific force while performing a muscle contraction. (D. I. McCloskey et al., 1983) Typical measurements involve reproduction of a force value in a limb, or a contralateral reproduction. (D. I. McCloskey et al., 1983) Slower speeds are used to test GTOs and Ruffini endings. (Lephart et al., 1997) Force control errors have been observed following other injuries, (Docherty, Arnold, & Hurwitz, 2006) but it is unknown how GTO function is modified following HSI. *Joint position sense* (JPS) testing involves reproduction of a specific joint angle, either passively or actively, and in the open or closed kinetic chain. The accuracy of joint positioning is recorded as a measure of error in degrees from the previously designated test position. (Goble, 2010)

To complete proprioception testing, a number of different instruments have been utilized ranging from custom-made devices to isokinetic dynamometers and various tracking devices. (Riemann et al., 2002) While many studies have identified

proprioceptive deficits following various injuries, some have not been able to reproduce the same findings. This discrepancy is most likely attributed to the wide range of equipment and methodologies used. (Riemann et al., 2002) Nonetheless, it is suspected that impairments in proprioceptive input could increase the likelihood of future re-injury, (Lephart et al., 1997) with inaccurate muscle coordination occurring as a result of decreased acuity. (Sole et al., 2012) Sensory impairments including decreased awareness of the limb in space and detecting force have been observed following other injuries. (Godinho et al., 2014; Juul-Kristensen et al., 2008; A. J. Lee, Lin, & Huang, 2006; Lephart, Kocher, Fu, Borsa, & Harner, 1992; Warner, Lephart, & Fu, 1996) Much attention has been given to proprioceptive deficits following ACL injury, (Lephart et al., 1992) such as decreased joint position sense, (Barrett, 1991) weight discrimination abilities, (Godinho et al., 2014; Héroux & Tremblay, 2005) and time to detect passive motion. (T. Friden, Roberts, Zätterström, Lindstrand, & Moritz, 1997) Similar findings have also been identified in unstable shoulder and ankle joints, (Hartsell, ; A. J. Lee et al., 2006; Warner et al., 1996) as well as in patients with osteoarthritis of the knee and lateral epicondylitis. (Hortobágyi, Garry, Holbert, & Devita, 2004; Juul-Kristensen et al., 2008) Proprioceptive deficits also appear to be part of the normal aging process regarding joint motion sensation and joint position, (Kaplan, Nixon, Reitz, Rindfleish, & Tucker, 1985; Kokmen, Bossemeyer, & Williams, 1978; C. Swanik et al., 2000) and since age has been identified as a risk factor for HSI, (Freckleton & Pizzari, 2013) this adds to the need for research in this area.

Resultant trauma to the spindle following strain injury may alter joint position sense during high-speed activities, which would lead to making contact with the

ground both sooner or later than expected. (Cameron et al., 2003) This inaccuracy impacts the length and torque production demands of the hamstrings, (Cameron et al., 2003) increasing the risk of HSI. (C. L. Brockett, Morgan, & Proske, 2001; Brughelli et al., 2010; R. Clark, Bryant, Culgan, & Hartley, 2005; Kilgallon, Donnelly, & Shafat, 2007) Cameron et al. (Cameron et al., 2003) examined movement discrimination during a standing leg swing task, to determine if it could be a risk factor for HSI. Diminished capabilities in limb awareness during a hip extension movement were detected to be a risk factor for HSI. (Cameron et al., 2003) It was suspected that inaccuracies in movement judgment during their testing protocol could be translated to running gait cycle, including positioning and timing errors that would alter the position of the lower leg or thigh. (Cameron et al., 2003) However, this study utilized a hip extension movement, so it is not clear how HSI affects JPS in a lengthening excursion where the muscles are susceptible to excessive strain. An evaluation of JPS in a position of hip flexion and knee extension is needed to best mimic the time of HSI occurrence. No other studies to date have investigated the potential involvement of motor control or proprioception as risk factors for HSI. It has been proposed that other aspects of proprioception may also be altered following HSI. (Cameron et al., 2003)

Force control errors have been observed following ankle sprain injuries, likely due to mechanoreceptor damage of muscles at the ankle joint, (Docherty et al., 2006) but it is unknown how GTO function is modified following HSI. Impaired GTO function will influence the ability to accurately detect force production at vulnerable positions. (Docherty & Arnold, 2008) During high-speed activity, feedback mechanisms are not suited to prevent injury in a timely manner; therefore, muscle

tension must be preset for functional demands via more exact feed-forward processes. (Docherty & Arnold, 2008) Previous studies of the upper extremity have utilized specific force tests designed to target feedback and feed-forward mechanisms in special patient populations and following fatigue. (Emge, Prebeg, Uygur, & Jaric, 2013; Jaric, Collins, Marwaha, & Russell, 2006; Krishnan & Jaric, 2008) For instance, a ramp-and-hold task allows for continuous adjustments to be made during the test trial, while an oscillation profile incorporates a frequency that does not allow for corrections and is exclusively based on feed-forward activity. (Jaric, Knight, Collins, & Marwaha, 2005; Jin, Uygur, Getchell, Hall, & Jaric, 2011) Force matching tasks with and without visual feedback have also been implemented to identify deficits following ankle sprain injuries. (Docherty & Arnold, 2008; Wright & Arnold, 2012) Inaccurate force control would interfere with such mechanisms necessary to avoid injury. (Docherty & Arnold, 2008) More specifically, greater recruitment of motor units may result from improper afferent signals, which in turn will cause an overestimation of the force required to complete the task and inappropriate regulation of muscle stiffness. (Docherty, Arnold, Zinder, Granata, & Gansneder, 2004)

Hence, the resultant effect of altered proprioceptive input on the sensorimotor system will lead to less than optimal muscle activation strategies and altered gait mechanics. (Sole et al., 2012) Experimental studies have observed fusimotor-spindle system changes in response to muscle pain, (Matre, Sinkjær, Svensson, & Arendt-Nielsen, 1998; Thunberg, Ljubisavljevic, Djupsjöbacka, & Johansson, 2002) suggesting that the mechanical strain and concomitant symptoms could alter motor function in the short and long-term. (Fyfe, Opar, Williams, & Shield, 2013) Premature hamstring onset, at initiation of a task, and decreased EMG amplitude during eccentric

contraction at end-range, have been reported in previously injured subjects. (Sole, Milosavljevic, Nicholson, & Sullivan, 2011; Sole et al., 2012) Sensorimotor control has been examined as a potential risk factor in HSI, specifically the synergistic role of the individual HS muscles. The biceps femoris and semitendinosis muscles are believed to function in complex coordinated sensorimotor patterns, (Higashihara, Ono, Kubota, Okuwaki, & Fukubayashi, 2010; Onishi et al., 2002; Schache, Dorn, Wrigley, Brown, & Pandy, 2013) with the biceps femoris most active during the middle to late swing phase and the semitendinosis most active in terminal swing. (Higashihara, Ono, & Nagano, 2013) Such a pattern highlights the importance of a coordinated sensorimotor system during gait as deviations from normal muscle activation patterns of the HS have been described as sequelae of previous HSI and a greater risk of re-injury. (M. D. A. Opar et al., 2012; Sole et al., 2012) For example, a single subject study measuring kinematic and force variables during sprinting observed a HSI occur during testing. (Schache, Kim, Morgan, & Pandy, 2010) Before the injury occurred, both an increased peak length and force were observed in the affected limb prior compared to the uninjured limb. (Schache et al., 2010) This information highlights the importance that sensorimotor system plays in the normal function of the hamstrings and the subsequent injury that results from deviations to the optimal activation patterns.

Sensorimotor influences are also suspected to be a culprit in the high re-injury rate following HSI, (Fyfe et al., 2013) but the research examining this hypothesis is sparse. Fyfe et al. (Fyfe et al., 2013) designed a conceptual framework to depict the role of neuromuscular inhibition following HSI. Due to pain driven neural response following muscle injury, inhibition causes atrophy, which is associated with eccentric

weakness, especially at longer muscle lengths. (Fyfe et al., 2013) Clinically, this becomes problematic when rehabilitation programs fail to address these maladaptations, specifically end-range activation. From a rehabilitative standpoint, injury pain results in avoidance of longer muscle lengths during the acute injury phase. Structurally, this results in a shortening of muscle fascicles that has a direct impact on the length-tension relationship, and decreases the angle of peak torque production. Consequently, this mechanism would also increase the risk for future HSI. (Fyfe et al., 2013) A number of studies have highlighted the ability to enhance sensorimotor performance through various methods including plyometrics, (K. A. Swanik et al., 2002; Waddington, Seward, Wrigley, Lacey, & Adams, 2000) co-contraction exercises, (Cramer et al., 2013; S. J. Lee, Ren, Chang, Geiger, & Zhang, 2014) JPS and force control training, (Jull, Falla, Treleaven, Hodges, & Vicenzino, 2007; Jull et al., 2002; O'Leary, Jull, Kim, & Vicenzino, 2007; Revel, Minguet, Gergoy, Vaillant, & Manuel, 1994) strengthening, (Docherty, Moore, & Arnold, 1998; O'Leary et al., 2007) vibration interventions, (Moezy, Olyaei, Hadian, Razi, & Faghihzadeh, 2008) balance training, (Cuğ M, Ak E, Ozdemir RA, Korkusuz F,Behm DG, 2012; Eils & Rosenbaum, 2001; Waddington, Adams, & Jones, 1999) and sport-specific exercise programs. (Bahr, Lian, & Bahr, 1997) This presents a possible area of training and rehabilitation programs to reduce the occurrence of HSI. If such a relationship with proprioception does exist, it seems reasonable that interventions aimed at enhancing performance of the sensorimotor system, and essentially resetting the spindle system, could be beneficial in the prevention of HSI.

Musculoskeletal Stiffness

Regulation of muscle stiffness occurs through the same afferent pathways that carry proprioceptive input to the CNS. (Johansson et al., 1991) However, the relationship between these neuromechanical measures remains to be established in HSI. (Docherty et al., 2004) Muscle stiffness is defined as the amount of tension or resistance that a musculotendinous unit produces in response to change in length, and is calculated as the ratio of change in force to the change in muscle length. (Oatis, 1993) Stiffness is linearly associated with muscle tension, (Ditroilo et al., 2011; Fukashiro, Noda, & Shibayama, 2001) therefore, more intense demands of activity result in greater levels of muscle stiffness. (R. J. Butler, Crowell, & Davis, 2003) More specifically, as velocity increases during running; the stiffness of the lower extremity also increases. (K. Granata, Padua, & Wilson, 2002) Stride parameters during gait are also associated with stiffness, as longer stride lengths are correlated with lower stiffness levels of the leg and vertical stiffness. (Farley & Gonzalez, 1996; McMahon & Cheng, 1990) Hence, a number of factors will influence muscle stiffness during sport. Future examination of this property and its regulation is warranted.

During active lengthening of muscles, the amount of strain that the tissue undergoes is believed to be due in large part to the compliance of the muscle tendons, (Fukashiro, Hay, & Nagano, 2006; Lieber, Leonard, Brown, & Trestik, 1991; Thelen et al., 2005; Thelen et al., 2005) and therefore any restrictions could increase the risk of future injury as the amount of strain that is experienced by the associated muscle would also increase. (Silder et al., 2010) The critical input provided by soft tissue afferents on the activity of the fusimotor system and thus the sensitivity of the muscle spindle has been recognized. (Johansson et al., 1991) During the late swing phase, the quadriceps muscles actively contract to extend the knee, while the hamstrings are

eccentrically loaded and lengthened. Sherrington (Sherrington, 1909) first proposed this concept of co-activation, where two afferent signals delivered to the agonist and antagonist occur simultaneously. A proper balance must be made between the excitation and inhibition reflexes of the motor neurons for the two muscles. (Sherrington, 1909) For instance, as the hamstrings start to stretch, the GTOs are stimulated and inhibit the muscle to permit further lengthening, while at the same time the spindle is rapidly stretched. A resultant reflex could cause the hamstrings to contract during this period of eccentric lengthening. These simultaneous reflexive actions cause competing excitatory (spindle) and inhibitory (GTO) signals, and an optimal balance will allow for adequate hamstring length change without too much of a stretch reflex. (Johansson et al., 1991) This is a conflict that has to be resolved during high-speed activity to prevent injury. Therefore, it is reasonable to expect that previous damage to such afferents would have an influence on the function of the fusimotor system. (Johansson et al., 1991) Impaired fusimotor drive may lead to potential sensory impairments as well as alterations in muscle tone and stiffness. (Johansson et al., 1991)

Contributions to Musculoskeletal Stiffness

Passive stiffness refers to the force exerted during a perturbation of a relaxed muscle. Force is produced by detachment of any intact cross-bridges between actin and myosin filaments, (Latash & Zatsiorsky, 1993; Proske & Morgan, 1999) and removal of slack within the connective tissues, (Proske & Morgan, 1999) which when combined are referred to as the series elastic component (SEC). The contributions of the connective tissues and membranes within the muscle to passive stiffness are referred to as the parallel elastic components (PEC). (Latash & Zatsiorsky, 1993) The

SEC and contractile component (CC) elements are positioned in series, and the PEC is located parallel to the contractile elements of the muscle. In a relaxed state, actin and myosin are able to slide freely and when activated they increase their overlap and shorten. If the muscle is performing an isometric contraction, tension is placed on the SEC resulting in a minimal stretch. (Martins, Pires, Salvado, & Dinis, 1998) Properties of viscoelastic muscle tissue are a critical component of movement as the stress-strain relationship is partly dependent on its fluid components, especially the response to mechanical stress. (Whiting & Zernicke, 2008) A greater slope of the stress-strain curve will result following a greater strain rate, which in turn will cause the stiffness of the muscle to increase. (Whiting & Zernicke, 2008) Therefore, due to the viscoelastic properties of muscle, a damper (viscous dashpot) is also depicted in the muscle-spring model. This represents the muscle's velocity dependent resistance to stretch, with a faster stretch capable of producing greater resistance to the change in length.

Short-range stiffness is measured during the initial perturbation movement, and consists of reverse pivoting of myofibril cross-bridges, producing a sudden increase in tension. (Proske & Morgan, 1999; Rack & Westbury, 1974; Sinkjaer, Toft, Andreassen, & Hornemann, 1988) *Total stiffness,* or long-range stiffness, entails the entire joint movement and is attributed to the cyclic motion of reversing cross-bridges, usually associated with an eccentric contraction. (Sinkjaer et al., 1988) At a lengthened state, the muscle tension is expected to plateau or decrease, producing what is referred to as a "frictional resistance." (Proske & Morgan, 1999) Lastly, the protein titin, located within the sarcomere, provides long-range elasticity to the myofibril, (Maruyama, Matsubara, Natori, Nonomura, & Kimura, 1977) and

contributes to stiffness of the muscle. During eccentric loading, lengthening of the sarcomeres is limited by titin in an attempt to reduce the risk of subcellular tissue damage. (Butterfield, 2010; Helmes, Trombitas, & Granzier, 1996) In these instances, titin may perform as a spring within the muscle system to provide a stabilization of sarcomeres and dissipation of forces. (Butterfield, 2010; Helmes, Trombitas, & Granzier, 1996) Hence, the hamstrings absorb energy through the deceleration that is subsequently stored and released during the stance phase. (LaStayo et al., 2003) Animal studies have verified that stiffness of the protein titin is closely related to stride frequency; further highlighting that it is an integral part of the muscle-spring system, and a potentially modifiable structure. (LaStayo et al., 2003; Lindstedt, Reich, Keim, & LaStayo, 2002; Reich, Lindstedt, LaStayo, & Pierotti, 2000) The ability of the HS to efficiently operate as a component of a functional mass spring system, with surrounding macroscopic musculoskeletal structures, is essential to performance and avoiding strain injury at high-speed in sport. Titin may also be active in the mechanical signal transmission process, where muscle tension is monitored and optimized through a feedback loop. (Tskhovrebova & Trinick, 2008) Thus, titin could also play a role in controlling force and strain. (Butterfield, 2010) In conclusion, titin may be influential in the lengthening of the muscles as part of the contractile extrafusal muscle fibers, as well as being closely related to muscle stiffness regulation and spindle activity. It is suspected that titin would be a substantial factor in the production of short-range stiffness, as well as the overall extensibility of the muscle.

Active stiffness involves a pre-contraction prior to the perturbation, and therefore results in higher values. (Rack & Westbury, 1974) It is directly related to the force capabilities of the muscle, (Morgan, 1977) as well as reflexive elements.

(Sinkjaer et al., 1988) With respect to length, active short-range stiffness is directly associated with the amount of cross-bridge formations present in the pre-contracted muscle, thus greater tension will be produced at an angle that has more cross-bridges intact. (Morgan, 1977) This means that active stiffness will also be closely tied to the muscle force production, and therefore greater strength will result in increased stiffness when a pre-contraction is maintained prior to a perturbation. (Morgan, 1977) Aside from these intrinsic components of stiffness, the reflexive contribution to tension has also been realized. (Sinkjaer et al., 1988) The reflexes of the muscles are suspected to be responsible for approximately one half of the total stiffness. (Sinkjaer et al., 1988) However, the reflexive contribution to stiffness varies greatly in healthy controls, which makes it a process where errors can occur, since reflexes are such a significant part of stiffness. (Sinkjaer et al., 1988; Sinkjaer & Magnussen, 1994) The same receptors that produce this reflexive contribution to stiffness are also accountable for establishing resting muscle tone. (Johansson, Sjölander, & Sojka, 1990; Sinkjaer et al., 1988) While stiffness regulation appears to be an area worthy of future research pertaining to risk of injury, since the timing of injuries is rapid, the ability to reproduce real life stimuli to capture CNS processes and modulation of muscle stiffness is limited.

Measurement of Musculoskeletal Stiffness

A number of methods have been designed to measure and quantify stiffness using instrumentation such as arthrometers, devices to provide perturbations, inverse dynamics, and analysis of movement. (McGinnis, Snyder-Mackler, Flowers, & Zeni, 2013; Shamaei, Sawicki, & Dollar, 2013) One of the benefits of using perturbations delivered by a motor is that it allows for application of a rotational force, and uses a

load cell to directly measure resistance to the movement. This offers the advantage of selecting precise parameters to mimic the mechanisms of sports related injuries such as the acceleration, velocity, and magnitude of the perturbation. As the perturbation is applied, stiffness changes may be observed, along with muscle responses, including the timing and amplitude of contraction. (Delahunt, 2007; Zinder, Granata, Shultz, & Gansneder, 2009) Previous research has suggested that "muscle tuning" can occur, where an individual can use certain strategies to optimize movement based on their own innate stiffness in order to avoid injury. (Nigg & Liu, 1999)

Strain injury may be reduced through an increase in the stiffness of the muscle spring system. (Lindstedt, LaStayo, & Reich, 2001; Lindstedt et al., 2002; Reich et al., 2000) This is because when stiffness is decreased, it may cause soft tissue injury by means of excessive joint motion during activity. (K. Granata et al., 2002) However, increased stiffness could reduce a muscle's ability to attenuate forces, most specifically during eccentric loading. (K. P. Granata, Wilson, & Padua, 2002; McHugh, Connolly, Eston, & Gleim, 1999; Wilson, Wood, & Elliott, 1991) Soft tissue injury risk may be increased due to higher levels of muscle stiffness. (R. J. Butler et al., 2003; Ekstrand, Gillquist, & Liljedahl, 1983; Watsford et al., 2010) Increased musculotendinous stiffness has been associated with greater peak forces, shock and loading rates, (R. J. Butler et al., 2003) as well as decreased excursion of the lower extremity; hence, force development may be asymmetrical between limbs during gait. (Watsford et al., 2010) Pruyn et al. (Pruyn et al., 2012) revealed that Australian Football League players sustaining lower extremity injuries had significantly greater bilateral leg stiffness differences as measured with a unilateral hopping task, compared to those that remained healthy. Furthermore, higher muscle stiffness will create a

resultant increase in ion and metabolite release within the muscle that leads to activation of afferent receptors. (Johansson, Djupsjöbacka, & Sjölander, 1993) This chain of events causes an even greater excitatory impact on the muscle spindle system. As a result, ongoing pain and increased stiffness may occur by means of a positive feedback loop, and the increased activation of muscle afferent chemosensitivity. (Johansson, Djupsjöbacka, & Sjölander, 1993) Therefore, others suspect that injury may be reduced with greater compliance of sarcomeres in series, (C. L. Brockett et al., 2001; Proske & Morgan, 2001) and better force absorption. (Wilson et al., 1991) Hence, this theory suggests that lower muscle stiffness may actually be more advantageous in prevention. (McHugh et al., 1999; Nosaka & Clarkson, 1997) This also suggests that that a direct relationship exists between extensibility and stiffness measures. (Wilson et al., 1991) However, these calculations are based on dampening oscillations of the upper extremity, and are not applicable to more direct measures of stiffness of the hamstrings. A third and final hypothesis is that consistent levels of stiffness may be more suitable during sport, because a more predictable mechanical behavior allows the nervous system to more easily optimize muscle recruitment strategies in a timely fashion. (Huxel et al., 2008) Further research is needed to explore optimal stiffness regulation strategies of the hamstrings and to uncover how function is altered following injury.

Muscle stiffness has been previously studied as a critical component in the transmission of forces during movement with respect to other sports related injuries (ACL, shoulder, ankle). (Wilson, Murphy, & Pryor, 1994) This area has not been studied extensively pertaining to HSI. The examination of muscle stiffness as a risk factor for HSI is limited and has not yet been studied in a previously injured

population. Scar tissue formation is suspected to result in much higher stiffness at the musculotendinous junction compared to healthy tissue. (Best & Hunter, 2000; Purslow, 2002) Stiffness was previously examined as a risk factor for HSI and it was found that increased bilateral stiffness was associated with a greater risk of injury. Additionally, lower hamstring stiffness was observed in the involved limb prior to the injury occurring, which was most likely attributed to decreased strength. (Watsford et al., 2010) However, this study included an oscillation protocol that calculated submaximal stiffness through a dampening response, as opposed to a motor device that more closely controls perturbation variables. A need still exists for future studies examining the role that stiffness plays in muscle injury. (R. J. Butler et al., 2003) Future research in this area may be able to provide insight for the development of improved intervention programs. (R. J. Butler et al., 2003; Hobara et al., 2008) Especially since stiffness has been identified as a modifiable factor, with a number of intervention studies demonstrating musculotendinous stiffness changes following strength, plyometric, isometric, eccentric, and general weight-training programs. (R. J. Butler et al., 2003) It is also important to consider other activity-related factors, such as fatigue, which can significantly influence muscle function.

Fatigue

Biomechanical and sensorimotor factors linked to injury are influenced by fatigue, (Rozzi, Lephart, & Fu, 1999) including measures of muscle strength and rate of force production, strategies of muscle activation and movement, and both joint and muscle stiffness. (Padua et al., 2006) Fatigue refers to an acute reduction in functioning that encompasses an elevated perception of effort to maintain a specific level of force production, as well as an ultimate incapacity to continue generating

force. (Enoka & Stuart, 1985) More specifically, peripheral fatigue refers to the alterations that take place in reference to the location of the neuromuscular junction or distal to it. While central fatigue is defined as a gradual decline in the volitional activity of the muscle while performing a task. (Gandevia, 2001) Supraspinal fatigue is a subcategory of central fatigue that explicitly refers to the inability of the motor cortex to continue to produce optimal signals from the higher CNS levels to the motor neurons, and then to the neuromuscular junction and contractile elements of the muscle. (Gandevia, 2001) This level of fatigue impacting descending excitatory motor drive may ultimately lead to a failure to maintain force production. (Gandevia, 2001) It is suspected that fatigue mainly occurs within the cells of the muscle itself. (Fitts, 1994) Understanding the exact physiological mechanisms of fatigue is a complex task, as the etiology of fatigue itself is believed to include numerous components influencing a variety of cellular locations. (Fitts, 1994) While significant advancements have been accomplished, there are still many unknowns regarding muscle fatigue. (Fitts, 1994)

Physiological Mechanisms of Fatigue

Enoka et al. (Enoka & Stuart, 1992) outlined four themes that have a potential influence on mechanisms of fatigue in research studies. *Task dependency* highlights that fatigue is capable of being accomplished by a number of mechanisms. Factors such as selected variables of the study design that can affect motivation, mode of contraction, intensity, time, and speed of the task will all influence the development of fatigue. (Enoka & Stuart, 1985) These details are capable of affecting motor neuron drive, motor unit activity, and cellular processes. (Enoka & Stuart, 1985) The importance of controlling and manipulating these variables during an investigation

will have a subsequent effect on fatigue mechanisms, which may be measured through various physiological aspects, including central drive, altered muscle activation patterns, neuromuscular propagation, excitation contraction (E-C) coupling, and metabolic processes. (Enoka & Stuart, 1985) Irrespective of the exercise parameters, such as duration or intensity, changes in E-C coupling and metabolic events seem to be contributing factors to muscle fatigue. (Fitts, 1994) Metabolic factors responsible for inducing fatigue during activity may include an increase in the concentrations of hydrogen (H^+) and phosphate (P_i), due to lactic acid buildup, and ATP breakdown that affects cross-bridge formations. (Fitts, 1994) Influences at other locations, such as the sarcoplasmic reticulum and proteins involved in regulation of the muscle contraction, also occur. (Fitts, 1994) Due to higher concentrations of extracellular potassium, membrane potential depolarization occurs, leading to a decrease in the release of calcium from the sarcoplasmic reticulum. (Sjøgaard, 1991)Further, it is also suspected that a reduced level of glycogen within muscles is also a contributing factor to fatigue during exercise of longer durations. (Fitts, 1994)

The *force fatigability relationship* represents the association between task requirements and the resultant level of fatigue that develops, indicating that higher force is capable of inducing greater fatigue. (Enoka & Stuart, 1985) Nonetheless, research demonstrates that the onset of fatigue will occur at any level of intensity with a neuromuscular activation task. (Enoka & Stuart, 1985) Based on this information, future research should aim to explore this relationship as means of probing the motor system alterations that are related to the changes observed in muscle activation patterns following fatigue. (Enoka & Stuart, 1985) *Muscle Wisdom* includes the concept of the sensory feedback hypothesis that considers the regulation of motor

neuron discharge though a muscle response controlled by a peripheral reflexive component. (Bigland-Ritchie, Dawson, Johansson, & Lippold, 1986) Muscles possess the ability to produce force in the most efficient manner through an adaptive decrease in motor unity activation, relaxation, and generated force. (Marsden, Meadows, & Merton, 1983) The role that fatigue has on performing skills that require sensory feedback is an important area to be examined in future research. (Enoka & Stuart, 1985) Lastly, *sense of effort* considers the actual perception of the subject's effort in force production originating from commands driven from the CNS, which create the corollary discharges that provide information to the brain regarding coming movements of the body. (D. I. McCloskey et al., 1983)

Fatigue and Hamstring Strain Injury

Fatigue has been investigated as a risk factor in a number of HSI studies; (M. Greig & Siegler, 2009; Pinniger, Steele, & Groeller, 2000; Small, McNaughton, Greig, & Lovell, 2010; Small, McNaughton, Greig, Lohkamp, & Lovell, 2009) however, HSI are also known to occur before the onset of fatigue as well. Various fatigue-inducing protocols have been used to analyze variables such as strength and kinematics, by means of general full-body fatiguing or muscle-specific fatigue protocols. Evidence suggests a temporal pattern exists with respect to HSI, as nearly one-half of all injuries occur during the final minutes of play in each half of competition. (Mohr, Krustrup, & Bangsbo, 2003; Woods et al., 2004) Analysis of EMG activity with fatigue has indicated that the biceps femoris activation increases in the later minutes of an intermittent fatigue protocol designed to replicate soccer match play. (M. P. Greig, Mc Naughton, & Lovell, 2006) This increased activity occurring with decreased strength of the HS, particularly eccentric strength, may be a result of the increased effort

required to control the limb during high-speed activity, while striving to maintain speed during sprinting. (M. P. Greig et al., 2006) Interestingly, halftime rest periods have not been shown to restore HS muscle strength at the start of the second half. (M. Greig & Siegler, 2009) It has been suggested that during fatigue, changes in sprinting technique serve as potential protective mechanisms. Previous studies have documented kinematic alterations such as decreased hip and knee flexion angles, decreased angular displacement of the lower leg, thigh, and trunk during the swing phase, as well as decreased angular velocity of the lower leg just before heel strike during sprinting in a fatigued state. (Pinniger et al., 2000; Small et al., 2009) These results are in conjunction with performance related variables such as an increase in 10-meter sprint times and a decrease in stride length during fatigued testing. (Small et al., 2009) These effects could be a means of compensating for the decreased ability of the HS to produce force. (Pinniger et al., 2000) Thus, altered kinematics could put an athlete at increased risk for HSI during the later portions of competition. (Small et al., 2009)

Strength related deficits have also been observed following fatigue protocols, including decrease in knee flexor and extensor peak torque production and a decrease in the functional strength ratio (eccentric HS to concentric quadriceps strength). (Rahnama, Lees, & Reilly, 2006; Small et al., 2010) Analysis of isometric strength and central motor output recorded every 15 minutes in male soccer players found that maximum voluntary torque was significantly decreased at the 45 minute mark of each half, compared to the start of each half (7.6% reduction). (Marshall, Lovell, Jeppesen, Andersen, & Siegler, 2014) In the first half, rate of torque development was also decreased at the 15 and 45 minute time points and at the 45 minute during the second

half at various segments following the onset of contraction (0-25, 0-50, and 0-75 milliseconds). Central motor output analysis showed that biceps femoris EMG during maximum voluntary contraction was significantly decreased at the 45 minute mark compared to the start (20.7% reduction). However, direct muscle stimulation to the HS showed no change in maximum M-waves (resting twitch evoked by electrical stimulation) throughout the fatigue protocol, which suggests that the HS were not peripherally fatigued. (Marshall, Lovell, Jeppesen, Andersen, & Siegler, 2014) These results are contradictory to previous reports that demonstrated fatigue was induced in both central motor output and peripherally within the muscle after competitive play. (Nybo et al., 2013; Rampinini et al., 2011) While these studies highlight significant alterations in hamstring function following fatigue, information pertaining to how hamstring muscle stiffness regulation is influenced under fatigue has not been reported.

Various protocols of different contraction types have been used in previous studies and fatigue is achievable regardless of the mechanism used. Isometric and concentric protocols have been shown to elicit both central and peripheral fatigue that cause reduced muscle strength. (Babault, Desbrosses, Fabre, Michaut, & Pousson, 2006) Both isometric and stretch-shortening contractions performed during functional tasks were able to produce similar levels of fatigue at the knee joint, in addition to comparable decreases in athletic performance and joint stiffness calculated with inverse dynamics. (Toumi et al., 2006) However, the inverse dynamics used to calculate stiffness may not accurately represent the loads experienced during sport, (McGinnis et al., 2013; Shamaei et al., 2013) and there may also be some compensatory strategies that influence these results. Comparison of intermittent and

sustained isometric contractions indicated that there is no difference between such protocols, (Gandevia, 2001) but isometric contractions have been associated with larger reductions in EMG activity (area under the curve) (~60%) compared to slight decreases produced by concentric contractions (~7%). (Kay, Gibson, Mitchell, Lambert, & Noakes, 2000) These results highlight the clear differences for types of muscle contractions with respect to neural drive when fatigued. (Kay et al., 2000)

Muscle specific fatigue protocols typically involve contraction of a muscle until the force production reaches a certain percentage of the subject's maximum voluntary contraction (MVC). Isometric fatigue protocols require the subject to maintain a target force set at a designated percentage of the MVC, with fatigue being reached when the subject can no longer keep force production above a preset percentage of the MVC for a certain period of time. Isometric protocols typically involve maintenance of a submaximal contraction (60% or less) as force production up to this percentage increases signs of fatigue as observed through EMG, but there appears to be no other advantages to producing a stronger contraction. (Bilodeau, Schindler-Ivens, Williams, Chandran, & Sharma, 2003) Decreased torque production during an isometric maximum voluntary contraction is well documented in the literature, along with a decrease in the EMG of the agonist muscle. (Patikas et al., 2002; Stephens & Taylor, 1970; Stephens & Taylor, 1972) Maintaining an isometric contraction to exhaustion, produces an increase in the EMG of the entire muscle; however, there is an overall decline in the firing rate of the motor units but more motor units are recruited, leading to the increased EMG. (Bigland-Ritchie et al., 1986) Maintaining a submaximal isometric contraction as long as possible results in central fatigue contributing to task failure, as demonstrated via twitch interpolation, which

portrays interrupted voluntary drive. (Löscher, Cresswell, & Thorstensson, 1996) However, isometric contraction protocols have shown that, the spindle receives a decreased signal from the fusimotor system when fatigued, (Bongiovanni & Hagbarth, 1990) along with decreased firing of the spindle. (Macefield, Hagbarth, Gorman, Gandevia, & Burke, 1991) Hence, the development of fatigue causes signals of peripheral decline to be transmitted via proprioceptive receptors, (Gandevia, 2001) disrupting the synchronized activity of alpha-gamma co-activation required to maintain optimal function. Alterations in spindle function can be measured in controlled conditions by means of examining reflexive changes in muscle activation through implementing a method that is capable of stimulating the receptor or their respective peripheral afferents. (Gandevia, 2001)

Neuromechanical Function and Fatigue

A number of studies have indicated that once fatigue occurs during running, there is a decrease in stiffness and running economy. (Dutto & Smith, 2002) Furthermore, temporary changes in stiffness have been previously induced by fatigue. (Avela & Komi, 1998; Ditroilo et al., 2011; Padua et al., 2006) Some have suspected that while central or peripheral fatigue contributes to muscle performance decreases, there is also a direct effect from elastic energy usage impairments, which is facilitated by the stiffness of the muscle. (Avela & Komi, 1998) Animal studies have shown that fatigue lowered the muscle's ability to absorb energy prior to reaching the yield point. Specifically, compared to the control group, the energy absorption was 70-92% less. (Mair, Seaber, Glisson, & Garrett, 1996) It is important to recognize that sub-optimal energy absorption during the late swing phase would place the hamstrings at increased

risk for injury, and it is unknown how this compromised function would interfere with muscle activity and stiffness regulation, particularly in end-range of motion.

It is suspected that once fatigue develops, an athlete is better able to make use of elastic energy stores during gait with higher stiffness. (Latash & Zatsiorsky, 1993) Therefore, a fine balance exists between the stiffness needed to reach optimal performance and to remain injury free. (McMahon & Cheng, 1990) During repetitive loading in athletics, the muscle's capability of absorbing loads is decreased, and therefore the recoil characteristics of the muscle may be diminished. (Komi, Hyvärinen, Gollhofer, & Mero, 1986) Ditroilo et. al (Ditroilo et al., 2011) observed that muscle stiffness (quadriceps) decreased with a cycling fatigue protocol, and decreases in stiffness, along with alterations in sensorimotor function, were associated with strength testing values. Interestingly, the group of subjects categorized as being "stiffer" displayed a greater decrease in musculoskeletal stiffness following the fatigue protocol. The onset of fatigue most likely diminished contractility of the muscles and resulted in a reduction in stiffness. (Ditroilo et al., 2011) It is unknown if changes in muscle stiffness are part of a protective mechanism that optimizes performance, or if such changes are associated with injury risk. (Dutto & Smith, 2002) At this time, there are no studies that have specifically investigated the role that fatigue plays in the stiffness of the HS in previously injured subjects.

As a muscle fatigues, decreased proprioceptive acuity in terms of movement detection into the direction of knee extension has been observed. (Rozzi et al., 1999) Animal experiments have documented decreased sensitivity to muscle length changes in a fatigued state; (Pedersen, Ljubisavljevic, Bergenheim, & Johansson, 1998) however, it is difficult to presume what occurs in voluntary contractions *in vivo* due to

the unknown behaviors of the fusimotor system. (Gandevia, 2001) During physical activity, sensorimotor function may be disrupted with the onset of fatigue, leading to an alteration of coordination. (Devlin, 2000) However, it is unknown how these mechanisms alter neuromechanical function of the hamstrings or what role previous injury has on these properties, particularly muscle stiffness regulation strategies and proprioceptive function. It is also hypothesized that fatigue not only causes physiological muscle changes, but also affects coordination, (Devlin, 2000) suggesting an additional area of research that may be increasing risk of HSI.

Anxiety

The influence that factors present during competitive activities, such as anxiety, have on the risk of sports injuries has been largely underestimated. (Junge, 2000) The interaction an individual maintains within their environment is a suggested area of research for determining contributing factors for HSI, although specific studies examining the role of such variables on HSI have not yet been completed. (Hoskins & Pollard, 2005) Previously, it was maintained that certain athletes were predisposed to sustaining athletic injury, or possessed an "injury proneness" based on personality traits. (Lysens et al., 1989; Taerk, 1977) Nonetheless, analysis of a number of empirical studies examining such a relationship has shown that a characteristic personality profile for an athlete considered being injury prone does not exist. (R. B. Brown, 1971; Junge, 2000; Valliant, 1980)

Anxiety has also been studied extensively with respect to athletic injuries; however, it is critical to distinguish personality trait anxiety, from situational anxiety related to competition, (Junge, 2000) especially since it has been demonstrated that general anxiety appears to have no direct impact on athletic injury. (Kerr & Minden,

1988; Lysens et al., 1989; Spielberger, Gorsuch, Lushene, & Vagg, 2010) Anxiety may be more clinically applicable when specifically defined as either state or trait anxiety, with *state* representing a sudden emotional response that is characterized by tension and apprehension. *Trait* anxiety is more synonymous with the aforementioned concept of "injury proneness," where an individual possesses a predisposition to interpret specific encounters as a threat with varying responses of state anxiety as a result of these often-competitive situations. (Spielberger & Spielberger, 1966) Competitive anxiety is one of the most studied aspects of sports psychology, (Woodman & Hardy, 2003) and is defined as one of the possible negative emotional responses to a stressor. (Whitehead, Butz, Kozar, & Vaughn, 1996) Anxiety in sport has been indicated as an important risk factor for injury as a number of studies support this relationship in collegiate football and track and field athletes, and gymnasts. (Blackwell & McCullagh, 1990; Hanson, McCullagh, & Tonymon, 1992; Kolt & Kirkby, 1994; Petrie, 1993) Competitive anxiety is recognized as a multidimensional conceptualization of anxiety, which includes both cognitive and somatic components. (Morris, Davis, & Hutchings, 1981) The impact on an individual is dependent on a number of factors such as the intensity and the directional interpretation of the stressor by the individual. Directional interpretation consists of a myriad of contributing elements including individual differences, control processes, cognitive bias, self-confidence, hardiness, and coping strategies. (Jones, Swain, & Hardy, 1993)

Andersen and Williams (Andersen & Williams, 1988; Williams, Tonymon, & Wadsworth, 1986) designed a theoretical framework that was a multi-factorial design incorporating psychological factors and the stress response. Based on this model, an individual's response to a stressful experience in sport will depend on their history of

stressors (previous injuries, life and daily stressors), individual personality (competitive anxiety, hardiness), and coping resources (behavior, social support, stress management skills). These factors will affect an individual's perception of an anxiogenic situation and ultimately the severity of the body's stress response. Thus, this response is dependent on the perception of a potential stressor and the physiologic and attention based processes that occur following exposure. (Andersen & Williams, 1988)

The Stress Response

The combined action of the hypothalamic-pituitary-adrenal (HPA) axis and the sympathetic/adrenomeduallary system are the means by which the body's organs are influenced by the brain in the presence of stressor. (Gold, Goodwin, & Chrousos, 1988) When exposed to acute stress, an increase in the secretion of cortisol and ACTH occurs as a result of increased corticotropin-releasing hormone (CRH) and arginine vasopressin (AVP) signals in response to the threatening stimuli. (Tsigos & Chrousos, 1994) The increase in CRH initiates a series of physiological and behavioral events, such as HPA axis and sympathetic nervous system activation. (Dunn & Berridge, 1990; Gold et al., 1988) These responses are part of the body's attempt to adapt to a stressor and include an increase in heart rate, blood pressure, and glucose. (Dunn & Berridge, 1990; Rock et al., 1984) Cortisol secretion is influenced by a combination of adrenal medulla hormones or cytokines and neuronal input originating from the adrenal cortex. (Hinson, 1990; Ottenweller & Meier, 1982) The circulation of ACTH has consequences on glucocorticoid production as it is the primary controller of its adrenal cortex secretions. The release of glucocorticoids is the end result of the HPA axis activation and homeostatic control and the bodily stress response ensues. (De Kloet,

1991) The effect of glucocorticoids span across various functions including the cardiovascular system, metabolism, and functions of muscles. (G. Chrousos, 2000)

Exposure to sudden stress leads the adrenal medulla to release norepinephrine (NE) and epinephrine and the sympathetic nerve terminals to discharge NE as well. (Tilders & Berkenbosch, 1986) As a result, arousal is heightened and vigilance is enhanced, while anxiety is increased as well. (G. P. Chrousos & Gold, 1992) Additional components of the CNS are also impacted by the stress system, including factors of information processing, initiation of action, and control of emotions. For instance, the mesocortical dopamine system is influenced, which provides innervation to the prefrontal cortex, an area of the brain purported to be connected to anticipatory processes and cognitive function. (Deutch, Clark, & Roth, 1990) The concentration of Acetylcholine (Ach) is also transiently increased during stress exposure, which is also a major factor that contributes to the stress response including physiological, emotional, and neuroendocrine changes. (Calogero, Bernardini, Gold, & Chrousos, 1988; Imperato, Puglisi-Allegra, Casolini, Zocchi, & Angelucci, 1989) While alterations in ACh levels remains a phenomenon that has yet to be fully understood; it is known that release of ACh also has the ability to activate the HPA axis. (Imperato et al., 1989)

It is hypothesized that a greater stress response would elevate injury risk through an increase in muscle tension, physical fatigue, visual field narrowing, decreased motor control, and higher levels of distractibility. (Gould, Guinan, Greenleaf, Medbery, & Peterson, 1999; Nideffer, 1983; Visser, De Looze, De Graaff, & Van Dieën, 2004) Increased muscle tension has been identified as the most reliable indicator of anxiety and is believed to be a more precise manifestation of CNS

stimulation when compared to other peripheral changes. (Hoehn-Saric & McLeod, 1993) When muscle tension increases, it is likely to alter motor control during activity and decrease muscle extensibility, leading to an increased risk of muscle strain. (Andersen & Williams, 1988) Under normal, low-stress conditions, higher cortical structures of the brain are responsible for maintaining an appropriate level of muscle tone. The monosynaptic spindle stretch reflex is so intensely robust that without cortical inhibitory action, muscle spasticity would result, producing inconsistent and uncontrolled movements. (Hall, 2010)

Anxiety is correlated with increased muscle tension as the inhibitory action of the cortical structures is lessened, resulting in a greater stretch reflex than would normally be required. (J. R. Davis et al., 2011) The influence of competitive anxiety on the disruption of inhibitory and excitatory signals to muscles has been recognized. (McHugh & Cosgrave, 2010) A high-anxiety situation will increase muscle spindle sensitivity, which will inadvertently pretension the hamstrings. As a result, the reflexive patterns meant to protect the muscle from injury could be disrupted. A number of studies have documented increased muscle tension based on EMG activity in anxious subjects compared to control subjects through the implementation of stress-inducing protocols. (Hoehn-Saric, Hazlett, Pourmotabbed, & McLeod, 1997; Weinberg, 1978) A preliminary study found that EMG activity of the gastrocnemius was well correlated with electroencephalography (EEG) activity, especially in the right hemisphere of anxious subjects, which was suspected to be synonymous with CNS arousal and increased muscle tension. (Hoehn-Saric et al., 1997) A second study using high trait anxiety subjects observed greater EMG activity for completion of a throwing skill that was designed to be competitive in nature. (Weinberg, 1978)

Increased muscle activity due to anxiety lead to a pattern of inefficient movement, suggesting that elevation of muscle tension is a consistent index of anxiety. (Pluess, Conrad, & Wilhelm, 2009) However, in terms of the presence of somatic symptoms resulting from anxiety, it has been suspected that a decoupling may take place between the individual's subjective report of symptoms and actual somatic measures. (Bechara, Damasio, & Damasio, 2000) Therefore, subjective questionnaires targeted to address muscle tension are recommended for use in conjunction with EMG measurements taken at different muscle locations. (Pluess et al., 2009)

In addition to changes in muscle properties, alterations in attention have also been emphasized as a major component in the stress-injury relationship. Visual field may be narrowed with decreases in peripheral vision also occurring and diminished visual cues, which may increase the risk of injury in contact sports, (Andersen & Williams, 1988) but it is also plausible that visual contributions to proprioceptive feedback could also be altered. A certain level of situational awareness is required to monitor a wide visual field, sort out unnecessary information, and to administrate high-level motor programs during intense athletic activity. (Nideffer, 1983) Anxiety during sporting events and its effect on vision and concentration has been linked to decreased performance and poor coordination. (Consiglio, Driscoll, Witte, & Berg, 2003; Ebersbach, Dimitrijevic, & Poewe, 1995) Even minor alterations in time to react or process information have the potential to influence judgment during movement or impair coordination for complex tasks during activity. (C. B. Swanik, Covassin, Stearne, & Schatz, 2007) The individual may become more hesitant or experience uncertainty during task completion in the presence of a highly stimulating environment, both of which result in increased muscle activity. (Dault, Frank, &

Allard, 2001; Desimone & Duncan, 1995; Lum, Enns, & Pratt, 2002) Recent evidence from our lab shows that unanticipated events cause changes in stiffness and sensorimotor function. (DeAngelis et al., 2014) During sport these mechanisms can be altered in the presence of startling events and potentially increase the risk of injury. It is possible that an anxious individual would present with an even greater startle response in a highly competitive sport environment, as increased stress could alter of muscle stiffness regulation strategies.

Previous research has demonstrated a relationship between competitive anxiety and injury frequency and severity. (Lavallee & Flint, 1996) Two studies assessing the effect of competitive anxiety measured via subjective scales (SCAT) found that Division – I collegiate football players with higher competitive anxiety levels experienced a greater number of more severe athletic injuries, and also missed more time from practice and games due to injury. (Blackwell & McCullagh, 1990; Petrie, 1993) A similar relationship was observed in collegiate track and field athletes between competitive anxiety and the severity of injuries that occurred. (Hanson et al., 1992) The CSAI-2 was used to investigate anxiety in competitive gymnasts and concluded that higher anxiety scores were associated with a higher frequency of injuries, as those athletes with four or more injuries had significantly higher anxiety scores than those with less than four injuries. (Kolt & Kirkby, 1994)

Sports psychology models have also focused on the cumulative impact of stressors that increase injury risk through a means of diminished perceptual and sensory motor reserves over time. (Andersen & Williams, 1988; Petrie, 1993) A recent studyrevealed that football players were at two times a greater risk of sustaining an injury that restricted play during periods of high academic stress, compared to lower

stress periods. (Mann, Bryant, Johnstone, Ivey, & Sayers, 2015) The HPA axis and SAM system allow for certain adaptations to stress to occur over time. When these mechanisms are deviated from their normal homeostatic functioning due to stress exposure, it is termed "allostasis," with the HPA axis and SAM system producing increased hormone levels. (McEwen, 1998) These changes have been associated with both acute and chronic cardiovascular neuropsychological disruptions. (McEwen, 1998) Athletes are consistently exposed to high allostatic loads by the nature of competitive sport, and the threshold to which an athlete can respond to such stressors will determine how well the load is managed by the individual. Further research should examine anxiogenic factors that increase the risk of athletic injury. (McCall et al., 2015) This information could be used to design interventions for decreasing injury rates by lessening competitive stressors through the implementation of coping strategies. (Galambos, Terry, Moyle, Locke, & Lane, 2005) Reducing the effect of anxiety might decrease the influence of muscle spindle sensitivity and increased tone on stiffness regulation during activity, which would otherwise result in excessive strain and higher likelihood of HSI.

Measuring Stress: Subjective & Laboratory Controlled Evaluation

A number of sport specific instruments exist to measure levels of competitive anxiety in athletes, (Martens, 1977; Martens, Burton, Vealey, Bump, & Smith, 1990) that are more suitable than general anxiety scales. (Burton, 1998) The earliest scales did not take into consideration the multidimensional aspect of anxiety, thus more modern instruments were designed. The Competitive State Anxiety Inventory-2 (CSAI-2) was developed to incorporate both the somatic and cognitive components of anxiety, (Mellalieu, Hanton, Fletcher, Hanton, & Mellalieu, 2006) and has become the

most widely used instrument to obtain measures of anxiety in athletes. (Vealey, 1990) Previous research has established such tools as valid and reliable means of measuring competitive anxiety, with temporal changes even being observed in scores as athletic competition nears closer. (Martens, Vealey, & Burton, 1990) Established norms are also available for reference based on competitive level, sport, and gender. Despite the evidence available supporting the applicability of such tools in competitive anxiety, questions still remain determining the relationship between anxiety scores and the effect on sports related behaviors including injuries and athletic performance. (Martens et al., 1990) More specifically, at this time it is unknown how the information from such scales relates to neuromechanical measures of stiffness regulation that can assess anxiety-induced alterations in muscle properties.

Another way to measure anxiety in a research setting is through the delivery of electric shock, which is a valid method of producing an aversive response in adult human subjects. Electric shock has been shown to be robust in producing anxiety, especially compared to other stimuli such as mental stressors and air blasts. (Grillon, Baas, Lissek, Smith, & Milstein, 2004; Noteboom, Fleshner, & Enoka, 2001) While various stressors have induced physiological and cognitive changes in salivary cortisol, blood pressure, subjective anxiety, heart rate, and electrodermal activity, electric shock delivery has also been able to produce increases in subjective tension, plasma epinephrine, and motor control. (Noteboom et al., 2001) The anxiety related response has been shown to exist from five minutes following the delivery of shocks, to up to 60 minutes later in animal studies, (M. Davis, 1989) and comparable results have also been demonstrated in human subjects. (A. O. Hamm & Stark, 1993; Lang, Greenwald, Bradley, & Hamm, 1993) During laboratory testing, stressors usually

43

elicit changes in physiological and cognitive measures via small increments, but a large variability exists between subjects. This has led to the recommendation that any measured variable should be monitored repeatedly throughout testing to obtain more precise measurements of stress-inducing protocols. (Noteboom et al., 2001)

A component commonly used to verify anxiety-producing conditions is the startle, typically a loud noise, visual display, or tactile stimulus that is sudden and intense in nature. (Grillon & Baas, 2003) The startle reflex is believed to be a valid and excellent tool for examining the human emotional response to aversive events or stimuli. (Grillon, 2002) A startle is usually delivered at random times during testing and the startle response is reflexive in nature, in that the end value is robust to biases of volitional movement and to human reaction times. (Grillon & Baas, 2003) The variability of the startle response is high, which represents the individual's changing inner state. (Grillon & Baas, 2003) Subjects diagnosed with anxiety disorders have displayed increased startle responses, (R. W. Butler et al., 1990; A. Hamm, Globisch, Cuthbert, & Vaitl, 1991) while elevated startles have also been recognized as a symptom in individuals with generalized anxiety disorder and post-traumatic stress disorder. (Grillon, Ameli, Foot, & Davis, 1993) Most studies rely on the acoustic startle to elicit a response, usually a quick, intense noise lasting up to 50 milliseconds long and within a range of 90-100 db. (Grillon & Baas, 2003) The effects of the startle are typically measured as the eye blink reflex with electromyography, which is accepted as the most reliable means of observing the startle response. (Landis & Hunt, 1939) Previous work from our lab has demonstrated that a rapid reflexive activation of the quadriceps produces an extension moment at the knee in response to a startle, which is manifested through higher stiffness in the short range of measurement.

(DeAngelis et al., 2014) This means that during high-speed activity, a startle reflex could result in excessive strain being placed on the hamstrings through an unexpected increase in knee extension during gait.

The startle is also implemented to further probe the response of an aversive stimulus presented to the subject. (Grillon & Baas, 2003) Animal studies have examined the effect of electric shock delivered in a series of up to 10 shocks, which have demonstrated an increase in the amplitude of the startle reflex. Electrical stimulation, and the threat of such, has commonly been used as a method to produce anxiogenic effects. When the threat of an electric shock is present, the startle response will increase, as even the placement of electrodes on the skin without shocks actually being delivered increases stress. (Grillon, Ameli, Woods, Merikangas, & Davis, 1991; Grillon & Ameli, 1998) The level of anxiety towards the electric shock will impact the startle response through the varying periods of testing (baseline/no threat, threat of shock, post-shock delivery). Grillon et al. (Grillon et al., 1993) found that subjects considered to be "high fear" based on a subjective scale (STAI-state), produced increased startle response in both the no threat and threat periods. Therefore, this testing method is believed to be an appropriate means to examine the effect that unanticipated events interferes with muscle stiffness regulation strategies, especially as an approach to more closely assess the role that higher levels of competitive anxiety may have in this process.

Conclusion

It is possible that poor HSI outcomes have been achieved thus far due to a lack of knowledge of correctly identified risk factors. The failure to focus on neuromechanical factors has potentially obstructed progress towards a decreasing

primary and secondary HSI rates. A multimodal approach will allow for the examination of various hamstring properties in a sample of injured and control subjects using novel techniques to identify deficits of the nervous system and related muscle function. Through the implementation of such methods, a sizeable contribution to the existing literature pertaining to HSI is possible. It is hypothesized that previously injured subjects will demonstrate proprioceptive deficits, decreased muscle activation at longer lengths, and alterations in hamstring stiffness regulation. Also, neuromechanical dysfunction may be intensified under fatigue and/or anxiety conditions in sport. Clarifying the complex interaction that fatigue and psychological influences have on the proposed variables may further explain the extremely high re-injury rate in sport.

Specific Aims and Hypotheses

AIM 1: Investigate how HSI alters proprioceptive and extensibility characteristics in controls and subjects with a previous history of HSI.

Hypothesis 1.1: injured limbs will demonstrate higher perceived hamstring tightness compared to controls, which will significantly decrease following a warm-up and static stretching protocol.

Hypothesis 1.2: extensibility (AKE) will not differ between groups under control conditions, but injured limbs will demonstrate a greater increase in extensibility (AKE) compared to healthy controls following a warm-up and stretch.

Hypothesis 1.3: injured limbs will demonstrate diminished joint position sense compared to healthy controls.

Hypothesis 1.4 injured limbs will demonstrate diminished force control compared to healthy control

AIM 2: Investigate how fatigue alters neuromechanical function in healthy controls and participants with a previous history of HSI.

Hypothesis 2.1: injured limbs will experience a greater increase in patient-reported hamstring tightness from the control to fatigue condition compared to healthy controls.

Hypothesis 2.2: force control will be diminished in all participants following the fatigue protocol, with greater errors produced in the previously injured group.

Hypothesis 2.3: muscle activation will be increased in all participants following the fatigue protocol, but with previously injured limbs exhibiting lower EMG activity, especially at end-range.

Hypothesis 2.4: hamstring stiffness will be altered in the previously injured limb, and decreased in all participants when fatigued, with the injured limb exhibiting impaired (lower passive reactive and higher active deactivation) stiffness regulation compared to controls.

Hypothesis 2.5: a positive relationship will exist between proprioception (force control and JPS) and stiffness, with greater proprioceptive errors associated with stiffness variability.

AIM 3: Investigate how anxiety alters hamstring muscle stiffness in healthy controls and participants with a previous history of HSI..

Hypothesis 3.1: heart rate will be increased in all participants at the mid-point and following the anxiety protocol, but participants with higher CSAI-2 scores exhibiting a larger increase compared to resting heart rate.

Hypothesis 3.2: muscle activation will be increased in all participants in the anxiety condition, with greater EMG activity in the previously injured group.

Hypothesis 3.3: hamstring stiffness will be altered in all participants following the anxiety protocol, with greater changes observed in the previously injured group.

Hypothesis 3.4: CSAI-2 anxiety scores will be related to hamstring stiffness, especially startle trials.

Hypothesis 3.5: heart rate will be significantly correlated with stiffness measures, with a higher heart rate associated with decreased reactive and increased deactivating stiffness.

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Chapter 2

**SENSORY DISCONNECT AND PROPRIOCEPTIVE DEFICITS
FOLLOWING HAMSTRING STRAIN INJURY**

Introduction

Hamstring strain injuries (HSI) are among the most common medical problems occurring in sport and recreation at the high school, collegiate, professional, and masters levels. (J. H. M. Brooks et al., 2006; J. H. Brooks et al., 2005; Feeley et al., 2008; Orchard & Seward, 2002; Posner et al., 2011; Seward et al., 1993; Woods et al., 2004) Despite increased interest in recent decades, incidence rates and the financial costs of HSI have continued to rise, while research examining possible mechanisms of injury remains inconclusive. (Brukner, 2015; Ekstrand, Walden, & Hagglund, 2016; Freckleton & Pizzari, 2013; Hickey et al., 2014) Although a number of risk factors have been examined to alleviate the uncertainty regarding prevention and rehabilitation of HSI, the relationship between the nervous system and muscle properties has been largely overlooked, particularly the neuromechanical decoupling that may interfere with the ability to attenuate musculotendinous loads. It is suspected that following HSI, disconnect occurs between sensory input and neuromuscular control during function, which may be due to peripheral or central mechanisms.

Extensibility is a risk factor for HSI that has been commonly explored, but definitive evidence establishing its role is lacking. (Orchard et al., 1997; Witvrouw, Danneels, Asselman, D'Have, & Cambier, 2003) Conflicting reports have revealed both decreased range-of-motion after injury, (Jonhagen, Nemeth, & Eriksson, 1994;

Worrell, Perrin, Gansneder, & Gieck, 1991) as well as insignificant differences

compared to healthy controls. (Hennessey & Watson, 1993; Rolls & George, 2004)

Following HSI, scar tissue formation may be interrupting normal tissue mechanics, as

histological studies have demonstrated increased strain and decreased compliance at

the musculotendinous junction in patients with a history of HSI. (Purslow, 2002;

Silder et al., 2010) However, it is also possible that the altered length-tension

relationship may be of neural origin, with a failure of receptors to detect precise length

changes of the muscle. Clinically, static stretching is widely utilized to increase

extensibility; (Bandy, Irion, & Briggler, 1997; Dadebo, White, & George, 2004)

however, it is not clear if previously injured limbs respond differently to stretching

due to viscoelastic or neural maladaptations following HSI. The contribution of the

nervous system must not be overlooked, as it functions to establish a "set point" and

tension level for a resting muscle. (Lin & Rymer, 1993) Furthermore, the protective

reflexes of the mechanoreceptors embedded with the muscle (spindles) and Golgi

tendon organs (GTOs) located at the musculotendinous junction, serve as key factors

in determining muscle length. (Hamill & Knutzen, 2006) Damage of these receptors

during strain injury or tethering of nerves within scar tissue following HSI may

contribute to altered extensibility. (D. Butler & Gifford, 1989; Lew & Briggs, 1997)

The spindle is specifically responsible for detecting modifying, and relaying peripheral

afferents information to the CNS. (Johansson et al., 1991) Through this process,

muscle activity is constantly monitored and adjusted by means of the stretch reflex.

(Hoffer & Andreassen, 1981) Meanwhile, GTOs provide for accurate detection of

musculotendinous forces throughout the range of movement. (Docherty & Arnold,

2008) Thus, the coordinated transmission of motor commands through reflexive and

descending pathways provides for muscle tone and continuous regulation of muscle stiffness during physical activity. (Johansson et al., 1991)

Trauma sustained to these mechanoreceptors during HSI could result in deafferentation and proprioceptive deficits. (Lephart et al., 1997) Sensory impairments following other musculoskeletal injuries, including errors in joint position sense (JPS) and force control have been reported. (Godinho et al., 2014; Juul-Kristensen et al., 2008; A. J. Lee et al., 2006; Lephart et al., 1992; Warner et al., 1996) Disturbance to spindle function may lead to inaccurate joint position sense, resulting in failure to adequately detect muscle length and loading rates critical for energy absorption during high-speed activities. This would lead to neuromuscular coordination errors that could increase the risk of HSI. (C. L. Brockett et al., 2001; Brughelli et al., 2010; Cameron et al., 2003; R. Clark et al., 2005; Kilgallon et al., 2007) Few studies have examined JPS after HSI, and force control in HSI patients has yet to be examined. (Cameron et al., 2003) Force control errors have been observed following other injuries and fatigue; (C. Brockett, Warren, Gregory, Morgan, & Proske, 1997; Docherty et al., 2006; Proske, 2005; Wright & Arnold, 2012) however, it is unknown how GTO function is modified following HSI. Improper afferent signals may result in inaccurate recruitment of motor units, which in turn, will overestimate or underestimate the force required for task execution and lead to stiffness dysregulation while the hamstrings are undergoing forceful lengthening. (Docherty et al., 2004)

Further, compromised mechanoreceptor function and inaccurate proprioceptive input may explain the subjective symptoms known to persist following HSI upon return to high-speed activity, despite a lengthy recovery period and rehabilitation. (Sole et al., 2012) This means that following muscle injury aberrant sensory

information is conveyed due to either receptor excitation or inhibition. Excitation of nociceptors and mechanoreceptors, during the acute phases of injury, manifests as feelings of heaviness and dullness in the limbs, which may further develop into prolonged sensitization to mechanical lengthening. (Villarreal et al., 2013; Yamashita et al., 1999) However, the subjective perception of tightness is a component of extensibility that has been neglected thus far in the literature. While "tight" is a non-specific term that is not recognized as a formal medical diagnosis, it is related to the patient-reported perception of decreased extensibility. (Kuilart et al., 2005) It remains to be determined if patient-reported tightness impacts functional measures, if perception of tightness is coupled with an actual decrease in range of motion, or if a discordant relationships manifests between sensory input and extensibility following HSI. Additionally, if neural maladaptations occur following HSI, an inability of the brain to successfully bind sensory input may result in an abnormal perception of tightness following injury. (Chiel, Ting, Ekeberg, & Hartmann, 2009; Treisman, 1996)

Hence, it is hypothesized that passive tissue maladaptations and diminished mechanoreceptor function may interfere with neuromechanical function following HSI. An uncoupling between muscle properties and the nervous system could lead to increased subjective tightness and poor patient-reported outcomes (PRO), in addition to functional impairments such as decreased extensibility, and lessened effects of a warm-up and stretch on the hamstrings. These potential consequences, in addition to reflexive motor reactions to discomfort associated with strain injury, may disrupt motor commands in the descending or reflex pathways from the muscle spindle system and lead to decreased proprioceptive acuity. (C. Swanik et al., 2000) Therefore, the purpose of this study was to examine both extensibility and patient-reported

outcomes, in combination with proprioceptive function using novel testing protocols in previously injured participants and healthy controls to identify potential neuromechanical maladaptations that exist following HSI that may be increasing the risk of future re-injury. This study may possibly be able to identify an inability of the brain to reconcile altered sensory input from the hamstrings after strain injury

Methods

Experimental design

A case control design was used in this study. Independent variables included group (previously injured [INJ], control [CON],), limb (injured/uninjured [INJ] or matched/unmatched [CON]), and condition (control, post warm-up/stretch). Dependent variables included hamstring extensibility (degrees), joint position sense (degrees), force control (Nm/kg), patient-reported hamstring tightness (%), and hamstring patient-reported functional outcomes (VISA-H).

Participants

Fifty-six participants (29 previously injured, 27 healthy controls) between the ages of 18-25 years were recruited to volunteer in this study (Table 1). The number of participants was calculated *a* priori with G*Power Version 3.1.9.2 (Heinrich-Heine-Universitat, Dusseldorf). All participants were current or former (within the last 2 years) members of collegiate varsity/club competitive teams and were active at least 3 days per week at the time of testing. Participants with a history of HSI had sustained the muscle strain within four years prior to testing. Injury was defined as an acute episode of sharp pain in the posterior thigh that resulted in absence of participation for a minimum of one day beyond the day of injury occurrence. (Dick, Agel, & Marshall, 2007) At the time of testing, all participants were medically cleared for return-to-play.

Mean time loss for HSI participants was 23.96 $\pm$ 31.58 days (range 3-120 days) and mean time since injury was 13.22 $\pm$ 12.74 months (range 1-48 months). Exclusion criteria included any current musculoskeletal injury, history of low-back/lower extremity surgery in the last six months, neurological conditions, or any history of ankle or knee surgery. All participants provided written informed consent, and the University of Delaware Institutional Review Board granted study approval.

Instrumentation

Hamstring extensibility was measured using the Active Knee Extension (AKE) Test ([Figure 1](#)). (Worrell et al., 1991) Joint position sense (JPS) was tested using the same movement utilized in the AKE Test. (Gajdosik & Lusin, 1983; Worrell, Sullivan, & DeJulia, 1992) The JPS target angle for each limb was calculated as 15° less than the participant's average extensibility value in the AKE test. (Stillman, 2000) Force control was measured using three different tests: force matching, ramp-and-hold, and oscillation tasks. (Emge et al., 2013; Jaric et al., 2005; Krishnan & Jaric, 2008) These tests were completed with the participant seated in a custom-built Stiffness and Proprioception Assessment Device (SPAD). (DeAngelis et al., 2014; Huxel et al., 2008; A. R. Needle et al., 2016) This device includes a servomotor with a lever arm attachment and an adjustable chair (Figure 3). A custom LabVIEW (National Instruments, Austin, TX) program was used to collect analog torque signals. Hamstring subjective tightness was quantified using a 10 item self-report questionnaire that required participants to select answers that most accurately reflected the tightness they experience while at rest, during activities of daily living, and during running/sport. Control condition tightness at the time of testing was assessed with a Visual Analog Scale (VAS), with end points of "no tightness at all" and "extreme

tightness" ([Appendix C](#)), which are commonly used in research studies to assess subjective information. (Cline, Herman, Shaw, & Morton, 1992) Functional outcomes were assessed using the Victorian Institute of Sport Assessment Scale (VISA-H), which is an 8-item scale that includes three domains pertaining to the hamstring muscles: function, pain, and activity. Use of this scale allows for a measure of the participants' presence of symptoms and level of physical activity. (Cacchio, De Paulis, & Maffulli, 2014).

Procedures

Following completion of the informed consent and subjective questionnaires, control condition AKE measurements were obtained. The participant remained supine on a treatment table and the pelvis and untested limb were secured to the table with a strap. To begin the test, the participant raised and maintained 90 degrees of flexion with the leg held against the crossbar of a custom-built device, with the knee in a relaxed position. The knee is then extended as far as possible while keeping the thigh in contact with the crossbar. Measurements were taken when the participant reached their maximum stretch and the angle at the knee joint was measured with an inclinometer and recorded. Order of testing limb was randomized and three trials were performed for each limb. Participants then completed a five-minute warm-up on a stationary bicycle followed by a static stretching protocol. (O'Sullivan et al., 2009) To perform the static stretching of the hamstring muscles, one limb was placed on a standardized elevated surface and the participant was instructed to slowly flex the trunk forward as far as possible and to hold the ankle with the hands for 30- seconds. (Bandy et al., 1997; O'Sullivan et al., 2009; Paoadopoulos, Siatras, & Kellis, 2005) The 30-second stretch was performed three times on each limb with a rest of 15-

seconds between stretches. Following the warm-up and stretch, the hamstring tightness VAS was repeated for both limbs. Hamstring extensibility was then retested using the same previously described methods.

For JPS testing, participants were asked to actively reproduce a specific joint angle following an initial movement of the limb to a target joint angle while wearing a blindfold to remove all visual feedback (Figure 2). The target angle was verified with an inclinometer and the position was held for five seconds. The participant was then directed to return their limb to the starting position and after a five second rest were instructed to reproduce the target angle as accurately as possible. Three trials were performed on each limb.

To complete force control testing, participants were seated on the SPAD (Figure 3) with the trunk and thigh secured, the back supported, and the hip in 90 degrees of flexion. The axis of rotation of the adapter arm attached to the servomotor was aligned with the lateral joint line of the knee. (DeAngelis et al., 2014) A pad projecting from the adaptor arm provided stabilization for the distal lower limb, while the upper thigh was also secured to the chair with a pad applying pressure to the thigh. A vacuum splint was placed over the distal lower leg and the ankle to mechanically secure the limb and to minimize force absorption of the soft tissues. (DeAngelis et al., 2014; Huxel et al., 2008) Maximum isometric voluntary contractions (MVICs) for the hamstrings were then performed prior to the start of force control testing. Familiarization procedures preceded each testing task and the sequence of the three force control tasks was randomized. For the force-matching task, participants were asked to replicate forces at two-counterbalanced target loads, 20% and 40% of MVIC. (Godinho et al., 2014; Simon & Ferris, 2008) Participants held at the target force for 5

seconds, using the display screen for feedback (Figure 4). Feedback was then removed and the participant was asked to reproduce the same force load for a five second trial. A short rest was provided between trials, and three trials will be completed at each target force. A 1-minute rest was provided before repeating the procedures for the 2nd target force. The ramp-and-hold task required the participant to trace a line shown on the computer monitor by pulling into knee flexion against a lever arm to produce a tension force. (Jin et al., 2011) The line remains constant at zero for two seconds, increasing thereafter gradually at a constant rate for five seconds, and finally remains constant for the final five seconds (Figure 5). (Jin et al., 2011) The oscillation task required the participant to produce an oscillating force within a pre-determined range of tension (between 20-40% MVIC), for 12 seconds at a selected frequency (1 Hz and 1.5 Hz) paced by a metronome (Figure 6). (Emge et al., 2013; Jaric et al., 2006) While the ramp-and-hold task profile required participants to trace a prescribed line that necessitates corrections based on feedback mechanisms, the oscillation task involved a higher frequency that does not permit for such corrections. (Jaric et al., 2006) Two trials of the ramp-and-hold and oscillation tasks were performed. The first of the two trials was used for analysis unless it was considered unsuccessful, for reasons such as a late initiation or stopping the force production before task completion. (Jaric et al., 2006)

Data Reduction

Hamstring extensibility was calculated as the mean maximum knee extension value across the three trials for each limb. Joint position sense errors were calculated as the average of the absolute error (AE) across three trials. Errors during the force-matching task were also analyzed as absolute and variable error, which were selected

to capture participants' accuracy, consistency, and overall performance. (Docherty et al., 2004; Wright & Arnold, 2012) Absolute error is indicative of error magnitude only and variable error represents the standard deviation of the trial error. (Wright & Arnold, 2012) Root-mean-square-error (RMSE) was calculated to assess ramp-and-hold performance as the difference between the target track for the task and the trial force production. (Jin et al., 2011) For the oscillation task, total AE was calculated as the absolute difference of the target lines for the peaks/valleys of the oscillation and the produced force of the trial. (Krishnan & Jaric, 2008) Scoring for the VISA-H is based on a total score of 100, with a higher score associated with better function and less pain during activity. Hamstring subjective tightness values were calculated by measuring the distance (mm) of the mark made by the participant from the left side (no tightness) of the VAS.

Statistical Analysis

A 2x2 repeated measures ANOVA was used to examine hamstring extensibility measures between groups across conditions (control, post warm-up/stretch). Joint position sense variables were assessed using independent and paired sample t-tests to compare the difference in error means (AE, VE) between limbs and groups. Force-matching values were tested using independent sample t-tests for each error variable at the two loads (20% and 40% MVIC). A 2 (group: INJ, CON) x 2 (condition; condition, post warm-up/stretch) repeated measures ANOVA was also used to assess hamstring subjective tightness. An independent sample t-test was used to compare group differences for the VISA-H. A Pearson's correlation coefficient was used to examine the relationship between tightness, extensibility, proprioceptive tests,

and the VISA-H. All data were analyzed using SPSS (Chicago, IL). The significance level was set a *priori* at a level of alpha = .05.

<h1 style="text-align:center">Results</h1>

Hamstring Extensibility

Table 2 presents inter-limb and group means and standard deviations for hamstring extensibility for the control and warm-up/stretch conditions. Independent samples t-tests revealed that in the control condition, the INJ group had significantly lower extensibility in the previously injured limb compared to the matched limb of controls (t=2.31, p=.025), as well as significantly lower extensibility in the contralateral limbs (t=2.21, p=.031). No significant differences between limbs were present in the control condition for the INJ and CON groups or following the warm-up/stretch in either group (p>.05). While a significant effect for group was present (F=4.80, p=.033) in the repeated-measures ANOVA, there was no significant effect for condition (F=43.76, p=.058), representing no significant changes in extensibility following a warm-up/stretch. Following the warm-up/stretch, significant differences existed between groups in the injured/matched limbs (t=1.97, p=.05) as well as in the contralateral limbs (t=2.34, p=.023), with the INJ group displaying lower extensibility (Figure 7). No significant inter-limb differences were observed following the warm-up/stretch (p>.05).

Joint Position Sense

Table 3 and Figure 8 contain inter-limb and group means and standard deviations for JPS testing. A significant difference between limbs was observed in the INJ group (t=4.00, p<.001), with the injured limb displaying greater absolute error (AE) compared to the uninjured limb. There was no significant difference between

limbs in the CON group (p>.05). The INJ group had significantly greater AE in the previously injured limb compared to the matched limb of the CON group (t=-3.39, p<.001), while no significant difference existed between groups for the contralateral limbs (p>.05). No significant differences in VE were observed between groups in the injured/matched limb or contralateral limbs (p>.05); however, values were higher in the INJ group.

Force Control

Table 4 and Figure 9 present means and standard deviations for each group for the force-matching task. At 20% MVIC, a significant difference existed between groups (p=.05), with the INJ group producing greater AE, while at 40% MVIC there was no significant difference between groups during force-matching (p>.05). No significant differences between groups were observed for VE at 20% or 40% MVIC (p>.05), although values were higher in the INJ group. Table 5 and Figure 10 display group means and standard deviations for the ramp-and-hold task. At 20% MVIC, the INJ group performed significantly worse with greater AE (t=-2.20, p=.027), while the same results were also observed at 40% MVIC (t=-2.31, p=.025), with greater AE in the INJ group. Table 6 displays group means and standard deviations for the oscillation task. There were no significant differences between the INJ and CON groups for the peaks or valleys of the oscillation task performed at 1 Hz or 1.5 Hz (p>.05).

Patient-Reported Hamstring Tightness

Table 7 and Figures 11 and 12 present inter-limb and group means and standard deviations for patient-reported hamstring tightness for the control and warm-up/stretch conditions. Results of independent samples t-tests showed that during the

control condition, the INJ group had significantly higher tightness in the injured limb compared to the matched limb of the CON group (t=-2.03, p=.048). Although the INJ group reported higher tightness in the injured limb, the results of paired samples t-tests showed that no statistical significant inter-limb differences existed in the INJ group, nor was there a significant difference between limbs in the CON group (p>.05). Both groups demonstrated a decrease in tightness following the warm-up and stretch, as a significant main effect for condition ($F_{[1,51]}$=9.75, p=.003) existed, along with a main effect for group ($F_{[1,51]}$=5.55, p=.022) that revealed higher overall tightness in the INJ group. The significant difference between groups remained following the warm-up/stretch, with the INJ group reporting higher tightness (t=-2.15, p=.036). After the warm-up and stretch, a significant inter-limb difference was observed in the INJ group (t=2.27, p=.031), with the previously injured limb showing higher tightness. No significant inter-limb difference existed in the CON group following the warm-up and stretch (p<.05).

VISA-H

A significant difference existed between groups for scores of the VISA-H (t=3.70, p=.001). The mean for the CON group was 94.5 ± 6.3 and the INJ group mean was 82.86 ± 15.5 out of a possible 100. The scores for the CON group ranged from 79-100% and the INJ group scores ranged from 50-100.

Correlations

A number of significant correlations existed between the tested variables. In the INJ group, patient-reported tightness during the control condition was significantly correlated with extensibility (AKE test) in the uninjured limb (r=-.389, p=.041), but not the injured limb (p>.05) (Figure 13). Additionally, patient-reported tightness in the

control condition (*r*=.355, *p*=.008) (Figure 14) and following the warm-up/stretch (*r*=.299, *p*=.028) was significantly correlated with JPS (AE) in the injured limb, but not the uninjured limb. Patient-reported tightness was also significantly correlated with errors in the ramp-and-hold task at both 20% (*r*=.402, *p*=.003) and 40% (*r*=.464, *p*<.001); however, no significant relationships existed between tightness and the force matching or oscillation tasks (*p*>.05). The VISA-H was significantly correlated with JPS AE in the injured/matched limb (*r*=-.405, *p*=.002) (Figure 15), but no relationship existed with any of the other tested variables (tightness, AKE, force control tasks). Lastly, no significant correlation was found between the time since injury and any of the tested variables.

Discussion

This study was the first to comprehensively examine sensory input and proprioceptive function of the hamstrings in a previously injured population. The main findings of this study show that HSI patients cannot accurately detect where the previously injured limb is in space or control appropriate force production compared to healthy limbs. Decreased accuracy of JPS or force control could have direct implications on the risk of future injury if an individual overstretches the limb during terminal swing or improperly produces the required forces during activity. Furthermore, an increased sensory perception of hamstring tightness also exists, which remains uncoupled from objective extensibility, and that does not appear to be modulated by a warm-up and stretch. Thus, the results of this study support that muscle spindles and GTOs may be damaged during strain injury or afferent signals could be altered due to neural tension caused by tethering of nerves within connective tissue of the muscle, leading to a neuromechanical decoupling associated with

100

proprioceptive deficits in previously injured limbs. (D. Butler & Gifford, 1989; Lew & Briggs, 1997) Although no joint damage occurs with HSI, these findings highlight the important role of these receptors to limb awareness. The methods used in this study serve as a model that could potentially be adapted to other commonly strained muscles, such as the quadriceps, adductors, and gastrocnemius, where either non-contractile connective or nervous tissue properties may alter normal neuromechanics.

Hamstring Extensibility

Our results indicate that extensibility is altered following HSI, as the INJ group displayed decreased extensibility compared to the CON group. The evidence supporting extensibility as a risk factor for HSI remains questionable, as well as the presence of extensibility deficits following HSI. (O'Sullivan, Murray, & Sainsbury, 2009; Rolls & George, 2004) However, a number of previous studies have identified decreased extensibility post-injury. (C. Askling, Saartok, & Thorstensson, 2006; C. M. Askling, Nilsson, & Thorstensson, 2010; Jonhagen et al., 1994; Reurink et al., 2013; Worrell et al., 1991) Our results are in agreement with these previous studies as we observed extensibility deficits in both the previously injured and the contralateral limbs. The bilateral deficit in extensibility suggests that a central mechanism could be involved in the INJ group; however, due to the retrospective nature of this study, we cannot ascertain if this observation was a cause or result of the HSI. Therefore, future studies should use reliable methodology to prospectively assess the effect of extensibility on HSI.

Lack of agreement amongst previous studies is likely attributed to the different methodologies used, and the results of previous work must be interpreted with caution as the population, time since injury, and tests used for measuring extensibility have

101

varied across previous studies. (Hennessey & Watson, 1993; Rolls & George, 2004; Sole et al., 2011) For example, in prospective studies assessing risk, extensibility was not found to be significantly correlated with HSI; however, the sit and reach test was used to assess extensibility, which has recognized limitations. (Orchard et al., 1997) Conversely, others have demonstrated the potential predictive capabilities of extensibility for HSI in high-level athletes. (P. S. Bradley & Portas, 2007; Henderson, Barnes, & Portas, 2010; Witvrouw et al., 2003) Lastly, the selection of rehabilitation protocols may also influence extensibility following HSI, which could lead to significant differences in extensibility at the time of return-to-play following HSI. (Silder et al., 2013) Nonetheless, based on our results, we may surmise that extensibility deficits remain after HSI, but future research should examine if extensibility improves in the weeks and months following return-to-play and if certain stretching protocols are more effective in returning range-of-motion.

Joint Position Sense

Significantly greater errors in JPS were observed in previously injured limbs compared to the contralateral limb and matched controls. Additionally, a significant inter-limb difference was observed in the INJ, which did not occur in the CON group. While a number of studies have investigated JPS following musculoskeletal injuries, such as ligament tears and tendinopathies, only one study has attempted to associate proprioception with HSI. (Cameron et al., 2003) The JPS results of our study are in agreement with previous work in injured groups for testing completed throughout the upper and lower extremities. (Godinho et al., 2014; Juul-Kristensen et al., 2008; A. J. Lee et al., 2006; Warner et al., 1996) More specifically, the 4.8˚ error that was measured in the HSI limb is comparable to those seen in other JPS studies performed

at the knee joint. (V. Baker, Bennell, Stillman, Cowan, & Crossley, 2002; Hortobágyi et al., 2004)

The only study to examine JPS of the hamstrings demonstrated diminished capabilities in limb awareness detected during a hip extension movement, which was concluded to be risk factor for HSI. (Cameron et al., 2003) The backward swing test that was used by Cameron et al. (Cameron et al., 2003) in this previous study may provide some insight to proprioceptive accuracy of the hamstrings as hip extensors, but the methods of our study allowed for examination in a position of muscle lengthening similar to late terminal swing when agonist and antagonist sensorimotor pathways are active, as eccentric load is the greatest and HSI is most likely to occur. (Chumanov et al., 2012; Heiderscheit et al., 2005) Additionally, our study was performed in a population that included previously injured limbs, which allowed for observation of maladaptations post-injury. Since the uninjured limb was not significantly different from that of controls, it is suspected that inaccurate JPS is a consequence of muscle strain that could increase the risk for secondary HSI. The limb could be receiving incorrect proprioceptive input from the muscle spindle regarding positioning of the leg during gait. If the position of the limb is not accurately detected during high-speed activity, the length-tension relationship of the hamstrings will be impacted with the heel striking the ground sooner or later than expected, (Cameron et al., 2003) leading to biomechanical and force absorption errors. Thus, torque demands could be altered, which could therefore increase the risk of mechanical strain during eccentric lengthening. (Cameron et al., 2003)

Force Control

In this study we observed greater errors during force control testing in the INJ group. The INJ group was significantly worse at the force matching task performed at 20% MVIC, but no statistical difference was observed at 40% MVIC. Aside from previous force control research at the ankle joint, we are unaware of any other studies investigating this measure following muscle strain injury. (Arnold & Docherty, 2006; Docherty et al., 2006) Despite lack of existing evidence, it is suspected that force control is just as important as JPS during activity. (Docherty & Arnold, 2008) Previous work has demonstrated impaired force control of the peroneals in participants with a history of ankle sprain injury. (Arnold & Docherty, 2006; Wright & Arnold, 2012) A larger magnitude of error has been observed at the higher loads (40% MVIC) compared to the lower load at the ankle. (Docherty & Arnold, 2008; Vuillerme & Boisgontier, 2008) Research suggests that higher force loads require a stronger muscle contraction with a concurrent increase in motor unit recruitment, leading to a greater number of mechanoreceptors engaged, and therefore provide increased proprioceptive input from the muscles. (Arnold & Docherty, 2006) As a result, force control may be preserved at higher loads, opposed to lower loads where damaged spindles and GTOs are not able to provide the appropriate feedback for monitoring force production. (Arnold & Docherty, 2006; Wright & Arnold, 2012)

This was the first study to examine force control of the hamstring muscles and to inspect potential force related proprioceptive deficits in a previously injured HSI population, possibly arising from impaired mechanoreceptor signals or changes in sense of effort. Our significant force-matching results at 20% MVIC showed that previous HSI interfered with the ability to accurately control force at lower loads,

while no group differences existed at the higher load. Thus, as in agreement with previous work, the reproduction of lower forces requires increased sensitivity compared to higher loads that was able to reveal force control deficits in the previously injured limbs. Such force control errors would be undesirable during sprinting, when near instantaneous changes in muscle tension and strain need to be monitored and controlled to avoid injury.

In the ramp-and-hold task, deficits were evident at both loads in the INJ group. Participants in the CON group were better able to regulate their force to trace a prescribed line with live visual feedback provided. A similar ramp-and-hold force control task was used in a study by Krishnan et al., (Krishnan & Jaric, 2008) that demonstrated increased hand function errors in multiple sclerosis patients. This is a task that requires reliance on the feedback mechanism. (Jaric et al., 2006) For such a task, errors may be originating from one or more areas of the sensorimotor system; however, in this study we are not able to determine where the errors are occurring. For example, in order to improperly replicate a target force, the participant may either incorrectly perceive the force, or if they perceive the target force correctly, improper reproduction of the force may occur at the peripheral receptors or at the central processing level. (Arnold & Docherty, 2006; Docherty et al., 2004) All of the above potential mechanisms are problematic, as they will lead to improper monitoring and control of force, which can lead to too little or too much of a muscle contraction during activity, possibly increasing the risk of strain injury. (Arnold & Docherty, 2006; Docherty et al., 2004)

Despite these findings, there did not appear to be any significant differences between groups for the oscillation task, which is based off of feed-forward activity.

(Jaric et al., 2005) The INJ group displayed more variability amongst the peaks and valleys of their oscillation trials, which could signify decreased neuromuscular control, but this difference did not reach statistical significance. More specifically, we do not know how much of this variability is considered "bad variance" and is a result of adaptation following HSI leading to abnormal task completion, or rather "good variance" where the CNS allows for increased variability for better neuromuscular execution of specific motor tasks. (Latash, Scholz, & Schöner, 2002; Park, Zatsiorsky, & Latash, 2010) The oscillation task results were unexpected as it was suspected that a predominately feedforward task would most likely be associated with increased injury risk, as feedback mechanisms are not quick enough to allow for adequate reactions to unanticipated perturbations during high-speed activity. (Docherty & Arnold, 2008) Since we observed that feedback, and not feedforward function, was associated with prior injury, future research must determine if this is a critical factor related to HSI re-injury risk. While previous research supports the importance of accurate feedforward mechanisms, Bernstein classically suggested that sole reliance on feedforward processes is not adequate for negotiating the demands of a challenging environment. (Bernstein, 1967; Docherty & Arnold, 2008) Hence, following HSI, deficits in feedback commands may be increasing the propensity for future injury.

Force control is comprised of two separate components, tension and effort, (Carson, Riek, & Shahbazpour, 2002) both of which could be altered following HSI, and may suggest central or peripheral involvement. While peripheral receptors partially contribute to perceived effort, central mechanisms are predominately responsible for generating the effort signal, (Burgess, Cooper, Gottlieb, & Latash, 1995; D. McCloskey, Ebeling, & Goodwin, 1974) whereas tension is likely derived

from the GTOs located peripherally in the musculotendinous structures. (Arnold & Docherty, 2006; Roland & Ladegaard-Pedersen, 1977) Mechanoreceptor damage may be interfering with proprioceptive input related to detecting or producing the correct force levels for the task. Freeman was the first to suggest that deafferentation results following musculoskeletal injury that could have direct consequences on proprioceptive acuity. (M. A. Freeman et al., 1965) The increased errors observed by the INJ group in both the force matching and ramp-and-hold tasks indicate that HSI is associated with such proprioceptive deficits, and highlights the need for further investigation into this function. During sport, improperly controlling force of the hamstrings could lead to suboptimal gait patterns or if inadequate eccentric contractions are maintained during deceleration, overstretching of the muscle may occur.

Force control deficits of the hamstrings could pose a risk to other musculoskeletal injuries, such as ACL tears, if the co-contraction between the quadriceps and hamstrings or other aspects of functional joint stability are disrupted. (Friemert et al., 2005; Li et al., 1999; D. A. Opar & Serpell, 2014) Errors in sufficiently detecting the necessary forces required for task completion during activity could lead to either more or less recruitment of motor units than desired for a specific movement. This could ultimately result in stiffness dysregulation, (Docherty et al., 2004) as afferent information is delivered to the CNS along the same pathways responsible for regulation of muscle stiffness. (Johansson et al., 1991) These mechanisms may be further affected by inaccurate sensory perceptions following HSI within the limb as well.

Patient-Reported Hamstring Tightness

Our results suggest that there is an altered sensory perception in the previously injured limb following HSI. The INJ group reported significantly higher tightness in the affected limb compared to the matched limb of the CON group, yet no significant difference existed in the contralateral limb between groups. While the tightness of the previously injured limb was reported as higher during the control condition in the INJ group compared to the uninjured limb, this inter-limb difference did not reach statistical significance. Anecdotally, tightness is a common complaint in HSI patients following return-to-play despite a full convalescence period. (Sole et al., 2012) This was the first study to measure and quantify patient-reported hamstring tightness in a previously injured population. From this study alone, we cannot confirm the exact cause of the altered tightness perceived in the previously injured limb, but we suspect that it may be originating from inaccurate sensory input caused by mechanoreceptor damage during strain injury or tissue scarring that involves neural tethering as a result of injury.

Influence of Warm-up and Stretching on Extensibility and Tightness

Based on our results, extensibility in both limbs in those with a history of HSI remains significantly decreased compared to controls. While extensibility increased following the warm-up and stretch, this increase was not significant compared to the control condition. No significant inter-limb differences were present in either group, nor did the gain in extensibility significantly differ between groups or limbs; however, the INJ group still showed significantly decreased extensibility compared to the CON group. O'Sullivan et. al. (O'Sullivan et al., 2009) studied HSI extensibility in previously injured participants and showed a significant increase in extensibility in

both previously injured and control participants using a passive knee extension test. Our results differ, as we did not observe a significant increase in extensibility, but are similar in that we also failed to observe a significant difference between groups. Discrepancy in results may be due to the use of an active extensibility measurement, which could have been further impacted by the proprioceptive and tightness maladaptations uncovered in this study.

A warm-up and stretch significantly decreased subjective tightness in all participants, but tightness scores remained significantly elevated in the previously injured limb, compared to both the uninjured limb and to the matched limb of controls. This was the first study to objectively measure patient-reported hamstring tightness. Higher perceived tightness in a previously injured limb has the potential to interfere with extensibility gains from stretching, since tolerance would be lower. Further, increased extensibility measured directly after a stretching protocol in previous studies has been attributed to a higher neurological tolerance to stretch, as opposed to an actual physical lengthening of the muscle. (Halbertsma & Goeken, 1994; Magnusson et al., 1996) Our results support the sensory theory of muscle extensibility, further representing a relationship between the perception of tightness and length achieved by a muscle during stretch. It is unknown if changes in stretch tolerance are of central or peripheral origin, (Weppler & Magnusson, 2010) but a central phenomenon may help to explain the decreased extensibility displayed in both limbs of the INJ group. Impaired spindle function may be interfering with the normal ability to develop a tolerance to stretching in those with a previous history of HSI. Alternatively, the neuroscience literature commonly refers to the phenomenon of how the brain functions to effectively "bind" sensory information, mostly pertaining to visual input,

and transforms it into a comprehensive concept, which remains an ongoing debate. (Seymour, Clifford, Logothetis, & Bartels, 2009; Treisman, 1996) Recently this theory has been applied to motor systems as well, to better understand the neuromechanical processing associated with the neural influences of complex human motion. (Chiel et al., 2009) We suspect that the deafferentation associated with neuromechanical *decoupling* following musculoskeletal injury could be representative of a disruption to this same binding model. (Needle et al., 2014) This study provides preliminary evidence identifying disconnect between incoming sensory input from the hamstring muscles and an inability of the brain to bind information required for a coherent perception of tightness.

Combined, our extensibility and tightness results highlight that tissue and/or neural maladaptations occur following HSI. These results bring into question traditional warm-up and stretching protocols for the hamstrings. This could mean that more dynamic or longer warm-up protocols could be needed to prepare those with a previous injury for activity in order to decrease the sensation of tightness and to possibly increase extensibility. Future studies should continue to examine the influence of warm-up and stretching strategies in previously injured participants, including jogging, static/dynamic stretching, and typical warm-up drills used by athletes.

Disconnect between Extensibility & Subjective Tightness

Extensibility in the INJ group was significantly correlated to patient-reported tightness in the uninjured limb under control conditions, but not in the previously injured limb. This was the first study to examine this relationship in HSI patients; however, altered sensation has been previously studied in patellofemoral pain

syndrome patients. The knee stiffness reported by participants was not associated with objectively measured mechanical stiffness. It was suggested that the perceived stiffness might be a misinterpretation of pain. (Hamstra-Wright et al., 2005) Our results are in agreement with the findings of this study, with a similar disconnect between tightness and extensibility. Patient-reported tightness was elevated in the previously injured limb, but this did not correlate with objective extensibility measures. This signifies that a discordant relationship exists in the previously injured limb following HSI, with the perception of tightness being uncoupled from actual extensibility of the muscle.

Perceiving increased tightness in a limb when extensibility does not actually differ between limbs could be a result of cortical reorganization, similar to phantom pain experienced by amputees. Following amputation, a redesign of the functional map of the cortical region is suspected to occur due to damage of the nervous system. (Flor, Elbert, Knecht, Wienbruch, & Pantev, 1995) This is hypothesized to be a process that is compensatory in nature to adaptively remodel activity within the cortical region that has diminished afferent signals, which may serve as an attempt to functionally recover. (Flor et al., 1995) These same mechanisms may consequently produce persistent hyperexcitability of nociceptors as a result of the prior memory of pain, (Willis, 1994) altered sensory inputs from nociceptive and non-nociceptive pathways once deafferentation occurs following injury. (Casey, 1991; Flor et al., 1995) Hence, a transformation of cortical architecture could take place following HSI as a result of somatosensory deafferentation, leading to persistent symptoms of tightness that do not align with objective measures of extensibility in the limb. Such maladaptations could increase injury risk by interrupting afferent signals associated

with neuromuscular control during high-speed activity. Aberrant sensation will disrupt the neuromechanical processing required to avoid injurious loads, and could be associated with the deficits in both JPS and force control that we observed in the previously injured limbs.

VISA-H and Correlation to Neuromechanical Function

Subjectively, HSI participants rated their pain, function, and activity levels significantly worse than controls, as measured by the VISA-H. Patient-reported outcomes have not been thoroughly explored in previous research. The Hamstring Outcome Score has been used as a screening tool for assessing risk, (Engebretsen et al., 2010) but has not been used specifically in previously injured participants or correlated to neuromechanical function. Based on our findings, the VISA-H may be an effective tool to assess patient outcomes in the clinical setting and to identify active individuals that may have lingering deficits following HSI, as we were able to identify a significant difference between groups. At the time of testing, all participants were active in their respective sports, although some participants were still engaged in modified activity since their injury. Nonetheless, all participants had been medically cleared to return-to-play, with the time since injury ranging from one month to four years. Although the VISA-H was originally designed to assess outcomes related to hamstring tendinopathy, we believe that the questions are pertinent to strain injury as well. Future research should determine the ability of the VISA-H to identify those at increased risk for re-injury in a HSI population.

Additionally, JPS absolute errors were also significantly correlated to patient self-reported outcomes measured by the VISA-H. Lower scores on function, pain, and activity measures were associated with greater JPS errors. This establishes a

relationship between self-reported factors and proprioception function, which highlights an often-overlooked component of HSI treatment and rehabilitation. Self-reported patient outcomes were previously associated with proprioception (force control) at the ankle joint, and our results are in agreement with this relationship.(Arnold & Docherty, 2006) These findings underline the importance of patient-reported outcomes following HSI, and the VISA-H may be a way to identify deficits in neuromechanical function. Thus, further research is warranted to further investigate these measures and their consequences on incidence rates.

Patient-Reported Tightness and Proprioception Correlations

Patient-reported tightness in all subjects was significantly correlated to absolute errors in JPS testing in the previously injured/matched limbs. Increased subjective hamstring tightness was associated with greater JSP errors; therefore, our results demonstrate the potential deleterious effects of altered sensory input on proprioceptive function of the hamstrings. Furthermore, patient-reported tightness was also significantly correlated with force control errors (RMSE) in the ramp-and-hold task at both 20% and 40% MVIC. This further substantiates that altered sensory information could negatively impact neuromechanical function, and is closely associated with proprioceptive deficits that could potentially increase injury risk. These observations further highlight the importance of subjective tightness as a patient-reported outcome (PRO) following HSI and its relevance to proprioceptive function.

Hamstring Interventions for Proprioception & Tightness

Evidence has supported interventions aimed at improving proprioception including manual therapy techniques, taping and bracing, and specific active joint

position training. (Borsa, Lephart, Kocher, & Lephart, 1994; Henriksen et al., 2004; Lephart & Henry, 1996) Since our results indicate that JPS is impaired following HSI, clinicians should consider assessing this proprioceptive function. Testing JPS can easily be accomplished using an inclinometer, which is accessible on most cellphones, or a goniometer. Feedback can be provided visually during training at the end of each trial for training purposes. The evidence to support specific force control training is less substantiated, with the majority of interventions focused on the cervical region. (Jull et al., 2007; O'Leary et al., 2007) This proprioceptive modality needs to be further examined with respect to its role as a risk factor for HSI, as well as its value as a clinical assessment tool and prevention and/or rehabilitation technique. Biofeedback devices are needed to objectively measure and monitor tension during active contractions in order to assess force control in the clinical setting, thus future work should also investigate user-friendly instruments that could easily be implemented in clinical practice for such purposes.

To alleviate tightness, recent case reports have suggested the use of alternative interventions for individuals that do not experience symptomatic relief from traditional stretching programs. (R. T. Baker, Hansberger, Warren, & Nasypany, 2015; Loutsch, Baker, May, & Nasypany, 2015) These include techniques such as reactive neuromuscular training, total motion release, and instrumented assisted soft tissue mobilization. Evidence supporting the efficacy of these approaches in decreasing patient-reported tightness is lacking, but these individual case reports demonstrated an improvement in extensibility. From a clinical perspective, the return-to-play decision following HSI should be made when all foreseeable risks have been diminished, (McCall, Lewin, O'Driscoll, Witvrouw, & Ardern, 2016) and the neuromechanical

deficits and their associations that were observed may be potential risk factors for re-injury. Current practices to treat and rehabilitate HSI may be missing such treatment components focused on alleviating the sensation of tightness in previously injured patients, and based on the results of this study, future consideration is warranted.

Limitations

Participants sustained injuries over a wide time frame ranging from one month to four years and experienced varying degrees of HSI severity based on time loss data. Participants were also members of a range of competitive sports and a more homogenous population may influence results in future studies. Additionally, a number of participants had a history of bilateral hamstring strains, which could have affected some our measures that were assessed bilaterally, such as extensibility and self-reported tightness. However, given this information we believe that if our participants were limited to unilateral HSI, the inter-limb differences may have been more pronounced than were revealed in this study, rather than lessening the significance of our results. Lastly, since self-report of injury was utilized in this study, as opposed to diagnosis via imaging, we do not know the exact severity of injuries sustained by participants. Severity of previous injuries and associated time loss may have influenced the results of this study, yet we were still able to observe significant findings despite the range of previous HSI characteristics. The variables we measured could certainly differ and improve at differing rates depending on the severity of the initial HSI.

Conclusion

The results of this study show that there are significant neuromechanical deficits that are present in individuals with a history of HSI, ranging from altered

patient-reported tightness and extensibility to impaired proprioception. As the first study to assess measures of patient-reported tightness in a HSI population, we were able to demonstrate that there is an abnormal sensory perception in the previously injured limb that occurs without any true objective hamstring extensibility deficits. Hence, a discordant relationship manifests between what patients perceive within the injured limb and mechanical function of the muscle following HSI. Therefore, clinicians should consider obtaining measures of patient-reported tightness after HSI and explore ways to reduce this sensation, especially since it is associated with proprioceptive deficits. Based on our results, we also conclude that decreased proprioceptive acuity following HSI should be investigated as a factor that may be increasing the risk of secondary injury in this population and as potential area to be implemented in the prevention and rehabilitation of HSI. Furthermore, impaired proprioception may be negatively impacting muscle activation and stiffness regulation. Future research is warranted to prospectively examine the risk of decreased proprioceptive function on injury, as well as the effect of specific interventions, such as joint position sense training and force control tasks on reducing such deficits and preventing HSI.

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Chapter 3

HAMSTRING STRAINS AND FATIGUE CAUSE FORCE CONTROL IMPAIRMENTS AND STIFFNESS DYSREGULATION

Introduction

Time loss from activity following a hamstring strain injury (HSI) averages 25 days, (J. H. Brooks et al., 2005; Feeley et al., 2008) and long term disability frequently results throughout the athletes' careers. (H. Liu et al., 2012) This prevents full return to pre-injury competitive status and negatively impacts health related quality of life. (Engebretsen et al., 2010; H. Liu et al., 2012; Sole et al., 2012; Verrall et al., 2001) In sport, the HSI reoccurrence rate ranks amongst the highest (12-34%) and the re-injury often results in more severe symptoms along with doubling of the recovery period. (J. H. M. Brooks et al., 2006; Koulouris et al., 2007; Malliaropoulos et al., 2011; Orchard & Seward, 2002) This is a frustrating experience for both the patient and clinician, (Sherry, Best, Silder, Thelen, & Heiderscheit, 2011) and many healthcare professionals lack confidence in safely returning individuals to activity following HSI. (Di Trani Lobacz, Glutting, & Kaminski, 2016) Furthermore, research remains contradictory with respect to potential risk factors, (Freckleton & Pizzari, 2013) and future studies are needed to elucidate the potential injurious mechanisms responsible for causing HSI.

Fatigue has been implicated as a risk factor for injury, since approximately one-half of HSI are known to occur during the later stages of practice and competition. (Woods et al., 2004) A range of fatigue-induced alterations including decreases in

eccentric strength, angular displacement and velocity, quadriceps and hamstring torque, functional strength ratios, and EMG activity of the hamstrings have been demonstrated. (M. Greig & Siegler, 2009; Pinniger et al., 2000; Rahnama et al., 2006; Small et al., 2010; Small et al., 2009) Therefore, when fatigue occurs, diminished muscle performance and running economy results, while the hamstrings function to maintain control of the limb during high-speed activity. (Avela & Komi, 1998; Dutto & Smith, 2002) Despite these documented fatigue-related changes in hamstring function, specific information pertaining to how proprioception and muscle stiffness regulation are influenced under fatigue have not been previously reported.

Evidence suggests that peripheral mechanoreceptor activity and sensitivity of the stretch reflex also diminishes with fatigue. (Avela & Komi, 1998; Lattanizio, Petrella, Sproule, & Fowler, 1997) Numerous laboratory experiments have demonstrated that the discharge and sensitivity of both muscle spindles and Golgi tendon organs (GTOs) are reduced following fatigue, either due to central or metabolic mechanisms. (Graham, Jammes, Delpierre, Grimaud, & Roussos, 1986; R. S. Hutton & Nelson, 1986) Thus, fatigue may cause improper proprioceptive input to be delivered through afferent pathways, which may result in impaired force control abilities. (Wright & Arnold, 2012) Furthermore, proprioceptive input may already be compromised if mechanoreceptors have sustained damage during a prior HSI and previous injury may further amplify the effects of fatigue. For instance, fusimotor-spindle system changes in response to pain have been observed, (Matre et al., 1998; Thunberg et al., 2002) which suggests that muscle strain and concomitant symptoms could alter force control and motor function. (Fyfe et al., 2013) These maladaptations may also be linked to hamstring tightness that is commonly reported after HSI. (Sole

et al., 2012) Further premature onset and decreased hamstring EMG amplitude during end-range eccentric contractions have been reported after HSI, (Sole et al., 2011; Sole et al., 2012) but it remains unclear if proprioceptive impairments and motor changes result in dysregulation of muscle stiffness in previously injured HSI patients.

Muscle stiffness is defined as the amount of tension or resistance that a musculotendinous unit produces in response to changes in length. (Oatis, 1993) Temporary decreases in muscle stiffness have already been observed by inducing fatigue at other muscles and joints. (Avela & Komi, 1998; Ditroilo et al., 2011; Dutto & Smith, 2002) A fine balance exists between the stiffness needed to allow for the critical timing of dissipation, absorption, and storing of energy during rapid eccentric lengthening and the subsequent powerful concentric contraction required for forward propulsion. (McMahon & Cheng, 1990) However, the pattern of stiffness regulation has not been directly measured in previously injured hamstrings. Sub-optimal stiffness may reduce a muscle's ability to attenuate forces (K. P. Granata et al., 2002; McHugh et al., 1999) and heighten the susceptibility of HSI, (Watsford et al., 2010) most specifically during eccentric loading, even as the limb moves within a normal range of motion. (Wilson et al., 1991) It is believed that the mechanical behavior of tissue must be predictable in order for the nervous system to properly tune muscle stiffness, (Nigg & Liu, 1999) and increased variability due to inaccurate proprioceptive input may interfere with this process.

Interruptions to neuromechanical function of the hamstrings may result in less than optimal muscle activation strategies and altered gait mechanics, (Sole et al., 2012) especially since the hamstrings are placed under intense sensorimotor demands as they operate to eccentrically decelerate the limb and produce torque. (Cameron et

al., 2003; Woods et al., 2004) Therefore, to avoid injury, precise excitation or inhibition of the hamstrings must occur at exact time periods during high-speed activities, otherwise excessive strain energy will result in structural myofibril damage involving sarcomere disruption. (J. Friden & Lieber, 1992; Lieber & Friden, 1993). Since HSI results from a straining mechanism, (Heiderscheit et al., 2005; Thelen et al., 2005) it is critical to identify how stiffness regulation is disrupted and what conditions interfere with optimal strategies. Hamstring stiffness has never been directly tested in a previously injured population, or simultaneously with conditions like fatigue that are believed to predispose to HSI. An examination of stiffness dysregulation in previously injured subjects is warranted to identify maladaptations in muscle activation and force attenuation strategies that may be contributing to future HSI risk during active lengthening.

Maladaptations of the sensorimotor system may represent an inability of the brain to appropriately bind sensory information due to the consequences of fatigue and previous injury on afferent signals. Central processing errors may be an underlying cause of abnormal force control and stiffness regulation, as well as increased patient-reported tightness. Resolution of binding errors in sensory input is required to allow for a stable motor performance during athletic maneuvers, in order to prevent excessive loading on the muscles. (Chiel et al., 2009) It is hypothesized that fatigue may interfere with the neuromechanical processes required for appropriate hamstring stiffness regulation, and that these effects may be amplified in previously injured hamstrings. Therefore, the purpose of this study was to examine neuromechanical contributions of fatigue and prior HSI on force control, patient-reported tightness, and

stiffness dysregulation to uncover potential mechanisms increasing the likelihood of injury.

Methods

Experimental Design

A case control design was used in this study. Independent variables included group (previously injured [INJ], control [CON]) and condition (control, fatigue). Dependent variables included force control (Nm/kg), patient-reported hamstring tightness (%), hamstring stiffness (Nm/°/kg), and muscle activation (EMG).

Participants

Fifty-five participants (28 previously injured, 27 healthy controls) between the ages of 18-25 years were recruited to volunteer in this study (Table 8). Participants in this study were the same sample that was used in the previous (Chapter 2) study. The number of participants was calculated *a* priori with G*Power Version 3.1.9.2 (Heinrich-Heine-Universitat, Dusseldorf). All participants were current or former (within the last 2 years) members of collegiate varsity/club competitive teams and were active at least 3 days per week at the time of testing. Participants with a history of HSI sustained the muscle injury within four years prior to testing. Injury was defined as an acute episode of sharp pain in the posterior thigh that resulted in absence of participation for a minimum of one day beyond the day of injury occurrence. (Dick et al., 2007) All HSI participants were medically cleared to return-to-play at the time of testing. Mean time loss from sport for HSI participants was 23.96 ± 31.58 days (range 3-120 days) and mean time since injury was 13.27 ± 12.98 months (range 1-48 months). Exclusion criteria included any current musculoskeletal injury, history of low-back/lower extremity surgery in the last six months, neurological conditions, or

any history of ankle or knee surgery. All participants provided written informed consent, and study approval was granted by the University of Delaware Institutional Review Board.

Instrumentation

Force control was measured using three difference tests: force matching, oscillation, and ramp-and-hold tasks. (Arnold & Docherty, 2006; Docherty et al., 2006; Emge et al., 2013; Jaric et al., 2005) These tests were completed with the participant seated in a custom-built Stiffness and Proprioception Assessment Device (SPAD). The SPAD is a modified isokinetic dynamometer that includes a servomotor (B-404-B-B4, Danaher/Kollmorgen, Radford, Va.) within a gearbox (UT018-050, 50:1, Danaher Motion, Radford, Va.), with a lever arm attachment and an adjustable chair (Figure3). (DeAngelis et al., 2014; Huxel et al., 2008; Thomas et al., 2013) A custom LabVIEW (National Instruments Co., Austin, TX) program was used to collect analog torque signals. Subjective tightness at the time of testing was assessed with a Visual Analog Scale (VAS), (Cline et al., 1992) with end points of "no tightness at all" and "extreme tightness" (Appendix C). Joint position sense (JPS) was tested using the same movement traditionally used to perform the Active Knee Extension Test. (Worrell et al., 1991) Hamstring muscle stiffness was also evaluated using the SPAD. A custom LabVIEW program allowed for control of high speed and specific range movements to be delivered. A torque reaction sensor (Model # T5400, Futek Advanced Sensor Technology, Irvine, CA) was used to collect analog torque values, which were synchronized with EMG and position data in a custom LabVIEW data collection program. Muscle activation was obtained using a wireless EMG system (TrignoTM^{TM} Wireless System 8138A-DST01, Delsys Inc., Boston, MA, USA).

Surface electrodes recorded medial and lateral quadriceps and hamstring activity with real-time display.

Procedures

Upon arrival in the laboratory, participants completed written informed consent and subjective questionnaires, followed by a five-minute warm-up on a stationary bicycle and a static stretching protocol. To perform the static stretching of the hamstring muscles, one limb was placed on a standardized elevated surface and the participant was instructed to slowly flex the trunk forward as far as possible and to hold the ankle with the hands for 30- seconds. (Bandy et al., 1997; O'Sullivan et al., 2009; Paoadopoulos et al., 2005) The 30-second stretch was performed three times on each limb. The hamstring tightness VAS was completed for both limbs, which served as the control condition value. (Cline et al., 1992) Next, JPS testing ([Figure 2](#)) was performed with the target angle for each limb calculated based off the participants' average hamstring extensibility as measured by the AKE test (15 degrees less than the average extensibility). (Worrell et al., 1991) Participants were asked to actively reproduce a specific joint angle following while wearing a blindfold to remove all visual feedback. (Hortobágyi et al., 2004) The investigator directed the participant to move their lower limb to the specified target angle while the hip was maintained at 90 degrees of flexion. The target angle was verified with an inclinometer and the position was held for five seconds. The participant was then returned their limb to the starting position, and after a five second rest, was instructed to reproduce the target angle as accurately as possible.

EMG electrodes were then applied to the medial and lateral hamstrings, and the participant was seated in the SPAD. Standard preparation protocols were followed

and placement of electrodes was completed in accordance with SENIAM guidelines for EMG data collection. (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000) The trunk and thigh were secured with the back supported, and the hip remained in 90 degrees of flexion. The axis of rotation of the adaptor arm was aligned with the lateral joint line of the knee. A pad projecting from the adaptor arm provided stabilization for the distal lower limb, while the upper thigh was also secured to the chair with a pad applying pressure to the thigh. A vacuum splint was placed over the distal lower leg and the ankle to mechanically secure the limb and to minimize force absorption of the soft tissues. (DeAngelis et al., 2014) The weight of the limb was measured at rest with the knee at a position of 50 degrees flexion to allow for gravity correction. Hamstring and quadriceps maximum isometric voluntary contractions (MVICs) were performed prior to testing. Three trials for each muscle group were completed to calculate average maximum strength values. (DeAngelis et al., 2014)

Muscle activation and hamstring stiffness were assessed during a rapid knee extension perturbation that was applied during each trial. The perturbation was delivered at an acceleration of $1000°/s^2$ and a velocity of $100°/s$ through a $40°$ extension arc (from 50 degrees of knee flexion to 10 degrees of knee flexion). Participants were asked to react to the perturbation during each stiffness trial based on specific instructions for two stiffness conditions: passive reactive stiffness (PRS) and active deactivation stiffness (ADS). For the PRS condition, participants were directed to remain completely relaxed until they sensed the hamstring lengthening perturbation and were instructed to contract their hamstrings as hard and fast as they could to resist the perturbation motion. The ADS trials involved maintaining a pre-contraction level at 30% MVIC prior to the start of the hamstring perturbation. Participants were

instructed to relax their muscles as quickly as possible once they detected the hamstring lengthening perturbation. The participant used visual feedback to stay within +/- 10 Nm to maintain the active contraction at the prescribed torque for the ADS trials. A 30 seconds rest period was provided between trials, and one-minute rest between conditions to prevent fatigue. The order of stiffness conditions was randomized.

To perform the force-matching task during force control testing, participants were asked to replicate forces at two-counterbalanced target loads, 20% and 40% of MVIC. (Godinho et al., 2014; Simon & Ferris, 2008) Participants held at the target force for 5 seconds, using the display screen for feedback (Figure 4). Feedback was then removed and the participant was asked to reproduce the same force load for a five second trial. A short rest was provided between trials, and three trials were performed at each target force. A 1-minute rest was provided before repeating the procedures for the 2nd target force. The ramp-and-hold task required the participant to trace a line shown on the computer monitor by pulling into knee flexion against a lever arm to produce a tension force. (Jin et al., 2011) The line remains constant at zero for two seconds, increasing thereafter gradually at a constant rate for five seconds, and finally remains constant for the final five seconds (Figure 5). (Jin et al., 2011) The oscillation task required the participant to produce an oscillating force within a pre-determined range of tension (between 20-40% MVIC), for 12 seconds at a selected frequency (1 Hz and 1.5 Hz) paced by a metronome (Figure 6). (Emge et al., 2013; Jaric et al., 2006) The ramp-and-hold task profile requires the subject to trace a prescribed line that necessitates corrections based on feedback mechanisms; however, the oscillation task involves a high frequency that does not permit for such corrections. (Jaric et al.,

2006) Two trials of the ramp-and-hold and oscillation tasks were then performed. The first of the two trials was used for analysis unless it was considered unsuccessful, for reasons such as a late initiation or stopping the force production before task completion. (Jaric et al., 2006) Familiarization procedures preceded each testing task. The sequence of the three force control tasks (force match, ramp-and-hold, oscillation) was randomized.

Fatigue was then induced using an isometric hamstring contraction protocol. (Jacobs, Uhl, Seeley, Sterling, & Goodrich, 2005) The participant remained seated in the SPAD and the hamstring MVIC was used to calculate the intensity level for determining when they reached fatigue, which was set at 50% MVIC. (Jacobs et al., 2005) Seated isometric contractions performed at submaximal levels have been shown to alter EMG amplitude with fatigue. (Bilodeau et al., 2003; Kellis & Katis, 2008) Participants were instructed to pull their lower leg against the adaptor arm as hard and as long as possible. While performing the isometric contraction, the participants torque production was displayed to both the investigator and participant. Continuous verbal feedback was provided throughout the fatiguing bout to encourage full effort. The participant maintained the contraction until the torque fell below the cutoff threshold for termination of the contraction, which was set for when the participant fell below 10% of the set target value (50% MVIC) for more than 2 seconds. (B. C. Clark, Collier, Manini, & Ploutz-Snyder, 2005) Once fatigue was achieved, stiffness, force control testing, and the subjective tightness VAS were repeated.

Data Reduction

Errors during the force-matching task were analyzed as absolute error, which is indicative of the magnitude of errors calculated by the average of the absolute value of

each trial error. (Docherty et al., 2004; Wright & Arnold, 2012) Root-mean-square-error (RMSE) was calculated to assess ramp-and-hold performance, as the difference between the target track for the task and the trial force production. (Jin et al., 2011) For the oscillation task, total AE was calculated as the absolute difference of the target lines for the peaks/valleys of the oscillation and the produced force of the trial. (Krishnan & Jaric, 2008) Hamstring patient-reported tightness values were quantified by measuring the distance (mm) of the mark made by the participant from the left side (no tightness) of the VAS, and was calculated as a percentage. Stiffness was normalized to body mass (Nm/°/kg) and calculated as the change in torque divided by the change in position; which was examined at short-range (0-4˚), mid-range (0-20˚), end-range (20-40˚), and long-range (0-40˚) stiffness. Raw EMG signals were band-pass filtered at a frequency of 20-400Hz, rectified, and low-pass filtered at 5Hz. EMG activity for each trial was normalized to quadriceps and hamstring MVICs. EMG variables include area under the curve (AUC) for intervals 150ms prior to the perturbation (PRE), and 0-250ms (POST-1) and 250-500ms (POST-2) after the perturbation. Co-activation activity between the medial and lateral quadriceps (MQ, LQ) and hamstrings (MH, LH) was also analyzed.

Statistical Analysis

A 2 (group) x 2 (condition; control, fatigue) repeated measures ANOVA was conducted to examine pre/post fatigue changes in force control variables (AE and RMSE), and also to test the differences in patient-reported hamstring tightness between groups. EMG and stiffness valaues were assessed with a 2 (group) x 2 (condition) ANOVA for each stiffness condition tested (PRS and ADS). Pearson correlation coefficients were calculated to determine the relationship between JPS,

force control, and stiffness measures in the control condition. All data were analyzed using SPSS (Chicago, IL). The significance level was set a *priori* at a level of alpha= .05.

Results

Force Control

Means and standard deviations for the force-matching task are contained in Table 9 and Figure 16. A significant condition by group interaction was revealed in the force-matching task at 40% MVIC ($F_{[1,49]}$=4.15, p=.022), with the INJ group displaying higher force control errors from control to fatigue. No significant differences were observed at 20% MVIC. In the ramp-and-hold task, a significant condition ($F_{[1,49]}$=7.58, p=.008) and group ($F_{[1,49]}$=4.56, p=.038) effect existed at 40% MVIC, with both groups performing worse during the fatigue condition and the INJ group having significantly greater error in force control overall (Table 10, Figures 17 and 18). No significant differences were observed at 20% MVIC in the ramp-and-hold task. No significant differences for condition or group existed in the oscillation task at either MVIC level (Tables 11 and 12).

Patient-Reported Hamstring Tightness

A significant effect of condition existed in the tested limb (injured/matched), with increased tightness reported after fatigue ($F_{[1,51]}$=4.52, p=.038). A significant effect for group was also observed ($F_{[1,51]}$=4.82, p=.033), as the INJ group reported higher tightness in the test limb (Table 13, Figure 19). Paired samples t-tests revealed a significant inter-limb difference in the INJ group (p=.001). No significant changes were observed in the CON group or the untested (uninjured) limb after fatigue (p>.05).

Hamstring Stiffness

Means and standard deviations for PRS values are found in Table 14 and Figure 20. For PRS trials, a significant effect for condition at short-range (0-4˚) was observed ($F_{[1,51]}$=4.54, p=.038), with both groups displaying an increase in hamstring stiffness after fatigue (Figure 21). Mid-range (0-20˚) stiffness remained unaffected by fatigue, but a significant effect for group existed ($F_{[1,51]}$=3.91, p=.05), with the INJ group having higher stiffness overall. At the end-range of stiffness (20-40˚), a significant effect for condition was also revealed (p=.001), with decreased stiffness displayed after fatigue. Long-range stiffness (0-40˚) significantly decreased overall with a main effect for condition observed ($F_{[1,51]}$=12.03, p=.002), as shown in Figure 22.

Means and standard deviations for ADS values are presented in Table 15. A significant effect for condition was observed during ADS trials with values increasing for short- (0-4˚, $F_{[1,51]}$=24.43, p<.001, Figure 23) and mid-range (0-20˚, $F_{[1,51]}$=4.30, p=.05) stiffness during the hamstrings' fatigued state. While no significant effect for group was revealed, 79% (22/28) of the INJ group displayed an increase in short-range stiffness compared to 54% (15/28) of participants in the CON group. At mid-range (0-20˚), the same trend was observed with 57% (16/28) of INJ and 39% (11/28) of the CON group showing an increase after fatigue in the ADS trials. At end-range (20-40˚), a significant effect for condition existed ($F_{[1,51]}$=8.37, p=.004), while a main effect for group was also observed ($F_{[1,51]}$=4.62, p=.040), with the INJ group having higher stiffness overall. Stiffness throughout the long-range (0-40˚) was significantly decreased in all subjects from the control to fatigue conditions ($F_{[1,51]}$=4.29, p=.024), but a significant effect for group was also revealed ($F_{[1,51]}$=10.249, p=.030), with the

INJ group displaying higher stiffness throughout compared to the CON group ([Figure 24](#)).

Muscle EMG Activation

Means and standard deviations for EMG during PRS trials are presented in [Tables 16](#) and [17](#). During PRS trials, a significant effect for condition was observed in the MH (POST-1 [$F_{[1,51]}$=3.93, p=.052], POST-2 [$F_{[1,51]}$=7.28, p<.001]) and MQ (POST-2 [$F_{[1,51]}$=6.13, p=.017]) ([Figure 25](#)). A significant effect for group was detected for ratios between the lateral quadriceps and hamstrings prior to the perturbation (PRE [$F_{[1,51]}$=4.13, *p*=.048]), with higher values observed in the INJ group overall. A significant effect for condition occurred for TTP ($F_{[1,51]}$=10.06, p=.003) with lower values observed with fatigue.

Means and standard deviations for EMG during ADS trials are presented in [Tables 18](#) and [19](#).For the ADS trials, a significant effect for condition existed in the MH throughout all analyzed time segments (PRE [$F_{[1,51]}$=4.62, *p*=.036], POST-1 [$F_{[1,51]}$=12.36, *p*<.001, POST-2 [$F_{[1,51]}$=8.94, *p*<.001) and for LQ once the perturbation was delivered (POST-1 [$F_{[1,51]}$=17.69, *p*<.001), POST-2 [$F_{[1,52]}$=6.44, *p*=.014)) ([Figure 26](#)). A significant effect for condition was also observed for the ratio of the LQ:LH (POST-1 [$F_{[1,51]}$=17.38, p<.001], POST-2 [$F_{[1,51]}$=17.81, p<.001]), as well as MQ:MH (POST-1 [$F_{[1,51]}$=4.92, p=.031], POST-2 [$F_{[1,51]}$=5.82,p=.019]), with EMG decreased for all values with fatigue. A significant effect for condition ($F_{[1,51]}$=4.58, p=.037) and group ($F_{[1,51]}$=3.91, p=.053) also existed for TTP during ADS trials.

Correlations

A significant, moderate correlation was revealed between the oscillation task performed at 1.5 Hz (peaks) and mid-range PRS (r=.29, *p*=.036). A significant,

moderate correlation was also observed between JPS (AE) and mid-range ADS ($r=.36$, $p=.006$) (Figure 27), while a strong correlation existed between JPS (AE) and both long- ($r=.54$, $p<.001$) (Figure 28) and end-range ($r=.523$, $p<.001$) stiffness. No other significant correlations were detected between the proprioceptive and stiffness variables.

Discussion

The results of this study indicate that fatigue interferes with the neuromechanical function of the hamstrings, while previous HSI amplifies impairments of force control, patient-reported tightness, and stiffness regulation. The mechanisms by which fatigue induced the changes observed in this study, could be related to peripheral or central neural processes. Based on our results, we can conclude that once the hamstrings are fatigued, detection and estimation of force loads are compromised. Concurrently, there is an increase in the perception of tightness within the hamstrings that is exaggerated in those with a previous history of HSI. This represents discordance of the sensorimotor system under fatigue potentially originating from aberrant sensory input, which could also be influenced by connective tissue properties of the hamstrings. These neuromechanical implications, in combination with a likely increase in the brain's sense of effort, subsequently lead to dysregulation of hamstring stiffness. Regardless of the exact mechanism, the impact of fatigue on hamstring function and performance are evident, (M. Greig & Siegler, 2009; Pinniger et al., 2000; Rahnama et al., 2006; Small et al., 2009) especially given the previously established temporal pattern of HSI in sport. (Woods et al., 2004)

Force Control

       This was the first study to examine force control of the hamstrings to evaluate the influence of prior HSI and highlight potential risk for future injury. Our results indicate that fatigue causes force control deficits, which appear to be aggravated by previous HSI. In the ramp-and-hold task, it was shown that fatigue impedes force control, irrespective of injury history. However, during the force-matching task, the INJ group performed significantly worse under fatigue. In our study fatigue resulted in an increase in AE only at the 40% load in the INJ group during the force-matching task and at 40% in the ramp-and-hold task, with no significant changes in the oscillating task. Previous research has identified that fatigue not only decreases maximum force production capabilities, but also leads to an increase in force control errors. (C. Brockett et al., 1997; Carson, Riek, & Shahbazpour, 2002; Proske, 2005; Vuillerme & Boisgontier, 2008; Wright & Arnold, 2012) While such impairments have been studied at other joints and muscles, (Arnold & Docherty, 2006; Docherty et al., 2004; Docherty et al., 2006; Docherty & Arnold, 2008; Dover & Powers, 2003; Hortobágyi et al., 2004; Kim, Choi, & Kim, 2014) force control has yet to be explored in the hamstrings. Wright and Arnold (Wright & Arnold, 2012) showed that individuals with a previous ankle sprain were less accurate than healthy controls in a force-matching task, and that fatigue caused an increase in errors in all participants. Additionally, a microneurography study performed in individuals with functional ankle instability by Needle et al. (A. R. Needle et al., 2013) demonstrated a diminished response of afferent signals delivered by muscle spindles, further displaying neural consequences after musculoskeletal injury. Therefore, the same consequences on the fusimotor system may be occurring at the peripheral mechanoreceptors located within

the hamstrings following strain injury or fatigue may alter the sense of effort, potentially leading to a less stable motor control pattern during sport. (Wright & Arnold, 2012)

The greater absolute errors observed in HSI limbs in our study are in agreement with the aforementioned studies. (Arnold & Docherty, 2006; Docherty & Arnold, 2008; Wright & Arnold, 2012) Both the injured and control groups were required to complete novel tasks using the hamstrings, and it is clear that the healthy controls were able to more precisely complete the tasks (force matching) with what is believed to be attributed to a more refined neuromuscular performance. (Wright & Arnold, 2012) Based on prior evidence, it was expected that fatigue would induce greater errors at both the 20% and 40% MVIC loads of the force control tasks. (C. Brockett et al., 1997; Carson et al., 2002; Vuillerme & Boisgontier, 2008) It is suspected that the lower load was not sufficient to produce significant changes once fatigued, and that the participants could have utilized their sense of effort to compensate for any effects of fatigue, especially due to the lack of visual feedback during the force-matching task. However, during the 20% MVIC trials of the ramp-and-hold task, participants were able to utilize feedback mechanisms to correct for errors at the lower force load. Conversely, the increased effort required at the 40% MVIC load may have been too much for the INJ group to overcome once fatigue developed. Since the INJ group significantly worsened in this task, it is also possible that impaired mechanoreceptor function may have contributed to the increased AE. Mechanoreceptors embedded within muscle, including the muscle spindles and GTOs, are responsible for the monitoring and control of force production. (Arnold & Docherty, 2006; Proske, 2005) Given their anatomical location, it is expected that

these structures may be injured during strain injury. While fatigue has been implicated as a risk factor for HSI in sport, no previous studies have examined the impact of fatigue on hamstring proprioceptive function to specifically target the effects of strain injury on mechanoreceptors.

Inaccurate force control could be problematic during high-speed activity, as errors in producing the appropriate amount of tension in the hamstrings could lead to greater strain during eccentric lengthening, if either too much or too little of a muscle contraction is created due to incorrect proprioceptive input. (Arnold & Docherty, 2006) According to the sensory feedback hypothesis, based on the concept of *muscle wisdom*, (Marsden et al., 1983) reflexive elements located in peripheral structures control the muscle response that is responsible for motor neuron discharge regulation. (Bigland-Ritchie et al., 1986) Muscles precisely monitor activation of motor units, relaxation, and force generation as efficiently as possible, which may be described as "tuning" performed in an effort to attenuate impact during movement. (Marsden et al., 1983; Nigg & Liu, 1999) Therefore, it is important to understand how fatigue impacts functions that are reliant on sensory feedback, (Enoka & Stuart, 1985) such as force control tasks.

Another possibility to consider is the role that fatigue has on sense of effort, which is the perceived level of effort that one deems necessary for a particular force load. The CNS delivers commands that determine sense of effort, and a corollary discharge is sent to the brain with a duplicate of the information pertaining to the body's movements. (D. I. McCloskey et al., 1983) Since force control is maintained via peripheral and central mechanisms of one's sense of effort, (Carson et al., 2002) as participants became fatigued, their sense of effort likely increased, leading to errors

from improperly over- or under-shooting the target force levels in the force matching and ramp-and-hold tasks. As Wright and Arnold (Wright & Arnold, 2012) have suggested, the increased absolute errors in the INJ group may be representative of a more unstable motor performance. Future research is required to determine the clinical consequences of the increased errors observed in this study that may lead to stiffness dysregulation and subsequent muscle strain injury. (Wright & Arnold, 2012)

Patient-Reported Hamstring Tightness

Overall, under a fatiguing condition, participants reported an increase in perceived tightness. However, it was only in the INJ group that a significantly higher tightness was reported compared to the contralateral (untested) limb. Hence, during sport, fatigue has the ability to alter the perception of tightness, but the effect appears to be amplified in previously injured hamstrings. This may be due to erroneous binding of sensory input or increased effects of metabolic events. An incorrect perception of tightness with fatigue, stemming from abnormal fusimotor drive or neural origins, may interfere with the processing required for monitoring and maintaining force control and other neuromechanical functions, including muscle stiffness regulation. As was observed in the current study, there were a number of force control deficits that were concurrently amplified by fatigue. Although this was the first study to assess patient-reported tightness of the hamstrings and there is no basis for comparison of similar results at this time, some theories exist to support potential mechanisms causing this sensory abnormality, both of which may influence the fusimotor system and neuromechanical function. First, while mechanoreceptors are sending one signal along afferent pathways during movement, it appears that the brain may be receiving or interpreting a variant signal, as a model for awareness of the

limbs is being formed. This indicates that with the onset of fatigue, there is a failure to resolve the "binding problem" of sensory input within the brain, leading to an altered and perhaps over-exaggerated sensation of tightness in the hamstring muscle of previously injured individuals. (Chiel et al., 2009; Treisman, 1996)

Secondly, it is well established that the onset of fatigue involves cellular and metabolic changes that are associated with alterations in force, velocity, and power, and may also contribute to muscle strain injury. (Fitts, 1994) It is suspected that these mechanisms may increase the perception of muscle tightness. Potential mechanisms include effects resulting from the decrease in Ca^{2+} and influence on inorganic phosphate (P_i), (Allen, Lee, & Westerblad, 1989; Millar & Homsher, 1990) such as impairments in relaxation capabilities. Higher amounts of P_i could slow down the re-uptake of Ca^{2+} into the sarcoplasmic reticulum, which would negatively impact relaxation. (Fitts, 1994) Additionally, P_i can prevent the binding between myosin to MgATP during the power stroke phase, which leads to an inhibition of myosin-actin separation and a decrease in the velocity of fibers. (Fitts, 1994) Hence, at the cellular level, this cascade of events could be sensed as tightness in the muscle if relaxation within the myofibril is not achieved. Furthermore, the signal produced by the mechanoreceptors in the hamstrings in this state would then be modified, indicating to the somatosensory cortex that an altered level of muscle tension exists, which may be intensified in previously injured limbs due to these metabolic processes.

As the first study to quantify hamstring tightness during fatigue in a previously injured population, we conclude that tightness is a patient-reported outcome that should be considered in future research investigations, and more importantly in the clinical setting. From our results, it is clear that an abnormal sensory input during

fatigue is being conveyed, and this is a quick assessment that can easily be performed by clinicians. This could be a method to identify other associated neuromechanical deficits when athletes become fatigued that increase the risk of injury.

Hamstring Stiffness

This was the first study to examine these neuromechanical measures in a population with previous HSI. In this study we evaluated stiffness throughout a joint range of 40° during eccentric lengthening, including two different conditions, one that required an excitatory response (passive reactive stiffness) and another that involved an inhibition of the muscle (active deactivation stiffness). Inclusion of these stiffness types allowed for examination of the hamstrings' ability to react to instantaneous events in sport that require quick, reactive muscle contractions or relaxation to avoid injurious straining mechanisms during high-speed movements.

During the passive reactive stiffness trials, participants reacted to a perturbation while being relaxed prior to the movement. We observed that short-range stiffness (0-4°) during these trials was significantly increased during the fatigue condition, which indicates that tension is increased in this state and an increase of cross-bridges that remain intact may occur. The force exerted in this condition is initially produced from the detachment of any intact cross-bridges between actin and myosin filaments, (Latash & Zatsiorsky, 1993; Proske & Morgan, 1999) as well as the result of connective tissues becoming more taut with early lengthening. (Proske & Morgan, 1999) In a fatigued hamstring, this would likely provide resistance to the rapid length changes that were imposed on the limb. Throughout the rest of the joint range, passive reactive stiffness was decreased with fatigue. Both CON and INJ groups were unable to stiffen their muscle in reaction to the perturbation after fatigue.

Ditroilo et al. (Ditroilo et al., 2011) showed that a cycling fatigue protocol resulted in a decrease in quadriceps stiffness and further extrapolated on the possibility of changes in tendon compliance as well. Previous work has also indicated that an increase in tendon compliance takes place during muscle contractions as an effect of static creep mechanisms. (Kubo, Kanehisa, & Fukunaga, 2005) Hence, the decrease in stiffness that we observed is in agreement with such studies that have demonstrated decreased musculoskeletal stiffness during fatigue. (Avela & Komi, 1998; Ditroilo et al., 2011; Dutto & Smith, 2002; Padua et al., 2006) Additionally, it is also plausible that temperature increases in tissues would influence musculotendinous viscoelasticity as well. (Kubo, Kanehisa, Kawakami, & Fukunaga, 2001) Nonetheless, such contributions still need to be elucidated and at this time, and it is a worthy consideration to explore and design programs to attenuate stiffness dysregulation through the onset of fatigue. (Ditroilo et al., 2011) However, during mid-range (0-20˚) the INJ group displayed significantly higher stiffness, indicating that previous injury causes stiffness dysregulation, which may be the result of passive tissue characteristics or impairments of the fusimotor spindle system. Regardless of the exact cause, increased mid-range stiffness could result in strain injury as the muscle attempts to lengthen during the late swing phase.

For the active deactivation stiffness trials, participants maintained a muscle contraction (30% MVIC) prior to the perturbation and relaxed the hamstring as soon as the movement was detected. Measurement of active stiffness, as in these trials, is directly associated with the force capabilities of the muscle, (Morgan, 1977) as well as the reflexive elements. (Sinkjaer et al., 1988) Short-range stiffness during active trials is primarily related to the amount of cross-bridge formations present in the pre-

contracted muscle, which means greater tension will be produced at an angle that involves more cross-bridges intact. (Morgan, 1977) The results of our study show that ADS is increased under fatigue, highlighting a possible increased risk for strain, as the muscle is less capable of relaxing upon command at both short- and mid-range.

Overall, long-range stiffness was significantly decreased with fatigue, but the INJ group demonstrated a significantly higher stiffness. This significant group difference underlines neuromechanical deficits following HSI, possibly resulting from maladaptations involving cross-bridges or reflexive properties. More so, given that reflexes are responsible for approximately one-half of total stiffness, (Sinkjaer et al., 1988) this provides a dangerous range where errors can occur, especially since reflexive contributions to stiffness must allow for rapid changes through athletic maneuvers even in healthy controls. (Sinkjaer et al., 1988; Sinkjaer & Magnussen, 1994) Furthermore, the same receptors responsible for producing these reflexive contributions to stiffness are also associated with determining resting muscle tone. (Johansson et al., 1990; Sinkjaer et al., 1988) Therefore, there could also be some implications for increased tightness as a result of these reflexive mechanisms, if such maladaptations are present in previously injured limbs.

Although no interaction effect was observed for stiffness and fatigue, the average values of the INJ group were consistently higher than controls throughout the entire joint range. The importance of these observations is strengthened by the percentage increase in stiffness per group that was revealed. Overall, more INJ participants experienced and increase in ADS from the control to fatigue conditions compared to fewer healthy controls. Such results warrant future research into the contributions of stiffness dysregulation to HSI risk. While we do not know the exact

risk of impaired stiffness for suffering an initial HSI, the results of this study provide some insight regarding potential mechanisms that could be considered to examine re-injury risk.

The input from peripheral mechanoreceptors is critical, (Johansson et al., 1991) especially during terminal swing as the quadriceps are actively contracting (knee extension) and the hamstrings are eccentrically loaded. With this co-activation involving the simultaneous delivery of two efferent signals to the agonist and antagonist muscles, a proper balance is required between the excitatory and inhibitory reflexes of the quadriceps and hamstring motor neurons. (Sherrington, 1909) More specifically, as the hamstrings start to stretch, the GTOs are stimulated and inhibit the muscle to permit further lengthening, while at the same time the spindle is rapidly stretched. Thus, an optimal balance of simultaneous reflexive actions between the competing excitatory (spindle) and inhibitory (GTO) signals is required for adequate hamstring length change without too much or too little of a stretch reflex. This means that during this period of eccentric lengthening a resultant reflex could inadvertently cause the hamstrings to contract. Hence, this is a conflict that has to be resolved during high-speed activity to prevent strain injury. Additionally, metabolic events during fatigue can interfere with normal fusimotor drive as higher stiffness levels have been previously suspected to be associated with an increase of released metabolites. As a result, this stimulates the chemoreceptors of afferent neurons, producing an even larger excitatory influence on the fusimotor-spindle system. (Johansson et al., 1993)

Muscle EMG Activation

Our results showed that muscle contraction was not significantly different between groups prior to the perturbation (~150 to 0 ms) during PRS trials, but the

values of the INJ group for EMG area were higher for all muscles (MQ, LQ, MH, LH). A lack of significant group or interaction effect is possibly due to the high variability that was observed for EMG analysis. Nonetheless, although not significant, the higher EMG area from ~150 to 0 ms before the movement could mean that the INJ group was activating their muscles more than the CON group to prepare for the perturbation. However, higher activation at this time point may potentially lead a limb to reach its threshold during high-speed activity, causing the pain free range as well as the strain-free period to shorten as the hamstrings are lengthened. (Sole et al., 2012) Future research is needed to investigate preparatory muscle activation patterns in previous injured patients.

While there was also no significant difference between groups during the two EMG areas analyzed following the perturbation (0-250ms, 250-500ms), the INJ group again displayed higher values for all muscles. This indicates that these participants may have been recruiting a greater number of motor units to resist the perturbation during the PRS trials. Previous work has demonstrated the complex coordinated sensorimotor patterns of the hamstrings, (Higashihara et al., 2010; Onishi et al., 2002; Schache et al., 2013) showing that while the biceps femoris is most active during the middle to late swing phase, it is suspected that the semitendinosus may be most active during terminal swing. (Higashihara et al., 2013) Despite no group difference, the onset of fatigue significantly decreased the EMG area of the medial hamstrings from the control condition in all subjects, likely due to the decreased torque production capabilities of the fatigued muscle. (M. Greig & Siegler, 2009) This could be why significant changes were observed in the medial hamstrings as the joint range tested

neared full extension, and perhaps a more functional fatigue protocol would have affected the biceps femoris more considerably.

During the PRS trials a significant increase in co-contraction between the LQ:LH was observed in INJ subjects from pre- to post-fatigue. This means that prior to the onset of the perturbation, the INJ group was using a neuromuscular strategy that included greater involvement of the quadriceps to prepare for the movement. The increase in co-contraction that was observed is in agreement with previous work examining EMG activity of the thigh during isometric fatigue, more specifically between the quadriceps and hamstrings during knee extension. (Psek & Cafarelli, 1993; Weir, Keefe, Eaton, Augustine, & Tobin, 1998) Both studies found that as fatigue of the vastus lateralis occurred, the co-activation of the biceps femoris was increased. Weir (Weir et al., 1998) and Psek (Psek & Cafarelli, 1993) concluded that such a mechanism is attributed to a simultaneous increase in central drive. We suspect that our results are representative of the same mechanisms, with the quadriceps increasing co-activation as the hamstrings fatigue, and thereby lessening the torque (and stiffness) during the eccentric loading applied during the perturbations. This may be representative of a bracing or protective strategy to reduce strain on the hamstrings as the muscle was eccentrically lengthened.

During the ADS trials, as fatigue was induced a decrease in quadriceps activation was observed in all subjects, possibly indicating a decreased utilization of the quadriceps to relax the hamstring via reciprocal inhibition. Co-contraction ratios between the medial and lateral quadriceps to the medial and lateral hamstrings ratios were also decreased from the control to fatigue condition. This raises some questions regarding neuromuscular activation patterns during sport, particularly as fatigue

occurs and how the quadriceps and hamstrings work in unison to avoid injurious mechanisms. Furthermore, while not significant likely due to large standard deviations, the INJ group not only displayed higher hamstring EMG values when fatigued, but experienced an increase from the control condition, while the CON group decreased. Under fatigue, it appears it may have been easier to relax the hamstring muscles, while the INJ group displayed an inability to relax at the onset of the perturbation compared to controls.

Abnormal patterns of muscle activation that were observed in this study may not only be responsible for increasing the risk of an initial or re-occurring HSI, but could also be a likely cause of the increased tightness reported by participants. (Sole et al., 2012) It is suspected that the presence of pain and discomfort would result in muscle inhibition, especially at longer muscle lengths. (Sole et al., 2011) Sole et. al (Sole et al., 2012) examined neuromuscular control via EMG analysis in a previously injured HSI population and found that the INJ group had significantly earlier onset of contraction in response to a weight-bearing task. Differences were attributed to feed-forward mechanisms, with the same results also observed in the uninjured limb, suggesting CNS involvement in conjunction with maladaptations in the peripheral muscle. Additionally, the authors suspected onset changes could be the result of altered proprioception, (Sole et al., 2012) which are supported by the results of our study. However, beyond this, our results are not in agreement with these findings, which may be due to the differences in contraction types between studies. Where our study required a rapid reaction to a perturbation, the previous study involved a standing movement from a bilateral to single-leg stance. Given the lengthening

experienced during the perturbations, our results may be more closely associated with hamstring function during sport.

Correlations

The significant correlations that were revealed between a number of the measured variables in this study provide preliminary evidence for a relationship between proprioceptive measures and hamstring stiffness dysregulation While it is recognized that stiffness is regulated through the same pathways that transmit proprioceptive input, (Johansson et al., 1990) this was the first study to examine these functions in a previously injured HSI population. The 1.5 Hz oscillation task during the control condition was significantly associated with passive reactive stiffness at mid-range, meaning that participants who produced greater oscillation errors had higher levels of mid-range stiffness. This establishes a relationship between feed-forward mechanisms involved with quick, cyclical control and the hamstrings' reaction to a quick perturbation. Since the INJ group had significantly higher stiffness in this range, we can deduce that increased stiffness is deleterious to force control capabilities. During athletic maneuvers, especially those that involve quick, reactive contractions, an athlete with sub-optimal stiffness may not correctly detect or estimate force loads, increasing the risk of HSI.

The other significant correlations were between JPS absolute error and ADS trials throughout multiple ranges of the stiffness testing. Participants with higher stiffness when they were trying to relax the hamstrings also had greater AE associated with locating their limb in space during JPS testing. When participants needed to detect sudden length changes with proprioceptors, they couldn't do it as well, which resulted in higher muscle stiffness. Docherty and Arnold (Docherty et al., 2004)

revealed a similar correlation at the ankle joint between stiffness and force-matching errors and to our knowledge, is the only other study that has attempted to correlate stiffness and proprioception. Because stiffness dysregulation occurs with near instantaneous changes in length, it can cause excessive strain leading to tears. Given the JPS errors in our study, they are not receiving or processing sensory input correctly from the periphery, which also appears to alter the ability to properly regulate muscle stiffness. Since the INJ group was significantly worse in JPS testing of the affected limb and had increased stiffness, these results suggest that HSI may lead to deterioration of proprioceptive function. A subsequent impact on stiffness due to deafferentation or mechanoreceptor damage and neural trauma may also ensue. (Docherty et al., 2004; M. A. Freeman et al., 1965)

Based on our results, both spindles and GTOs may be injured to some degree during HSI, which could be the cause of the altered proprioceptive function and stiffness dysregulation observed in this study. (Avela, Kyrolainen, Komi, & Rama, 1999; M. C. Brown & Butler, 1976; Hubbard, 1996) This was the first study to establish such a relationship between JPS and stiffness of the hamstrings, and our findings indicate that there are sensorimotor deficits associated with HSI that have not yet been thoroughly addressed at this time. Future research is warranted to prospectively examine the observed impairments and their potential influence on subsequent HSI.

Limitations

We did not measure the perception of fatigue during the isometric bout, which is a limitation of this study, along with the assumption that participants gave a full effort during the fatigue inducing protocol. Aside from the cellular and physical

effects of fatigue immediately occurring during an athletic event, the psychosocial aspect of fatigue should also be considered. Previously, the perception of fatigue has been linked to musculoskeletal injuries during a competitive season. (A. M. Smith, Stuart, Wiese-Bjornstal, & Gunnon, 1997) Both preseason and midseason fatigue, measured with a psychometric scale, were significantly correlated to injuries in hockey players. (A. M. Smith et al., 1997) Based on this information, if an individual had a greater perception of fatigue during testing it could have impacted their results, perhaps amplifying the influence of fatigue. Future studies should consider this psychosocial facet of fatigue when examining potential risk factors of HSI, possibly chronic and acute measures.

Additionally, we cannot rule out that there were extraneous factors impacting our results, such as metabolic events onset by fatigue. For instance, the increase in intracellular Ca^{2+} due to sarcoplasmic reticulum inhibition during fatiguing activity, results in the onset of cell degradation. (Fitts, 1994) Furthermore, during more endurance type activities, fatigue may be associated with a decrease in glycogen stores within the muscle. (Fitts, 1994) Another factor to consider is that a unilateral assessment of force control and stiffness did not allow for the contralateral limb to undergo the fatiguing bout. Hence, we do not know if significant changes exist in the uninjured limb or also, if a significant inter-limb difference would still exist for tightness if both legs were fatigued. It is possible that if a central mechanism is responsible for the altered sensory input, then an aberrant increase in the contralateral limb might also be expected compared to healthy controls, but future research is still needed to examine these possibilities. Lastly, the sample of previously injured

participants that completed this study may have influenced results, as they reported varying degrees of injury severity and missed playing time.

Conclusion

The results of this study add to the growing body of knowledge that implicates fatigue as a risk factor for HSI. We identified neuromechanical deficits in a previously injured population; including, force control impairments, altered hamstring tightness, and stiffness dysregulation, as well as highlighted the impact of fatigue with respect to these variables. Additionally, the results of this study suggest that the brain may not be capable of properly binding the sensory input from a previously injured muscle, suggesting a more complex disconnect within the somatosensory system. In this study, we have exposed neuromechanical deficits that warrant future study and consideration in clinical practice. Follow-up research should examine the role that the observed findings have on both initial and re-occurring HSI, while considering the multifactorial interaction between neuromechanical properties and the challenging internal and external surroundings of sport. (Chiel et al., 2009) Study designs should be aimed at uncovering the importance of and the relationship between the nervous and musculoskeletal systems to better understand the mechanisms of HSI.

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Chapter 4

THE EFFECTS OF ANXIETY ON HAMSTRING STIFFNESS DYSREGULATION

Introduction

Competitive anxiety in sport has remained a suspected risk factor for musculoskeletal injury, yet its influence on the likelihood of injury has been largely underestimated. (Junge, 2000) Previous research has established a relationship between anxiety and various sports related injuries, (Blackwell & McCullagh, 1990; Hanson et al., 1992; Kolt & Kirkby, 1994; Petrie, 1993) but evidence remains contradictory. (Hanson et al., 1992; Junge, 2000) Moreover, the influence of anxiety on hamstring strain injury (HSI), one of the most commonly occurring injuries in competitive sport, has not yet been specifically examined. (Hoskins & Pollard, 2005; Orchard & Seward, 2002; Posner et al., 2011; Woods et al., 2004) The mechanism by which competitive anxiety could increase incidence of injury may be associated with the stress response, which leads to an increase in muscle tension, physical fatigue, visual field narrowing, distractibility, and a decrease in motor control, (Andersen & Williams, 1988; Gould et al., 1999; Nideffer, 1983; Visser et al., 2004) thereby ultimately creating an indirect influence on muscle properties. Changes in muscle tension may be of the highest concern with regards to HSI as such increases can disrupt complex coordination processes during high-speed activity and lead to a greater risk of non-contact straining mechanisms. (Andersen & Williams, 1988; Nideffer, 1983)

During situational periods of anxiety in sport, the inhibitory action of the higher cortical structures within the brain that are responsible for maintaining an appropriate level of muscle tone is lessened. (J. R. Davis et al., 2011; Hall, 2010) Therefore, an anxiety producing (anxiogenic) or startling events will increase muscle spindle sensitivity and produce a greater stretch reflex than would normally be required. (J. R. Davis et al., 2011) For the hamstrings, this may inadvertently produce an undesirable pre-tensioning during sprinting when the muscles must undergo rapid eccentric lengthening. Further, the reflexive patterns and resultant stiffness regulation meant to protect the hamstrings from strain injury could be disturbed. Hence, anxiety may cause the hamstrings to stiffen and increase injury risk, with potentially greater implications in athletes reporting pre-existing muscle tightness, but this has not been directly studied before. (Hoskins & Pollard, 2005)

A variety of instruments, such as subjective questionnaires have been implemented to study the effects of anxiety in sport. (Blackwell & McCullagh, 1990; Hanson et al., 1992; Kolt & Kirkby, 1994; Lavallee & Flint, 1996; Petrie, 1993) The Competitive State Anxiety Inventory-2 (CSAI-2) is one of the most commonly used scales, (Cox, Martens, & Russell, 2003) which includes assessments of both cognitive and somatic components of anxiety, but the relationship between subjective anxiety and hamstring function has not been directly studied and remains unclear. (Mellalieu et al., 2006; Vealey, 1990) Stress-inducing protocols, such as the delivery of electric shocks and mental stressors, have been used in the laboratory setting to produce aversive responses in physiological and cognitive measures, and changes in heart rate and muscle tension believed to be the most robust. (Grillon et al., 2004; Noteboom et al., 2001) The use of a startle, typically a loud noise, visual display, or tactile stimulus

170

that is sudden and intense, is often implemented with stress protocols to either probe or verify anxiogenic conditions. (Grillon & Baas, 2003; Leumann, Sterchi, Vollenweider, Ludewig, & Früh, 2001) Previously, anecdotal evidence suggested that a stress response produces increased muscle tension, which results in an inappropriate startle magnitude during exposure to an unanticipated event. More recent studies have demonstrated that the startle response will significantly affect muscle activation patterns and stiffness regulation strategies, (DeAngelis et al., 2014) but this has not yet been examined in the hamstring muscles or participants with a history of previous HSI.

Based on HSI re-injury rates, frustration of patients and medical personnel, and the increase in incidence rates over the last decade, (Ekstrand et al., 2016; Lempainen et al., 2014; Orchard & Seward, 2002) the failure of current hamstring management plans is evident, and there is a need for alternative strategies to be explored. Through the study of the complex interaction of anxiety and neuromechanical function of the hamstrings, further clarification of causes for the extremely high HSI and re-injury rates may be uncovered. (Feeley et al., 2008; Orchard & Seward, 2002; Woods et al., 2004) Therefore, the purpose of this study was to examine the effects of anxiety on hamstring stiffness regulation in previously injured HSI participants compared to healthy controls. We hypothesize that the use of an electric shock anxiety-inducing protocol will be able to produce alterations in hamstring muscle activation and contribute to stiffness dysregulation, which may be representative of similar mechanisms that occur in the competitive environment of sport. The results of this study could substantiate incentives for addressing competitive anxiety as part of prevention and rehabilitation programs for HSI, more specifically if greater alterations

are observed in previously injured participants, which may be representative of anxiety associated with re-injury.

Methods

Experimental Design

A case control design was used in this study. Independent variables included group (previously injured [INJ] and control [CON]), condition (control, anxiety), stiffness trial (startle, non-startle), stiffness type (passive reactive and active deactivation), and competitive anxiety score (CSAI-2). Dependent variables included heart rate (bpm), hamstring stiffness values (Nm/°/kg), and muscle activation (EMG).

Participants

Fifty-one participants (25 previously injured, 26 healthy controls,) between the ages of 18-25 years were recruited to volunteer in this study. Participants in this study were the same testing sample as the previous two studies (chapter 2 and 3). The number of participants was calculated *a* priori with G*Power Version 3.1.9.2 (Heinrich-Heine-Universitat, Dusseldorf). Participant demographic information is contained in Table 20. All participants were current or former (within the last 2 years) members of collegiate varsity/club competitive teams and were active at least 3 days per week at the time of testing. Participants with a history of HSI sustained the muscle strain within four years prior to testing. Injury was defined as an acute episode of sharp pain in the posterior thigh that resulted in absence of participation for a minimum of one day beyond the day of injury occurrence. (Dick et al., 2007) All participants were medically cleared to return-to-play at the time of testing. Mean time loss for HSI participants was 25.00 ± 33.60 days (range 3-120 days) and mean time since injury was 13.66 ± 13.58 months (range 1-48 months). Exclusion criteria

included any current musculoskeletal injury, history of low-back/lower extremity surgery in the last six months, neurological conditions, history of ankle or knee surgery, pregnancy, cardiac conditions, anxiety conditions, or metal plates in the left wrist. All participants provided written informed consent and study approval was granted by the University of Delaware Institutional Review Board.

Instrumentation

Competitive anxiety was assessed using the multi-dimensional Competitive State Anxiety Inventory-2 (CSAI-2, Appendix C) that measures anxiety (cognitive and somatic) and self-confidence. (Martens et al., 1990) It is a 27-item scale that the participant answers based on a 4-point scale in regards to how they feel in relation to sports competitions, more specifically immediately prior to an athletic event. The CSAI-2 has been used extensively in research studies examining anxiety in sport. (Cox et al., 2003; Ostrow, 1996) Scores for each component range from 9-36 with a higher score indicative of a higher level of anxiety or a higher level of confidence. Heart rate was monitored using a Polar Heart Rate Monitor (FT7) (Polar Electro, Lake Success, NY) as an indication of psychophysiological responses. (Goodie, Larkin, & Schauss, 2000) A computer operated by the investigator using AcqKnowledge Software (BIOPAC Systems, Goleta, California, USA) was used to control stimulus presentation.

Hamstring muscle stiffness was evaluated using a custom built Stiffness and Proprioception Assessment Device (SPAD, Figure 3). (DeAngelis et al., 2014; Huxel et al., 2008; A. R. Needle et al., 2016) The device includes a servomotor (B-404-B-B4, Danaher/Kollmorgen, Radford, Va.) with a gearbox (UT018-050, 50:1, Danaher Motion, Radford, Va.) attached adaptor arm and adjustable chair. A custom LabView

(National Instruments Co., Austin, TX) program allowed for control of high speed, torque and specific range movements to be delivered. A torque reaction sensor (Model # T5400, Futek Advanced Sensor Technology, Irvine, CA) was used to collect analog torque values, which were synchronized with EMG and position data in a custom LabView data collection program. Muscle activation was obtained using a wireless EMG system (TrignoTM^{TM} Wireless System 8138A-DST01, Delsys Inc., Boston, MA, USA). Self-adhesive Ag/AgCL bipolar surface electrodes (Phillips Medical Systems, Andover, Massachusetts, USA) recorded medial and lateral quadriceps and hamstring activity with real-time display. Standard preparation protocols were followed and placement of surface electrodes was completed in accordance with SENIAM guidelines for EMG data collection. (Hermens et al., 2000)

Procedures

Upon arrival in the laboratory, participants completed written informed consent and the CSAI-2. Participants were fitted for a heart rate monitor (WearLink+ Transmitter) that transferred the heart rate signal to the monitor device. (Naugle, Naugle, Fillingim, & Riley, 2014; Perciavalle et al., 2014) The transmitter was worn around the chest region and used according to the manufacturer's guidelines. EMG electrodes were then applied and the participant was seated in the SPAD. The trunk and thigh were secured with the back supported, and the hip remained in 90 degrees of flexion. The axis of rotation of the adaptor arm was aligned with the lateral joint line of the knee. A pad projecting from the adaptor arm provided stabilization for the distal lower limb, while the upper thigh was also secured to the chair with a pad applying pressure to the thigh. A vacuum splint was placed over the distal lower leg and the ankle to mechanically secure the limb and to minimize force absorption of the soft

174

tissues. (DeAngelis et al., 2014) The weight of the limb was measured at rest with the knee at a position of 50 degrees flexion to allow for gravity correction. Hamstring and quadriceps maximum isometric voluntary contractions (MVICs) were performed prior to testing. Three trials for each muscle group were completed to calculate average maximum strength values. (DeAngelis et al., 2014)

Hamstring stiffness and muscle activation were assessed during a knee extension perturbation that was applied during each trial. Participants were given headphones to wear for the duration of testing to eliminate external auditory cues. The perturbation was delivered at an acceleration of $1000°/s^2$ and a velocity of $100°/s$ through a 40° extension arc (from 50 degrees of knee flexion to 10 degrees of knee flexion). (DeAngelis et al., 2014) Participants were asked to react to the perturbation during each stiffness trial based on specific instructions for two stiffness types: passive reactive stiffness (PRS) and active deactivation stiffness (ADS). For the PRS trials, participants were directed to remain completely relaxed until they sensed the perturbation occurring and were instructed to contract their hamstrings as hard and fast as they could against the perturbation. Relaxation was confirmed via the torque box reading prior to delivery of the perturbation. (DeAngelis et al., 2014) The ADS trials involved a pre-contraction at 30% MVIC prior to the start of the perturbation, and participants were directed to relax their muscles as quickly as possible once they detected the perturbation. Participants used visual feedback to stay within +/- 10 Nm to maintain an active contraction at the prescribed torque for ADS trials. Three control trials and one acoustic startle trial were completed for each stiffness condition. The acoustic startle trial involved the presentation of a 10ms, 100db beep sound delivered through headphones at 100 milliseconds before the perturbation controlled by a

customized LabVIEW program. Participants were instructed that an acoustic startle or "loud sound" could happen randomly throughout the testing. (DeAngelis et al., 2014) A 30 seconds rest period was provided between trials and one-minute rest between stiffness types to prevent fatigue. The order of stiffness types was randomized. (Needle et al., 2016)

Following control stiffness measures, an anxiety inducing protocol was implemented to elicit a stress response. (Grillon & Ameli, 1998; Grillon et al., 2004; Raio, Brignoni-Perez, Goldman, & Phelps, 2014) Mild electric shocks were delivered through two surface electrodes placed on the median nerve of the left wrist (Figure 29) by a constant current stimulator (STIMSOD, BIOPAC Systems, Goleta, California, USA). (Grillon & Ameli, 1998) The duration of the electrical stimulation was 100 milliseconds and the current was set at 50 pulses per second, with the highest possible level set at 60 volts. (Grillon et al., 2004; J. Liu et al., 2014; Raio et al., 2014) Electrical stimulation was delivered in two anxiety-inducing blocks of five minutes each. A colored light on the monitor screen placed in front of the participant was used to cue the possibility of an electrical stimulus. A red light indicated that it was not possible to receive an electrical stimulation, while a yellow light signified that shocks may be delivered. (Noteboom et al., 2001) These no-threat and threat periods alternated in 20-second durations. (Noteboom et al., 2001) Participants were told that it was possible to receive up to eight electrical stimulations during threat periods. (Noteboom et al., 2001) The pattern of electrical stimulations varied across the 20s cycles; however, the pattern remained consistent across participants. To further heighten the stress response, participants were informed the magnitude of shocks would vary. Heart rate was assessed during three 10-second epochs: baseline, at the

middle of the anxiety protocol, and the end of shock delivery. (Noteboom et al., 2001) Following completion of the electric shock protocol, participants were warned that delivery of shocks was possible for the duration of the follow-up stiffness testing.

Data Reduction

Baseline, mid-, and end-electric shock protocol heart rate measures (bpm) were used for analysis. CSAI-2 scores were calculated for each of the three components (somatic anxiety, cognitive anxiety, self-confidence) of the questionnaire. Stiffness was normalized to body mass (Nm/°/kg) and calculated as the change in torque divided by the change in position, which was examined at short-range (0-4˚), mid-range (0-20˚), end-range (20-40˚) and long-range (0-40˚) stiffness. Raw EMG signals were band-pass filtered at a frequency of 20-400Hz, rectified, and low-pass filtered at 5Hz. EMG activity for each trial was normalized to quadriceps and hamstring MVICs. EMG variables included area under the curve (AUC) for intervals of 150ms prior to perturbation, and 500ms post-perturbation, denoted as PRE [-150 to 0ms], POST-1 [0 to 250ms], and POST-2 [250 to 500ms].

Statistical Analysis

A repeated-measures ANOVA was used to assess changes in heart rate across the three measurement time points (baseline, mid-, post-shock). An independent samples t-test was used to assess group differences in the CSAI-2. A 2 (group; control, injured) x 2 (condition; control, anxiety) ANOVA was implemented to examine the changes in pre to post anxiety stiffness measures for control and acoustic trials for each of the stiffness condition, as well as for EMG variables for each of the stiffness types tested (PRS and ADS). Correlation coefficients were calculated to determine the relationship between CSAI-2 scores and stiffness, heart rate measures and CSAI-2

anxiety scores, and heart rate and stiffness. All data were analyzed using SPSS (Chicago, IL). The significance level was set a *priori* at a level of alpha = .05.

Results

CSAI-2

No significant differences existed between groups for any of the three components of the CSAI-2. Means for the cognitive, somatic, and self-confidence components were 18.4 ± 5.04, 17.8 ± 4.6, and 25.2 ± 6.6 for the INJ group and 19.7 ± 5.9, 20.2 ± 5.1, and 21.8 ± 6.4 for the CON group, respectively.

Heart Rate

A significant main effect for time was observed for heart rate (Figure 30). Heart rate at the end of the shock protocol (68.61 ± 11.16 bpm) was significantly higher compared to the baseline (66.43 ± 9.01bpm, p=.04) and mid-shock (64.57 ± 8.88 bpm, $F_{[1,48]}$=20.07, p<.001). A main effect for group was also observed as the average values for INJ group was significantly higher overall compared to the CON group ($F_{[1,48]}$=6.99, p=.01).

Hamstring Stiffness

Means and standard deviations for PRS trials are contained in Table 21. A significant effect for condition was observed, where short-range stiffness (0-4°) was significantly ($F_{[1,48]}$=4.41, p=.042) increased during anxiety trials compared to the control condition (Figure 31). A significant effect for condition was also demonstrated for mid- ($F_{[1,48]}$=5.76, p=.019), long- ($F_{[1,48]}$=20.24, p<.001), and end- ($F_{[1,48]}$=21.27, p<.001, Figure 32) range stiffness as values were significantly decreased during anxiety trials compared to control conditions. Stiffness means and standard deviations for the ADS trials are found in Table 22. For ADS trials, a significant effect for

condition existed for short-range stiffness, with an observed increase during anxiety trials compared to control trials ($F_{[1,48]}$=17.27, p<.001). No other significant differences were detected for the ADS trials.

The delivery of an acoustic startle during the control condition resulted in a significant increase in short-range ($F_{[1,48]}$=6.01, p=.018) and mid-range ($F_{[1,48]}$=4.41, p=.041) stiffness for the PRS trials (also contained in Table 21). During control ADS trials, the startle caused a significant increase in long- ($F_{[1,48]}$=6.14, p=.017) and end- ($F_{[1,48]}$=8.87, p=.005) range stiffness. For the PRS anxiety condition, following the delivery of electric shock, the startle produced a significant increase in short-range ($F_{[1,48]}$=7.88, p=.007), mid-range ($F_{[1,48]}$=23.86, p<.001), as well as long-range ($F_{[1,48]}$=4.85, p=.03) stiffness. In anxiety ADS trials (Table 22), the startle produced a significant increase in long- ($F_{[1,48]}$=4.70, p=.035) and end- ($F_{[1,48]}$=6.34, p=.015) range stiffness, as well as a significant decrease in mid-range stiffness ($F_{[1,48]}$=12.78, p=.001). However, there was no significant difference in stiffness values during the startle trials between the control and anxiety condition for PRS or ADS (p>.05).

Effect of Anxiety on Muscle EMG Activation

Results for PRS EMG trials are found in Table 23 and Figure 33.During the preparatory phase (PRE) of PRS trials, a significant condition by group interaction was observed for LH, with the INJ group decreasing and CON group increasing EMG AUC values from the control to anxiety conditions ($F_{[1,48]}$=4.06, p=.050). At POST-1, a significant condition by group interaction existed for both MQ ($F_{[1,48]}$=4.14, p=.047) and LQ ($F_{[1,48]}$=7.85, p=.007), as well as the LH ($F_{[1,48]}$=6.99, p=.011). While the MQ and LH demonstrated lower EMG AUC, the LQ displayed a decrease in the INJ group and an increase in the CON group. At POST-2, a significant decrease in MQ AUC

($F_{[1,48]}$=7.95, p=.007) as well as a significant condition by group interaction for the LH ($F_{[1,48]}$=4.31, p=.043) was observed from the control condition to anxiety. EMG of the LH during POST-2 increased in the CON group, while activity was decreased in the INJ group.

For the ADS trials (Table 24 and Figure 34), a significant effect for condition was observed for the MH ($F_{[1,48]}$=4.44, p=.040) and LH ($F_{[1,48]}$=8.67, p=.005) as shown in Figure 35, with an increase in EMG AUC displayed from control to anxiety at PRE. At POST-1, a significant decrease in EMG AUC was exhibited for the MQ ($F_{[1,48]}$=8.72, p=.005) and LQ ($F_{[1,48]}$=11.45, p=.001), while the MH significantly increased from control to anxiety ($F_{[1,48]}$=4.85, p=.032). The AUC for the MQ was also decreased at POST-2 ($F_{[1,48]}$=5.12, p=.028).

Influence of Startle Response on Muscle EMG Activation

EMG AUC startle values are also presented in Tables 23 and 24. A significant effect for condition in PRS existed for all muscles: MQ ($F_{[1,47]}$=11.11, p=.002), LQ ($F_{[1,47]}$=5.87, p=.019), MH ($F_{[1,47]}$=13.11, p=.001), LH ($F_{[1,47]}$=13.80, p=.001), with a demonstrated increase during the startle trial at PRE in the control condition. Immediately following the perturbation, at POST-1, EMG AUC was significantly increased for MH ($F_{[1,47]}$=6.03, p=.018) and LH ($F_{[1,47]}$=10.57, p=.002) in all participants. No significant differences were detected at POST-2 during the control condition. The same significant increases were observed between non-startle and startle trials during the anxiety condition; however, the startle also led to an increase in EMG AUC for MQ at POST-1 ($F_{[1,47]}$=7.97, p=.007), and MQ ($F_{[1,47]}$=5.09, p=.029) and LH ($F_{[1,47]}$=5.40, p=.025) at POST-2. There were no significant differences

between control startles and anxiety startles ($p>.05$), except for LH ($F_{[1,47]}=4.56$, $p=.038$) at PRE, which was decreased during the anxiety condition.

During control ADS trials, a startle resulted in a significant increase in PRE EMG AUC of the MQ ($F_{[1,48]}=5.84$, $p=.019$) and LQ ($F_{[1,48]}=4.18$, $p=046$). After the perturbation, at POST-1, LH values were significantly decreased ($F_{[1,48]}=4.96$, $p=.030$), while LQ EMG was significantly decreased at POST-2 ($F_{[1,48]}=4.15$, $p=.047$). The same observations were found for the startles delivered during the anxiety condition, with the exception of the LQ at POST-2, which was not significant following the electric shock delivery. Comparison of startle trials between conditions revealed that there was no significant difference in EMG AUC for the quadriceps and hamstrings during the analyzed periods, except for the MQ, for which a significant condition by group interaction was displayed. Increased values in the INJ group were observed in the startle delivered during the anxiety condition ($F_{[1,48]}=4.76$, $p=.034$).

CSAI-2, Heart Rate, and Stiffness Correlations

A significant correlation was observed between cognitive anxiety and short-range PRS startle trials during the anxiety condition ($r=.289$, $p=.042$). Participants that reported higher cognitive anxiety displayed higher short-range stiffness. Additionally, significant correlation during the anxiety condition also existed between mid-range stiffness PRS startle trials and self-confidence scores on CSAI-2 ($r=-.304$, $p=.032$). Participant scores of lower confidence were associated with higher PRS mid-range stiffness during startle trials. A significant correlation also existed between mid-range stiffness ADS trials and the cognitive portion of the CSAI-2 ($r=.305$, $p=.029$). A higher stiffness while attempting to deactivate the hamstrings was associated with higher scores of cognitive anxiety during the control condition. No significant

correlations were present between somatic anxiety or self-confidence and ADS of the hamstrings.

A significant correlation was revealed between stiffness testing performed during the anxiety condition and changes in heart rate. During PRS trials, increased short-range stiffness was significantly associated with a greater increase in heart rate during the shock protocol ($r=.31$, $p=.028$). A weak, negative relationship was observed between decreased mid-range stiffness and changes in heart rate ($r=-.358$, $p=.010$), with lower mid-range stiffness associated with a greater increase in heart rate. Significant, correlations were also observed between heart rate changes from the start to the end of the shock protocol and the somatic and self-confidence components of the CSAI-2. Higher somatic anxiety scores were associated with smaller changes in heart rate ($r=-.39$, $p=.005$,), while higher self-confidence scores were correlated with a greater change in heart rate ($r=.29$, $p=.040$).

Discussion

The primary findings of this study indicate that anxiety interacts with neuromechanical properties of the hamstrings, contributing to altered muscle activation patterns and stiffness dysregulation. This was the first study to elicit a stress response and explore these measures in an athletic and previously injured HSI population. While we identified changes to muscle function, we also established a number of correlations between heart rate and self-reported anxiety, as well as anxiety and stiffness dysregulation. We believe the results of this study provide preliminary evidence for the inclusion of subjective and objective measures of anxiety in sports rehabilitation programs for HSI. Additionally, the findings warrant prospective research to explore the link between competitive anxiety and HSI or re-injury.

Electric Shock Delivery

Under stressful conditions, such as the delivery of electric shocks or competitive sporting events, attention is heightened and the threat that is perceived by the individual can become the central focus of the brain. (G. P. Chrousos, 1992) This causes an increase in respiratory and heart rates, while blood flow is redirected towards the brain, heart, and muscles to provide enhanced energy supply. (G. P. Chrousos & Gold, 1992) Our study produced a significant increase in heart rate from the start to end of the shock protocol, as well as from mid-shock to the end of the shock delivery. These observations verify that the shock delivery was able to produce anxiety, yet we do not know at this time if these findings are clinically significant. Interestingly, the INJ group presented with higher heart rates throughout the protocol, which may represent higher level of anxiety in individuals that have sustained a HSI.

Electric shock protocols have been used as anxiogenic tool to elicit a robust response in the laboratory setting, known to last up to 60 minutes. (J. R. Davis et al., 2011; Grillon & Ameli, 1998; Grillon et al., 2004; A. O. Hamm & Stark, 1993; Lang et al., 1993; Noteboom et al., 2001; Raio et al., 2014) Various stressors (mental stressors, air blasts) have demonstrated physiological and cognitive changes in salivary cortisol, blood pressure, subjective anxiety, heart rate, and electrodermal activity, while electric shock has additionally been shown to produce an increase in subjective tension, plasma epinephrine, and impaired motor control. (Noteboom et al., 2001) Further, significant increases from the start to end of anxiety-inducing protocols have been reported. (Grillon & Davis, 1997; Hodges & Spielberger, 1966; Noteboom et al., 2001) Early work has shown that delivery of a stimulus that is perceived to be noxious, and of an unknown intensity, has been shown to increase anxiety with an

associated acceleration of heart rate. (Deane, 1961) More recently, Noteboom et al. (Noteboom et al., 2001) revealed that delivery of electric shocks resulted in a significant increase in heart rate at the end of the shocks (74.4 bpm) from the baseline (72.3 bpm) and mid-stress (70.3 bpm) periods of the protocol. The averages for HR were much lower in our study and are likely attributed to the collegiate athlete status of our participants. Our observed changes in HR strongly agree with this previous study, as not only did we observe a similar sized increase from baseline to the end of the shock delivery, and from mid- to end, but also the same trend showing a decrease in heart rate from the start to mid-shock delivery was consistent. These patterns are representative of the nervous system responses to the shock stressor.

Recent studies have shown that the delivery of an aversive stimulus results in a HR deceleration and then a subsequent HR acceleration. (Adenauer, Catani, Keil, Aichinger, & Neuner, 2010; M. M. Bradley, Hamby, Löw, & Lang, 2007; J. C. Smith, Bradley, & Lang, 2005) Deceleration has been noted especially when an individual anticipates an unpleasant stimulus within a specific time period, as in the interval between threat presentation and shock delivery. (Deane, 1961) The HR deceleration is indicative of parasympathetic nervous system activity involving the brain's processing of sensory information and the recognition of the stimulus. Depending on the perceived intensity of the stimulus, a greater deceleration could be expected with a prolonged initiation of the HR acceleration that follows. (Adenauer et al., 2010; M. M. Bradley & Lang, 2000; Libby, Lacey, & Lacey, 1973) Acceleration is due to sympathetic activity that results from the cognitive processes that occur to produce the appropriate recognition and readiness for the "fight or flight" or even a freezing response. (Adenauer et al., 2010; M. M. Bradley & Lang, 2000; Libby, Lacey, &

Lacey, 1973) Hence, when an athlete experiences competitive anxiety in sport, it is expected that similar objective changes representative of a nervous system response will occur that may be associated with motor impairments, such as altered muscle activation and stiffness regulation.

Anxiety and Hamstring Stiffness Dysregulation

This was the first study to examine the effect of anxiety on neuromechanical function, more specifically on stiffness regulation strategies. The delivery of electric shock had a significant impact on the excitatory and inhibitory abilities of the hamstrings in response to a rapid perturbation. Stiffness dysregulation was evident as we observed an inability to optimally stiffen the hamstrings during the PRS trials, while stiffness was higher during attempted relaxation during ADS trials for the anxiety condition. This means that anxiety could lead to an overstretching of the hamstrings due to sub-optimal stiffness levels resulting from errors in either excitatory or inhibitory signals.

Evidence suggests that anxiety can impair the cortical inhibition of the stretch reflex, which would produce a greater response required by the fusimotor system than usual and subsequently increase muscle tension through interruption of the normal cortical stretch reflex. (J. R. Davis et al., 2011) In order to appropriately regulate muscle stiffness prior to the completion of movement, the brain must rapidly reconstruct an internal model of external surroundings, which is for the most part an unconscious process. (Amaral & Strick, 2013) The frontal lobe of the brain plans movements, while the parietal region is associated with somatosensory integration and carrying out motor commands.(Amaral & Strick, 2013) Anxiety may interrupt the neural network between the frontal and parietal lobes and their projection on the

cerebral cortex that are related to the cognitive processes for making decisions

regarding neuromuscular control. (Baumeister, 2013; Schweizer, Grahn, Hampshire,

Mobbs, & Dalgleish, 2013) Therefore, competitive anxiety may interfere with the

execution of routine athletic movements due to hesitation or "overthinking," that

interferes with feedforward mechanisms, potentially leading to straining mechanisms.

(C. B. Swanik, 2015)

The results of this study support this theory as an increase in short-range

stiffness was observed during both PRS and ADS trials, which is indicative of greater

tension and likely an increased number of intact cross-bridges under the anxious state.

Hence, anxiety can lead to an increased likelihood of muscle strain, as stiffness may

be too high early in the joint range when the hamstrings still need to allow for

lengthening or to permit rapid, cutting movements during sport.

While these occurrences have not been explored in athletic populations,

increased muscle tension and arousal appear to be the commonest of all manifestations

in patients with diagnosed anxiety disorders. (Hoehn-Saric et al., 1997) The results of

this study add to the existing body of knowledge that demonstrates a number of

physiological responses to stress including increased heart rate, blood pressure, blood

flow, sweating, visual field narrowing, distractibility, cortisol, muscle activity, and

decreased motor control. (Gould et al., 1999; Hoehn-Saric et al., 1997; Nideffer, 1983;

Pluess et al., 2009; Visser et al., 2004; Weinberg, 1978) While our results are likely

due in part to increased tension; a number of the aforementioned responses could have

also contributed to the increased short-range stiffness in the PRS/ADS trials, as well as

the decreased stiffness from mid- to end-range in the PRS trials. For instance,

attentional alterations, such as visual field narrowing and increased distractibility, may

have influenced all participants' ability to appropriately react to the perturbations; (Landers, Qi, & Courtet, 1985; Nideffer, 1983; Weinberg, 1978) however, these were not directly measured in this study. Situational awareness is a key component of maintaining a wide visual field, sorting out unnecessary information, and organizing high-level motor programs in dynamically complex athletic environments. (Landers, Qi, & Courtet, 1985; Nideffer, 1983; Weinberg, 1978)

Anxiety has the potential to adversely affect one's ability to properly detect sensory input via a modification to the ascending pathways. (Grillon & Davis, 1997; Melzack & Wall, 1983) This may lead to an altered sensory perception that could extenuate stimuli in an effort to lessen the shock as a coping mechanism to diffuse and imminent unpleasant situation. (Grillon & Davis, 1997; Willer, Dehen, & Cambier, 1981) In this study, if sensory input was altered so that detection of the perturbation was delayed or the onset was not perceived accurately, stiffness would be diminished due to an attenuated reaction. Decreased performance and poor coordination have already been linked to anxiety and our results support that even minor alterations in time to react or process information can cause stiffness dysregulation during perturbations. This could impair coordination or rapid judgment of movements during high-speed activity because simultaneous interactive processes between feedforward and feedback mechanisms are necessary to appropriately maintain neuromuscular control. (Riemann & Lephart, 2002; C. B. Swanik, Lephart, Swanik, Stone, & Fu, 2004; C. B. Swanik et al., 2007) For example, psychosocial stress in labor workers has been associated with an increased risk of on the job injuries. (Glasscock, Rasmussen, Carstensen, & Hansen, 2006; Murata, Kawakami, & Amari, 2000; Sutherland & Cooper, 1991) In sports, an athlete could become uncertain or hesitant during task

completion if placed in a highly stimulating environment, possibly increasing the risk of HSI. (Dault et al., 2001; Desimone & Duncan, 1995; Lum et al., 2002)

Startle Response and Hamstring Stiffness

Based on the results of this study, the hamstrings stiffen when a startle is experienced during eccentric lengthening, not just in the short-range, but also throughout the entire joint range. The acoustic startle used in this study was meant to replicate sudden noises or sensory disruptions that can be encountered during athletic events, (Leumann et al., 2001) such as an alarming yell or unexpected approach of an opponent. As used in our study, the startle (loud noise, visual display, tactile stimulus) is most often delivered at random time points throughout testing. (Grillon & Baas, 2003) The delivery of a startle has been shown to stimulate an unanticipated event and also to verify anxiety-producing conditions. (Grillon, 2002; Grillon & Baas, 2003) DeAngelis et al (DeAngelis et al., 2014) showed that an acoustic startle applied prior to a knee flexion perturbation results in increased short-range stiffness and decreased long-range stiffness. For the quadriceps, increased short-range stiffness was likely due to interferences in neuromuscular control, and that stiffness was subsequently decreased throughout the completion of the perturbation range as a result of the startle. (DeAngelis et al., 2014) Thus, rapid reflexive activation of the quadriceps results in an extension moment at the knee in response to a startle, manifested via increased stiffness in the short-range. (DeAngelis et al., 2014) During high-speed activity, such a sudden extension moment could induce a rapid and unanticipated lengthening of the hamstrings at critical time periods, which could expose the hamstrings to strain, especially if the startle occurs during the late swing phase.

The impact of a startle on the hamstring muscles during a knee extension perturbation in our study is partially in agreement with these results during control conditions. The influence of an unanticipated, acoustic startle on hamstring neuromechanical function had not been previously examined. While we did observe a similar increase in short-range stiffness during similar PRS trials, mid-range stiffness was also significantly increased, while no significant changes in long-range stiffness occurred. However, during the anxiety condition, a significant increase in short-range, along with mid- and long-range stiffness was exhibited during startle trials. The observed stiffness dysregulation indicates that an unanticipated event may increase the likelihood of a straining mechanism during critical time periods in high-speed activities.

The ADS trials required participants to volitionally relax their hamstrings at detection of the perturbation, and the delivery of the startle resulted in an increase in long- and end-range stiffness during the control and anxiety conditions, along with a decrease in mid-range stiffness under anxiety. This means that the startle disrupted the hamstrings ability to relax during lengthening, which is possibly related to interruptions in the cyclic motion of reversing cross-bridges. (DeAngelis et al., 2014) At times during sprinting when the hamstrings must relax to allow for lengthening or avoiding an injurious movement, being startled by an unanticipated event may increase stiffness, thereby placing the muscle at a greater risk for strain. Thus, the initiation of the startle response due to sudden, unanticipated events during activity may override the motor patterns that are normally preplanned for execution of functional tasks. (M. Davis, 1984) While future research is needed to connect these observations to direct injury risk, these results also bring into consideration the use of

startling into prevention and rehabilitation programs to better prepare athletes for unanticipated events during competitive play. (DeAngelis et al., 2014)

Attempts to produce a startle in the laboratory setting have shown a lessened response with repeated delivery. (Blumenthal et al., 2005; DeAngelis et al., 2014) However, the results of our study showed that following the anxiety protocol, the startle response remained heightened. No significant decreases in startle magnitude were observed for hamstring stiffness between trials. The unpredictable shock delivery used in this study is known to prolong the aversive response perceived by participants, which is not always produced with other stressors. (Grillon et al., 2004) Further, Grillon et al (Grillon et al., 1991) showed that under the consistent threat of an electric shock, the startle response may even be increased with anxiety. Since our participants were told that shocks could continue to occur during the stiffness testing, even after the shock protocol ended, this likely maintained their anxiety and prolonged the ability to be startled.

Impact of Anxiety on Muscle EMG Activation

The analysis of muscle activity patterns measured via EMG during testing of stiffness allowed for more detailed information to be obtained, particularly beyond connective tissue contributions, such as the components of active and functional activations associated with reacting to perturbations. (Sinkjaer et al., 1988) Our study demonstrates that during PRS trials, where participants attempt to react quickly to a perturbation, anxiety interferes with the normal muscle activation patterns that are required to appropriately stiffen the hamstrings, and some group differences were revealed. During the preparatory phase (-150 to 0 ms), a significant group by condition effect revealed that the INJ produced less LH activity, while an increase was displayed

in the CON group under anxiety. At the onset of the perturbation [0-250 ms] in PRS trials, EMG AUC of the MQ and LQ was lower compared to the control condition, and the INJ group displayed a larger decrease in activity. Meanwhile, following the perturbation (250-500ms), a decreased MQ EMG AUC was observed during anxiety compared to the control condition, while a larger decrease in the LH of the INJ group was displayed. Both of these observations may signify that the INJ group was more severely influenced by anxiety, demonstrated through the inability to adequately activate the hamstrings in response to the perturbation. These EMG findings support our stiffness results and indicate that a dysregulation occurs with reactive capabilities of the hamstrings under anxiety. An anxious athlete may not be able to properly activate and stiffen their hamstring to avoid overstretching and potentially strain-inducing mechanisms during sprinting. Overall, in both groups, activity of the LH remained significantly decreased under anxiety, which represents continued stiffness dysregulation throughout the perturbation and possible increased risk of straining mechanisms.

During the ADS trials, muscle activity for both the medial and lateral hamstrings increased under anxiety, despite the participants' efforts to relax at the onset of the perturbation. Meanwhile, following the perturbation, medial hamstring activity remained increased. A decreased ability to deactivate the muscles on command in sport may result in a straining mechanism, especially during the eccentric lengthening phase of gait. Decreased quadriceps EMG AUC was also observed in the anxiety condition at perturbation onset, and medial quadriceps activity remained decreased following the perturbation compared to the control condition. These results indicate that the quadriceps no longer assisted to decrease the hamstring contraction

191

via reciprocal inhibition as was observed in the control trials. This means that not only may the hamstrings be affected by anxiety, but also risk of injury could be linked to alterations in quadriceps activity.

The impact of high anxiety on the disruption of inhibitory and excitatory signals to muscles has been recognized. (McHugh & Cosgrave, 2010) During sprinting, if altered muscle activation contributes to stiffness dysregulation, the protective abilities meant to prevent overstretching of the hamstrings may be disrupted, especially in the dangerous range of terminal swing. Various stress-inducing studies have documented increased muscle tension via EMG activity in groups of anxious participants compared to controls. (Hoehn-Saric et al., 1997; Weinberg, 1978) For example, Pleuss et al (Pluess et al., 2009) monitored EMG activity in a group of high-trait anxiety participants during a throwing movement of competitive nature. Increased muscle activity due to anxiety resulted in inefficient movement patterns; meaning elevated muscle tension is likely a consistent index of anxiety. (Pluess et al., 2009) However, in our study, participants were required to produce a strong, rapid contraction in response to a perturbation that mimics the eccentric loading of the hamstrings during running gait, which may have produced results that are in disagreement with other studies that have shown increased activation.

Startle Response and Muscle EMG Activation

The results of this study showed that an acoustic startle has significant effects on muscle activity during completion of a specific task. When a startle was delivered during the control condition, prior to the perturbation, increased EMG AUC was produced for all muscles of the thigh compared to non-startle trials. Thus, the startle

interfered with normal muscle activation patterns; representing the potential for unanticipated events to disrupt movement execution. Once the perturbation was applied, both the lateral and medial hamstrings produced increased activity, which could overload the hamstrings as they lengthen to achieve heel strike during sprinting. Therefore, even under normal, non-threatening conditions, a startling event can alter muscle activation patterns and dysregulate hamstring stiffness. Following the onset of anxiety caused by shock delivery, the same observations were made, along with increased EMG AUC of the medial quad and lateral hamstring after the perturbation (0-250 ms). As in stiffness testing, the startle response for muscle activation was maintained across conditions, except for LH, which was decreased during the preparatory phase. Thus, under anxiety, the startle may have interfered with preparatory feedforward processes required to properly activate the biceps femoris prior to the delivery of the perturbation.

During the ADS trials, the startle also disrupted the ability to de-activate or relax the hamstrings at the onset of the perturbation. A significant increase in activity of both quads was revealed in the preparatory phase, indicative of a knee extensor moment in response to the startle. Once the perturbation was delivered, activity of the lateral hamstring was less during a startle compared to a non-startle trial, which may be attributed to the increased variability of analyzing single startle trials in a group of participants, opposed to an average of three trials as in the non-startle trials. Alternatively, decreased LH activity at POST-1 could be indicative of too much relaxation as it is decreased compared to control conditions. The final phase of the perturbation (250-500 ms) showed a decrease in lateral quadriceps activity, which may

be associated with a decreased ability of the quadriceps to reciprocally inhibit the hamstrings when necessary to avoid straining mechanisms.

Compared to control startles, the application of a startle following the shock protocol caused the same results, with the exception of no significant decrease in the in the lateral quadriceps at perturbation onset. Comparison of control and anxiety startles revealed that there was no significant difference in the startle response, with the exception of an increased value for the medial quadriceps EMG AUC upon delivery of the perturbation in the INJ group. If the INJ group had a higher level of anxiety as a result of the electric shocks, it is possible that they were more startled compared to controls, producing a greater quadriceps reaction as a result of the knee extension moment.

Unanticipated events have been shown to elicit a CNS startle response that causes alterations in neuromuscular activity. (M. Davis, 1984; Koch, 1999) For example, Moffit et al (Moffit, Sitler, Swanik, Tierney, & Sachs, 2012) showed that the delivery of a startle resulted in an increase in hamstring activity during a jump-landing task, which is in agreement with the results of the current study. In both the PRS and ADS trials, an increase in EMG was observed in the preparatory phase and it is suspected that through increased muscle pre-activation, the detection of unanticipated perturbations will occur more rapidly as the muscle spindle is more sensitive to changes in length. (Dietz, Noth, & Schmidtbleicher, 1981; Dyhre-Poulsen, Simonsen, & Voigt, 1991) This also results in an intensified stretch reflex within the pre-activated muscle, which creates a greater capacity to react to perturbations during activity. (Dyhre-Poulsen et al., 1991) When such events occur, changes in muscle feedback and feed-forward mechanisms take place, and this could have implications

on muscle stiffness regulation strategies responsible for attenuating forces in the limbs. (M. Davis, 1984; M. Freeman & Wyke, 1966; Koch, 1999; Lacroix, 1981) Interruptions of these preparatory and reactive mechanisms would be expected to influence the optimal levels of muscle recruitment during activity and potentially lead to over-loading or stretching of the hamstrings. (Rozzi et al., 1999; C. B. Swanik et al., 2004; C. B. Swanik, Lephart, Giraldo, Demont, & Fu, 1999)

Heart Rate, CSAI-2, and Stiffness Correlations

We observed significant correlations between subjective and objective measures of anxiety and this was the first study to examine these relationships with respect to HSI. Our results establish a connection between changes in heart rate and muscle stiffness regulation. A greater change in HR was associated with an increase in passive reactive short-range stiffness and a decrease in mid-range stiffness. This means that participants who experienced a stronger stress response due to the electric shocks demonstrated dysregulated stiffness strategies while rapidly reacting to the perturbation. These results potentially implicate anxiety as risk factor for muscle strain injury due to the observed effects on muscle tension. Despite the lack of significant group differences in the CSAI-2, the correlations we observed with heart rate changes and stiffness dysregulation signify its importance and may warrant consideration into clinical practice. Thus, anxiety scores may be more useful in identifying individuals who may sustain a first-time injury

Aside from objective measures, such heart rate changes, there were some significant relationships between the CSAI-2 and stiffness. Cognitive anxiety was correlated with increased mid-range stiffness during ADS trials, with participants rating anxiety higher producing higher stiffness while trying to relax the muscles. The

same cognitive scores were associated with increased short-range stiffness during PRS startle trials. Although correlations were weak, these relationships indicate that subjective measures of cognitive anxiety could identify tension under anxiety. This information warrants consideration of patient-reported cognitive anxiety as a potential screening tool for increased muscle tension to identify athletes at risk for HSI.

Our results are also in support of a weak relationship between changes in heart rate and subjective anxiety (CSAI-2) measures. A greater change in HR from the control condition to the end of the shock delivery was associated with lower somatic anxiety scores, as well as a higher level of self-confidence. These findings are contrary to our original hypotheses and the lack of a strong, positive correlation could indicate disconnect between how an individual perceives their somatic stress response and physiological changes, or that their anxiety may be situation specific to athletics. One of the first studies to analyze changes in heart rate in a group of participants considered "high" and "low" anxiety performed by Hodges et al., (Hodges & Spielberger, 1966) demonstrated a significant increase from a no-threat to threat condition, yet there was no observed significant difference between the high and low anxiety groups. (Hodges & Spielberger, 1966) A significant correlation between heart rate and subjective anxiety was also observed in the same study, along with others, revealing larger changes in heart rate associated with higher anxiety. (Beatty & Behnke, 1991; Hodges & Spielberger, 1966)

While our observations conflict with previous research, there are other reports that also indicate that a direct relationship may not exist between subjective and objective measures of anxiety. (Beatty & Behnke, 1991; Grillon & Davis, 1997; Hodges & Spielberger, 1966) For example, Grillon et al., (Grillon & Davis, 1997)

found that a correlation between subjective anxiety scores and startle measures did not exist. Cognitive appraisal has been recognized as a critical factor in the psychophysiological stress response, (Hodges & Spielberger, 1966) which may explain the results of both the aforementioned and present study. Some participants in our study, especially those with previous exposure to electrical stimulation as a therapeutic modality, may not have perceived the shock as a threat. In such cases, changes in heart rate may not have correlated with subjective anxiety, despite the fact that they may still experience competitive anxiety during sport. However, further research is needed to explore this relationship due to the lack of strength of this correlation. (Bechara et al., 2000)

Although some evidence in this study supports the applicability of subjective competitive anxiety scales, some questions remain regarding their efficacy in sport. Particularly, regarding the relationship between such tools and risk of athletic injury, (Martens et al., 1990) more specifically the link to neuromechanical measures that can identify anxiety-induced changes in muscle properties. However, Swanik et al (C. B. Swanik et al., 2007) previously established a relationship between neurocognitive function, as measured by the Impact Test, and risk for non-contact ACL tears. It was concluded that variables such as reaction time and processing speed were potential causes of errors in neuromuscular control and coordination, leading to ACL tears. While the neurocognitive design of the Impact test differs from the cognitive questions of the CSAI-2, which questions concern about competition and performance, it is possible that the same influence on neuromuscular control may cause the observed alterations in muscle activity and stiffness. The lack of a significant correlation between the somatic component of the CSAI-2 and muscle stiffness may be in part

due to a previously described decoupling between the subjective report of symptoms and objective somatic measures. (Bechara et al., 2000) Future research should examine the impact of this relationship on subsequent HSI risk, as well as interventions aimed at modulating the effects of anxiety on sub-optimal stiffness regulation strategies.

Competitive Anxiety and Interventions

Previous studies have explored the relationship between anxiety in sport and risk of other types of musculoskeletal injury. (Blackwell & McCullagh, 1990; Hanson et al., 1992; Kolt & Kirkby, 1994; Lavallee & Flint, 1996; Petrie, 1993) It remains one of the most studied aspects of sports psychology to date, but has never been thoroughly explored with respect to HSI. (Woodman & Hardy, 2003) Across various sports, competitive anxiety has been shown to result in a greater frequency of more severe injuries, increased time out of practice and games, and higher incidence of injury. (Blackwell & McCullagh, 1990; Hanson et al., 1992; Kolt & Kirkby, 1994; Petrie, 1993) Others have attempted to establish anxiety as an aftereffect of injury in athletes, but this has never been examined in HSI patients. (Crossman & Jamieson, 1985) This could help to explain prolonged symptoms and risk after injury. For example, kinesiophobia has been reported to hinder full return-to-play following ACL reconstruction. (Flanigan, Everhart, Pedroza, Smith, & Kaeding, 2013) Subjective questionnaires can quantify this psychosocial construct and have also been associated with knee function scores. (Flanigan et al., 2013; Kvist, Ek, Sporrstedt, & Good, 2005) Anxiety is reasonably expected following HSI due to the pain, frustration, and difficulty returning to pre-injury levels of competition, along with prior history and re-injury episodes. (Ievleva & Orlick, 1991) Thus, in order for clinicians to increase the

efficacy of prevention and rehabilitation programs, the contribution of neuropsychological traits to injury risk should be considered, including incorporation of subjective questionnaires to identify HSI related anxiety in sport. (C. B. Swanik, 2015)

Understanding how anxiety may increase injury risk enables future research designs to examine interventions for mitigating the negative consequences of competitive anxiety in sport. Perna et al (Perna & McDowell, 1995) showed that a cognitive behavioral therapy program designed to reduce injury risk, found that collegiate rowers sustained one-half less injuries and had less missed playing time following the intervention. (Perna, Antoni, Baum, Gordon, & Schneiderman, 2003) Additionally, this same type of training program is recognized to reduce cortisol levels and negative affect in collegiate athletes. (Perna, Antoni, Kumar, Cruess, & Schneiderman, 1998) Based on this information, clinicians could utilize a number of methods to lower anxiety in competitive sports, including relaxation techniques, imagery, and cognitive restructuring to dampen the physiological impact of stressors, which has been demonstrated in non-athletic patients. (Antoni et al., 1991; DeGood & Redgate, 1982; Esterling et al., 1992; Green, Green, & Santoro, 1988; Lutgendorf et al., 1997)

More recent sports psychology models have placed focus on the cumulative impact of stress that could increase risk of injury due to diminished sensory and motor inputs. (Andersen & Williams, 1988; Petrie, 1993) The implementation of various interventions for managing stress may positively modulate neural pathways and the HPA axis responsible for orchestrating the body's response, thereby reducing the negative impact of physiological events associated with anxiety. (Barron, Noakes,

Levy, Smith, & Millar, 1985; Perna & McDowell, 1995) Future research should examine the influence of training interventions on reducing anxiety-related deficits in conjunction with standard neuromuscular control programs, including altered muscle activity and stiffness dysregulation.

Limitations

This study utilized a laboratory model to induce a stress response in collegiate athletes with a stimulus that has been shown to be robust in producing anxiety. While success has been demonstrated in the research setting, it is not clear if these results are directly comparable to the anxiety an athlete experiences during a competitive event. Future research in the sport setting is needed to fully confirm our findings. Furthermore, the effectiveness of the electric shock is determined by how it was perceived by participants. While did not measure perceived anxiety during shock delivery, we did measure heart rate changes, which likely was representative of participants' response to the stressor. Overall, the average of the INJ was higher compared to the CON group, so it is possible that the INJ group had higher resting HR overall, but it was still within normal range for HR. However, the knowledge of undergoing hamstring testing could have elicited a stress response prior to the start of the shock delivery as well. Lastly, follow-up research may explore additional stressors that are anxiogenic to the athletic population as the response may have been dulled in participants with previous exposure to electrical stimulation.

Conclusion

The results of this study provide preliminary evidence that suggests competitive anxiety maybe an important consideration in hamstring rehabilitation programs. This is the first time that neuromechanical implications have been revealed

with respect to hamstring function in a state of anxiety. Anxiety appears to cause stiffness dysregulation in the capacity to either volitionally activate or relax the hamstring muscles. Also, unanticipated events disrupt optimal stiffness regulation patterns and muscle activation strategies, which may have the potential to place an individual at risk for injury during athletic play. Clinicians should consider the implementation of specific strategies targeted to reduce competitive anxiety in sport and prepare athletes for the presence of unanticipated events in sport in rehabilitation and prevention programs. Future research should further explore the clinical applicability of our observations and subsequent risk of injury in prospective studies.

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Chapter 5

DISCUSSIONS & CONCLUSIONS: HAMSTRING STRAIN INJURIES ARE ASSOCIATED WITH SENSORY DISCONNECT AND STIFFNESS DYSREGULATION THAT ARE AMPLIFIED BY FATIGUE AND ANXIETY

Discussions

Mechanoreceptors play a critical role in the delivery of proprioceptive information to the CNS and constantly monitor and adjust muscle tone and activity via reflexive pathways. (Grigg, 2010; Hoffer & Andreassen, 1981; Johansson et al., 1991) Trauma to peripheral receptors sustained during musculoskeletal injury has been recognized to result in deafferentation that impairs proprioceptive function, (M. A. Freeman et al., 1965) which has remained relatively unexplored as a risk factor for HSI. (Cameron et al., 2003) Inaccurate proprioceptive input and diminished fusimotor-system activity is suspected to negatively impact sensorimotor function, leading to impaired muscle activation and stiffness regulation strategies. (Sole et al., 2012) Previous research has indicated that alterations in afferent signals ultimately lead to more permanent neural maladaptations following injury, (Johansson et al., 1991; Kapreli & Athanasopoulos, 2006) including reorganization of the brain's cortical activation. Additionally, pain plasticity of the CNS associated with modified mechanoreceptor sensitivity of muscle spindles and GTOs resulting from tissue trauma, inaccurate proprioceptive function, and altered sensory perception have been recognized. (Cook, Woolf, Wall, & McMahon, 1987; Haigh, McCabe, Halligan, & Blake, 2003; Hamstra-Wright et al., 2005) While this evidence supports poor

outcomes following ligamentous and joint pathologies, (Baumeister, Reinecke, & Weiss, 2008; Grooms, Appelbaum, & Onate, 2015; Hamstra-Wright et al., 2005; Kapreli & Athanasopoulos, 2006) evidence is lacking with respect to mechanisms of HSI. The persistent symptoms of tightness and the inability to return to pre-injury training levels, along with the high re-injury rate following HSI, may be a sign of aberrant sensory signals delivered to the CNS or central processing errors representing the brain's failure to correctly integrate abnormal afferent input. (Kandel, Schwartz, Jessell, Siegelbaum, & Hudspeth, 2000; H. Liu et al., 2012; Malliaropoulos et al., 2011; Orchard & Seward, 2002)

However, in addition to injurious mechanisms, other sports-related factors, such as fatigue and anxiety, have been associated with modified fusimotor system function. (Avela & Komi, 1998; Hall, 2010) Neuromechanical changes may result from peripheral or central mechanisms within the nervous system under fatigue or anxiety, including cortical inhibition, leading to increased tone and an altered stretch reflex. (Avela & Komi, 1998; Hall, 2010) These effects may be amplified in a previously injured muscle, but the neuromechanical coupling between hamstring muscle properties and the nervous system has not been previously explored. Therefore, the purpose of this dissertation was to examine if HSI causes neuromechanical decoupling associated with proprioceptive input and stiffness dysregulation, and to explore how fatigue and anxiety interfere with restoration of hamstring function.

Sensory Disconnect and Neuromechanical Deficits Following Hamstring Strain Injury

The quantification of patient-reported tightness has provided new insight into neuromechanical relationships associated with proprioceptive function following HSI. In agreement with our initial hypothesis 1.1, tightness was significantly increased in the previously injured limb, which did appear to decrease following a warm-up and stretch. However, contrary to hypothesis 1.2, we did observe a significant difference in extensibility between groups, with no observable difference in extensibility following a warm-up and stretch between groups. Additionally, our results do support hypotheses 1.3 and 1.4 as previously injured limbs performed significantly worse in joint position sense and force control tasks.

Further, HSI patients with worse force control and more JPS errors also reported higher hamstring tightness. Thus, our data shows a link between patient-reported tightness and the accuracy of limb position and force load detection that is disrupted after HSI. However, the patient-reported tightness did not correlate with objective hamstring extensibility measures, highlighting sensory disconnect in the previously injured limb. This may indicate that the afferent signals from the spindles and GTOs are diminished or compromised, and that a decoupling between the muscle mechanoreceptors and CNS occurs following HSI. Interestingly, HSI participants' errors in JPS were also correlated with their significantly worse patient-reported functional outcomes scores. This link between perceived tightness in the hamstrings, proprioceptive acuity, and function may represent the brain's inability to correctly bind sensory input and create the appropriate efferent response for task-specific performance and safe execution of athletic maneuvers.

Since proprioceptive input is carried to the CNS along the same afferent pathways that regulate muscle stiffness, (Johansson et al., 1991) the neuromechanical decoupling described here would likely interrupt normal fusimotor-spindle function. Because our HSI participants demonstrated stiffness dysregulation, both in the ability to quickly react and relax in response to rapid perturbations, this suggests that HSI results in CNS maladaptations that are not fully resolved after injury. Overall, increased mid-range passive reactive stiffness and end- and long-range active deactivation stiffness were observed in HSI participants, which may increase the risk of near instantaneous and excessive muscle strain during high-speed activity. Hence, based on these findings we provide evidence that HSI disrupts the sensorimotor function needed for the nervous system to properly tune muscle stiffness. (Nigg & Liu, 1999) The methods of this study were designed to mimic the eccentric loading during the late swing phase, when injury susceptibility is known to be the highest, (Chumanov et al., 2012; Heiderscheit et al., 2005) and the observed sensory disconnect and stiffness dysregulation in previously injured limbs, suggests that an increased risk for strain could exist in the presence of neuromechanical decoupling. Further, our results suggest that these findings are aggravated by fatigue and anxiety in athletic participants.

Neuromechanical Associations between Fatigue, Anxiety, and Stiffness Dysregulation

The results of our study support the hypotheses that fatigue and anxiety, both common occurrences in competitive sport, also have deleterious effects on neuromechanical properties, possibly due to their influence on the CNS. Fatigue has been shown to diminish peripheral mechanoreceptor input and sensitivity of the

fusimotor-spindle system. (Avela & Komi, 1998; Lattanizio et al., 1997) As the first study to examine the influence of fatigue on hamstring neuromechanical relationships, our results on force control, tightness, and stiffness regulation provide evidence for new areas of HSI rehabilitation that have not been previously reported.

The findings of this study partially support our hypotheses regarding fatigue and previous HSI. While tightness was significantly increased in the HSI limb following fatigue, the observed increase was not different compared to the CON group (2.1). However, our results do confirm hypothesis 2.2, as force control was diminished with fatigue, and the previously injured limb demonstrated greater deficits compared to controls. The impact of fatigue on muscle activation did not support our initial hypothesis (2.3), since a lack of interaction effects occurred. For stiffness testing, our results confirm the presence of altered stiffness regulation in previously injured limbs (2.4), along with a significant decrease in all participants with fatigue. Nonetheless, stiffness regulation of the INJ group was not more affected than CON during the fatigue condition. Increased short-range and decreased long-range PRS, and increased short- and mid-range ADS values were observed following fatigue, representing a decreased propensity to dissipate, absorb, and store energy during rapid muscle lengthening. (McMahon & Cheng, 1990) Lastly, our findings support a relationship between proprioceptive and stiffness measures (2.5), with more JPS errors associated with higher stiffness (ADS).

Anxiety had a similar detrimental effect leading to episodes of stiffness dysregulation following a stress-inducing protocol. As hypothesized (3.1), we observed a significant increase in heart rate following shock delivery, but a strong correlation between subjective anxiety (CSAI-2) and heart rate was not observed. Our

findings are in partial agreement with hypothesis 3.2, as we observed a significant increase in ADS EMG activity, but a decrease was demonstrated for PRS trials. Muscle tension has been previously demonstrated to be a correlate of anxiety, attributed to alterations of the fusimotor-spindle system induced by cortical inhibition under stress. (J. R. Davis et al., 2011; Hoehn-Saric et al., 1997; Weinberg, 1978). More importantly, our results support hypothesis 3.3 in that anxiety increases both ADS and PRS in the short-range, while significantly decreasing PRS through the mid- and long-range. Interestingly, in support of hypothesis 3.4, cognitive anxiety (CSAI-2) was significantly correlated with both PRS (startle trials) and ADS (control trials) conditions. Lastly, the association between physiological and neuromechanical responses of anxiety (hypothesis 3.5) was evidenced by the significant correlation between change in heart rate and stiffness values, with a greater change in HR associated with anxiety induced stiffness dysregulation. The increased short-range and decreased long-range PRS suggest that anxiety interferes with CNS processing required to optimally stiffen the hamstrings. Additionally, the application of an acoustic startle was capable of disrupting hamstring stiffness regulation as well.

Hence, both fatigue and anxiety interact with neuromechanical function of the hamstrings via different mechanisms. These adverse consequences appear to be further amplified by previous injury in some instances, highlighting a new area of hamstring rehabilitation that could be explored to potentially lessen straining mechanisms due to stiffness dysregulation.

Conclusions

The findings of this study support that neuromechanical deficits exist following hamstring strain injury. A sensory disconnect is evident in HSI patients,

with concurrent implications on the ability to accurately estimate force and limb location, and to optimally regulate stiffness. Whether these disturbances are due to mechanoreceptor damage, passive tissue changes with neural involvement, or central processing errors in the brain, individuals with a history of HSI may remain at an increased risk for injury if proper interventions are not employed to alleviate these maladaptations. As a result of injury, the brain may not be able to properly reconcile abnormal sensory input leading to binding errors, which result in an internal model that does not replicate peripheral features in the limb. (Chiel et al., 2009; Kandel et al., 2000; Treisman, 1996) Furthermore, these important functions are influenced by fatigue and anxiety, as previously injured participants were more severely affected by in some instances. However, healthy controls also demonstrated alterations in neuromechanical processes, which signify that these measures could possibly have implications on first time HSI as well.

Research Implications

From the results of this study, we can provide various recommendations for future research. First, while we have identified a range of neuromechanical deficits in a previously injured HSI population in the laboratory setting, future research should continue to explore variables such as JPS, tightness, and patient-reported anxiety within the sporting arena for improved ecological validity. A more in-depth analysis utilizing electroencephalography may also be warranted to verify CNS involvement at the cortical level. Research is also needed to examine if specific rehabilitation protocols are able to attenuate the neuromechanical deficits identified in the previously injured participants of this study, and if such alterations resolve over time and possibly prolong the risk of future strain. Execution of the discussed suggestions could further

elucidate mechanisms of HSI and highlight best practices for the management of HSI. Prospective studies should be performed to determine if stiffness dysregulation, force control deficits, and altered muscle activation patterns are strictly a consequence of HSI, or if they are contributing risk factors to straining mechanisms.

Clinical Implications

The results of this study provide a number of clinically applicable recommendations that neuromechanical dysfunction exists following HSI and such deficits should be addressed in rehabilitation programs. For example, assessment and retraining of inter-limb JPS and extensibility imbalances, as well as the ability to appropriately control force production are methods by which a clinician can mitigate the deleterious effects of HSI, as they have been effective following other injuries. (Jull et al., 2007; Jull et al., 2002; O'Leary et al., 2007; Revel et al., 1994) Most importantly, clinicians should include patient-reported hamstring tightness into evaluation and treatment protocols, as an abnormal perception exists in the previously injured limb that does not correlate with extensibility. Also, we have further established the importance of this patient-reported measure through correlations with proprioceptive function. Various modalities and manual therapy exercises should be attempted to identify a means of alleviating patient-reported hamstring tightness in the clinical setting. Additionally, due to the influence of fatigue demonstrated in this study, interventions focused on preventing or rehabilitating HSI should consider training the hamstrings under fatigue, to possibly modulate the deficits in force control, muscle activation, and stiffness regulation that were observed following the isometric bout. Lastly, clinicians should acknowledge the important interaction between competitive anxiety and stiffness dysregulation that was demonstrated in this study. Efforts should be made to identify athletes at risk for an increased stress response and to prepare individuals for unanticipated events. Implementing interventions to address the neuromechanical deficits displayed in this study may help to decrease the high incidence rate of HSI.

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Appendix A

TABLES

	CON	INJ
N	27	29
Age (yrs)	20.67 ± 1.64	20.44 ± 1.23
Height (cm)	172.63 ± 9.14	173.06 ± 10.17
Mass (kg)	70.88 ± 11.69	70.73 ± 14.14
Time since injury (months)	-	13.22 ± 12.74 range 1 - 48
Time loss from sport (days)	-	23.96 ± 31.58 range 3 - 120
Number of HSI	-	1.79 ± 0.94 range 1 - 4

Table 1   Participant demographics for extensibility and proprioceptive testing.

Active Knee Extension Test (°)			
		Baseline	**Warm-up/Stretch**
CON	**Injury Matched Limb**	66.39 ± 10.48	67.54 ± 11.97
	Non-injury Matched Limb	65.89 ± 11.08	67.13 ± 11.11
INJ	**Injured Limb**	**58.48 ± 14.19 ***	**60.33 ± 14.62 ***
	Non-injured Limb	**58.18 ± 14.17 ***	**59.14 ± 13.69 ***

Table 2   Group means and standard deviations for the active knee extension (AKE) test between groups and limbs.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significantly less extensibility than the matched limb in the CON group (p<0.05).

Joint Position Sense (°)		
	AE	**VE**
CON **Injury Matched Limb**	2.15 ± 1.66	2.09 ± 1.47
Non-injury Matched Limb	1.71 ± 1.49	1.39 ± .858
INJ **Injured Limb**	**4.88 ± 3.24 *a**	2.42 ± 1.71
Non-injured Limb	2.64 ± 2.15	1.73 ± 1.59

Table 3   Group means and standard deviations for joint position sense (JPS) errors between groups and limbs.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significantly greater errors compared to matched limb in CON group. ªSignificantly greater errors compared to the contralateral limb.

Force Matching Task (Nm/kg)		
	AE	VE
CON **20% MVIC**	.2194 ± .1188	.1492 ± .0884
CON **40% MVIC**	.3777 ± .2288	.2571 ± .1080
INJ **20% MVIC**	**.3194 ± .2315 ***	.1711 ± .1025
INJ **40% MVIC**	.3743 ± .2237	.3067 ± .1907

Table 4   Group means and standard deviations for the force matching task errors between groups performed at 20% and 40% MVIC.

CON: Healthy controls. INJ: Previously injured hamstring participants. AE: Absolute error. VE: Variable error. *Significantly greater error compared to the CON group.

Ramp-and-Hold Task (Nm/kg)		
		RMSE
CON	**20% MVIC**	.1871 ± .0564
	40% MVIC	.1105 ± .0362
INJ	**20% MVIC**	**.2829 ± .2105 ***
	40% MVIC	**.1482 ± .0732 ***

Table 5   Group means and standard deviations for the ramp-and-hold task between groups.

CON: Healthy controls. INJ: Previously injured hamstring participants. RMSE: root-mean-square error. *Significantly greater error compared to the CON group.

Oscillation Task (Nm/kg)		
	Peaks AE	**Valleys AE**
CON **1 Hz**	.1087 ± .0562	.1305 ± .1016
CON **1.5 Hz**	.1171 ± .0703	.1561 ± .0855
INJ **1 Hz**	.1093 ± .0928	.1656 ± .1243
INJ **1.5 Hz**	.1495 ± .1186	.2110 ± .1467

Table 6   Group means and standard deviations for the oscillation task (peaks and valleys) errors between groups performed at 1 Hz and 1.5 Hz.

CON: Healthy controls. INJ: Previously injured hamstring participants. AE: Absolute error.

Patient-Reported Hamstring Tightness (%)			
		Baseline	**Warm-up/Stretch**
CON	**Injury Matched Limb**	22.28 ± 17.84	14.60 ± 14.09
	Non-injury Matched Limb	21.08 ± 17.42	15.04 ± 14.68
INJ	**Injured Limb**	**34.75 ± 26.47 ***	**25.00 ± 20.13 *a**
	Non-injured Limb	26.86 ± 25.44	18.32 ± 20.15

Table 7   Group means and standard deviations for patient-reported tightness measures during the control condition and following the warm-up and static stretching.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significantly higher tightness compared to the matched limb in CON group. ªSignificantly higher tightness compared to the contralateral limb

	CON	INJ
N	27	28
Age (yrs)	20.67 ± 1.64	20.43 ± 1.23
Height (cm)	172.63 ± 9.14	172.53 ± 9.94
Mass (kg)	70.88 ± 11.69	70.73 ± 14.14
Time since injury (months)	-	13.27 ± 12.98 range 1 - 48
Time out of sport (days)	-	23.96 ± 31.58 range 3 -120
Number of HSI	-	1.79 ± 0.94 range 1 - 4

Table 8   Participant demographics for fatigue stiffness testing.

Force Matching Task - Absolute Error (Nm/kg)			
		Baseline	**Fatigue**
CON	**20% MVIC**	.2328 ± .1279	.3139 ± .2491
	40% MVIC	.4550 ± .3549	.3082 ± .1991
INJ	**20% MVIC**	.3194 ± .2315	.3300 ± .2800
	40% MVIC	.3743 ± .2249	**.4162 ± .3880***

Table 9   Group means and standard deviations for the force matching tasks errors performed at 20% and 40% MVIC during control and fatigue conditions.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant group by condition interaction for fatigue.

Ramp-and-Hold Task - RMSE (Nm/kg)			
		Baseline	**Fatigue**
CON	**20% MVIC**	.1871 ± .0573	.2075 ± .0794
	40% MVIC	.1107 ± .0353	**.1299 ± .0529***
INJ	**20% MVIC**	.2829 ± .2116	.2928 ± .0249
	40% MVIC	.1482 ± .0728	**.2094 ± .1984*a**

Table 10   Means and standard deviation for the ramp-and-hold task root mean square error (RMSE) during the control and fatigue conditions.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant condition effect with greater errors during fatigue. ªSignificant effect for group with INJ participants producing greater errors overall.

Oscillation Task (Peaks) - Absolute Error (Nm/kg)		
	Baseline	**Fatigue**
CON **1 Hz**	.1356 ± .0948	.1118 ± .0771
1.5 Hz	.1314 ± .1014	.1609 ± .1213
INJ **1 Hz**	.1091 ± .0926	.1349 ± .0992
1.5 Hz	.1495 ± .1190	.1235 ± .1080

Table 11   Means and standard deviations for the oscillation task errors (peaks) in the injured/matched limb between groups performed at 1Hz and 1.5 Hz.

CON: Healthy controls. INJ: Previously injured hamstring participants.

Oscillation Task (Valleys) - Absolute Error (Nm/kg)			
		Baseline	**Fatigue**
CON	**1 Hz**	.1393 ± .1080	.1433 ± .1014
	1.5 Hz	.1786 ± .1279	.1609 ± .1477
INJ	**1 Hz**	.1653 ± .1235	.1235 ± .0970
	1.5 Hz	.2110 ± .1477	.1532 ± .0992

Table 12   Means and standard deviations for the oscillation task errors (valleys) in the injured/matched limb between groups performed at 1Hz and 1.5 Hz.

CON: Healthy controls. INJ: Previously injured hamstring participants.

Patient-Reported Tightness (%)			
		Baseline	**Fatigue**
CON	**Injury Matched Limb**	14.6 ± 14.1	**21.0 ± 19.7***
	Non-injury Matched Limb	15.0 ± 14.7	16.6 ± 15.3
INJ	**Injured Limb**	25.0 ± 20.13	**31.0 ± 22.8*a**
	Non-injured Limb	18.3 ± 20.1	15.8 ± 17.3

Table 13   Means and standard deviations for patient-reported tightness in the injured/matched limbs and contralateral limbs between groups in the control condition and following the fatigue/testing protocol.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significantly higher tightness following the fatiguing bout. [a]Significantly higher tightness in the injured limb compared to the contralateral limb.

		Normalized PRS Values (Nm/°/kg)			
Group	Condtition	Short Range (0-4°)	Mid Range (0-20°)	End Range (20-40°)	Long Range (0-40°)
CON	Baseline	0.5536 ± 0.0963	0.0668 ± 0.0390	0.2544 ± 0.0948	0.2174 ± 0.0712
	Fatigue	0.5622 ± 0.1001*	0.0633 ± 0.0485	0.2396 ± 0.0999*	0.2072 ± 0.0723*
INJ	Baseline	0.5598 ± 0.0756	0.0963 ± 0.0699	0.2879 ± 0.0884	0.2418 ± 0.0650
	Fatigue	0.5710 ± 0.0898*	**0.0809 ± 0.0364ª**	0.2546 ± 0.0833*	0.2189 ± 0.0617*

Table 14   Group means and standard deviations for passive reactive stiffness values during control and fatigue conditions.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant effect for condition with an increase in short range stiffness and decrease at mid, end, and long range. ªSignificantly higher stiffness in the INJ group overall compared to the CON group.

Group	Condtition	Normalized ADS Values (Nm/°/kg)			
		Short Range (0-4˚)	Mid Range (0-20˚)	End Range (20-40˚)	Long Range (0-40˚)
CON	Baseline	0.5844 ± 0.0990	0.1204 ± 0.0634	-0.0904 ± 0.0606	-0.0260 ± 0.0406
	Fatigue	0.5988 ± 0.1014*	0.1268 ± 0.0699*	-0.1069 ± 0.0500*	-0.0355 ± 0.0540*
INJ	Baseline	0.5842 ± 0.1014	0.1100 ± 0.0589	-0.0525 ± 0.0858	0.0009 ± 0.0624
	Fatigue	0.6098 ± 0.1038*	0.1294 ± 0.0584*	-0.0747 ± 0.0613*a	-0.0115 ± 0.0419*a

Table 15   Group means and standard deviations for active deactivation stiffness values during control and fatigue conditions.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant effect for condition with an increase in short and mid range stiffness, and decrease at end and long range. [a]Significantly higher stiffness in the INJ group overall compared to the CON group at end and long range.

Group	Condtition	PRE EMG Area (-150 ~ 0 ms)				POST-1 EMG Area (0 ~ 250 ms)				POST-2 EMG Area (250 ~ 500 ms)			
		MQ	LQ	MH	LH	MQ	LQ	MH	LH	MQ	LQ	MH	LH
CON	Baseline	0.36 ± 0.37	0.77 ± 0.62	0.34 ± 0.17	0.38 ± 0.23	1.49 ± 0.75	1.89 ± 1.15	5.26 ± 2.67	4.28 ± 2.63	2.05 ± 1.15	1.50 ± 0.80	9.84 ± 5.14	7.95 ± 3.67
	Fatigue	0.35 ± 0.38	0.78 ± 0.65	0.28 ± 0.12	0.34 ± 0.22	1.25 ± 0.78	1.84 ± 1.31	4.39 ± 2.65*	4.04 ± 3.12	1.48 ± 0.83*	1.34 ± 0.78	8.65 ± 6.13*	6.97 ± 4.06
INJ	Baseline	0.60 ± 0.91	0.99 ± 0.76	0.53 ± 0.85	0.51 ± 0.40	2.43 ± 2.34	2.39 ± 1.68	9.29 ± 11.43	7.35 ± 8.30	2.31 ± 1.72	1.62 ± 1.15	12.8 ± 11.4	10.27 ± 7.9
	Fatigue	0.62 ± 0.92	1.01 ±0.81	0.54 ± 0.61	0.64 ± 0.79	2.08 ± 2.39	2.12 ± 1.44	7.31 ± 6.65*	6.98 ± 10.50	2.16 ± 2.37*	1.48 ± 1.06	11.5 ± 12.5*	10.1 ± 14.65

Table 16   Group means and standard deviations for EMG (area under the curve) during passive reactive stiffness trials.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant condition effect for fatigue resulting in lower activation.

Group	Condtition	PRE EMG Area (-150 ~ 0 ms)		POST-1 EMG Area (0 ~ 250 ms)		POST-2 EMG Area (250 ~ 500 ms)	
		MQ:LH	LQ:LH	MQ:LH	LQ:LH	MQ:LH	LQ:LH
CON	Baseline	0.54 ± 0.64	0.45 ± 0.34	3.73 ± 4.28	1.76 ± 0.86	2.61 ± 1.58	1.93 ± 1.12
	Fatigue	0.48 ± 0.45	0.43 ± 0.33	4.79 ± 6.89	1.89 ± 1.44	1.89 ± 1.20	1.75 ± 1.23
INJ	Baseline	1.24 ± 3.35	**0.76 ± 0.62***	6.31 ± 9.00	2.38 ± 1.64	2.91 ± 2.38	2.01 ± 1.66
	Fatigue	0.61 ± 0.83	**0.78 ±0.83***	4.44 ± 5.79	2.44 ± 2.46	2.86 ± 3.74	1.86 ± 1.55

Table 17   Group means and standard deviations for EMG (coactivation; Q:H) during passive reactive stiffness trials.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant group effect for resulting in a higher co-contraction ratio in the INJ group overall.

Group	Condtition	PRE EMG Area (-150 ~ 0 ms)				POST-1 EMG Area (0 ~ 250 ms)				POST-2 EMG Area (250 ~ 500 ms)			
		MQ	LQ	MH	LH	MQ	LQ	MH	LH	MQ	LQ	MH	LH
CON	Baseline	0.93 ± 0.57	1.06 ± 0.68	5.80 ± 3.50	5.10 ± 3.27	3.14 ± 2.01	3.47 ± 2.46	11.97 ± 8.40	10.38 ± 6.40	1.65 ± 1.50	1.71 ± 1.37	2.04 ± 2.34	2.28 ± 2.15
	Fatigue	0.85 ± 0.55*	1.07 ± 0.67	5.47 ± 3.25	5.17 ± 3.10	2.34 ± 1.35*	2.74 ± 1.73*	11.69 ± 7.93	10.02 ± 5.58	1.04 ± 0.69*	1.25 ± .74*	1.35 ± 1.71	1.56 ± 1.75
INJ	Baseline	0.98 ± 0.98	1.15 ± 0.84	4.37 ± 2.03	4.57 ± 6.69	3.28 ± 2.35	3.62 ± 2.65	10.3 ± 6.27	11.25 ± 19.77	1.45 ± 0.92	1.65 ± 1.53	2.62 ± 4.15	3.72 ± 11.45
	Fatigue	0.96 ± 0.99*	1.17 ± 0.82	5.23 ± 4.15	5.44 ± 6.97	2.80 ± 2.52*	3.05 ± 2.61*	12.67 ± 15.02	12.89 ± 21.35	1.16 ± 1.29	1.40 ± 1.87*	2.40 ± 3.62	2.76 ± 6.59

Table 18   Group means and standard deviations for EMG (area under the curve) during active deactivation stiffness trials.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant condition effect for fatigue resulting in increased activation.

Group	Condtition	PRE EMG Area (-150 ~ 0 ms)		POST-1 EMG Area (0 ~ 250 ms)		POST-2 EMG Area (250 ~ 500 ms)	
		MQ:LH	LQ:LH	MQ:LH	LQ:LH	MQ:LH	LQ:LH
CON	Baseline	1.15 ± 0.80	1.40 ± 1.04	3.60 ± 2.26	3.89 ± 1.99	1.44 ± 1.32	1.37 ± 0.94
	Fatigue	1.06 ± 0.79	1.38 ± 1.01	3.02 ± 1.83*	3.26 ± 1.85*	0.79 ± 0.52*	1.01 ± 0.74*
INJ	Baseline	1.30 ± 1.48	1.57 ± 1.26	3.96 ± 3.33	3.78 ± 2.28	1.15 ± 0.98	1.10 ± 0.85
	Fatigue	1.24 ± 1.42	1.58 ± 1.25	3.64 ± 3.78*	3.34 ± 2.10*	1.03 ± 1.69*	0.85 ± 0.63*

Table 19   Group means and standard deviations for EMG (coactivation; Q:H) during active deactivation stiffness trials.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant condition effect for fatigue resulting in increased co-activation ratios.

	CON	INJ
N	26	25
Age (yrs)	20.65 ± 1.67	20.6 ± 1.64
Height (cm)	172.62 ± 9.33	173.73 ± 9.94
Mass (kg)	70.78 ± 11.91	73.54 ± 17.65
Time since injury (months)	-	13.66 ± 13.58 range 1 - 48
Time loss from sport (days)	-	25.00 ± 33.60 range 3 - 120
Number of HSI	-	1.80 ± 0.96 range 1 - 4

Table 20   Table 1: Participant demographics for anxiety stiffness testing.

Group	Condition	Normalized PRS Values (Nm/°/kg)			
		Short Range (0-4°)	Mid Range (0-20°)	End Range (20-40°)	Total Range (0-40°)
CON	Control	0.5448 ± 0.0895	0.0666 ± 0.0430	0.2518 ± 0.0853	0.2132 ± 0.0642
	Control Startle	0.7138 ± 0.6133[a]	0.1434 ± 0.1788[a]	0.2404 ± 0.0939	0.2257 ± 0.1306
	Anxiety	0.5525± 0.0924*	0.0547 ± 0.0381*	0.2169 ± 0.0752*	0.1883± 0.0584*
	Anxiety Startle	0.5913 ± 0.1334[b]	0.1080 ± 0.0818[b]	0.2293± 0.1202	0.2066 ± 0.0915[b]
INJ	Control	0.5591 ± 0.0631	0.0994 ± 0.0772	0.3009 ± 0.0747	0.2535 ± 0.0545
	Control Startle	0.6174 ± 0.1641[a]	0.1087 ± 0.0882[a]	0.2835 ± 0.0849	0.2471 ± 0.0760
	Anxiety	0.5664 ± 0.0672*	0.0796 ± 0.0536*	0.2650 ± 0.0847*	0.2269 ± 0.0631
	Anxiety Startle	0.5955 ± 0.0996[b]	0.1279 ± 0.0833[b]	0.2743 ± 0.0915	0.2403 ± 0.0692[b]

Table 21   Group means and standard deviations for passive reactive stiffness values.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant condition effect for non-startle anxiety trials. [a]Significant condition effect for startles delivered during control trials. [b]Significant condition effect for startles delivered during anxiety trials.

Group	Condition	Normalized ADS Values (Nm/°/kg)			
		Short Range (0-4°)	Mid Range (0-20°)	End Range (20-40°)	Total Range (0-40°)
CON	Control	0.5713 ± 0.0919	0.1069 ± 0.0595	-0.1102 ± 0.0595	-0.0403 ± 0.0298
	Control Startle	0.5718 ± 0.1643	0.0777 ± 0.0940	**-0.0811 ± 0.1667[a]**	**-0.0179 ± 0.2279[a]**
	Anxiety	**0.5862 ± 0.0990***	0.1067 ± 0.0668	-0.1146 ± 0.0441	-0.0430 ± 0.0267
	Anxiety Startle	0.5761 ± 0.1239	**0.0571 ± 0.0873[b]**	**-0.0721 ± 0.0930[b]**	**-0.0152 ± 0.0780[b]**
INJ	Control	0.5897 ± 0.0763	0.1113 ± 0.0672	-0.0983 ± 0.0639	-0.0282 ± 0.0412
	Control Startle	0.5177 ± 0.2872	0.0897 ± 0.1048	**-0.0708 ± 0.0943[a]**	**-0.0128 ± 0.2151[a]**
	Anxiety	**0.6056 ± 0.0756***	0.1281 ± 0.0604	-0.0952 ± 0.0626	-0.0231 ± 0.0423
	Anxiety Startle	0.6138 ± 0.2632	**0.0948 ± 0.1008[b]**	**-0.0805 ± 0.0831[b]**	**-0.0115 ± 0.0633[b]**

Table 22   Group means and standard deviations for active deactivation stiffness.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant condition effect for non-startle anxiety trials. [a]Significant condition effect for startles delivered during control trials. [b]Significant condition effect for startles delivered during anxiety trials.

| Group	Condition	PRE EMG Area (-150 ~ 0 ms)				POST-1 EMG Area (0 ~ 250 ms)				POST-2 EMG Area (250 ~ 500 ms)			
		VM	VL	MH	LH	VM	VL	MH	LH	VM	VL	MH	LH
CON	Control	0.42 ± 0.46	1.0 ± 1.2	0.44 ± 0.33	0.43 ± 0.37	1.75 ± 0.96	2.35± 1.87	5.70 ± 3.27	5.20 ± 5.35	2.05 ± 1.09	1.71 ± 1.07	9.19 ± 2.96	8.20 ± 5.01
	Control Startle	**1.16 ± 1.63[a]**	**1.46 ± 1.54[a]**	**2.95 ± 4.50[a]**	**3.50 ± 6.43[a]**	2.50 ± 1.40	2.93 ± 2.23	**8.53 ± 5.70[a]**	**9.86 ± 11.59[a]**	2.17 ± 1.29	1.68 ± 1.24	9.73 ± 5.86	11.01 ± 14.58
	Anxiety	.44± 0.47	0.97 ± 1.0	0.50 ± 0.48	**0.54± 0.62***	1.61 ± 1.01	**2.43 ± 2.10***	5.39 ± 4.82	**5.20 ± 6.89***	**1.89 ± 1.14***	1.72 ± 1.58	9.11 ± 5.95	**8.48 ± 8.13[a]**
	Anxiety Startle	**0.78 ± 1.57[b]**	**1.13 ± 1.11[b]**	**1.55 ± 3.08[b]**	**1.64 ± 3.44[b]**	**2.87 ± 2.67[b]**	**3.17 ± 3.20[b]**	8.92 ± 8.18	**8.95 ± 11.99[b]**	**2.21 ± 1.59[b]**	2.10 ± 2.57	9.51 ± 6.15	**9.33 ± 9.67[b]**
INJ	Control	.77± .89	1.15 ± 1.36	0.48 ± 0.53	0.45 ± 0.39	3.09 ± 2.44	2.89 ± 2.36	7.61 ± 5.27	6.34 ± 4.83	2.73± 1.73	1.70 ± 1.03	10.17 ± 3.81	9.18 ± 3.43
	Control Startle	**1.26 ± 1.04[a]**	**1.43 ± 1.56[a]**	**3.48 ± 6.46[a]**	**3.03± 4.81[a]**	4.91 ± 9.27	3.43 ± 3.83	**11.72 ± 14.39[a]**	**8.67 ± 9.36[a]**	3.23 ± 3.07	1.81 ± 1.40	12.63 ± 13.58	10.01 ± 6.55
	Anxiety	.77 ± 0.97	1.15 ± 1.39	1.04 ± 3.77	**0.38± 0.41***	2.35 ± 2.12	**2.33 ± 2.32***	8.80 ± 15.47	**4.42 ± 3.42***	**2.27± 1.72***	1.39 ± 0.93	11.3 ± 15.72	**7.42 ± 3.17[a]**
	Anxiety Startle	**1.13 ± 1.00[b]**	**1.29 ± 1.43[b]**	**2.27 ± 3.82[b]**	**1.47 ± 1.45[b]**	**2.84 ± 2.67[b]**	**4.42 ± 2.26[b]**	12.28 ± 21.68	**7.59 ± 6.77[b]**	**2.54 ± 1.81[b]**	1.45 ± 0.97	12.25 ± 12.21	**9.39 ± 7.15[b]**

Table 23   Group means and standard deviations for EMG (area under the curve) during passive reactive stiffness trials.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant condition effect for non-startle anxiety trials. [a]Significant condition effect for startles delivered during control trials. [b]Significant condition effect for startles delivered during anxiety trials.

Group	Condition	PRE EMG Area (-150 ~ 0 ms)				POST-1 EMG Area (0 ~ 250 ms)				POST-2 EMG Area (250 ~ 500 ms)			
		VM	VL	MH	LH	VM	VL	MH	LH	VM	VL	MH	LH
CON	Control	0.77 ± 0.51	1.12 ± 1.10	4.66 ± 2.15	4.54 ± 5.98	3.20 ± 2.05	3.63 ± 2.65	8.73 ± 3.80	9.77 ± 15.45	1.67 ± 1.41	1.88 ± 1.59	0.81 ± .74	1.45 ± 2.90
	Control Startle	1.70 ± 2.19ª	1.91 ± 2.09ª	4.73 ± 2.56	4.80 ± 7.15	3.37 ± 2.74	3.74 ± 2.79	7.49 ± 3.68	7.50 ± 9.75ª	1.64 ± 1.78	1.68 ± 1.60ª	0.95 ± 1.72	1.96 ± 5.59
	Anxiety	0.80 ± 0.55	1.12 ± 1.03	5.36 ± 3.04*	4.24 ± 3.14*	2.63 ± 1.70*	3.16 ± 2.34*	9.88 ± 4.59*	9.97 ± 10.17	1.41 ± 1.20*	1.96 ± 2.37	0.90 ± 0.79	1.37 ± 2.26
	Anxiety Startle	1.21 ± 5.15b	1.63 ± 1.49b	5.31 ± 4.17	5.01 ± 7.88	2.47 ± 1.33	3.33 ± 2.46	7.97 ± 5.85	7.39 ± 10.29b	1.17 ± 1.18	1.54 ± 1.38	0.97 ± 1.88	1.30 ± 2.77
INJ	Control	1.14 ± 0.89	1.29 ± 1.38	3.89 ± 1.34	3.28 ± 1.48	5.06 ± 5.98	4.11 ± 2.91	9.17 ± 6.45	7.83 ± 5.54	2.41 ± 2.79	2.03 ± 1.49	1.60 ± 4.08	1.41 ± 2.38
	Control Startle	3.03 ± 5.78ª	3.00 ± 5.91ª	4.85 ± 2.82	3.55 ± 1.83	4.49 ± 4.47	4.31 ± 3.57	10.03 ± 8.77	6.97 ± 4.92ª	1.45 ± 1.39	1.63 ± 1.59ª	1.37 ± 2.44	1.11 ± 1.61
	Anxiety	1.18 ± 0.94	1.29 ± 1.45	5.36 ± 5.33*	4.24 ± 3.14*	4.16 ± 5.09*	3.33 ± 2.56*	11.96 ± 10.67*	10.14 ± 9.05	1.54 ± 1.35*	1.50 ± 1.17	2.22 ± 4.30	1.91 ± 3.58
	Anxiety Startle	2.75 ± 5.15b	2.43 ± 2.97b	7.05 ± 11.62	4.81 ± 4.32	4.05 ± 3.30	3.87 ± 3.05	12.26± 16.87	8.41 ± 7.84b	1.66 ± 1.38	1.61 ± 1.28	2.29 ± 5.21	1.79 ± 4.02

Table 24   Group means and standard deviations for EMG (area under the curve) during active deactivation stiffness trials

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant condition effect for non-startle anxiety trials. ªSignificant condition effect for startles delivered during control trials. bSignificant condition effect for startles delivered during anxiety trials.

Appendix B

FIGURES
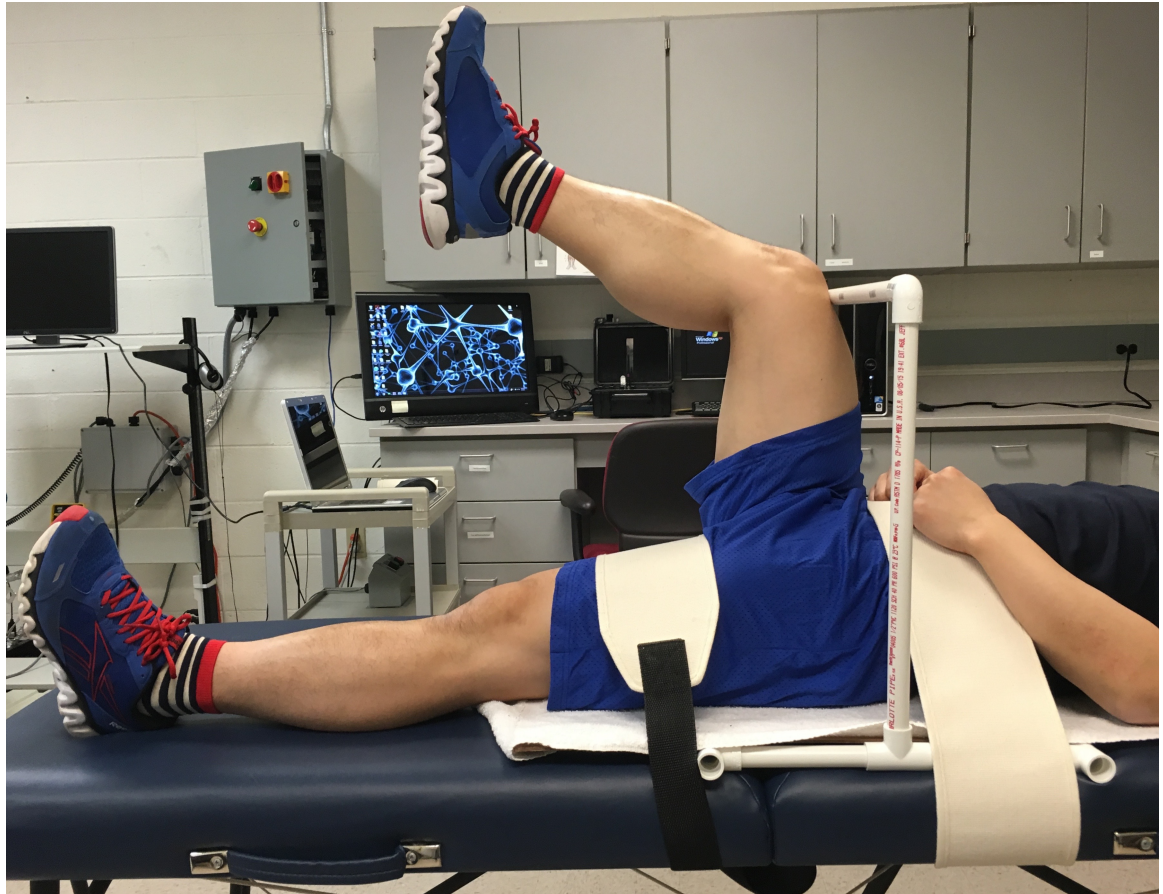
Figure 1   Active Knee Extension Test performed with the pelvis and untested
limb secured to the table, and test limb maintained at 90° hip flexion
against crossbar.
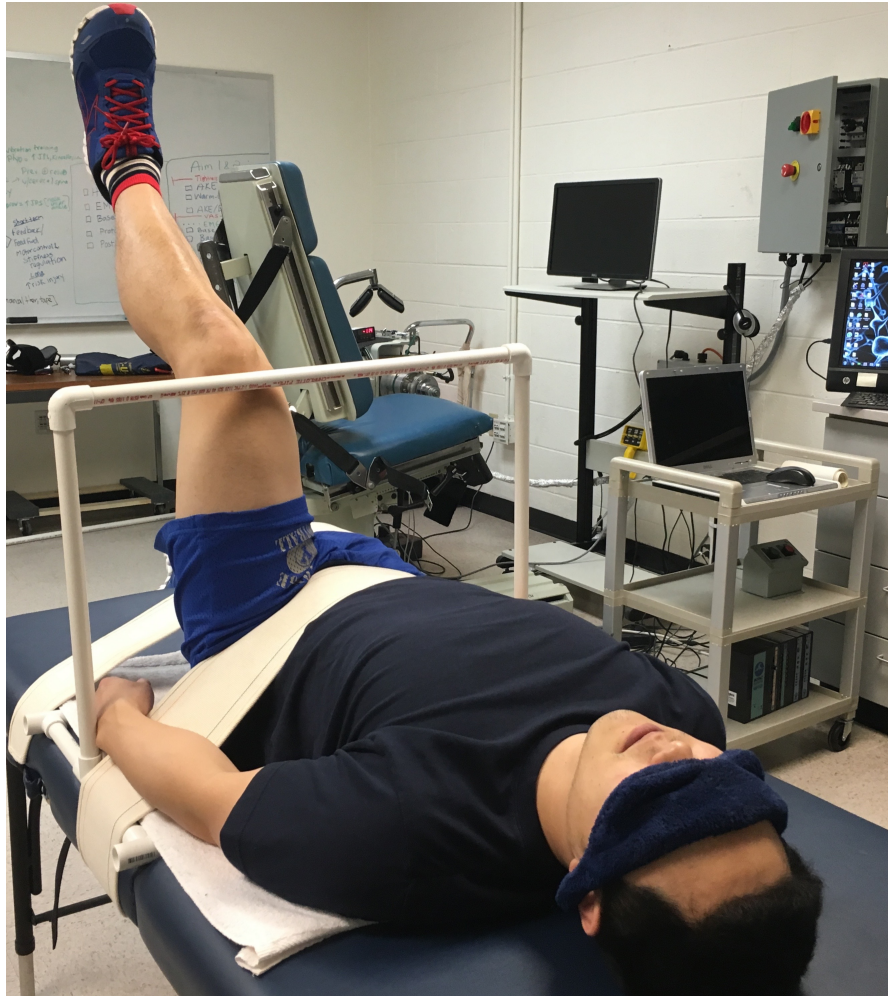
Figure 2   Joint position sense testing set-up with participant blindfolded and pelvis and untested limb secured to the table. Test limb remains against crossbar as target angle is attempted.
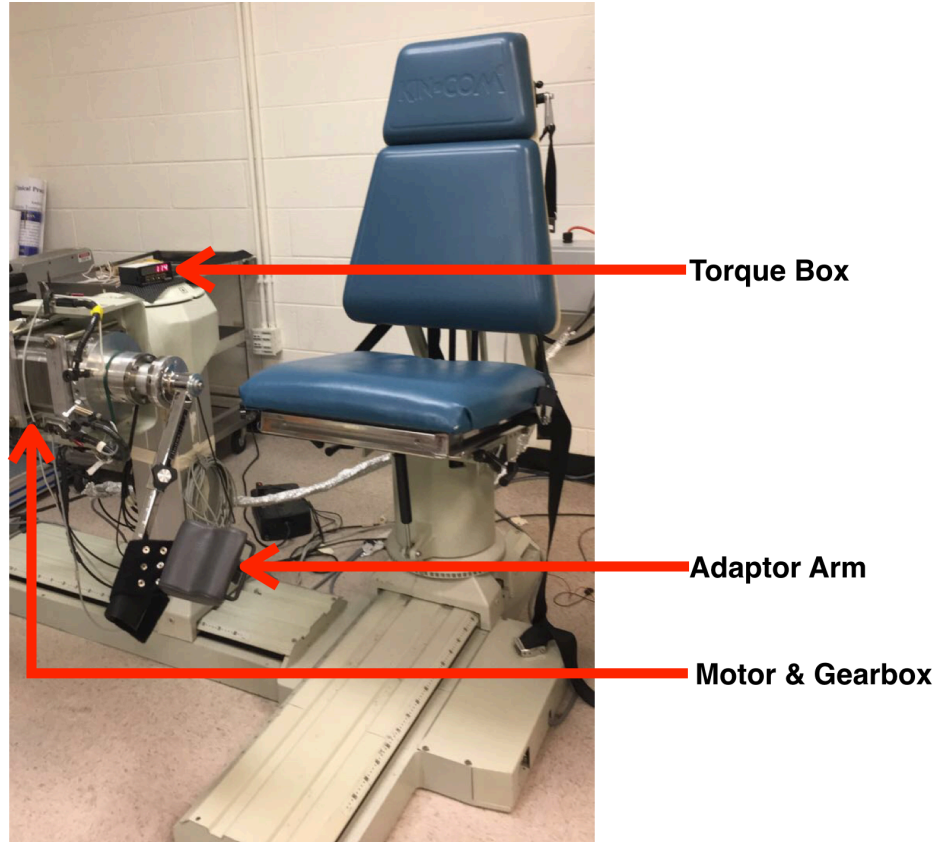
Figure 3   Stiffness and Proprioception Assessment Device (SPAD) used during force control and stiffness testing
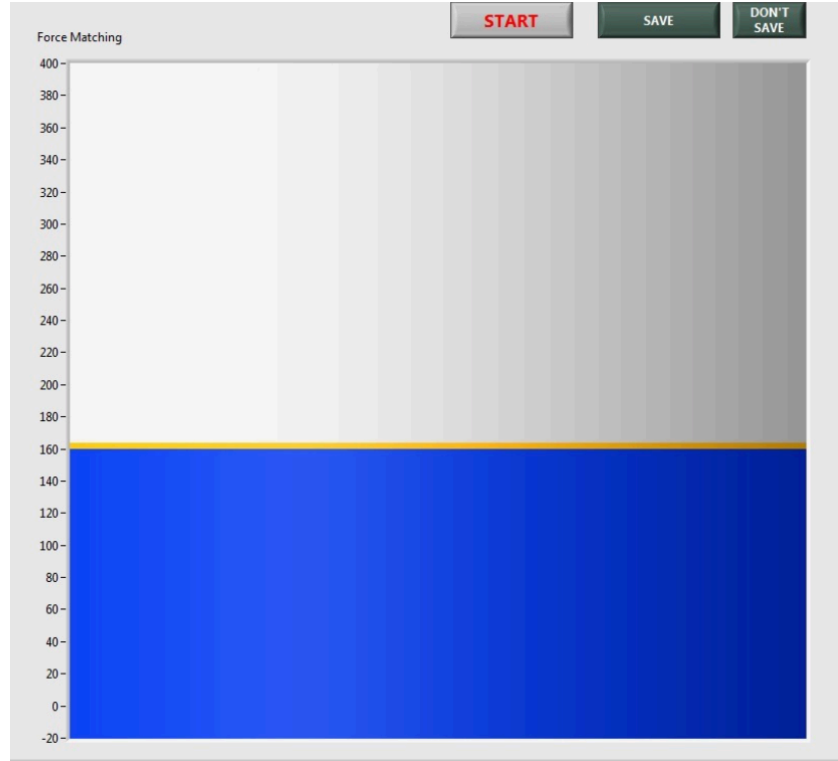
Figure 4   Visual feedback presented on the display screen during the 1st trial for each force load during the force-matching task. Visual feedback is removed for the following three trials of force matching trials.
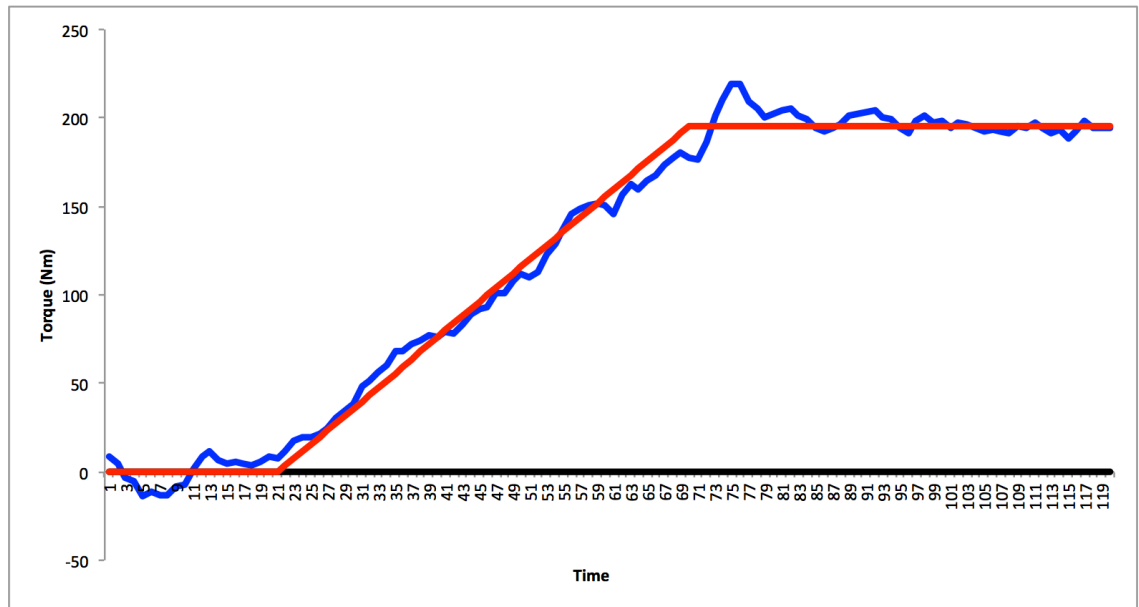
Figure 5   Profile of the ramp-and-hold task with exemplar performance trial. Plot remains at zero for two seconds and then ramps for five seconds, followed by a five second plateau.
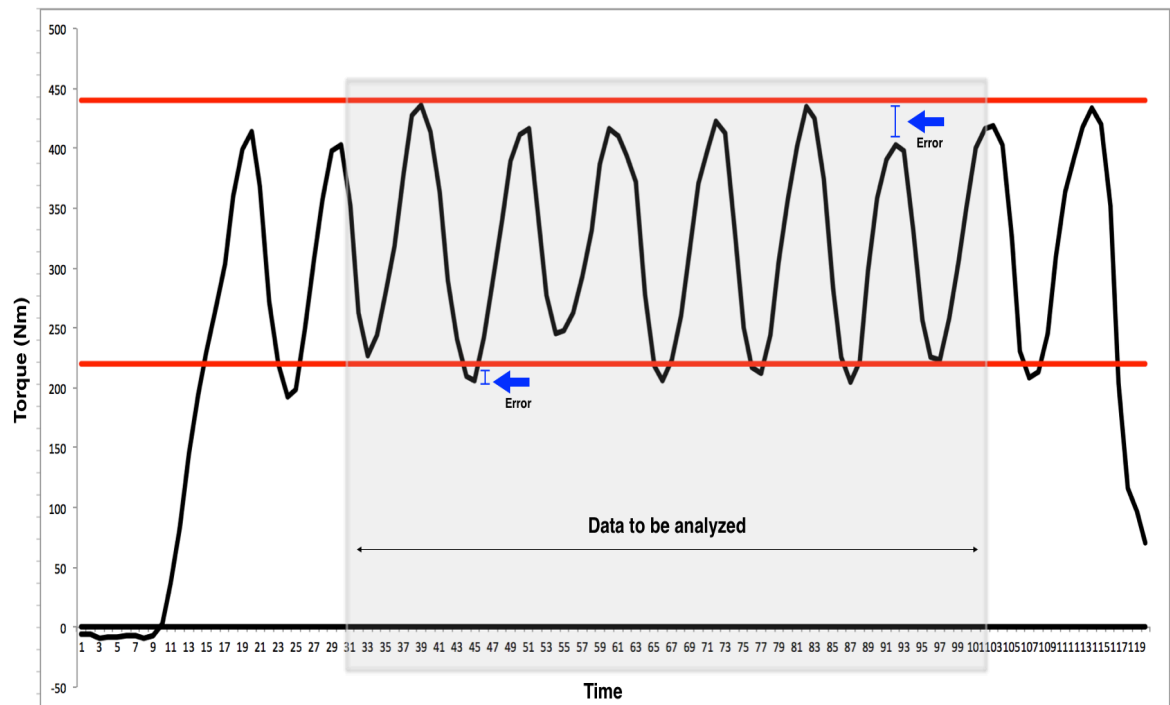
Figure 6 Exemplar trial of oscillation task performance. Upper and lower parallel lines are placed at 40% and 20% of the maximum voluntary isometric contraction for each participant.
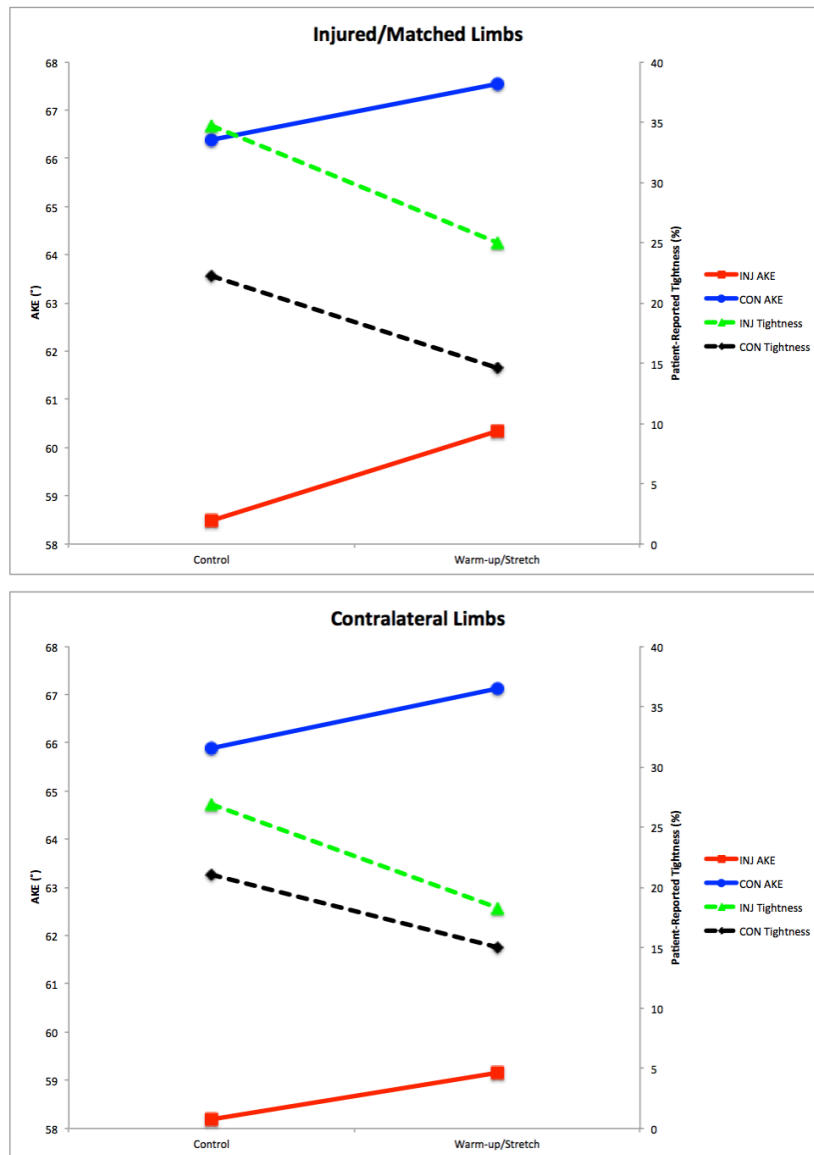
Figure 7   Means from control condition to completion of the warm-up and
            stretch for patient-reported tightness and extensibility (AKE) in both
            the previously injured/matched and contralateral limbs between
            groups.

CON: Healthy controls. INJ: Previously injured hamstring participants. AKE: active

knee extension test.
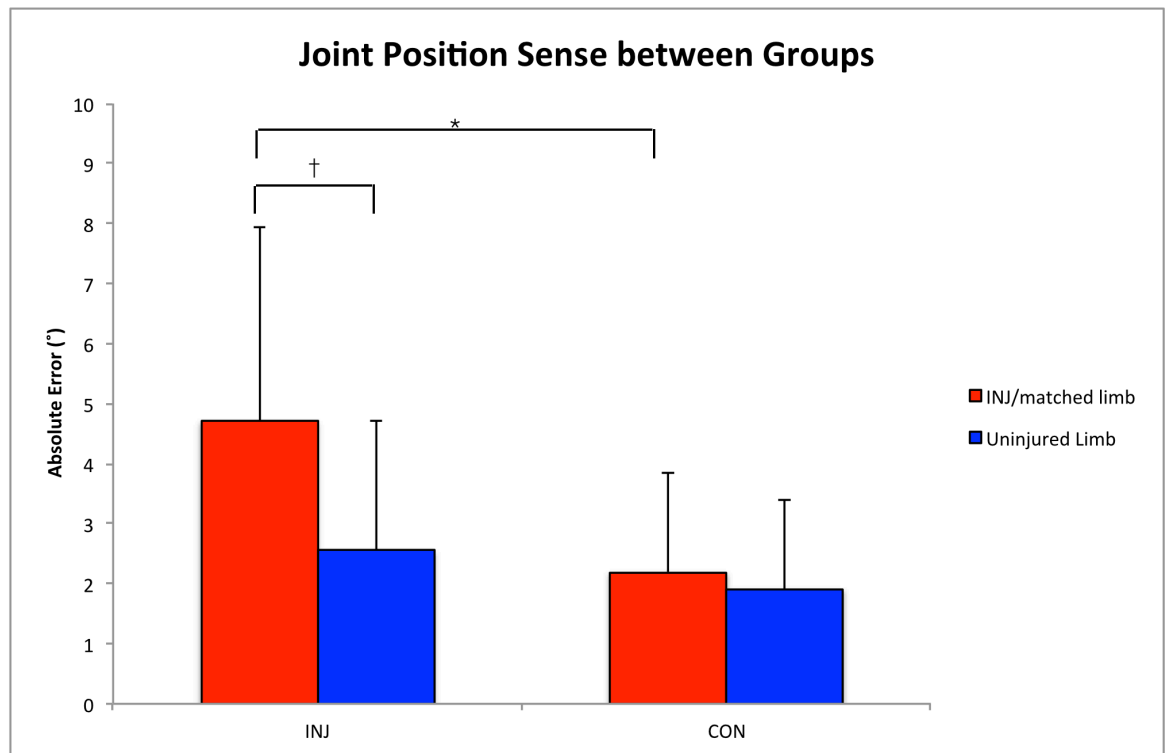
Figure 8   Joint position sense errors between groups for the injured/matched and
              contralateral limbs.

CON: Healthy controls. INJ: Previously injured hamstring participants.

*Significantly greater absolute error compared to the matched limb in CON group.

†Significantly greater absolute error compared to the contralateral limb.
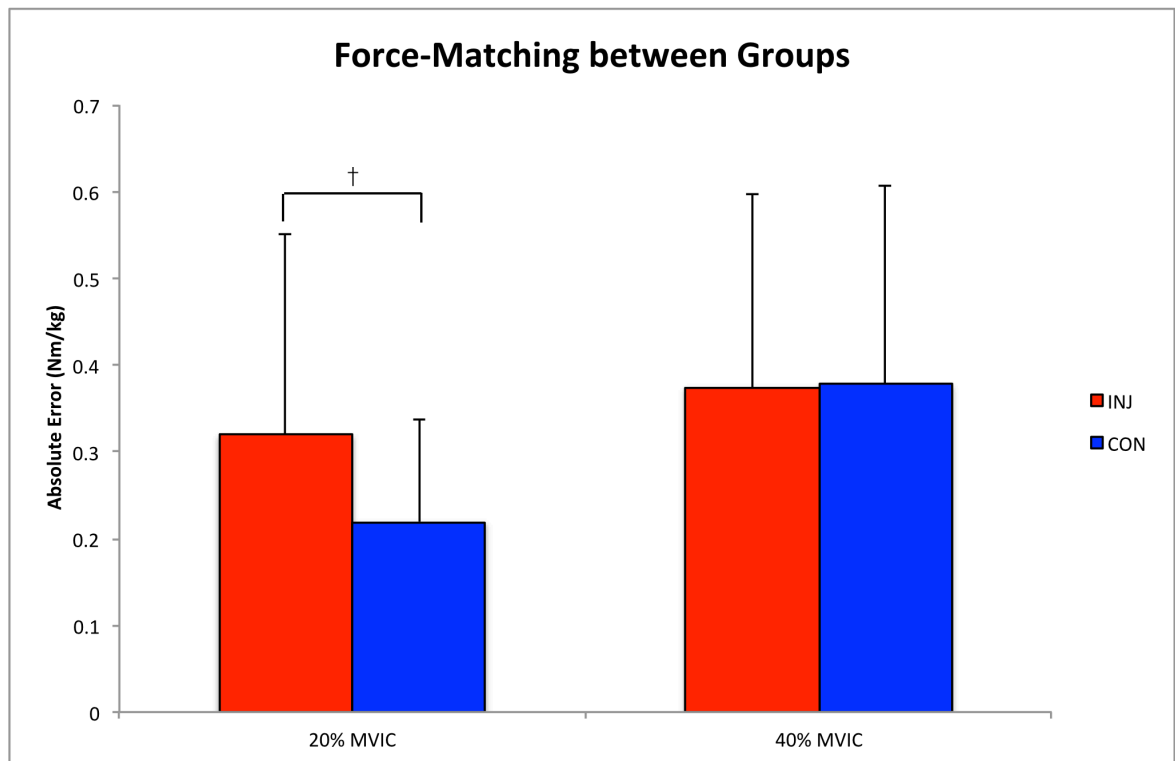
Figure 9   Force matching errors between groups for the force-matching task
performed at 20% and 40% of the participants' MVIC.

CON: Healthy controls. INJ: Previously injured hamstring participants. MVIC:

Maximum voluntary isometric contraction. [†]Significantly greater absolute error
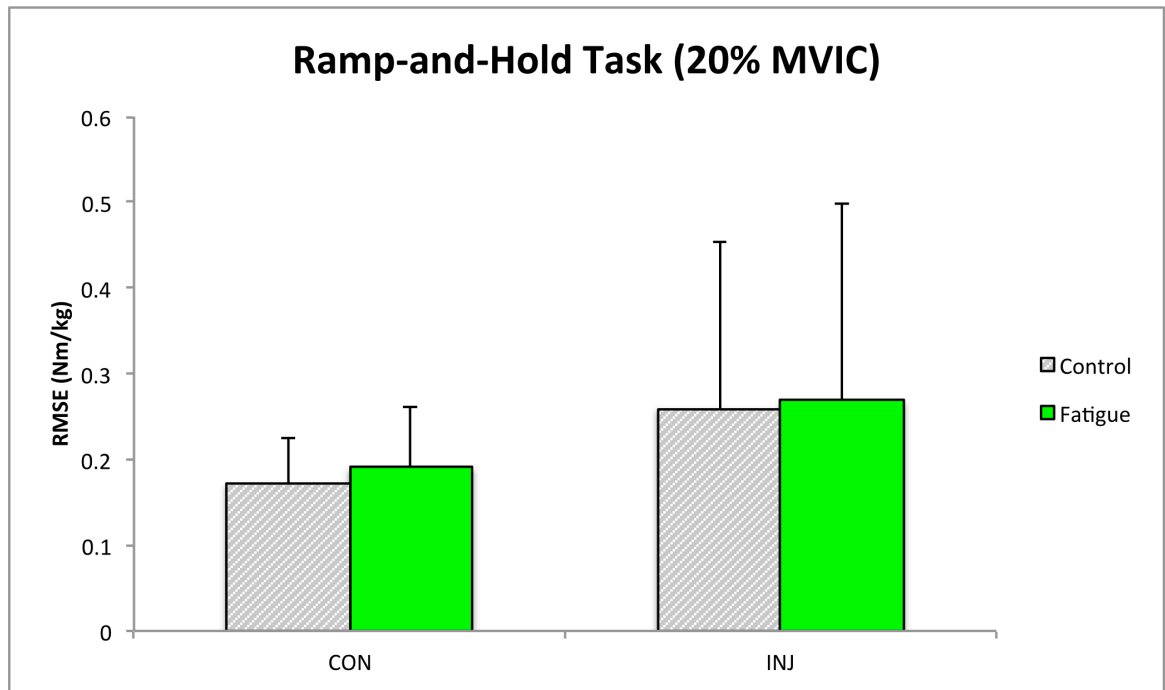
compared to the matched limb in CON group.
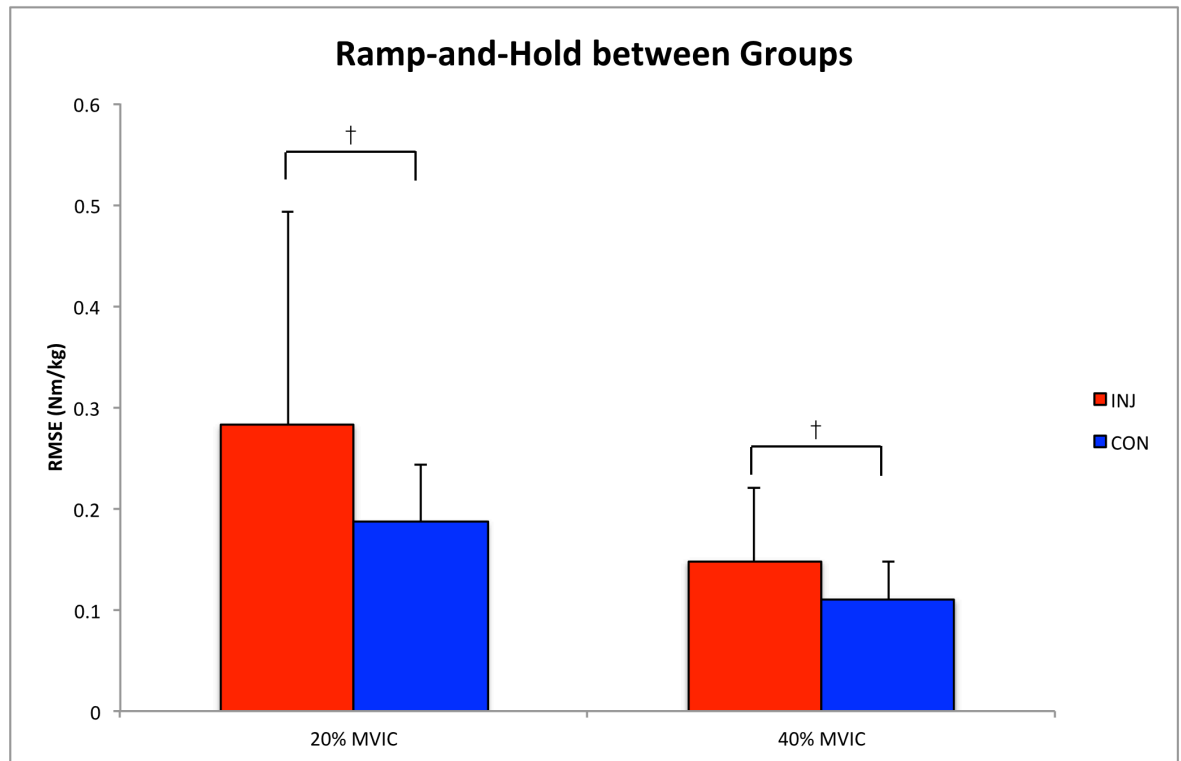
Figure 10   RMSE for the ramp-and-hold task performed at 20% and 40% MVIC between groups.

CON: Healthy controls. INJ: Previously injured hamstring participants. RMSE: root mean square error. MVIC: Maximum voluntary isometric contraction. [†]Significantly greater absolute error compared to the matched limb in CON group.
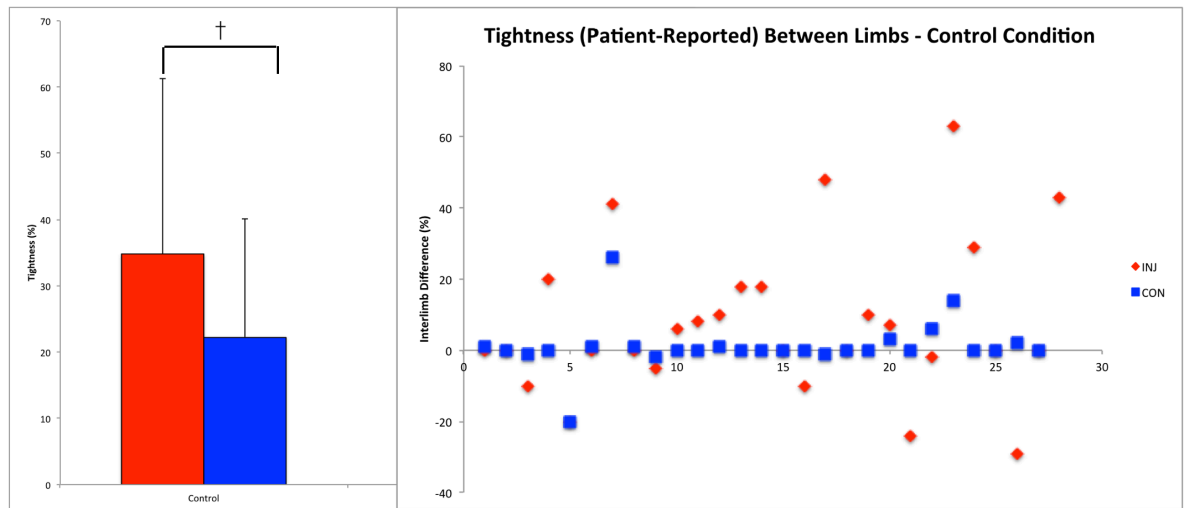
Figure 11   Patient-reported tightness between groups and individual data points
for inter-limb differences between groups measured in the control
condition.

CON: Healthy controls. INJ: Previously injured hamstring participants.

†Significantly higher tightness in the previously injured limb compared to the

matched limb in CON group during control conditions.
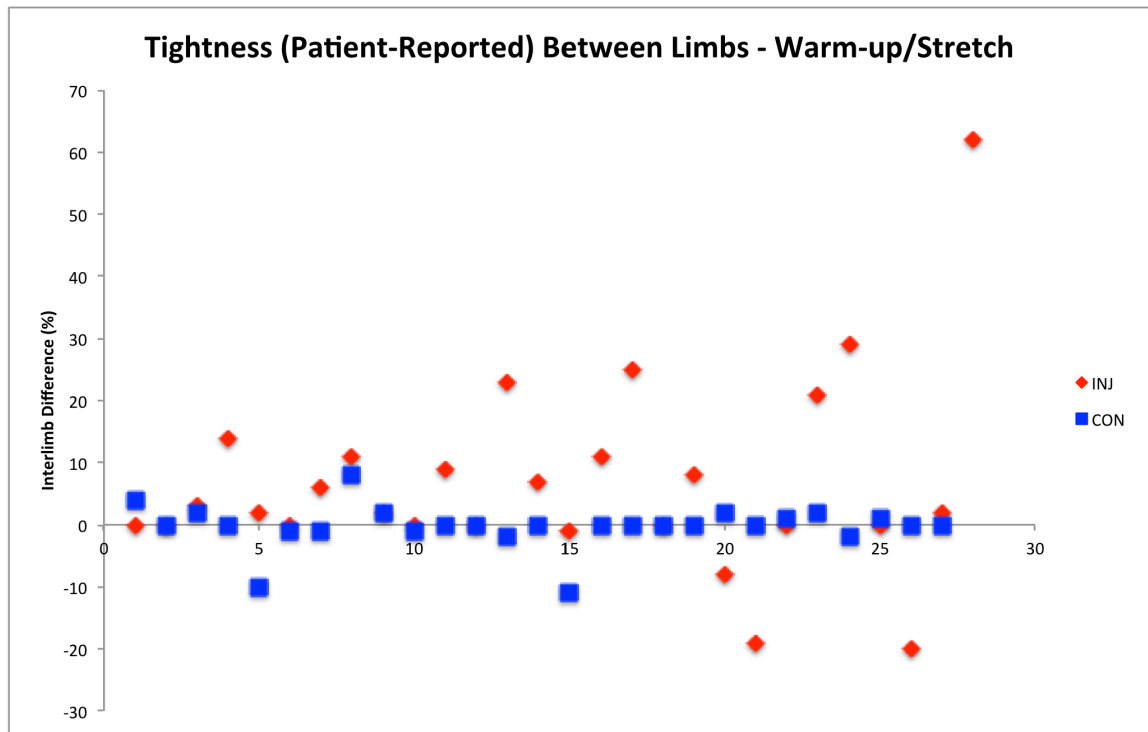
Figure 12   Individual data points for inter-limb differences in patient-reported
tightness between groups measured following the warm-up and
stretching protocol.

CON: Healthy controls. INJ: Previously injured hamstring participants
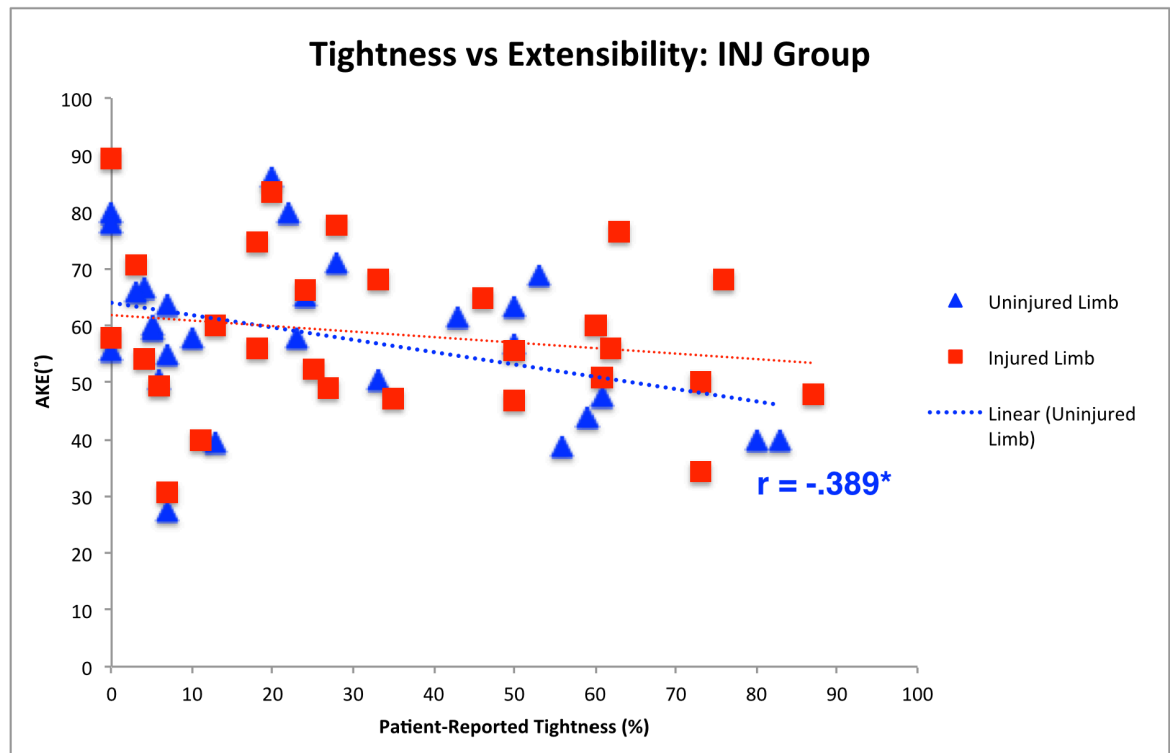
Figure 13   Relationship between patient-reported tightness (%) and extensibility (˚).

AKE: Active Knee Extension Test.*Significant correlation (p<.05)
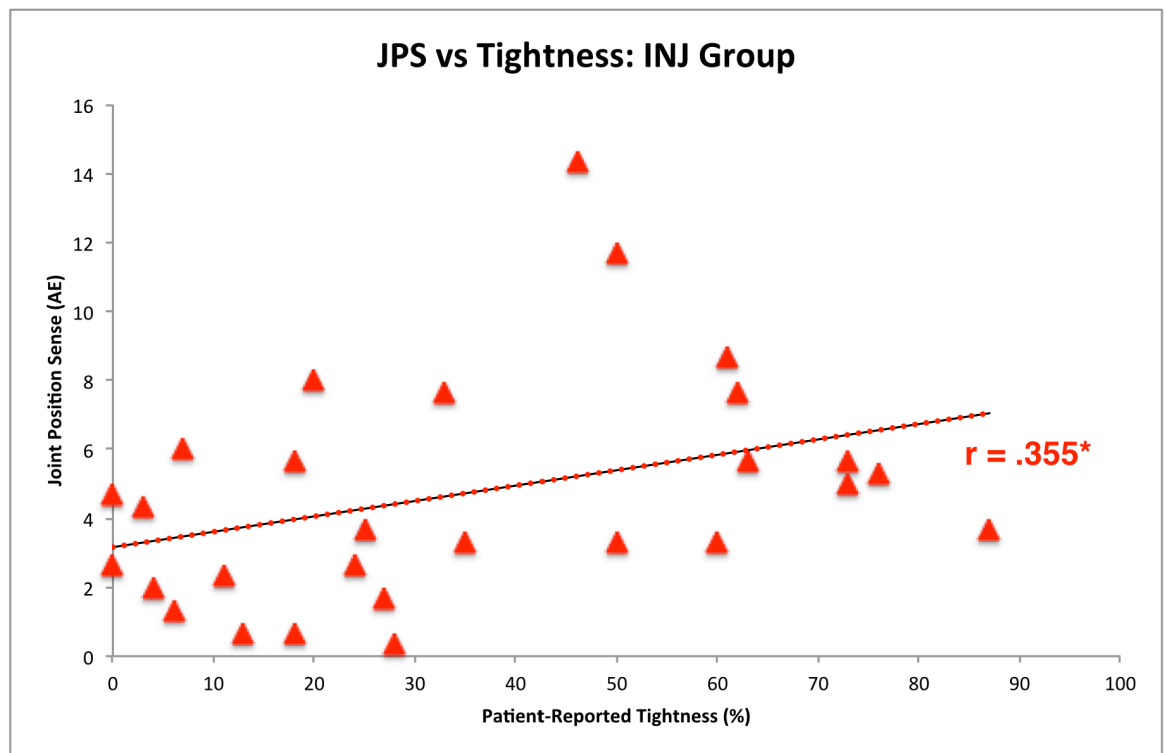
Figure 14   Relationship between patient-reported tightness (%) and joint position
sense absolute error (˚).

*Significant correlation (p<.05)
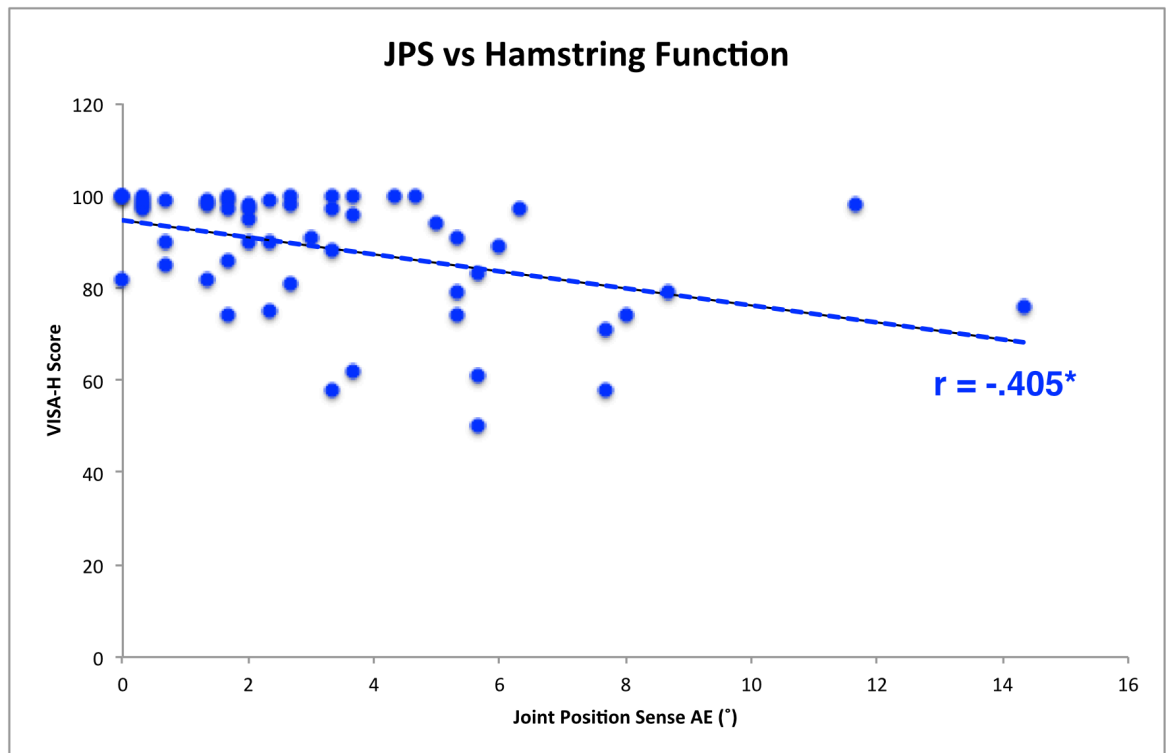
Figure 15   Relationship between joint position sense absolute error (˚) and patient reported hamstring function.

VISA-H: Victoria Institute for Sport Assessment Scale. *Significant correlation (p<.05)
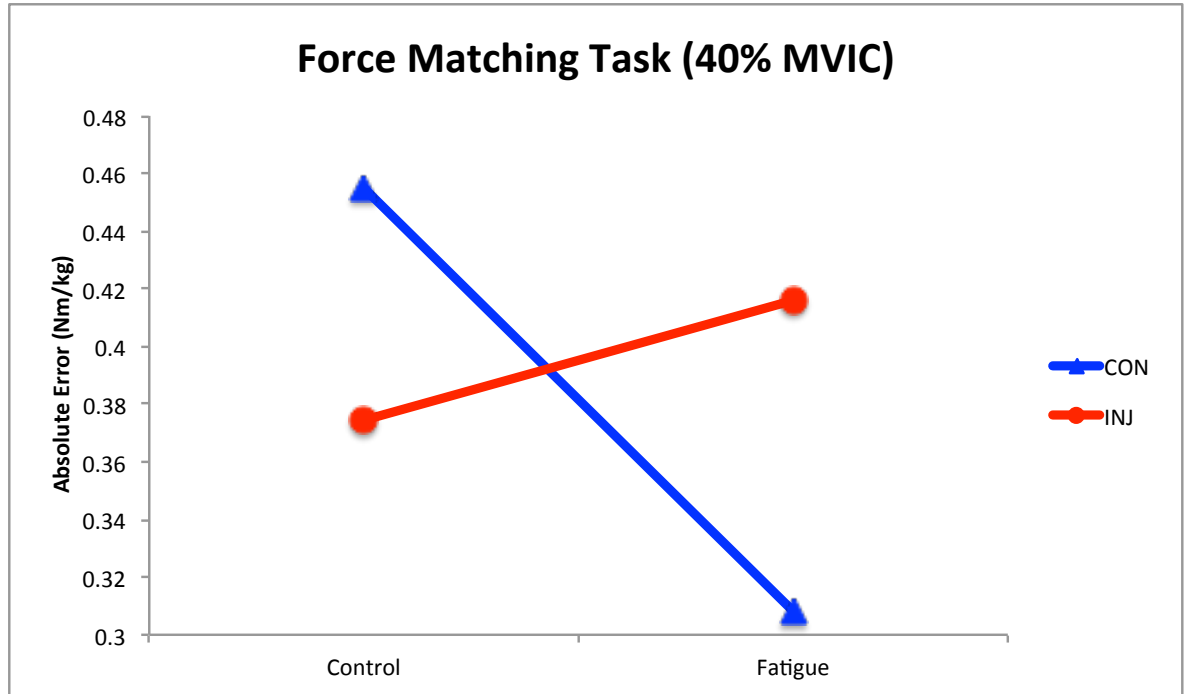
Figure 16 Group absolute errors from the control to fatigue conditions for the force-matching task performed at 40% MVIC

CON: Healthy controls. INJ: Previously injured hamstring participants. MVIC: maximum voluntary isometric contraction

Figure 17   Group means and standard deviations for the ramp-and-hold task
performed at 20% MVIC.

CON: Healthy controls. INJ: Previously injured hamstring participants. MVIC:

maximum voluntary isometric contraction
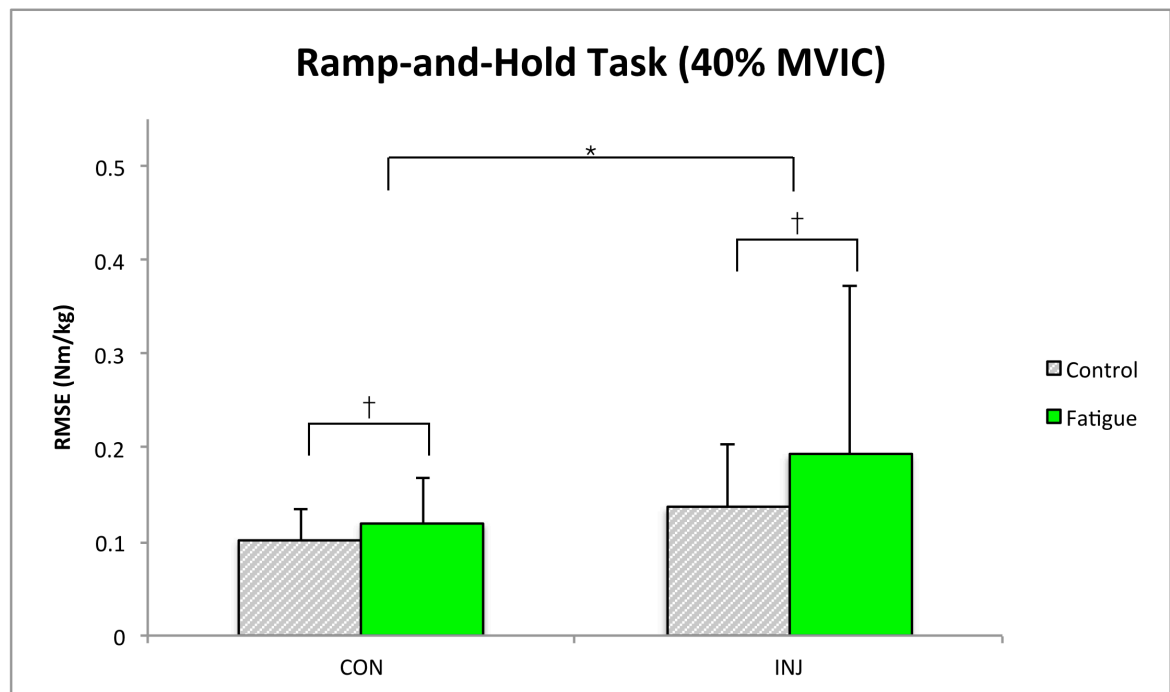
Figure 18   Group means and standard deviations for the ramp-and-hold task performed at 40% MVIC.

CON: Healthy controls. INJ: Previously injured hamstring participants. MVIC: maximum voluntary isometric contraction. [†]Significant effect for condition with increased errors observed under fatigue. *Significant effect for group with the INJ group producing greater errors overall.
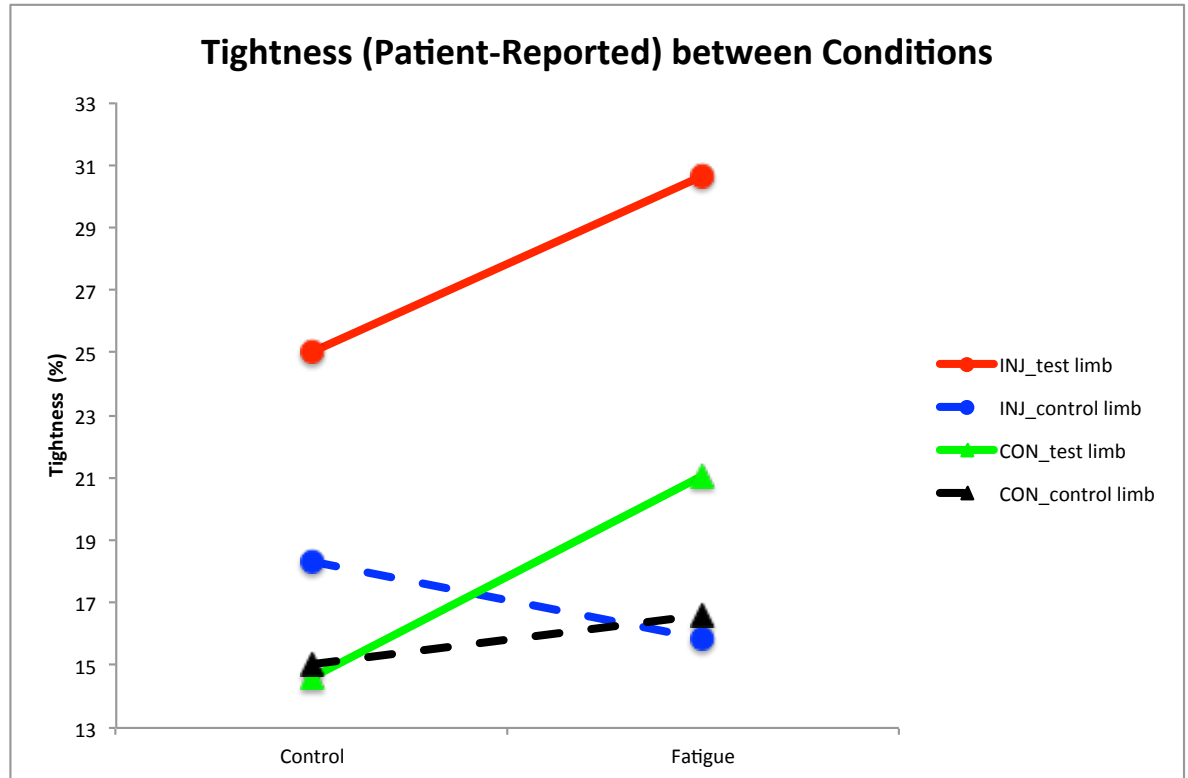
Figure 19   Patient-reported tightness in the injured/matched limb and contralateral
limb between groups from the control to fatigue conditions.

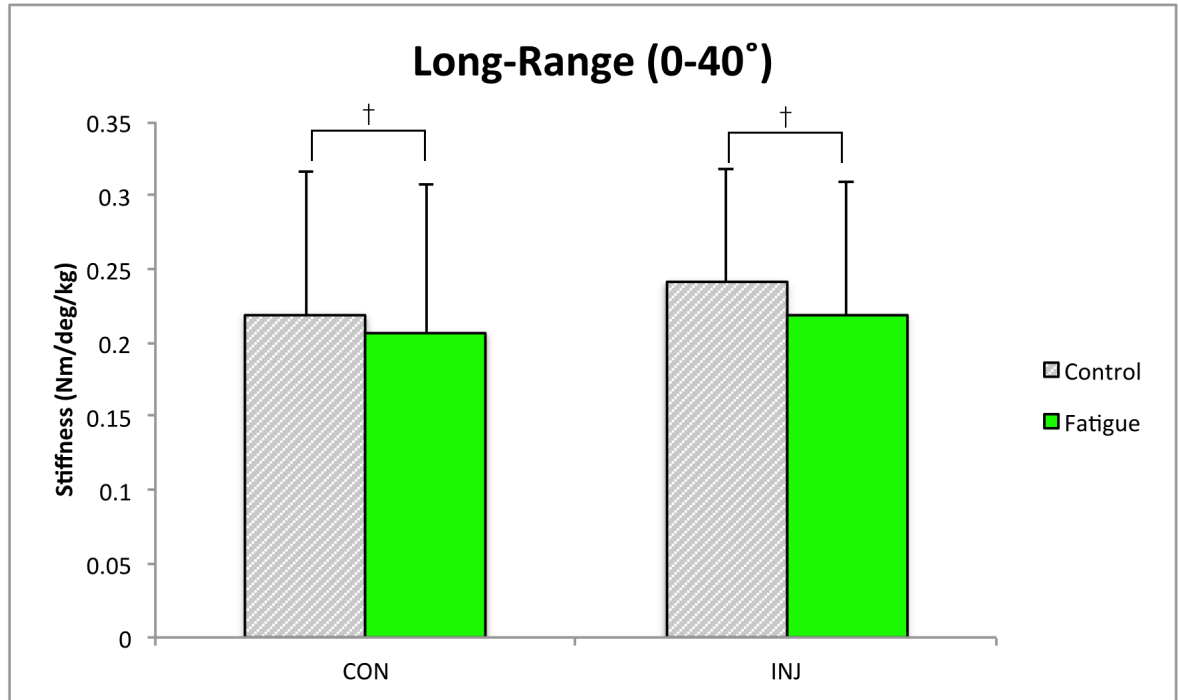CON: Healthy controls. INJ: Previously injured hamstring participants.
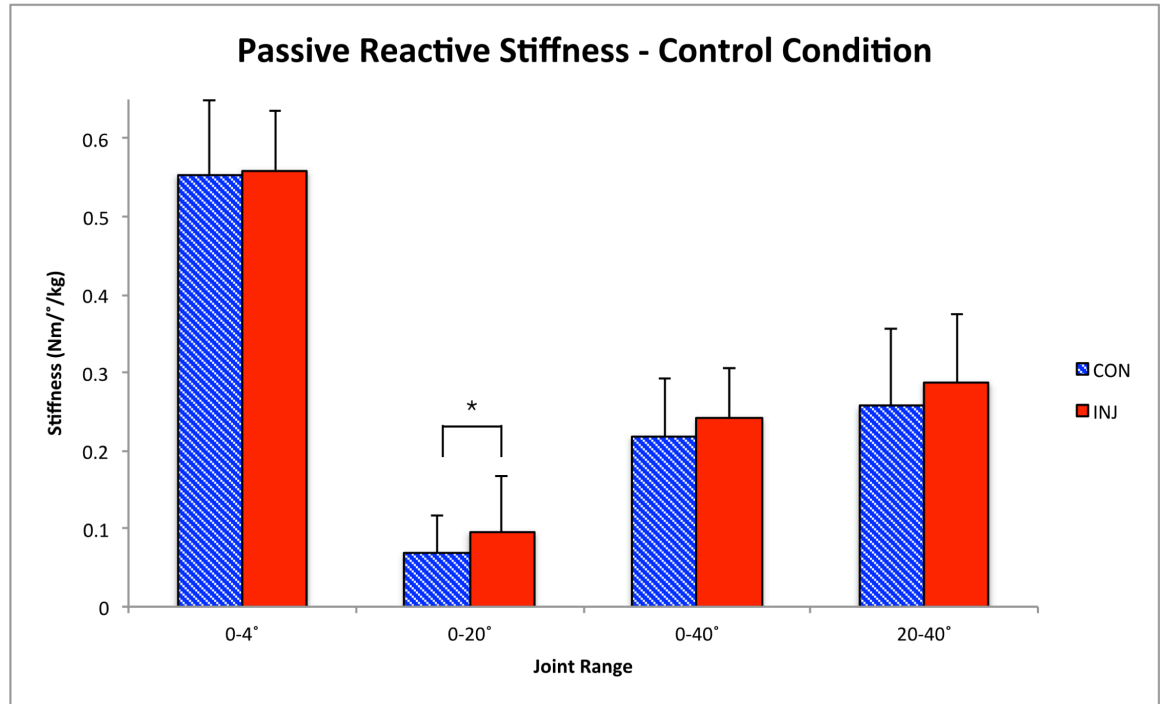
Figure 20   Group means and standard deviations for passive reactive stiffness
performed during the control condition.

CON: Healthy controls. INJ: Previously injured hamstring participants.

*Significantly higher stiffness at mid-range (0-20˚) in the INJ group.
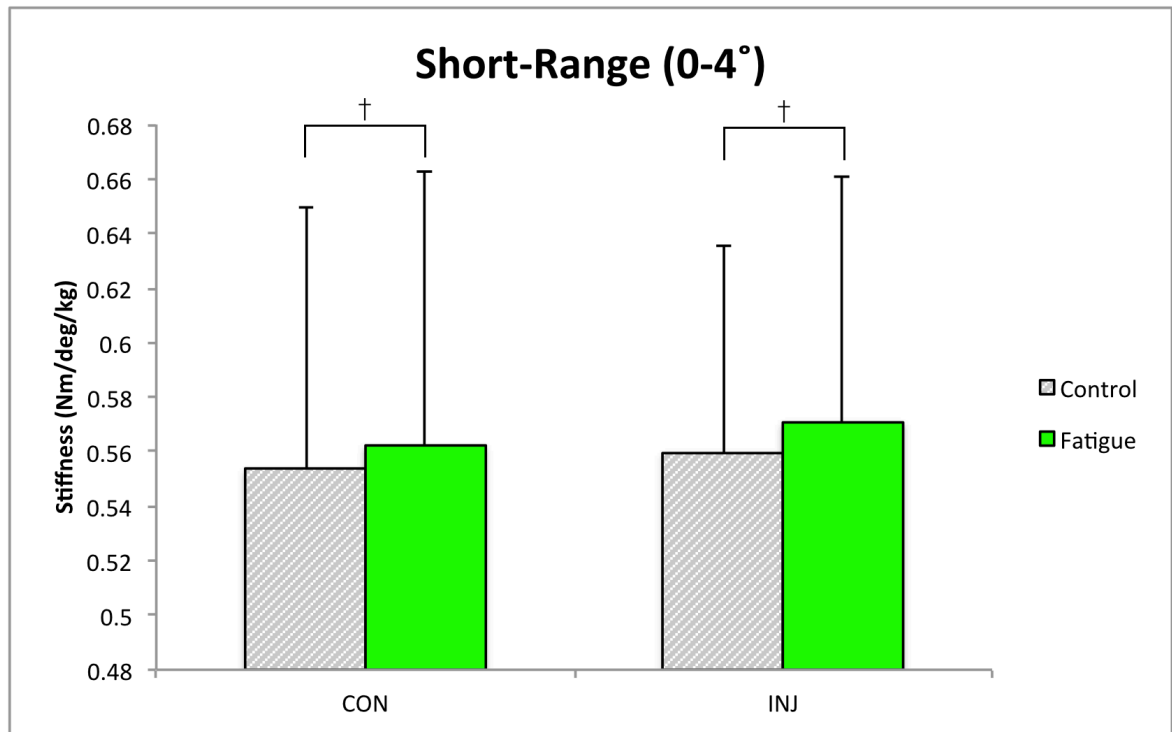
Figure 21   Group means and standard deviations for short-range passive reactive
stiffness performed during control and fatigue conditions.

CON: Healthy controls. INJ: Previously injured hamstring participants. [†]Significant

effect for condition with increased stiffness under fatigue.

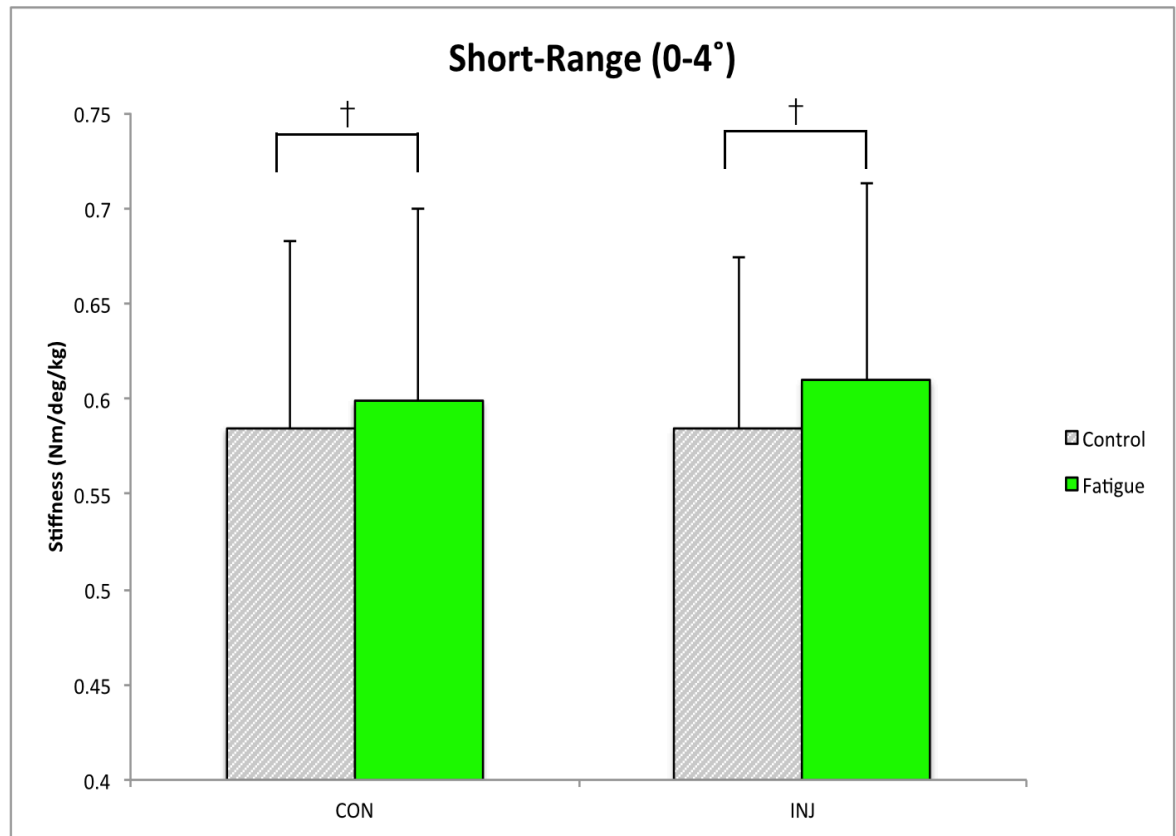Figure 22   Group means and standard deviations for long range passive reactive
stiffness during the control and fatigue conditions.

CON: Healthy controls. INJ: Previously injured hamstring participants. [†]Significant

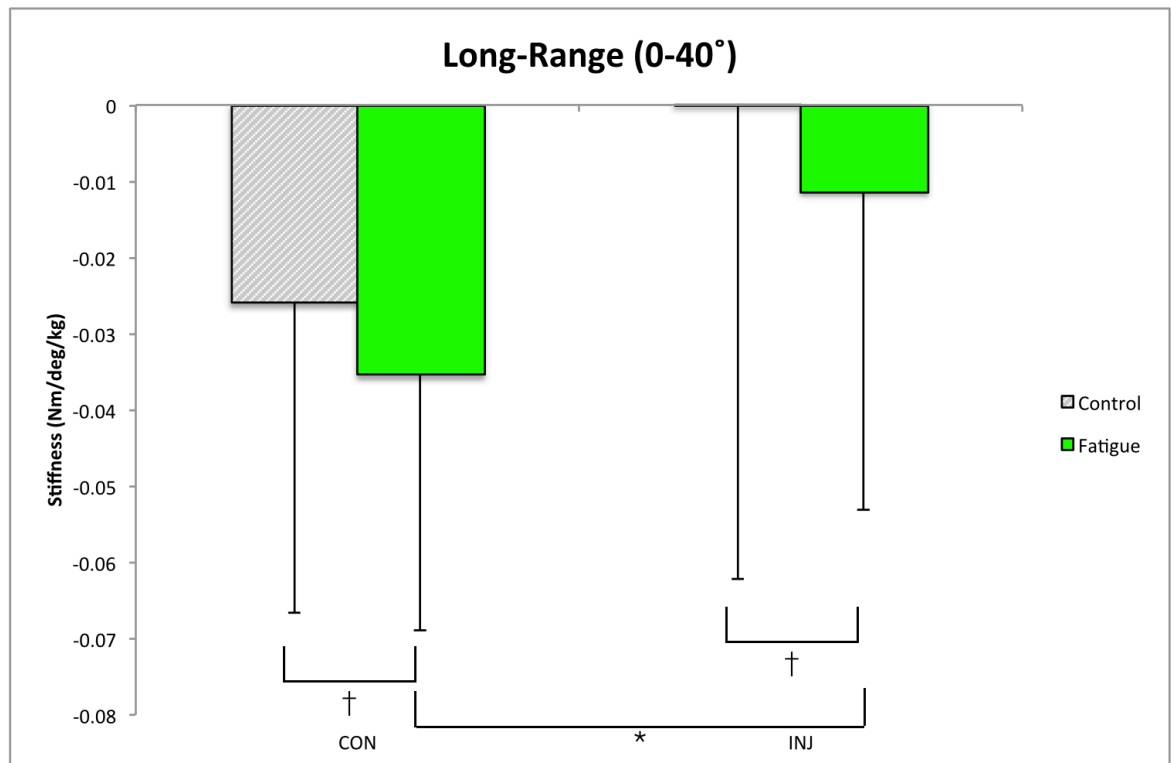effect for condition with decreased long-range stiffness under fatigue.

Figure 23   Group means and standard deviations for short-range active deactivation stiffness from the control to fatigue condition.

CON: Healthy controls. INJ: Previously injured hamstring participants. [†]Significant effect for condition with increased short-range stiffness under fatigue.

Figure 24   Group means and standard deviations for long-range active
deactivation stiffness from the control to fatigue condition.

CON: Healthy controls. INJ: Previously injured hamstring participants. [†]Significant effect for condition with decreased short-range stiffness under fatigue. *Significant effect for group with higher long-range stiffness in the INJ group overall.
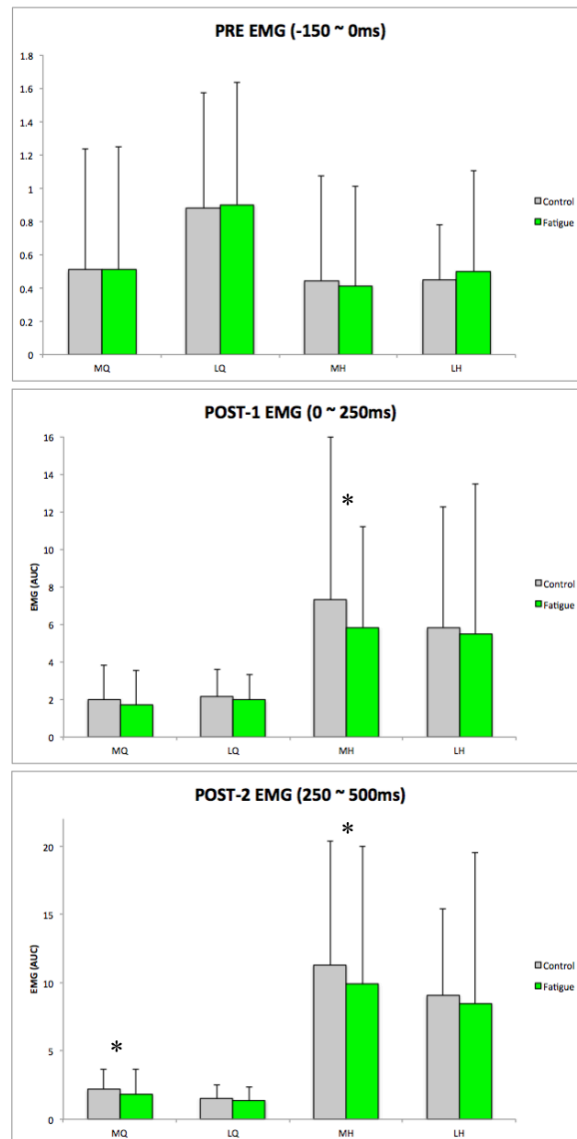
Figure 25   Quadriceps and hamstrings EMG activation for passive reactive stiffness trials before (PRE; -150 to 0ms) and after (POST-1; 0-250ms and POST-2; 250-500ms) the perturbation delivery during the control and fatigue conditions.

MQ: medial quadricep, LQ: lateral quadriceps, MH: medial hamstring, LH: lateral hamstring. AUC: area under the curve. *Significant difference between conditions.
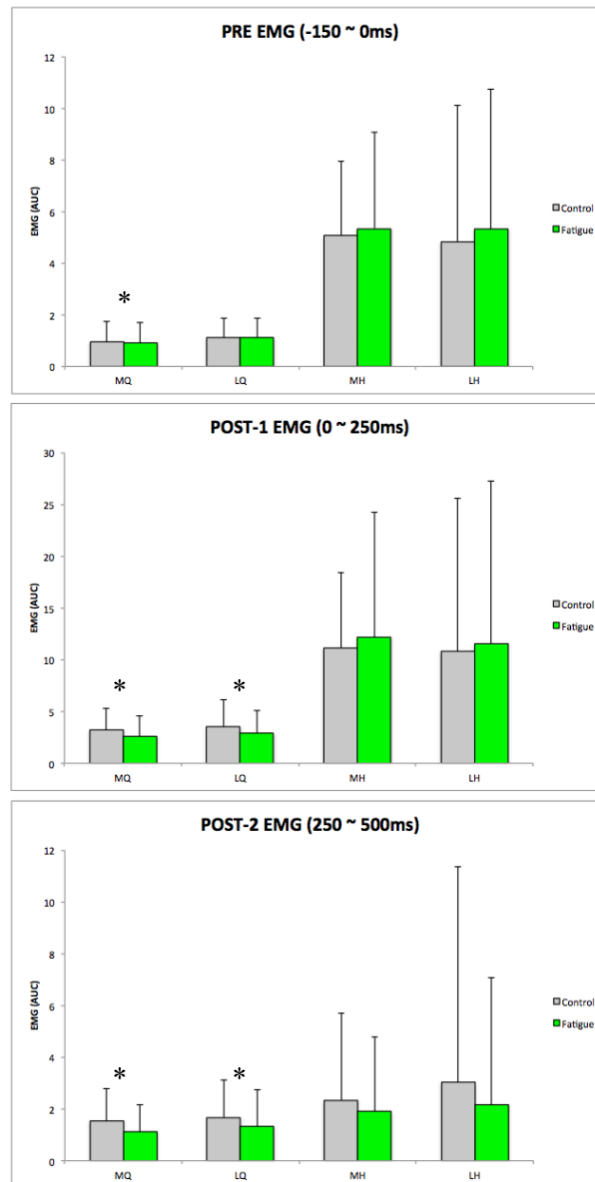
Figure 26   Quadriceps and hamstrings EMG activation for active deactivatiion
stiffness trials before (PRE; -150 to 0ms) and after (POST-1; 0-250ms
and POST-2; 250-500ms) the perturbation delivery during the control
and fatigue conditions.

MQ: medial quadricep, LQ: lateral quadriceps, MH: medial hamstring, LH: lateral

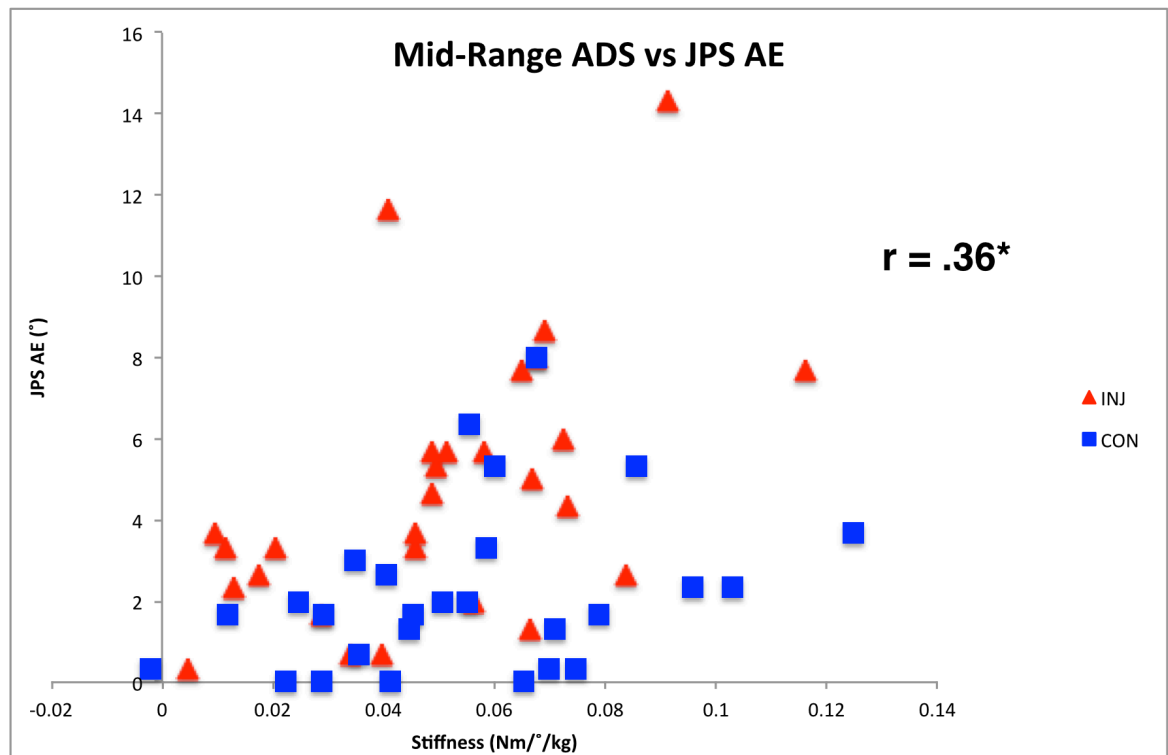hamstring. AUC: area under the curve. *Significant difference between conditions.

Figure 27   Relationship between mid-range (0-20˚) active deactivation stiffness
              (Nm/˚/kg) and joint position sense absolute error (˚).

INJ: previously injured group. CON: healthy control group. JPS AE: joint position sense absolute error. ADS: active deactivation stiffness. *Significant correlation (p<.05).
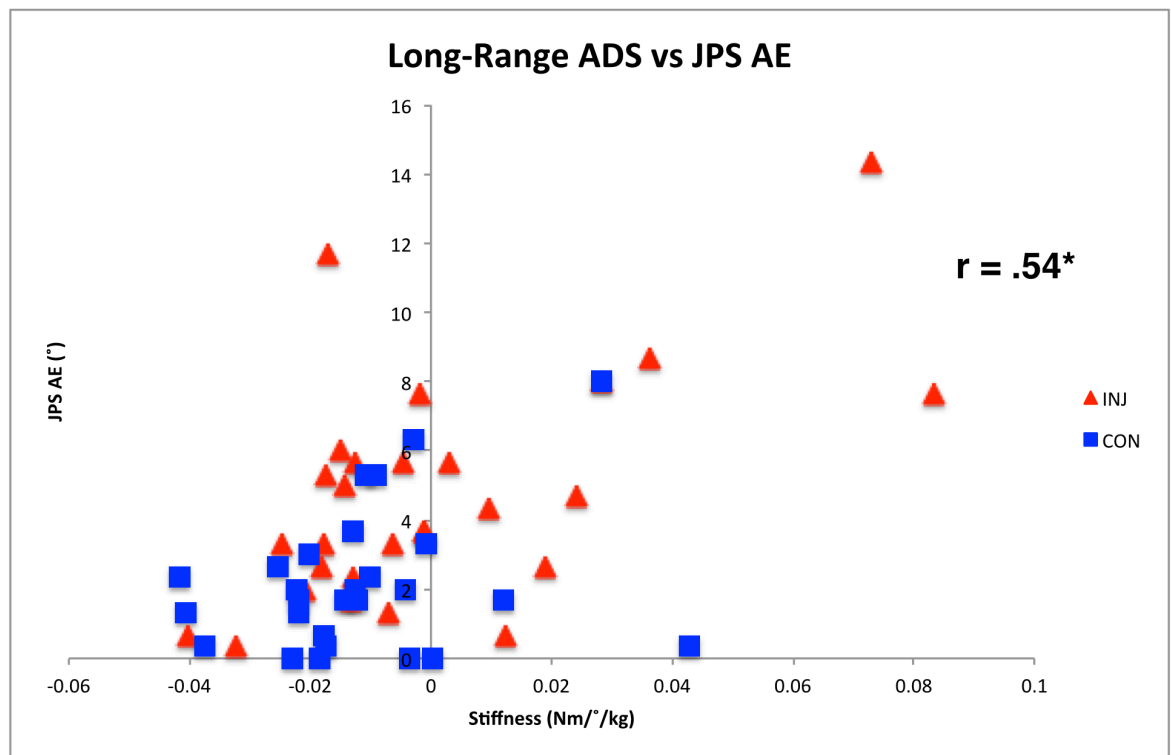
Figure 28   Relationship between long-range (0-40˚) active deactivation stiffness (Nm/˚/kg) and joint position sense absolute error (˚).

INJ: previously injured group. CON: healthy control group. JPS AE: joint position sense absolute error. ADS: active deactivation stiffness. *Significant correlation (p<.05)

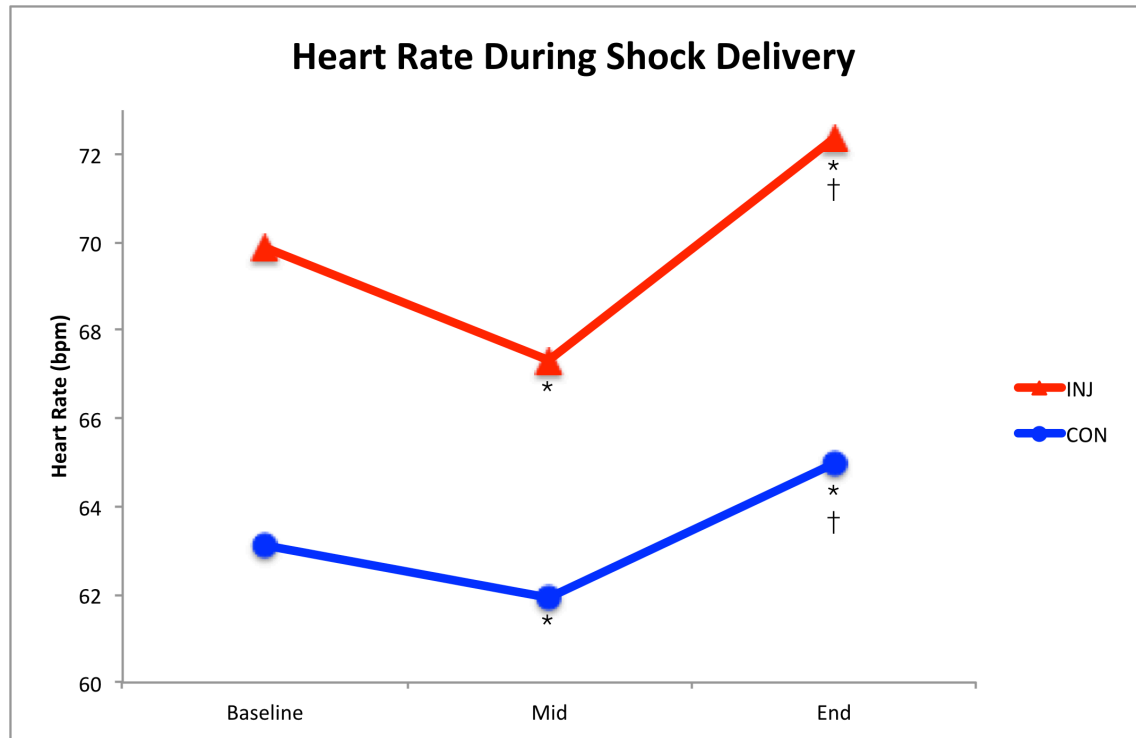Figure 29   Electrode placement for delivery of mild electrical shocks.

Figure 30   Heart rate (bpm) at the start, mid-point, and at the end of shock delivery.

CON: Healthy controls. INJ: Previously injured hamstring participants. *Significant difference compared to baseline heart rate. †Significant difference compared to mid-shock heart rate.
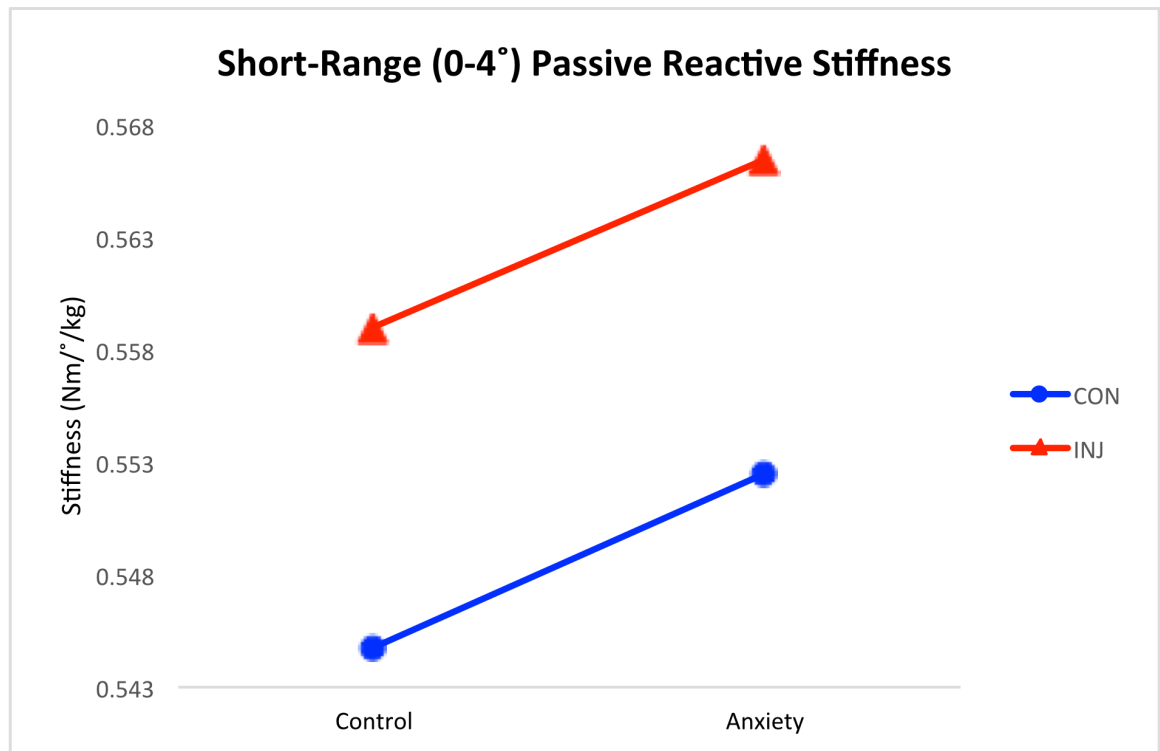
Figure 31   Short-range (0-4˚) passive reactive stiffness from the control condition
            to post-shock delivery (anxiety condition) in the healthy control and
            previously injured groups.

CON: Healthy controls. INJ: Previously injured hamstring participants. Significant
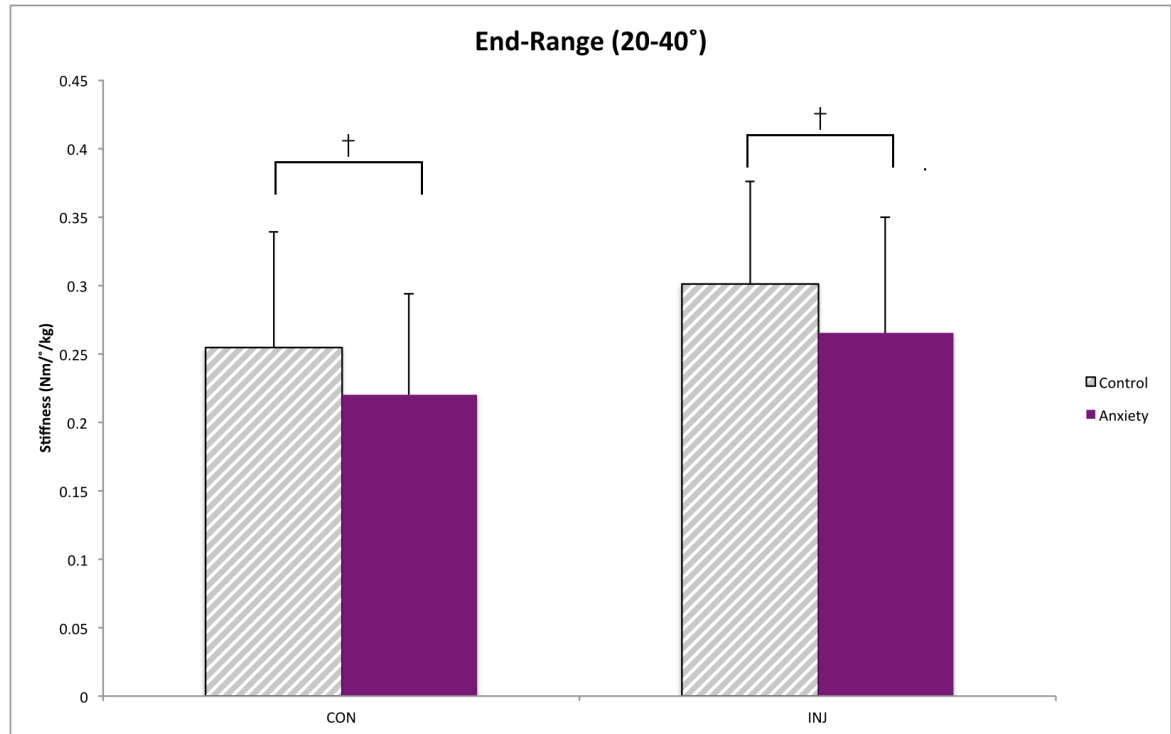condition effect for anxiety.

Figure 32   End-range passive reactive stiffness from during control and anxiety
conditions in the healthy control and previously injured groups.

CON: Healthy controls. INJ: Previously injured hamstring participants. [†]Significant condition effect for anxiety).

Figure 33   Quadriceps and hamstrings EMG activation for passive reactive stiffness trials before (PRE; -150 to 0ms) and after (POST-1; 0-250ms and POST-2; 250-500ms) the perturbation delivery during the control and anxiety conditions.

MQ: medial quadricep, LQ: lateral quadriceps, MH: medial hamstring, LH: lateral hamstring. AUC: area under the curve. *Significant difference between conditions.
†Significant group by condition interaction with lower activation in INJ group.
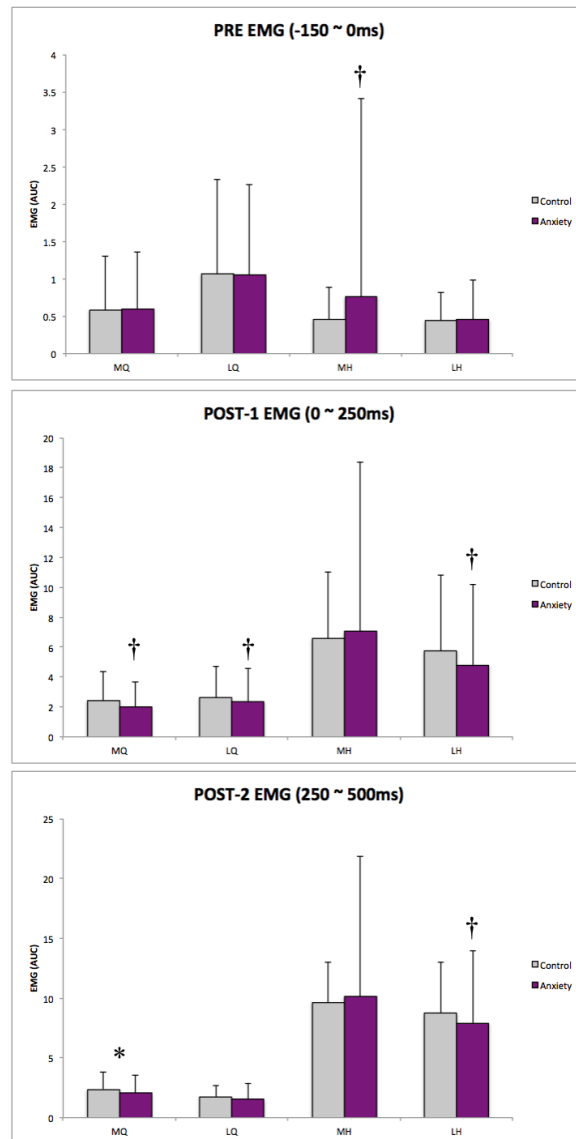
Figure 34   Quadriceps and hamstrings EMG activation for active deactivation
             stiffness trials before (PRE; -150 to 0ms) and after (POST-1; 0-250ms
             and POST-2; 250-500ms) the perturbation delivery during the control
             and anxiety conditions.

MQ: medial quadricep, LQ: lateral quadriceps, MH: medial hamstring, LH: lateral

hamstring. AUC: area under the curve. *Significant difference between conditions.

Figure 35   EMG activity during active deactivation stiffness testing of the medial
            and lateral hamstrings from the control to anxiety conditions between
            groups.

CON: Healthy controls. INJ: Previously injured hamstring participants. Significant

condition effect for anxiety for medial and lateral quadriceps and hamstrings during

the preparatory phase (0-150ms prior to perturbation).

Figure 36   Passive reactive stiffness for the control and startle conditions for all participants at short-, mid- and long-range.

*Significant main effect for the startle condition. Startle was an acoustic sound delivered 100 ms prior to the perturbation.
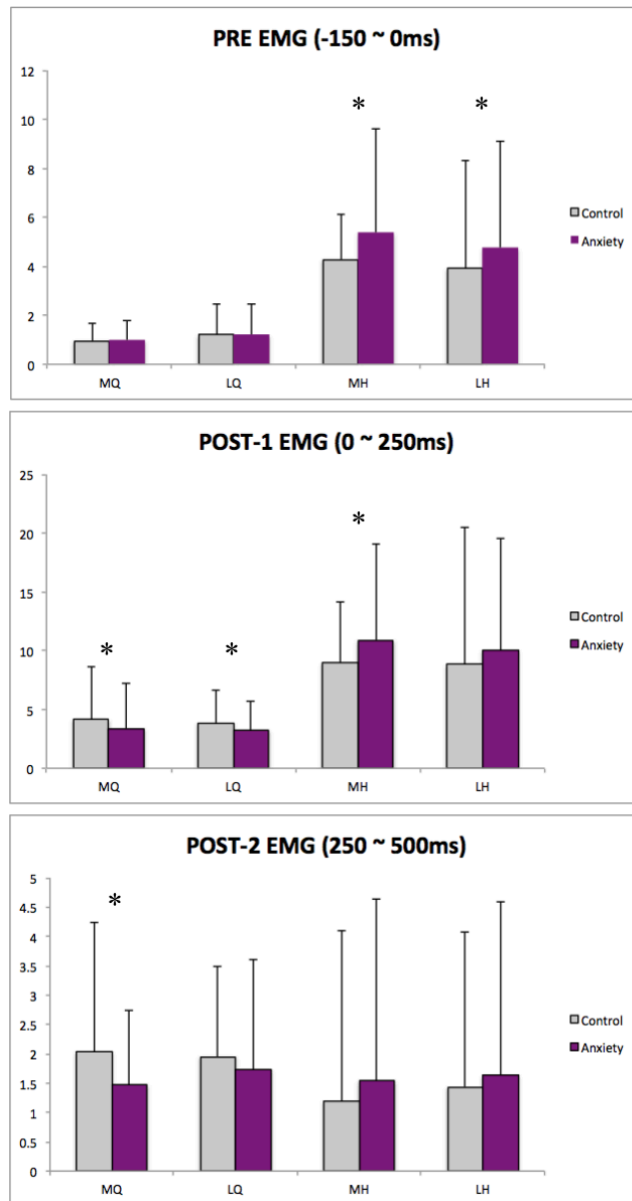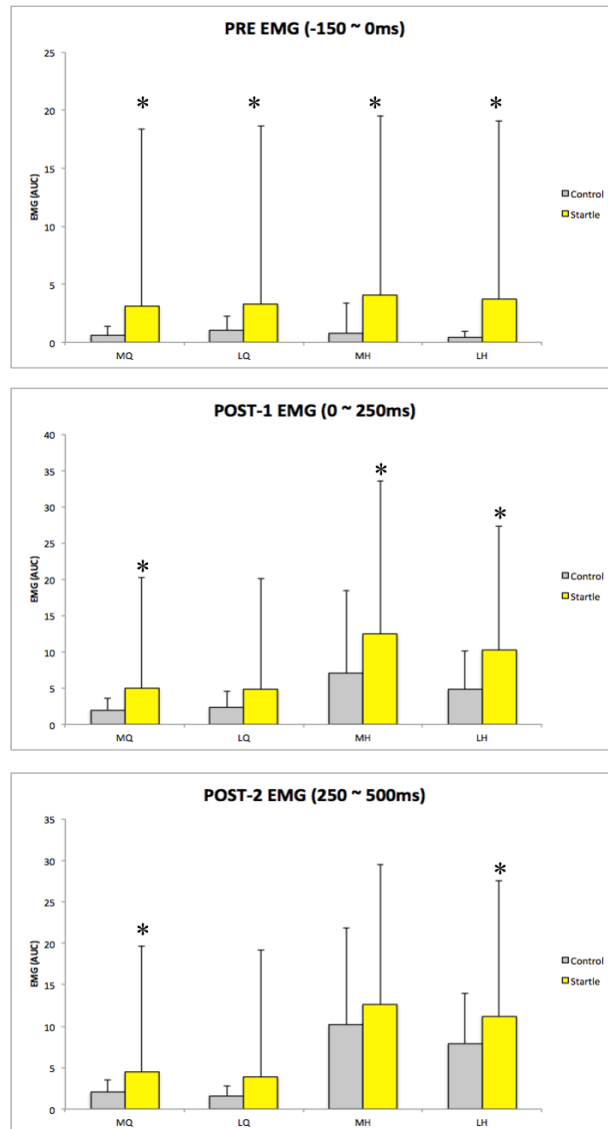
Figure 37   Quadriceps and hamstrings EMG activation for active deactivation
stiffness trials before (PRE; -150 to 0ms) and after (POST-1; 0-250ms
and POST-2; 250-500ms) the perturbation delivery during the control
and startle conditions.

MQ: medial quadricep, LQ: lateral quadriceps, MH: medial hamstring, LH: lateral

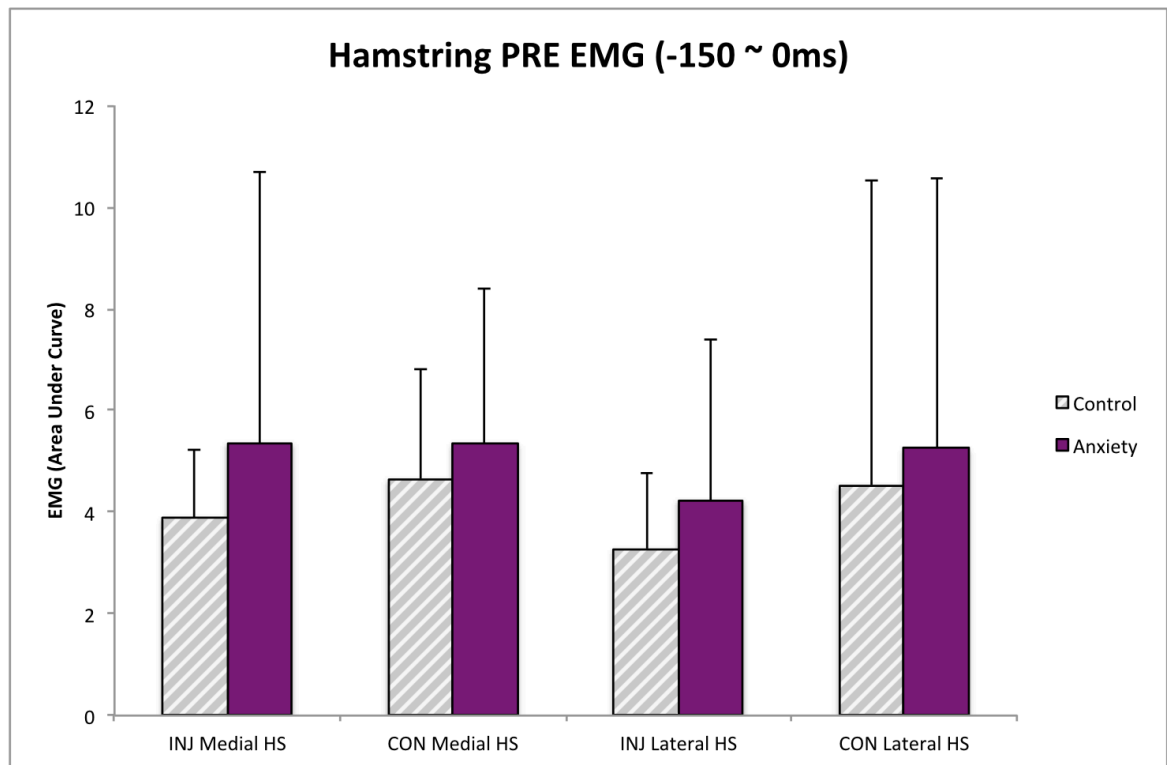hamstring. AUC: area under the curve. *Significant difference between conditions.

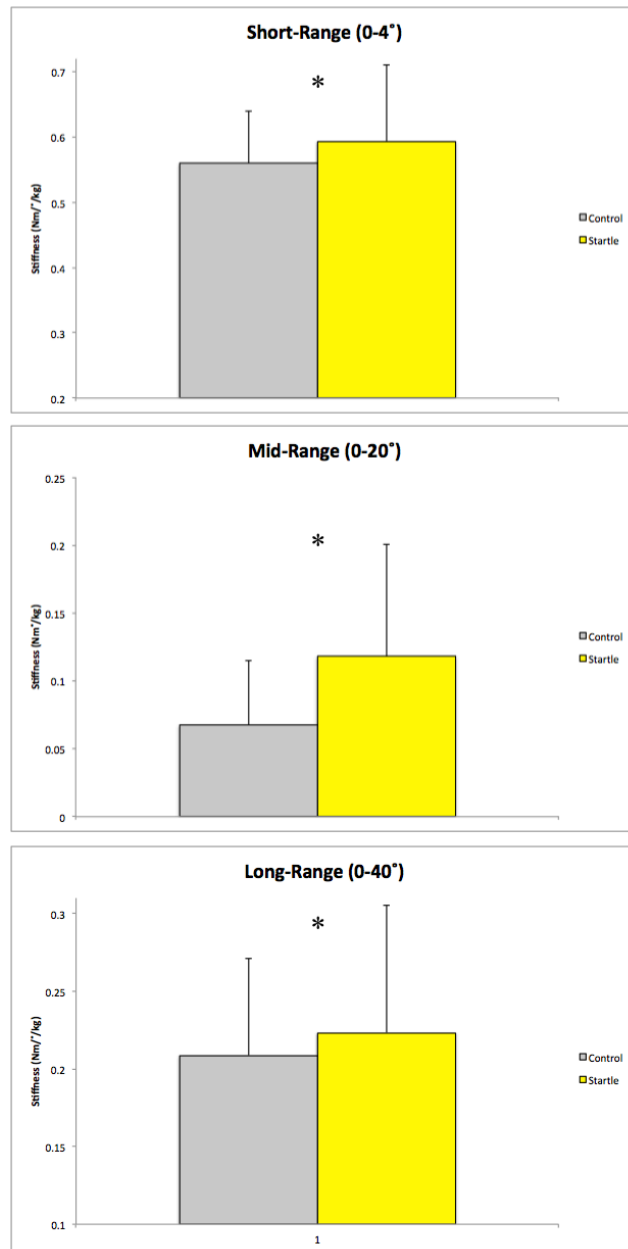Startle was an acoustic sound delivered 100ms prior to the perturbation.

Figure 38   Passive reactive stiffness for the control and startle conditions for all participants at mid- and long-range.

*Significant main effect for the startle condition. Startle was an acoustic sound delivered 100 ms prior to the perturbation.
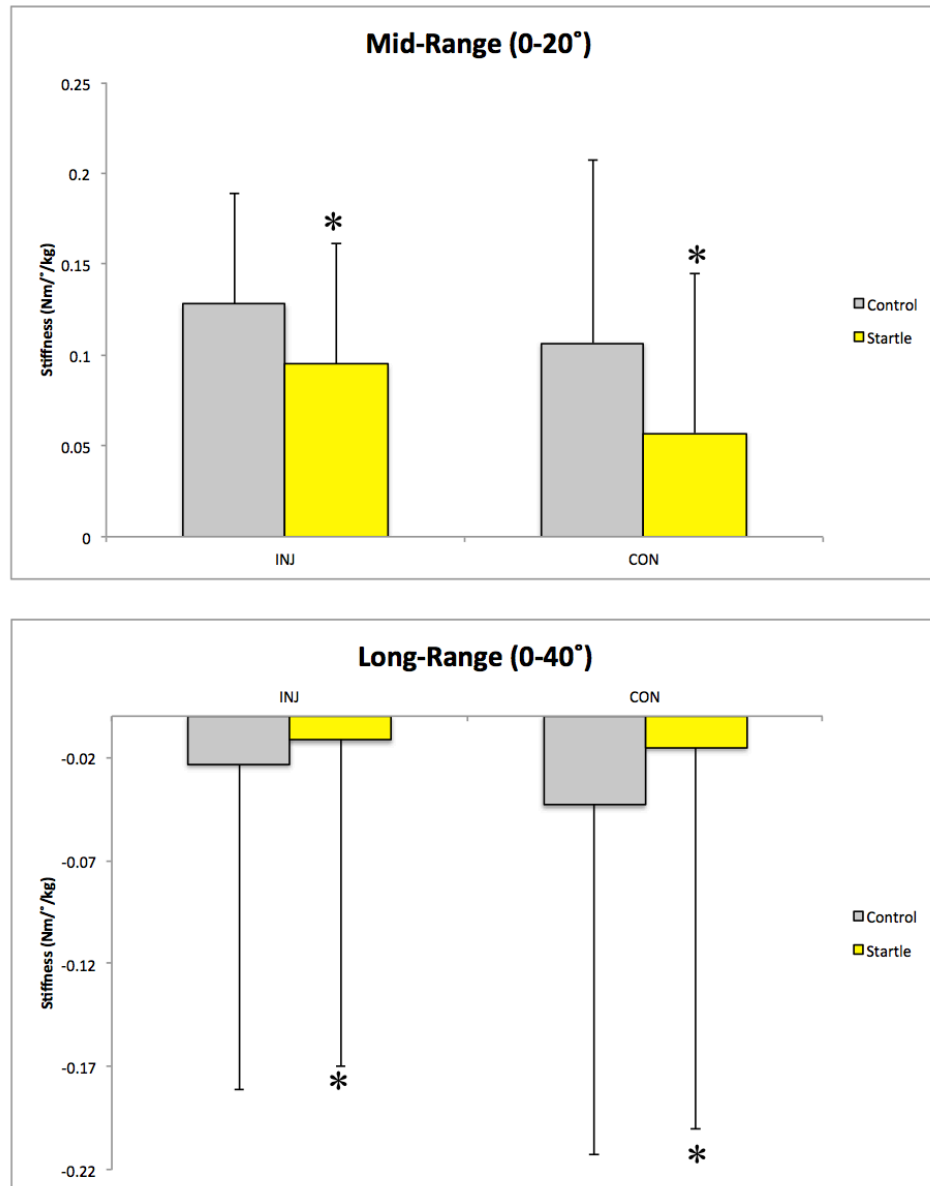
Appendix C

QUESTIONNAIRES

CSAI-2

Instructions: Complete the following scale on two separate occasions: during a quiet time before practice when you are fairly relaxed, and during a competitive situation that you feel is highly stressful. If you are not currently active in competition, recall such situations as clearly as possible and record your responses.

The following are several statements that athletes use to describe their feelings before competition. Read each statement and circle the appropriate number to indicate how you feel right now, at this moment. There are no right or wrong answers. Do not spend too much time on any one statement.

	Not at all	Somewhat	Moderately so	Very much so
1. I am concerned about this competition.	1	2	3	4
2. I feel nervous.	1	2	3	4
3. I feel at ease.	1	2	3	4
4. I have self-doubts.	1	2	3	4
5. I feel jittery.	1	2	3	4
6. I feel comfortable.	1	2	3	4
7. I am concerned I may not do as well in this competition as I could.	1	2	3	4
8. My body feels tense.	1	2	3	4
9. I feel self-confident.	1	2	3	4
10. I am concerned about losing.	1	2	3	4
11. I feel tense in my stomach.	1	2	3	4
12. I feel secure.	1	2	3	4
13. I am concerned about losing.	1	2	3	4
14. I am concerned about choking under pressure	1	2	3	4
15. I'm confident I can meet the challenge.	1	2	3	4
16. I'm concerned about performing poorly.	1	2	3	4
17. My heart is racing.	1	2	3	4
18. I'm confident about performing well.	1	2	3	4

19. I'm worried about reaching my goal.	1	2	3	4
20. I feel my stomach sinking.	1	2	3	4
21. I feel mentally relaxed.	1	2	3	4
22. I'm concerned that others will be disappointed with my performance.	1	2	3	4
23. My hands are clammy.	1	2	3	4
24. I'm confident because I mentally picture myself reaching my goal.	1	2	3	4
25. I'm concerned I won't be able to concentrate.	1	2	3	4
26. My body feels tight.	1	2	3	4
27. I'm confident of coming through under pressure.	1	2	3	4

Scoring: This scale is called the Competitive State Anxiety Inventory-2 (CSAI-2), a sport-specific state anxiety scale developed by Martens, Vealey, and Burton (1990). The scale divides anxiety into three components: cognitive anxiety, somatic anxiety, and a related component-self-confidence. Self-confidence tends to be the opposite of cognitive anxiety and is another important factor in managing stress. To score the CSAI-2, take all the scores for each item at face value with the exception of item 14, where you "reverse" the score. For example, if you circled 3, count that as 2 points (1 = 4; 2 = 3; 3 = 2; 4 = 1). Total your scores in the following manner:

___ Cognitive state anxiety: Sum items 1, 4, 7, 10, 13, 16, 19, 22, and 25.
___ Somatic state anxiety: Sum items 2, 5, 8, 11, 14, 17, 20, 23, 26.
___ Self-confidence: Sum items 3, 6, 9, 12, 15, 18, 21, 24, and 27.

Your scores for each will range from 9 to 36, with 9 indicating low anxiety (confidence) and 36 indicating high anxiety confidence.

**University of Delaware
Modified Hamstring Tightness Scale**

1. RIGHT NOW, I would describe the muscle tightness in my **RIGHT** hamstring as:

No Tightness |————————————————————————| Extremely Tight

2. RIGHT NOW, I would describe the muscle tightness in my **LEFT** hamstring as:

No Tightness |————————————————————————| Extremely Tight

University of Delaware
Hamstring Strain Injury Study Inclusion Questionnaire

Age: _____   Sex: M/F   Weight: _____   Height: _____   Leg Dom: R / L

1. Are you currently physically active at least 3 days per week?   **YES**   **NO**

2. Are you currently a member of an athletic team?   **YES**   **NO**
   If yes, what sport?_____ Position: _____

3. Do you have/have a history of any heart conditions? (Pacemaker, arrhythmias, etc.)   **YES**   **NO**
   If yes, explain:_____

4. Do you currently have an injury of your low back or lower extremity?   **YES**   **NO**
   If yes, explain:_____

5. Have you had an injury of your low back or lower extremity in the last 6 months?   **YES**   **NO**
   If yes, explain:_____

6. Do you have any history of neurological conditions? (Herniated discs, nerve injury, etc.)   **YES**   **NO**
   If yes, explain:_____

7. Have you ever injured a hamstring muscle?   **YES**   **NO**

   If yes, answer the following:

   RIGHT   LEFT   BOTH   How many injuries? R _____   L _____

   How long ago? _____

   What were you doing at the time of injury? _____

   Did you have any bruising/black and blue following the injury? YES   NO

   How long were you unable to return to physical activity after the injury? ____

291

VICTORIAN INSTITUTE OF SPORT ASSESSEMENT SCALE FOR PROXIMAL HAMSTRING TENDINOPATHY
VISA-H

1. **For how many minutes can you sit/can your drive a car pain free?**

Points ☐

0 mins | 0 1 2 3 4 5 6 7 8 9 10 | 100 mins

2. **How much pain do you have during or immediately after stretching your posterior thigh/hamstring (keeping knee straight)?**

Points ☐

Strong severe pain | 0 1 2 3 4 5 6 7 8 9 10 | No pain

3. **How much pain do you have during or immediately after normal running?**

Points ☐

Strong severe pain | 0 1 2 3 4 5 6 7 8 9 10 | No pain

4. **How much pain do you have during or immediately after sprinting?**

Points ☐

Strong severe pain | 0 1 2 3 4 5 6 7 8 9 10 | No pain

5. **How much pain do you have during or immediately after a full weight-bearing lunge?**

Points ☐

Unable | 0 1 2 3 4 5 6 7 8 9 10 | No problem

6. **How much pain do you have during or immediately after lifting an object from the floor (keeping knee straight)?**

Points ☐

Strong severe pain/ unable | 0 1 2 3 4 5 6 7 8 9 10 | No pain

7. **Are you currently undertaking sport or other physical activity?**   Points ☐

0 ☐ Not at all
4 ☐ Modified training ± modified competition
7 ☐ Full training ± competition but not at the same level as when symptoms began
10 ☐ Competing at the same or higher level when symptoms began

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8. Please complete EITHER A, B or C in this question.

- If you have **no pain** while undertaking sport please complete **Q8a only**
- If you have **pain while undertaking sport but it does not stop you** from completing the activity, please complete **Q8b only.**
- If you **have pain that stops you from completing sporting activities,** please complete **Q8 c only**

8a. If you have no pain while undertaking sport, for how long can you train/practise?

0-20 mins	21-40 mins	41-60 mins	61-90 mins	>90 mins	Points	
☐	☐	☐	☐	☐		
0	**7**	**14**	**21**	**30**		

or

8b. If you have some pain while undertaking sport, but it does not stop you from completing your training/practice, for how long can you train/practise?

0-15 mins	16-30 mins	31-45 mins	46-60 mins	>60 mins	Points	
☐	☐	☐	☐	☐		
0	**4**	**10**	**14**	**20**		

or

8c. If you have pain that stops you from completing your training/practice, for how long can you train/practise?

NIL	1-10 mins	11-20 mins	21-30 mins	>30 mins	Points	
☐	☐	☐	☐	☐		
0	**2**	**5**	**7**	**10**		

TOTAL SCORE ☐ **/100**   ☐ **%**

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<center>**Appendix D**</center>

<center>**INFORMED CONSENT TO PARTICIPATE IN RESEARCH**</center>

Title of Project: Neuromechanical Factors of Hamstring Strain Injury

Principal Investigator(s): Andrea Di Trani, MS, ATC and C. Buz Swanik, PhD, ATC (advisor)

You are being invited to participate in a research study. This consent form tells you about the study including its purpose, what you will be asked to do if you decide to take part, and the risks and benefits of being in the study. Please read the information below and ask us any questions you may have before you decide whether or not you want to participate.

WHAT IS THE PURPOSE OF THIS STUDY?
The purpose of this study is to learn more about the deficits of the nervous system that occur following a hamstring strain injury, such as negative changes to one's proprioception, which includes sensation of the position of your joints and movement of you limbs, and perception of force and weight. We are also interested in examining changes in the amount of force produced in a muscle during movement (stiffness). We aim to further examine the influence that fatigue and competitive anxiety have on such muscle related properties of proprioception and stiffness. This research project will serve as the dissertation of the primary investigator.

WHY ARE YOU BEING ASKED TO PARTICIPATE?
You are being asked to take part in this study because you fall within the age requirements for this study of being between the ages of 18-30 years. We are recruiting a sample of approximately 40 current for former athletes (varsity, club, and recreational sports teams) from the University of Delaware local community that currently exercise at least 3-4 times per week. Inclusion criteria for this study are being a current athlete or former athlete (a member of a sports team [varsity, club, or recreational] within the last 5 years) with a history of a hamstring strain injury (injured group) or no history of a hamstring injury (control group). You will be excluded if you have a history of hip, knee, or ankle surgery, currently suffering from low back pain, have a history of a neurological condition (herniated disc, nerve injury, seizures, etc.), cardiac condition (arrhythmia, pacemaker, etc.), metal plates in your left wrist, decreased hearing, or any diagnosed anxiety condition.

WHAT WILL YOU BE ASKED TO DO?
As part of this study you will be asked to complete a number of questionnaires: one pertaining to your injury history, a scale describing the amount of tightness you experience in your hamstrings, a scale about your pain, function, and activity, and psychological scales related to stress/anxiety. Prior to each testing session you will be asked to complete was 5-minute warm-up on a stationary bicycle. Two testing sessions will take place on two separate days. Testing session one will include a series of tests related to your flexibility (See Figure 1 – Active Knee Extension Test), ability to accurately move and sense your leg, and ability to differ the amount of force you produce during specific tasks (force sense testing). For the test assessing movement and movement sense, you will be asked to wear a blindfold during the test to remove visual cues.

<center>294</center>

Also during this session we will use a machine referred to as the Stiffness and Proprioception Assessment Device (SPAD – See Figure 2) to measure the tension produced in your hamstrings by moving your leg while seated. You will be asked to either "relax" or "pull your leg" prior to your leg being moved. For the duration of testing on this machine, you will be wearing a pair of headphones and will be exposed to a loud noise (100-110db) at random times throughout testing. After obtaining baseline measures for this test, we will have you perform a fatiguing test of your hamstrings to see how the results of this test are changed. The fatigue test will involve pulling your leg against the machine until your force production decreases below a certain level. Electromyography (EMG) will be used to measure your muscle activity, which involves placement of electrodes on your skin. The second testing session will involve the use of the same machine (SPAD) to test your muscle tension, but will also include the delivery of electrical stimulations to your wrist as a means of increasing your stress levels prior to the muscle tension testing. The stimulations will be localized to your wrist and a number of safety mechanisms will be employed for your safety. Electromyography (EMG) will be used during this testing session to measure muscle activity, as well as a heart rate monitor to measure and collect your heart rate (beats per minute) during this testing protocol. You will be asked to wear a strap around your lower chest beneath your clothing.

All testing will take place in the Human Performance Lab located on the University of Delaware's South Campus. Your participation in this study will involve up to 3 hours over 2 visits to our lab (test session 1 will last 2 hours, test session 2 will last 1 hour).

Figure 1: Active Knee Extension Test: This test is used to measure flexibility of the hamstring muscle
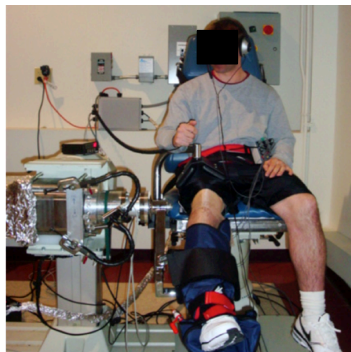

Figure 2: Stiffness and Proprioception Assessment Device (SPAD)

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?
Possible risks of participating in this research study include muscle strain during the testing or the possibility of experiencing some muscle soreness 1-2 days following testing. A warm-up and rest periods will be included to reduce this risk. There is a risk of experiencing discomfort during the electrical stimulation (mild electric shock) portion of this study, but no long term-effects are anticipated as a result of participation. There is a risk of being exposed to a high-peak voltage electrical stimulation. The primary investigator will employ multiple safety measures during testing to decrease the likelihood of this occurring. You may terminate the electrical stimulation at any time

during testing, which would result in being withdrawn from the study. Along with the stress-inducing portion of testing, participants may experience an increase in level of stress via electrical stimulation or psychological questionnaires.

WHAT IF YOU ARE INJURED DURING YOUR PARTICIPATION IN THE STUDY?
If you are injured during research procedures, you will be offered first aid at no cost to you. If you need additional medical treatment, the cost of this treatment will be your responsibility or that of your third-party payer (for example, your health insurance). By signing this document, you are not waiving any rights that you may have if injury was the result of negligence of the university or its investigators. If you are injured during this study you will be excluded from participating.

WHAT ARE THE POTENTIAL BENEFITS?
You will not benefit directly from taking part in this research. However, the knowledge gained from this study may contribute to our understanding of the most commonly occurring injuries in sport. By identifying deficits related to the nervous system and muscle functioning, future intervention programs may be put into place to reduce the risk of future hamstring injury. Additionally learning more about the interaction of fatigue and competitive anxiety on the nervous system and associated muscle properties may improve clinical prevention and intervention efforts in the athletic setting.

NEW INFORMATION THAT COULD AFFECT YOUR PARTICIPATION:
During the course of this study, we may learn new information that could be important to you. This may include information that could cause you to change your mind about participating in the study. We will notify you as soon as possible if any new information becomes available.

HOW WILL CONFIDENTIALITY BE MAINTAINED? WHO MAY KNOW THAT YOU PARTICIPATED IN THIS RESEARCH?
Participant information will be kept confidential and a code number will be assigned to your files. Any documents with identifying information (code number list) will be kept in a locked file in the Athletic Training Laboratory. When the study is completed and the data have been analyzed, the list will be destroyed. Data will be kept secure in electronic storage formats and saved indefinitely. Your name will not be used in any report. We will make every effort to keep all research records that identify you confidential to the extent permitted by law. The findings of this research may be presented or published. If this happens, no information that gives your name or other details will be shared.
The confidentiality of your records will be protected to the extent permitted by law. Your research records may be viewed by the University of Delaware Institutional Review Board, which is a committee formally designated to approve, monitor, and review biomedical and behavioral research involving humans. Records relating to this research will be kept for at least three years after the research study has been completed.

WILL THERE BE ANY COSTS TO YOU FOR PARTICIPATING IN THIS RESEARCH?
There are no costs associated with participating in this study.

WILL YOU RECEIVE ANY COMPENSATION FOR PARTICIPATION?
You will receive no payment for participating in this research study. If your course instructor provides extra credit for research participation, the PI can verify your participation if necessary.

DO YOU HAVE TO TAKE PART IN THIS STUDY?
Taking part in this research study is entirely voluntary. You do not have to participate in this research. If you choose to take part, you have the right to stop at any time. If you decide not to participate or if you decide to stop taking part in the research at a later date, there will be no penalty or loss of benefits to which you are otherwise entitled. Your decision to stop participation, or not to

participate, will not influence current or future relationships with the University of Delaware. As a student, if you decide not to take part in this research, your choice will have no effect on your academic status or your grade in the class. If, at any time, you decide to end your participation in this research study please inform our research team by telling the investigators in person or via the e-mail addresses listed below. Failure to complete any portion of this research study will lead to participant termination.

WHO SHOULD YOU CALL IF YOU HAVE QUESTIONS OR CONCERNS?
If you have any questions about this study, please contact the Principal Investigator, Andrea Di Trani at (302) 831-8222 or aditrani@udel.edu, or C. Buz Swanik (advisor) at (302) 831-2306 or cswanik@udel.edu.
If you have any questions or concerns about your rights as a research participant, you may contact the University of Delaware Institutional Review Board at hsrb-research@udel.edu or (302) 831-2137.

Your signature on this form means that: 1) you are at least 18 years old; 2) you have read and understand the information given in this form; 3) you have asked any questions you have about the research and those questions have been answered to your satisfaction; 4) you accept the terms in the form and volunteer to participate in the study. You will be given a copy of this form to keep.

_____   _____
_____
Printed Name of Participant   Signature of Participant   Date

_____   _____ _____
Person Obtaining Consent   Person Obtaining Consent   Date
   (PRINTED NAME)   (SIGNATURE)

DATE: August 19, 2016

TO: Andrea DiTrani, MS
FROM: University of Delaware IRB

STUDY TITLE: [791703-3] Neuromechanical Factors of Hamstring Strain Injury

SUBMISSION TYPE: Continuing Review/Progress Report

ACTION: <u>Approved for Data Analysis Only</u>
APPROVAL DATE: August 19, 2016
EXPIRATION DATE: August 18, 2017
REVIEW TYPE: Expedited Review

REVIEW CATEGORY: Expedited review category (8)

Thank you for your submission of Continuing Review/Progress Report materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation.

Please remember that <u>informed consent</u> is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.

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