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ACUTE EFFECTS OF DYNAMIC STRETCHING ON FLEXIBILITY AND AGONIST-ANTAGONIST
MUSCLE ACTIVITY

A Thesis
Presented to
Eastern Washington University
Cheney, Washington

In Partial Fulfillment of the Requirements
For the Degree
Master of Science in Physical Education

By
Lance T. Beisley
Fall 2015

THESIS OF LANCE T. BEISLEY APPROVED BY

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MASTER'S THESIS

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ABSTRACT

Flexibility is an important determinant of health and important in sport performance. ADS and SPST are the methods most often used in training flexibility for sport. Although ADS appears to dominate SPST in measures of power and agility, the mechanisms are unclear. The purpose of this study was to delineate the effects of ADS on AROM and agonist-antagonist mean and peak EMG. The ADS protocol involved three sets of ten repetitions of leg kicks while in the supine position with the pelvis and contralateral limb fixed in extension. Participants moved the leg at the hip in a kicking motion to a point of mild discomfort while maintaining knee extension. Surface EMG (Telemetry DTS; Noraxon U.S.A. Inc.) was used to assess mean and peak activation of the RF and BF during the final 5 degrees of HF as well as calculate CI. Integrated Webcam (v. 6.1.7601.18208; Microsoft Corporation; 30 Hz) was used to monitor HF. Peak Motion Analysis (v. 9.0; Vicon) was used to interpolate HF to 60Hz and digitize the video record to obtain HF during the first and tenth repetition of each set. Separate 1x6 repeated measures one-way ANOVAs revealed significant differences in HF, RF_(mean), RF_(peak), and BF_(peak). HF increased at every time-point following the first repetition despite decreasing significantly from set one to set two. A within-set increase in RF_(mean) and RF_(peak) was observed although returned to baseline following each set. HF, RF_(mean), RF_(peak), BF_(mean), and BF_(peak) increased over the course of the protocol, although BF_(mean) was non-significant. No significant alterations were observed in CI. These findings support the limited association between flexibility and opposing muscle activity as well as a diminishing effect of stretching in AROM.

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Chapter 1

Introduction

Flexibility has been placed among other physical abilities as a determinant of health and overall well-being. Health professionals now include flexibility training in general exercise programs for adults (American College of Sports Medicine, 2011; Kenney, Wilmore, & Costill, 2012) in order to counteract the age-related reduction in tissue compliance (Gajdosik et al., 2005) and concomitant reduction in flexibility. Similar to other physiological abilities, targeted efforts can elicit both short- and long-term alterations in flexibility. Training that focuses on a specific type of flexibility (e.g. active, static, ballistic) is referred to as flexibility training. Thus, active flexibility training encompasses those training methods utilized by athletes and coaches to improve the active range of motion (AROM) of a given joint or set of joints.

The modes of flexibility training most prominent in sport are static passive stretching (SPST) and active dynamic stretching (ADS). SPST is characterized by a sustained stretch at the end ROM (eROM) while the individual is relaxed requiring no active effort by the participant (Dallas et al., 2014). In contrast, ADS is characterized by active involvement of one's own effort to move one or more joints through their available ROM (Fletcher & Anness, 2007). The ADS protocol employed by Fletcher & Anness (2007), for example, involved movements that mimicked the sprint cycle such as flick-backs and running high knees. Participants were required to perform these movements over 20 meters with a brief recovery between efforts. It has been demonstrated that ADS is more effective in the pre-exercise warm-up, enhancing

performance in explosive movements (Faigenbaum, Bellucci, Bernieri, Bakker, & Hoorens, 2005; Fletcher & Anness, 2007; Fletcher & Jones, 2004; Little & Williams, 2006; McMillian, Moore, Hatler, & Taylor, 2006; Moran, McGrath, Marshall, & Wallace, 2008; Yapicioglu et al., 2013). Investigations utilizing ADS have employed anywhere from 1 to 3 sets of 8-30 stretches targeting a wide range of muscle groups. Fletcher & Anness (2007) demonstrated that even a modest dosage of ADS (16 repetitions in each exercise) can elicit a significant acute improvement in sprinting ability. Conversely, it appears that SPST reduces explosiveness by altering proprioceptive function and the force-length characteristics of the muscles involved (Bacurau et al., 2009; Dallas et al., 2014; Fletcher & Jones, 2004; Little & Williams, 2006; McMillian et al., 2006; McNeal & Sands, 2003). Finding a flexibility training method that improves AROM without sacrificing the force-producing characteristics or joint stabilizing effects of the muscles involved is necessary in order to optimally prepare for athletic activities.

The impact of physical parameters such as strength, speed, endurance, and flexibility on athletic performance are well known (Lloyd & Oliver, 2014). The role of flexibility in aesthetic sports such as gymnastics and ballet is evidenced by the strong correlation between competition performance and scores on assessments of AROM (Sands & McNeal, 2014). Success in these sports requires not only a great deal of joint mobility but also proper motor control and strength/power as the athlete actively achieves challenging body positions. In sports such as artistic gymnastics, diving, and dance, the ability to actively move a limb through its available AROM is essential for proper skill execution. The magnitude (empirical value) and quality (aesthetic value) of

AROM is determined by several factors including the recruitment and sufficiency of agonist muscles, active tension and passive compliance of antagonist muscles, and the sensorimotor capabilities of the individual (Magnusson et al., 1997). As such, flexibility training that diminishes explosiveness or impairs motor control strategies would reduce performance in these sports and increase injury risk as fatigue and hypo-activation would render surrounding musculature insufficient to overcome resistive forces while facilitating proper joint articulation. Further investigation is needed in order to determine the effectiveness of ADS on AROM and the response of agonist and antagonist musculature. In order to better understand the implications of active flexibility training for enhancing AROM, its effects on muscle activity and AROM need to be clearly delineated.

Three mechanisms are thought to determine AROM. The passive properties of the human musculotendinous unit (MTU), neurogenic control of joint movement, and individual stretch tolerance are all involved in dictating flexibility (Magnusson et al., 1997). Receiving the greatest amount of attention is the passive mechanism. Researchers have attempted to explain the transient changes in ROM through alterations in MTU stiffness alone. The theory regarding neurogenic constraint as it relates to changes in antagonist muscle activation seems promising, although heavily characterized by contradictions and paradoxical findings. Finally, data describing the sensory theory and its influence on flexibility are sparse and inconclusive. Rather than a single mechanism explaining changes in ROM, it is more likely that AROM is determined

by a combination of several factors. Nonetheless, further investigation is needed in order to clarify the mechanisms driving alterations in AROM.

The simultaneous activation of two muscles that functionally oppose one another is known as co-activation (Ervilha, Graven-Nielsen, & Duarte, 2012; Kato, Vieillevoye, Balestra, Gulssard, & Duchateau, 2010; Quinzi, Camomilla, Felici, Mario, Sbriccoli, 2015). Co-Activation has been observed in several movements such as the round-house kick in karate (Quinzi et al., 2015) and the drop jump (Arai, Ishikawa, & Ito, 2013). Authors speculate that co-activation assists in proper joint articulation and serves to take up slack in the MTU prior to forceful loading. The presence of co-activation is of concern to athletes and coaches as these functionally opposing forces have an impact on motor ability and AROM. Considering the relationship between net torque and joint movement, alterations in the active forces produced by surrounding musculature likely result in changes in movement range. In theory, increasing activation of agonist muscles while reducing antagonist muscle activation may have an acute effect on the balance of forces surrounding the joint, thus altering AROM.

Purpose of the Study

Due to its importance in physical performance, flexibility is a highly prized quality in many popular sports. While ADS has been demonstrated to increase subsequent performance of speed- and power-based tasks, there is a lack of knowledge regarding the effects of ADS on AROM and, more specifically, co-activation. In order to determine the best strategy for optimizing AROM, practitioners must have an understanding of how these factors determine AROM so that targeted attempts can be made to improve

performance. Therefore, the purpose of this study was to investigate the effects of ADS on AROM and co-contraction of the hip musculature as described by the rectus femoris and biceps femoris.

Null Hypothesis

H0: There will be no significant difference in peak or mean muscle activation, hip flexion eROM, or co-activation index (CI) occurring across 3 sets of 10 repetitions of a flexibility protocol involving ADS in hip flexion.

Delimitations

This study protocol was implemented on a sample of convenience recruited from Eastern Washington University in Cheney, WA. The sample was limited to physically active participants. This selection criteria was used to prevent the application of the findings of this study to sedentary individuals.

Studies that have utilized ADS of the lower extremity have included large dynamic movements in order to target a variety of muscle groups related to sprinting or jumping tasks (Faigenbaum et al., 2005; Fletcher & Anness, 2007; Fletcher & Jones, 2004; Little & Williams, 2006; McMillian et al., 2006; Moran et al., 2008; Yapicioglu et al., 2013). In the present study, ADS was confined to leg kicks, accomplished through controlled flexion of the hip joint while lying in a supine position with both knees kept in extension. This movement was selected for this study based on its high specificity and simplicity. Narrowing the task to a specific joint afforded a high amount of certainty in the muscle recruited and structures undergoing mobilization.

Although several muscles are involved in hip flexion (Levangie & Norkin, 2001), this study was designed to describe only those changes in co-activation of the RF and BF muscles. RF and BF have been used in previous research (Herda, Cramer, Ryan, McHugh, & Stout, 2008) to describe changes in muscle activation incurred from stretching. The superficial locations of the RF and BF allowed a high amount of accuracy when interpreting the electromyography (EMG) amplitude readings.

Limitations

Subjects may have varied in their effort during the stretching protocol. Between-subject variations in stretch perception may have introduced variations in the effectiveness of the stretching protocol. Movement in the frontal and transverse planes was not measured.

Assumptions

It was assumed that participants followed the instructions given by test administrators and were compliant to the protocol (i.e. pelvis remained in contact with the floor and strenuous activity was avoided prior to testing). It was assumed that alterations in the location of motor end plates relative to electrode placement did not occur during the testing protocol. There was also an assumption that movement in the frontal and transverse planes either did not occur or remained consistent within each participant.

Significance of the Study

As the need for flexibility training grows in recognition among athletes and the general population, so too does the need for understanding the mechanisms associated

with improved AROM. Clarifying the effects of ADS on AROM and neuromuscular behavior will improve understanding of the underlying physiological effects of this training method. Further understanding of the contribution of neuromuscular factors to AROM will offer critical information for developing targeted flexibility training programs.

Summary

The need is growing for improved flexibility training techniques. The importance of flexibility in athletes as well as the general public is well documented. Characteristics of subjectively scored sports such as artistic gymnastics and diving introduce a unique aspect of flexibility which requires further understanding. In this chapter, a framework was developed to describe the need for the study, the purpose was explained, null hypothesis stated, delimitations described, limitations and assumptions identified, and significance of the study outlined.

Chapter 2

Review of Literature

This study was designed to investigate the effects of repeated dynamic stretches in hip flexion on agonist and antagonist muscle activation as described by the rectus femoris and biceps femoris. To lay the foundation for this study, an overview of the soft tissue and neurological features which may restrict joint ROM in healthy individuals will be presented. This will be followed by a discussion of the various methodologies used to enhance ROM and the means by which these methodologies affect the modifiable components of acute joint ROM. Finally, a brief review of the anatomy and kinesiology related to sagittal plane motion of the coxofemoral (hip) joint will be presented. These topics will provide the basis for understanding the relevance of the present study and hypotheses guiding the investigation.

Determinants of Flexibility

The human MTU is a complex network of contractile, connective, and neural tissues. The connective tissue web provides support for the contractile muscle fibers, passively facilitating the coordination of active and skeletal tissues to allow movement; the quantity and quality of which continually regulated by the neurological system. Since the contractile activity observed during stretching is mediated by both reflexive and voluntary mechanisms, these facets are collectively referred to as the “active” component (Borg & Caulfield, 1980; Taylor, Dalton, Seaber, & Garret, 1990). The complexity of the musculoskeletal system limits generalizations regarding optimal tissue compliance, length-tension characteristics, and neurophysiological function. However,

because all forms of stretching aim to mediate alterations to either the active component, passive component, or both, the effects of each component on flexibility warrant understanding.

Passive Determinants of Flexibility

Studies have consistently demonstrated that passive MTU lengthening, by moving a joint through a range opposite that of the muscle being stretched, results in a concomitant increase in passive resistive forces in the stretched MTU. By deforming the muscular, tendinous, and periarticular soft tissues of the MTU, a curvilinear increase in passive resistive forces is observed which rises slowly at relatively lax joint angles and then sharply increases as the joint nears its eROM (Duong, Low, Moseley, Lee, & Herbert, 2001; Gajdosik, 2006; Gajdosik et al., 2005; Gajdosik, Lentz, McFarley, Meyer, & Riggan 2006; Hufschmidt & Mauritz, 1985; Klinge, Magnusson, Simonsen, Aagaard, Klausen, & Kjaer, 1997; Magnusson, 1998; Magnusson et al., 1997; Magnusson, Aagaard, & Nielson, 2000; Magnusson, Simonsen, Aagaard, Gleim et al., 1995; Magnusson, Simonsen, Aagaard, & Kjaer, 1996; Magnusson, Simonsen, Aagaard, Moritz, & Kjaer, 1995; Magnusson, Simonsen, Dyhre-Poulsen, et al., 1996; McHugh, Magnusson, Gleim, & Nicholas, 1992; McNair, Dombroski, Hewson, & Stanley, 2001; McNair, Hewson, Dombroski, & Stanley, 2002; Nordez, McNair, Casari, & Cornu, 2010; Robi, Jakob, Matevz, & Matjaz, 2013; Ryan, Herda, Costa, Walter, & Cramer, 2012; Singer, Dunne, Singer, & Allison, 2003; Taylor, et al., 1990). These forces are thought to be the result of elastic energy retained during tissue lengthening. While the joint position is

maintained, tissues of the MTU continue to deform at a diminishing rate, characterized by a reduction in passive tension over time.

Extracellular matrix. The connective tissue framework that supports the contractile elements of muscle is vital for optimal movement. This meshwork, comprised of longitudinal fibers as well as a supportive lattice, binds myocytes into bundles and serves to align individual muscle fibers as contraction occurs (Borg & Caulfield, 1980). This extracellular matrix is thought to contribute to stretch resistance (Borg & Caulfield, 1980; Magnusson, Simonsen, Aagaard et al., 1996; Purslow, 1989; Rowe, 1981). The collagen ultrastructure is comprised of three levels (Borg & Caulfield, 1980; Purslow, 1989; Rowe, 1981). The endomysium is an elaborate lattice of in-series fibers associated with individual contractile units. It maintains proper alignment of the individual fibers that are grouped into units called fascicles. The perimysium, on the other hand, spirals around groups of fascicles to create bundles. Surrounding the entire muscle is a collagenous sheath called the epimysium. The epimysium supports the collective function of the contractile fibers by grouping them into single muscular units.

MTU lengthening results in a modest increase in passive resistive forces (Purslow, 1989). This characteristic is thought to originate in the perimysium. At resting length, fibers of the perimysium are crimped, or folded (Purslow, 1989, Robi et al., 2013). The tensile forces experienced as the MTU elongates cause the fibers of the perimysium to de-crimp, or straighten. Once the fibers of the perimysium approach maximal alignment, however, the collagenous fibers are no longer suited to absorb

forces through elastic de-crimping and an extreme rise in passive resistive forces occurs (Purslow, 1989).

Series vs. parallel elastic. It is generally held that the functional MTU is comprised of an active contractile element, series elastic components (SEC) responsible for contractile force transmission, and parallel elastic components (PEC) which distribute forces evenly throughout the MTU (Borg & Caulfield, 1980; Magnusson, Simonsen, Aagaard et al., 1996; Rowe, 1981; Williams & Goldspink, 1984). Resistance to stretch at shorter MTU lengths is thought to be from forces associated with deformation of in-series tissues (Lindstedt, LaStayo, & Reich, 2001; Wang, McCarter, Wright, Beverly, & Ramirez-Mitchell, 1993). Evidence suggests that only at extreme lengths do PEC contribute to stretch resistance (Purslow, 1989). The primary SEC thought to be involved in the storage of elastic energy during MTU lengthening is a protein molecule within the endosarcomeric matrix called titin (or connectin). As the anchor between the z-disc and myosin filament of the sarcomere, it is likely that the elastic behavior of titin is necessary for maintaining proper sarcomere alignment in relaxed muscle (Lindstedt et al., 2001), preserving the ability of the muscle to generate active force at various lengths. It is believed that titin is of primary importance in the tissue response observed during MTU lengthening (Gajdosik et al., 2005; Gajdosik, 2006; Gajdosik & Lentz et al., 2006; Lindstedt et al., 2001; Weppeler & Magnusson, 2010; Singer et al., 2003; Wang et al., 1993).

Load-Response of Soft Tissues

The load-response seen in skeletal muscle tissue is said to be the result of both viscous and elastic, or “viscoelastic” (VE) elements (Gajdosik et al., 2005; Magnusson, 1998; McNair et al., 2002; Nordez et al., 2010; Robi et al., 2013; Ryan et al., 2012; Singer et al., 2003; Taylor, et al., 1990). Elasticity is a force-dependent characteristic that describes the resultant change in tension as a tensile force is applied to a tissue. This elasticity allows the deformed structures to return to their resting form when unloaded, independent of rate or duration of deformation. Viscosity, however, describes the time- and rate-dependent release of tensile strain. This time-dependent reduction in stiffness as a tissue is held in a constant position is known as viscoelastic stress relaxation (VSR; Magnusson, 1998). VE creep, on the other hand, refers to the change in tissue compliance (and associated change in ROM) in response to a constantly held torque (Ryan, et al., 2012).

Static vs. cyclic. Taylor et al. (1990) created the original model of stress relaxation using intact rabbit MTU. Their quantitative model of tissue response to tensile loading has since been confirmed in vivo (Gajdosik et al., 2005; Gajdosik, 2006; Gajdosik & Lentz et al., 2006; Magnusson, Simonsen, Aagaard, Gleim et al., 1995; Magnusson, Simonsen, Aagaard, Moritz et al., 1995; Magnusson et al., 1997; Magnusson, 1998; McNair et al., 2002; Nordez et al., 2010; Singer et al., 2003). Force- and time-dependent load-responses of the viscoelastic MTU have been demonstrated under both static (Gajdosik & Lentz et al., 2006; Magnusson, Simonsen, Aagaard, Moritz et al., 1995; Magnusson et al., 1997; Magnusson, 1998; Nordez et al., 2010; Ryan et al.,

2012) and cyclic (Gajdosik et al., 2005; Gajdosik & Lentz et al., 2006; McNair et al., 2002; Singer et al., 2003; Taylor et al., 1990) stretch conditions. The time-courses of both static and cyclic stretching show a non-linear time-dependent deterioration of both passive tension and stiffness that diminishes in magnitude over the length of the applied stretch.

Of most importance to the present study are those studies that employed cyclic-type conditioning. Stretch rate (offered in degrees of joint motion per second) is an important metric to consider when examining cyclic, continuous stretching. McNair et al. (2002) observed greater stiffness at initial eROM in faster compared to slower stretch rates. Lack of reflexive muscle activity observed in these conditions suggests that differences seen in VSR between stretch rates is isolated to the passive properties of the tissues being stretched. Since increased time under tension before reaching maximal elongation is greater in slow- compared to fast-applied stretching force, their findings suggest that VSR can be elicited at submaximal tissue lengths (i.e. during the onset of tensile strain prior to eROM). In a comparison of fast and slow stretch rates, McNair et al. (2002) also demonstrated that although greater stiffness was observed initially in the fast-applied stretch condition, stiffness was found to be equal in both conditions after two minutes of cyclic stretching. These findings suggest that total time under tension is more crucial in eliciting VSR than the stretch-rate or number of cycles performed.

Mechanisms of VSR. Two primary mechanisms are thought to be in effect and explain the occurrence of VSR. Alterations in autogenic contractile activity is one mechanism explored. Given that studies examining VSR in human MTU fail to observe

significant amounts of muscle activity during stretch (Condon & Hutton, 1987; Klinge et al., 1997; Magnusson, Simonsen, Dyhre-Poulsen, et al., 1996), alterations in muscle activity are unlikely to explain the VSR seen in these studies. Mechanical properties of various soft tissues in series with the muscles being stretched are more likely to dictate passive stiffness and VE characteristics.

Stretch Tolerance

Weppeler and Magnusson (2010) reviewed the current state of knowledge regarding the response of MTU to tensile loading. In their review, previous work (Magnusson et al., 1997; Magnusson, 1998) was cited that they believed indicated another mechanism that explains VSR (Weppeler & Magnusson, 2010). Magnusson et al. (1997) compared the VE behavior of “tight” subjects to those with “normal” flexibility. Based on what is understood regarding the positive relationship between tissue elasticity and extensibility, one would expect to observe a decrease in passive resistive forces as greater eROM is achieved as well as increased MTU stiffness in “tight” compared to normal subjects. Despite an increase in maximal ROM, however, Magnusson et al. (1997) observed that “tight” subjects were able to tolerate less resistive forces at eROM compared to normal subjects. These findings suggest that the two groups differed in their tolerance to stretch rather than MTU stiffness. Further evidence in support of the sensory theory was discovered by Magnusson (1998) when it was observed that an increase in passive ROM was accompanied by an increase in MTU stiffness. Although lacking a large degree of evidence, these findings suggest that a psychological determinant may exist to explain differences in VSR in human subjects.

Neurological Determinants of Flexibility

Muscle activity, of either volitional or reflexive origin, is an important component to consider in flexibility training as it may limit AROM while also providing the nervous system the means to prevent extreme ranges of movement. Although the contractile activity of the muscular system may limit ROM, it may be necessary for joint stability and distributing forces appropriately throughout the skeletal system. Thus, understanding the means by which the nervous system moderates human movement is central when creating effective flexibility training strategies.

Muscle spindles. Muscle Spindles are the primary means of detecting changes in muscle length. The positioning of muscle spindles parallel to extrafusal muscle fibers allows them to undergo changes in length in synchrony with the fibers in which they are embedded (Golpayegani & Jafari, 2009). Sensory feedback provided by muscle spindles is coded as either static or dynamic. Nuclear bag fibers, positioned midway between each insertion, are responsible for detecting dynamic changes in muscle length (Alter, 2004). These fibers are innervated by low-threshold, fast-adapting, afferent fibers that provide velocity-specific feedback. When the nuclear bag fiber is rapidly lengthened, afferent impulses stimulate further α -motoneuron excitation and muscular contraction. This reflex pathway is known as the stretch reflex. This spinal reflex results in the excitation of the muscle from which the stretch was detected and occurs relatively quickly, within about 30 ms of the onset of stretch (Manning, McDonald, Murnaghan, & Bawa, 2013).

Each nuclear bag fiber is anchored between two nuclear chain fibers. These fibers, innervated by slow-adapting afferent nerve fibers, provide continually feedback on muscle length. Innervation of striated intrafusal contractile fibers located at both ends of the chain fibers allows higher brain centers to modify velocity- and length-specific sensitivity via a process known as gamma bias. As the MTU shortens, intrafusal fiber contraction takes up slack in the chain fibers in order to preserve their ability to detect dynamic changes in muscle length. Close coordination between intrafusal and extrafusal contractile fibers, such as that seen in more typical movements (e.g. walking) is characterized by a “quiet” muscle spindle (Hultborn, 1972). More novel movements, however, can result in hyper-activation of muscle spindle afferents due to reduced coordination between intra- and extrafusal contractile fibers. Because muscle spindle afferents terminate at the cerebellum without reaching the sensory cortex (Solomonow & Krogsgaard, 2001), stretch sensitivity and adaptation to that sensitivity is beyond voluntary control. Thus, hyper-activity of afferent input on the α -motoneuron excitation pathway cannot be consciously moderated and can impair proper motor control during novel movement patterns.

Golgi tendon organs. Golgi tendon organs (GTO), embedded in the aponeuroses of muscle-tendon junctions in series with contractile filaments, detect changes in tensile strain within the muscle. During intense muscular contraction, extreme tensile strain activates high-threshold GTO afferents that inhibit excitatory motoneuron cells of the same muscle. As the activation of the contracting muscle is inhibited, the tensile strain is reduced, consequently diminishing afferent discharge from the GTO. This feedback

system is known as autogenic inhibition. In the past, it was speculated that changes in flexibility elicited from static passive stretching were related to autogenic inhibition (Alter, 2004). Current evidence (Mitchell et al., 2009), however, challenges the presence of autogenic inhibition as it relates to acute changes in flexibility. It is currently held that GTOs are selectively sensitive to tension generated by active muscular contraction and passive stretch likely fails to generate sufficient strain (or the correct type of strain) to facilitate autogenic inhibition (Fowles, Sale, & MacDougall, 2000).

Articular mechanoreceptors. Located in joint soft tissues are several nerve bodies that detect strain and compressive forces generated by the fine articulations that occur during joint movement and loading. Pacinian corpuscles are low-threshold, fast-adapting receptors that code dynamic mechanical changes within the joint. The high rate at which these receptors adapt to mechanical stimulation makes them less ideal for static sensitivity compared to dynamic (Solomonow & Krogsgaard, 2001). Ruffini nerve endings, on the other hand, provide constant position feedback due to their low-threshold, slow adapting sensitivity (Carli, Farabollini, Fontani, & Meucci, 1979; Solomonow & Krogsgaard, 2001). Golgi receptors are present not only in aponeurosis of MTU but also in menisci and joint ligaments (Solomonow & Krogsgaard, 2001). Similar to those found in the aponeurosis of MTU, sensory coding triggered by these high-threshold, slow-adapting nerve endings is generated only under conditions of extreme mechanical loading (Solomonow & Krogsgaard, 2001). Bare nerve endings, although present in joint ligaments, provide exclusively nociceptive, or pain-related, feedback (Solomonow & Krogsgaard, 2001).

Neurological Response to Stretching

It has been demonstrated that passive stretch, under voluntary relaxation, fails to elicit muscle activity greater than levels observed at rest (Condon & Hutton, 1987; Klinge et al., 1997; Magnusson, Simonsen, Dyhre-Poulsen, et al., 1996). The lack of notable muscle contraction during this stretching method allows soft tissues to elongate during stretch, unimpeded by contractile resistive forces. Much of what is known regarding the viscoelastic properties of human MTU is based on conditions of either volitional relaxation or denervated animal models. In locomotion, however, movement is accomplished via the excitation-inhibition of a number of neural pathways regulating muscular contraction. This being the case, complete relaxation is neither attainable nor desired as muscle contraction is a critical component in facilitating proper joint motion. On the other hand, it is believed that excessive muscle contraction may limit ROM by reducing compliance of in-series tissues. Gajdosik (2006) investigated the effect of low-level plantarflexor contraction on viscoelastic torque-deformation compared to control participants in whom negligible muscle activity was detected. Their findings contradicted the commonly held theory that contractile activity impedes alterations in flexibility, specifically VSR in human MTU. Thus, the role of contractile activity in flexibility training remains to be clearly defined.

Reciprocal inhibition. It was initially thought that voluntary agonist contraction would facilitate greater muscle compliance due to a mechanism known as reciprocal inhibition. As Sherrington (1947) described, reciprocal inhibition is a simple reflex in which agonist muscle excitation consequentially increases stretch receptor afferent

discharge, inhibiting antagonist α -motoneuron excitability via the Ia-inhibitory interneuron pathway. Although this model of excitation-inhibition is still evident in the stretch reflex in vivo (Manning et al., 2013), a more complex model has since been defined that limits use of these Sherringtonian concepts.

Evidence of a more complex system of excitation-inhibition can be seen in stretch conditions utilizing agonist contraction (Azevedo, Melo, Correa, & Chalmers, 2011; Condon & Hutton, 1987; Mitchell et al., 2009; Moore & Hutton, 1980; Osternig, Robertson, Troxel, & Hansen, 1987; Osternig, Robertson, Troxel, & Hansen, 1990; Reis et al., 2013). Based on the classical understanding of reciprocal inhibition, one would expect antagonist muscle activity to subside during agonist-assisted stretching. Paradoxically, however, it has been demonstrated that PNF stretching methods utilizing agonist contraction also facilitate greater excitation in antagonist musculature during stretch (Condon & Hutton, 1987; Moore & Hutton, 1980; Osternig et al., 1987; Osternig et al., 1990). Etnyre & Abraham (1986) attributed these paradoxical findings to limitations related to the use of surface electrodes. They submitted that the co-activation observed in studies utilizing surface EMG may be the result of electrode cross-talk. In this regard, they found that reciprocal inhibition was more evident when assessed using indwelling electrodes. On the contrary, Mitchell et al. (2009) found no such evidence when sampling stretching techniques with both surface and indwelling electrodes. Since interelectrode cross-talk is related to electrode proximity (Mitchell et al., 2009) one might expect the likelihood of electrode cross-talk error to be reduced

when located on the skin compared to indwelling electrodes placed several centimeters below the skin surface.

Co-Activation. The simultaneous activation of two muscle groups that functionally oppose one another is known as co-activation (Ervilha et al., 2012; Quinzi et al., 2015). As mentioned previously, co-activation likely serves a protective role by ensuring proper joint articulation. Arai et al. (2013) suggests that co-activation as it relates to movements utilizing stretch shortening cycles, aids in tendon utilization by reducing slack in the MTU prior to subsequent loading. Evidence of co-activation during the pre-contact phase in drop jumps has been confirmed and demonstrated to increase as drop-height increases (Arai et al., 2013). Furthermore, co-activation appears to be a learned trait specific to task familiarity and expertise. Quinzi et al. (2015) observed differences in co-activation between younger and older karate practitioners during a kicking task, although it is unclear whether these changes are the result of learning or the aging process. As mentioned previously, AROM is greatly influenced by both the force of agonists aiding the stretching movement as well as the antagonists providing resistive forces. Therefore, the balance of agonist and antagonist contractile activity and resultant net torque about the joint likely influence AROM. Studies have used CI (Arai et al., 2013; Quinzi et al., 2015) and co-activation ratio (Kato et al., 2010) to describe this agonist-antagonist relationship. Arai et al. (2013) calculated CI by dividing agonist muscle activity by that recorded in the antagonist muscle. If the relationship between agonist and antagonist muscle activity presents a consideration for flexibility,

experimental evidence of an alteration in CI may provide a better understanding of the effects of active flexibility training on AROM.

During the forceful extension phase of round-house kicks, Quinzi et al. (2015) reported significantly greater antagonist (BF) muscle activity in experienced karate practitioners compared to less experienced. This increased antagonist activation prior to impact contributed to greater CI. This observation in more experienced karate practitioners suggests that this pre-activation is a skill that is learned through repetition. Quinzi et al. (2015) proposed that increased CI may serve to protect the knee from forces experienced on impact by actively stabilizing the joint. The stabilization theory has been adopted by many authors who have observed similar findings during articular manipulation (Azar, Kallakuri, Chen, & Cavanaugh, 2011; Dhaher, Tsoumanis, & Rymer, 2003; Grigg & Hoffman, 1996; Kang, Choi & Pickar, 2002; Khalsa, Hoffman & Grigg, 1996; Pagani, Willwacher, Kleis, & Bruggemann, 2013). An alternative theory to the protection-related alteration in CI, however, may be related to the performance of round-house kicks in uncontrolled settings. In other words, rather than activating antagonist musculature to protect the knee, this activation may be a pre-contraction of the musculature that, upon completion of the kick, is used to reset the leg in preparation for a subsequent movement.

Co-Activation of knee flexors and extensors has been observed in patients suffering from joint instability related to osteoarthritis (Pagani et al., 2013). Additionally, investigations applying mechanical load to knee (Dhaher et al., 2003; Grigg & Hoffman, 1996; Khalsa et al., 1996) and vertebral (Azar et al., 2011; Kang et al., 2002) joint

capsules report elevated excitation of surrounding musculature. It is widely accepted that such excitation serves as a protective mechanism related to force distribution and articular stabilization. These perturbations activate low-threshold, slowly adapting mechanoreceptors within the joint capsule that, in an effort to stabilize the joint and reduce excessive compressive loads, activate surrounding musculature. Since it has been demonstrated that hip joint movement results in mechanical loading of hip joint capsule ligaments (Fuss & Bacher, 1991; Martin et al., 2008; Wingstrand & Wingstrand, 1997), it is reasonable to postulate that the paradoxical excitation of antagonist musculature during agonist-assisted stretching is at least partly explained by afferent discharge related to mechanical stress experienced within the joint during movement.

Regardless of the source of the antagonist muscle activation, its presence holds implications for this study. The increased CI observed during a kicking task (Quinzi et al., 2015) suggests that, even when attempting to achieve maximal ROM, antagonist musculature is activated. What remains unclear is both the occurrence and magnitude of alteration in CI during the course of repetitive kicking and if this alteration affects AROM by either modifying active resistive forces or involvement of agonist musculature.

Pre-Performance Warm-Up

SPST as part of a pre-exercise warm-up routine has been commonplace with the belief that its inclusion increases performance and reduces injury risk (Behm & Chaouachi, 2011; Little & Williams, 2006). Solid evidence that supports the use of SPST in the pre-exercise warm-up for these purposes is lacking. In its place, coaches have begun implementing ADS, characterized by active involvement of one's own effort to

move one or more joints through their available ROM (Fletcher & Anness, 2007), as part of the pre-exercise warm-up routine.

In an attempt to identify the optimal stretching method to enhance performance, authors have compared SPST and ADS protocols on tasks related to sport performance (Bacurau et al., 2009; Dallas et al., 2014; Faigenbaum et al., 2005; Fletcher & Anness, 2007; Fletcher & Jones, 2004; Han, Lee, & Cho, 2011; Little & Williams, 2006; McMillian et al., 2006; Moran, 2008; Yapicioglu et al., 2013). These investigations have confirmed the superiority of ADS over SPST before tests of explosive strength and speed (Faigenbaum et al., 2005; Fletcher & Anness, 2007; Fletcher & Jones, 2004; Little & Williams, 2006; McMillian et al., 2006; Moran, 2008; Yapicioglu et al., 2013) while also demonstrating the performance-inhibiting effects of SPST compared to control conditions in which no stretching was used (Bacurau et al., 2009; Dallas et al., 2014; Fletcher & Jones, 2004; Little & Williams, 2006; McMillian et al., 2006). Although two studies (Little & Williams, 2006; McMillian et al., 2006) offered contradictory findings regarding performance enhancement following SPST, the large number of tests demonstrating either a negligible or detrimental effect of SPST contraindicate its use prior to athletic type activities.

Stretching Methods

Static stretching. It has been demonstrated in highly controlled settings that SPST affects both mechanical factors through increased compliance of in-series components as well as neuromuscular factors through the inhibition of muscular activation during maximal voluntary contractions (Fowles et al., 2000; Herda, Cramer,

Ryan, McHugh, & Stout, 2008). It has been speculated that the diminished neuromuscular activity observed following SPST may be due in part to acute MTU length changes, likely culminating in altered proprioceptive feedback. Evidence, however, suggests that this “stretching-induced force deficit” (Herda et al., 2008, pp. 809) may persist long after normal neural activity is restored (Fowles et al., 2000) and may even be present when no alterations in muscle activity are observed (Yapicioglu et al., 2013). This being the case, the lingering deficit in force-generating capacity, observed particularly at joint angles at which the MTU is shortened (Herda et al., 2008), is likely due to increased tissue compliance. As elongation of in-series tissue occurs, the area of cross-linkage between actin and myosin is reduced at shorter muscle lengths, placing the muscle fascicles in a less optimal range of the force-length curve.

Dynamic stretching. In light of the detrimental effects of SPST immediately prior to dynamic activity, ADS has been adopted by many coaches and athletes and implemented to a greater degree in the pre-exercise warm-up routine. Research has demonstrated its superiority to SPST when implemented prior to speed (Fletcher & Jones, 2004; Moran, 2008; Siatras, Papadopoulos, Mameletzi, Gerodimos, & Kellis, 2003), power (Faigenbaum et al., 2005; McMillian et al., 2006) and agility tasks (Faigenbaum et al., 2005; Little & Williams, 2006; McMillian, et al., 2006). Rather than inducing a force deficit as observed with SPST, the active neuromuscular processes of ADS seem to facilitate improved performance in high-speed motor tasks. Hypotheses explaining the increased performance observed from ADS suggest that the enhancement of motor capacity may stem from 1) facilitated motor control through the

rehearsing of movement patterns, 2) increased peripheral blood flow and metabolic rate driven by the active nature of ADS, or 3) elevated body temperature, which may promote faster signal transmission (Herda et al., 2008; Little & Williams, 2006; McMillian et al., 2006).

It is important to recognize the distinction between ADS and ballistic stretching. Although active in nature, ballistic stretching is characterized by “oscillating” (Wallmann, Christensen, Perry, & Hoover, 2012, pp. 542) or rapid “bouncing” (Jaggers et al., 2008, pp. 1846; Mahieu et al., 2007, pp. 494) at eROM for 30-100 seconds. Ballistic stretching programs appear to have negligible effects on passive resistive torque (Mahieu et al., 2007), sprinting performance (Wallmann et al., 2012), and vertical jump height (Jaggers et al., 2008).

Hip Anatomy

The hip, or coxofemoral joint, is a diarthrodial ball-and-socket joint connecting the femoral head to the acetabulum of the pelvis. While strong capsular ligaments and a relatively large amount of bony congruence in its articulations contribute to passive stability, surrounding musculature provides additional stability through a wide range of joint positions. Its main functions include maintaining upright posture and ambulation (Hewitt, Glisson, Guilak, & Vail, 2002), although it is also suited for a range of planar and rotational articulations which allow for more dynamic movements such as those seen in sport (Martin et al., 2008). The iliofemoral ligament, the pubofemoral ligament, and the ischiofemoral ligament contribute to the passive stability of the hip. The position of these ligaments allows them to prevent joint distraction in nearly all physiological

positions (Fuss & Bacher, 1991). Similar to that of the glenohumeral joint (Habermeyer, Schuller, & Wiedemann, 1992), atmospheric pressure also plays a role in coxofemoral joint stability (Prietzel et al., 2014), although to a much greater extent in the hip than what has been observed in the glenohumeral joint. From the vacuum created by the acetabular fossa, negative intra-articular pressure adds to those forces acting distal to proximal, preventing coxofemoral distraction or dislocation (Levangie & Norkin, 2001). According to findings by Prietzel et al. (2014), this pressure gradient forms a passive stabilizing force of roughly 200 N. Since the characteristics of this gradient depend on the size and shape of the femoral head (Prietzel et al., 2014), the stabilizing force of the acetabular fossa vacuum varies between individuals. Thus, some may be predisposed to coxofemoral dislocation, although occurrence of such an injury is rare.

Hip flexion is accomplished primarily by the iliacus, psoas major, tensor fascia lata, sartorius, and rectus femoris (Levangie & Norkin, 2001). Flexion of the hip results in the lengthening of the muscles lying on the posterior aspect of the thigh. These include the semimembranosus, semitendinosus, and biceps femoris (collectively the hamstrings) and gluteus maximus. When the knee is extended, the three muscles spanning both the hip and knee joints (semimembranosus, semitendinosus, and long head of the biceps femoris) are placed in a pre-lengthened position. For this reason, these three muscles of the hamstring group reach their maximal functional length prior to the gluteus maximus as the hip is moved into flexion.

Hip Motion in Sport

Each sport has its own set of factors that determine overall success (Farana & Vaverka, 2012). The optimization of these foundational factors through training results in improved performance. For example, one of the foundational factors among those that determine performance in artistic gymnastics is skill technique (Farana & Vaverka, 2012). The extreme body positions demanded by skills in artistic gymnastics requires a large degree of AROM (Meylan & Cronin, 2014), thus making AROM a foundational factor in artistic gymnastic performance. Greater AROM leads to more desirable technique and thus better scores in competition. Hip motion specifically has been examined in gymnastics (Heinen, Vinken, & Velentzas, 2012; Mkaouer, Jemni, Amara, Chaaben, & Tabka, 2012) as well as sprinting (Ansari, Paul, & Sharma, 2012) and soccer kicking (Alcock, Gilleard, Hunter, Baker, & Brown, 2012; Manolopoulos, Papadopoulos, & Kellis, 2006; Marques-Bruna, Lees, & Grimshaw, 2008; Shan & Westerhoff, 2005). Greater magnitude of hip flexion motion in sprinting has been associated with increased positive ground reaction forces (Ansari et al., 2012). Ansari et al. (2012) suggested that an increase in ground reaction forces would directly increase sprinting velocity. Furthermore, Shan and Westerhoff (2005) observed greater hip flexion and extension ROM in the kicking mechanics of more skilled soccer players compared to less skilled players. These findings suggest an association between hip flexion AROM and performance.

Summary

It appears that some combination of passive, active, and psychological components dictate movement in humans. Movement of a joint in a singular direction introduces strain to antagonistic tissues. The passive resistive forces generated by antagonist MTU stiffness must be overcome at least in part by active involvement of agonist musculature. The impact of agonist contraction on changes in antagonist MTU stiffness is not clearly defined nor understood. The superiority of active dynamic stretching compared to passive static stretch is evident in the performance of sport-related tasks. Although not clearly identified, it is likely that the active neuromuscular involvement that accompanies ADS offers a unique performance-enhancing benefit. In order to better understand the implications of active flexibility training for enhancing AROM, its effects on muscle activity and AROM need to be clearly delineated. This chapter reviewed the current literature on the acute effects of flexibility training and the impact of various methods of training on the passive and active determinants of flexibility.

Chapter 3

Methods

This study assessed the acute effects of repeated dynamic hip flexion exercise (achieved via supine single leg kicking) on hip flexion AROM and muscle activity as assessed by the EMG amplitude of agonist and antagonist muscles. This chapter will outline characteristics of the sample that participated, instrumentation that was used, experimental procedures that were employed, and statistical analyses that were performed.

Participants

A convenience sample of male and female college-aged physically active participants were recruited for this study. Based on an effect size estimated to be moderate, a sample size estimator (Friendly, n.d.) suggested a sample of 23 subjects. However, many of the investigations reviewed in the previous chapter found significant alterations in ROM and EMG activity in samples ranging from 9 to 14 subjects (Arai et al., 2013; Condon & Hutton, 1987; Cheng & Rice, 2013; Herda et al., 2008; Herda et al., 2013; Kato et al., 2010; Quinzi et al., 2015) and as few as 5 (Etnyre & Abraham, 1986). Based on the statistically significant findings of these investigations, the sample size we expected to be necessary to provide meaningful results was 15. To be eligible for the study, participants were required to indicate participation in at least 150 minutes of moderate intensity or 75 minutes of vigorous intensity physical activity per week (i.e. the minimal amount of physical activity necessary to evoke improvements in cardiovascular fitness among adults; American College of Sports Medicine, 2011).

Potential participants were excluded if they reported a history of muscle strain to the hip flexor or extensor muscles, lower back pain at the time of participation, or any other injury or illness that would have interfered with the movement task of this research or with normal activation of the involved muscles. A questionnaire (Appendix A) was used to assess physical activity habits, experience with dynamic stretching of the hamstrings, medical issues contraindicating participation in the study, and leg dominance.

Participants were instructed to avoid strenuous exercise within 48 hours of testing (Bacurau et al., 2009; Cheng & Rice, 2013).

Instrumentation

Muscle activity of the RF and BF of the right leg was recorded (1500 Hz) using surface EMG (Telemetry DTS; Noraxon U.S.A. Inc., Scottsdale, AZ). Bipolar, silver/silver-chloride electrodes were placed on the skin surface parallel to the muscle fibers, located in accordance with recommendations from Konrad (2006). Although optimal control over knee flexion through bracing would be ideal to prohibit alterations in force-tension characteristics, a reduction in muscle activity facilitated by the use of bracing techniques has been demonstrated (Barlow, Donovan, Hart, & Hertel, 2015; Davis, Pietrosimone, Ingersoll, Pugh, & Hart, 2011; Feger, Donovan, Hart, & Hertel, 2014; Pagani et al., 2013). Therefore, no external control of knee angle was utilized. Knee flexion angle for each repetition was measured from the video record and reported. Participants who failed to maintain proper knee extension, as defined by 5% above and below the mean calculated across analyzed trials were excluded from analysis.

Hip flexion AROM was assessed from the video record from a single camera sampling at 30 Hz. The Integrated Webcam (v. 6.1.7601.18208; Microsoft Corporation, Redmond, WA) was positioned orthogonal to the sagittal plane of motion, at an approximate height corresponding to standing knee level. An interpolation process was employed on the digitized frames to provide additional data based on the characteristics of the movement occurring prior to and immediately following the interpolated frame, providing 60 Hz of kinematic data.

Experimental Procedures

Data collection occurred in the PEHR Human Performance Lab. Consent forms (Appendix B), approved by the University Institutional Review Board, were distributed to potential participants no less than 24 hours prior to data collection. Participants meeting selection criteria participated in one familiarization session followed no less than 24 hours later by a single testing session. During the familiarization session, instruction on proper leg kick execution was provided. Participants practiced the motion under the supervision of the investigator.

The testing session consisted of repetitions of leg kicks of the right leg in the supine position. Participants were required to wear shorts and remove shoes in order to allow access to the thigh area and provide a clear line of sight to the lateral malleolus of the ankle. To facilitate measurement of angular kinematics from the recorded video, reflective markers were adhered to the lateral malleolus, tibiofemoral joint line, and greater trochanter of the right leg. Prior to electrode and marker placement, participants performed a standardized 5 minute warm-up on a cycle ergometer at a

pace sufficient to elicit light sweating (Woods, Bishop, & Jones, 2007). The skin overlying the belly of each muscle was then prepared by shaving, lightly abrading, and scrubbing with isopropyl alcohol (Konrad, 2006). Once instrumented with markers and electrodes, participants then laid down on a yoga-type mat overlying a wood platform (3/4 inch plywood), resting on their elbows. A Velcro® strap anchored to the platform secured the left leg to the platform with the knee in extension. A second Velcro® strap placed across the anterior superior iliac spines bilaterally secured the pelvis to limit rotation during hip flexion and extension (Cheng & Rice, 2013; Magnusson, Simonsen, Aagaard et al., 1996). Once in this position, participants kicked the leg by flexing the right hip in a controlled manner to the point of mild discomfort, but not pain. This end-point criteria has been used in previous studies using ADS (Fletcher & Jones, 2004; Little & Williams, 2006). The velocity of sagittal plane hip motion was not controlled as this was self-determined according to individual physical abilities. Participants performed 3 sets of 10 leg kicks with 20 seconds of rest between sets (Little & Williams, 2006). This amount of stretching has been demonstrated in dynamic stretching interventions to elicit significant alterations in ROM and motor abilities (Bacurau et al., 2009; Fletcher & Anness, 2007; Fletcher & Jones, 2004; Little & Williams, 2006).

Data Analyses

The raw EMG signal were full-wave rectified and smoothed using a 50 ms root mean square (RMS) window (Konrad, 2006). The first and last trial of each set were used for analysis (R_{1-1} R_{1-10} R_{2-1} R_{2-10} R_{3-1} R_{3-10}). Peak and mean activation of each muscle occurring within the final 5° of hip flexion leading up to eROM were recorded. Video

files were imported and analyzed using Peak Motion Analysis software (v. 9.0; Vicon, Centennial, CO). Manual digitization of the reflective markers generated angular data for the hip and knee. Absolute hip flexion angle was defined from the thigh segment (tibiofemoral line to greater trochanter) relative to a horizontal reference line through the greater trochanter. Knee flexion angle was defined between the lower leg (lateral malleolus to tibiofemoral line) and the thigh segments so that greater values indicate greater knee extension.

CI was used to describe the relationship between RF (agonist) and BF (antagonist) activity during the stretching maneuvers. CI has been used to describe agonist-antagonist co-activation in the lower extremity (Ervilha et al., 2012; Kato et al., 2010; Quinzi et al., 2015). As described by Arai et al. (2013), CI was calculated by dividing the mean BF EMG by the mean RF EMG recorded in the final 5° of hip flexion.

All data were analyzed for significance using IBM SPSS Statistics for Windows, Version 21.0 (IBM Corp., Armonk, NY). Differences in peak and mean RMS EMG for each muscle across repetitions was assessed using separate 1x6 repeated-measures one-way ANOVAs (R_{1-1} R_{1-10} R_{2-1} R_{2-10} R_{3-1} R_{3-10}). Differences in CI and hip flexion eROM were also evaluated using separate 1x6 repeated-measures one-way ANOVAs. Significant F-ratios ($p \leq 0.05$) were followed up by LSD-adjusted post-hoc comparisons.

Chapter 4

Results

Participants

Seventeen participants (male $n = 9$; female $n = 8$) were gathered for this study by convenience from Eastern Washington University in Cheney, Washington. Each participant's mean knee flexion angle was calculated across all trials. During one of six analyzed kicks, one male participant allowed their knee to flex beyond 5% of their individual mean. Because the maintenance of knee extension was critical in interpreting the results of this study as they specifically relate to the musculature surrounding the hip joint, this participant's data was excluded from the statistical analyses. All participants reported right leg dominance, as indicated by which leg they prefer to kick a ball. Demographic information of the sixteen participants analyzed is displayed in Table 1.

Table 1

Participant Demographics

Characteristic	Males	Females
n	8	8
Height (in.) ^a	70.8 ± 3.3	64.3 ± 2.3
Weight (lbs.) ^a	186.5 ± 33.7	133.8 ± 12.7
Age (years) ^a	22.6 ± 1.5	22.5 ± 2.9

^aMean ± SD

Hip Flexion

Figure 1 shows the means \pm SD of HF across each set. The repeated measures one-way ANOVA revealed a significant change in HF across repetitions ($F = 20.98$, $p < 0.001$, $\text{partial } \eta^2 = 0.583$). HF was significantly greater in all repetitions compared to R_{1-1} (R_{1-10} : 12.3 ± 2.3 deg., $p < 0.001$; R_{2-1} : 9.63 ± 2.20 deg., $p = 0.001$; R_{2-10} : 14.94 ± 2.78 deg., $p < 0.001$; R_{3-1} : 14.70 ± 2.40 deg., $p < 0.001$; R_{3-10} : 16.01 ± 2.99 deg., $p < 0.001$). A significant increase in HF was found from R_{2-1} to R_{2-10} (5.31 ± 1.36 deg., $p = 0.001$) but not from R_{3-1} to R_{3-10} . Significantly greater HF was also observed in R_{3-10} compared to R_{1-10} (3.75 ± 1.53 deg., $p = 0.027$) and R_{2-1} (6.38 ± 1.57 deg., $p = 0.001$). A decrease in HF emerged during the first and second recovery periods. Although the decrease during the second recovery period, from R_{2-10} to R_{3-1} , was non-significant, the decrease from R_{1-10} to R_{2-1} (-2.63 ± 1.10 deg., $p = 0.03$) was found to be significant.

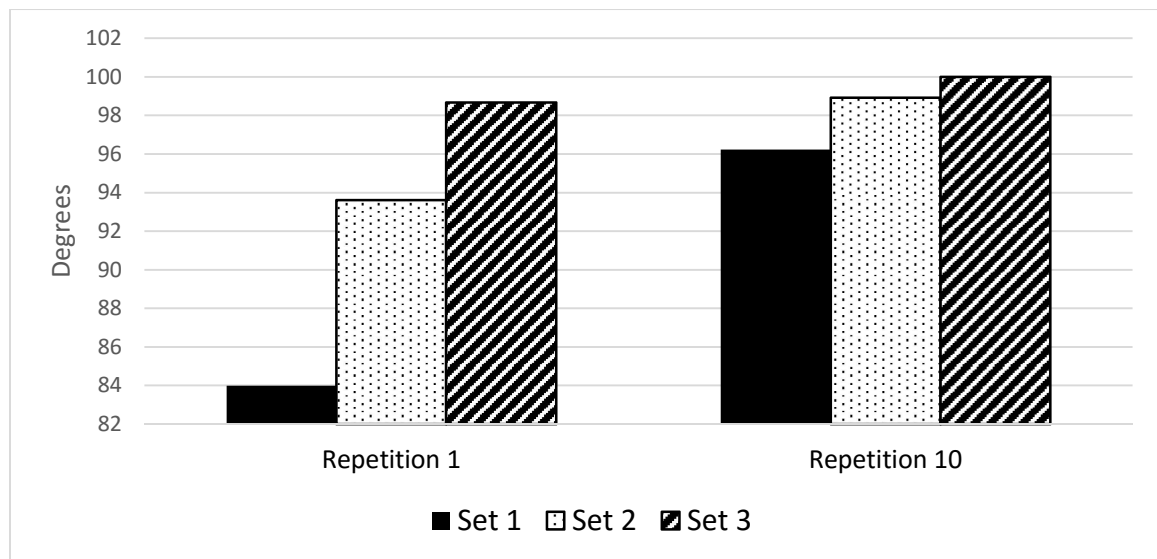


Figure 1. HF observed in the first and tenth of repetition of each set. $n = 16$

Knee Flexion

Mean KF ranged from 159.9 ± 8.1 deg. (R_{3-1}) to 163.1 ± 6.4 deg. (R_{1-1}). No significant differences were observed in knee flexion across repetition ($F = 2.006$, $p = 0.087$).

Electromyography

A significant effect of repetition was observed in both $RF_{(mean)}$ and $RF_{(peak)}$ ($F = 4.278$, $p = 0.017$, *partial* $\eta^2 = 0.222$; $F = 4.073$, $p = 0.019$, *partial* $\eta^2 = 0.214$, respectively).

$RF_{(mean)}$. $RF_{(mean)}$ is displayed in Figure 2. Significant increases in $RF_{(mean)}$ were observed from R_{2-1} to R_{2-10} ($39.4 \pm 8.9\%$, $p < 0.001$) and from R_{3-1} to R_{3-10} ($42.3 \pm 12.8\%$, $p = 0.005$) but not from R_{1-1} to R_{1-10} . No significant differences were seen in $RF_{(mean)}$ between R_{1-1} , R_{2-1} , or R_{3-1} , nor between R_{1-10} , R_{2-10} , or R_{3-10} . Significant increases were observed in $RF_{(mean)}$ from both R_{1-1} and R_{2-1} to R_{3-10} ($37.4 \pm 15.1\%$, $p = 0.026$; $46.3 \pm 12.7\%$, $p = 0.002$; respectively).

$RF_{(peak)}$. Significant increases in $RF_{(peak)}$ were observed from R_{2-1} to R_{2-10} ($52.8 \pm 8.5\%$, $p < 0.001$) and from R_{3-1} to R_{3-10} ($33.0 \pm 12.9\%$, $p = 0.022$) but not from R_{1-1} to R_{1-10} . No significant differences were seen in $RF_{(peak)}$ between R_{1-1} , R_{2-1} , or R_{3-1} , nor between R_{1-10} , R_{2-10} , or R_{3-10} . $RF_{(peak)}$ during R_{3-10} was found to be significantly greater than both R_{1-1} ($34.4 \pm 16.4\%$, $p = 0.043$) and R_{2-1} ($57.5 \pm 17.7\%$, $p = 0.005$).

$BF_{(mean)}$. The change in $BF_{(mean)}$ between repetitions merely approached significance ($F = 2.76$, $p = 0.069$, *partial* $\eta^2 = 0.155$). A trend, however, was observed that suggested an overall increase in $BF_{(mean)}$ across trials. This can be seen in Figure 2.

$BF_{(peak)}$. A significant change in $BF_{(peak)}$ was discovered between repetitions

($F = 2.929$, $p = 0.047$, $partial \eta^2 = 0.163$). $BF_{(peak)}$ increased significantly from R_{1-1} to R_{2-10} ($39.6 \pm 18.6\%$, $p = 0.05$) and from R_{1-1} to R_{3-10} ($64.3 \pm 21.9\%$, $p = 0.01$). $BF_{(peak)}$ also increased significantly from R_{1-10} to R_{3-10} ($50.5 \pm 14.4\%$, $p = 0.003$).

Co-Activation Index. CI is displayed in Figure 2. No significant differences were observed in CI between repetitions ($F = 2.0$, $p = 0.153$, $partial \eta^2 = 0.118$). Although not supported by statistical analyses, it appears in Figure 2 that $RF_{(mean)}$ had a greater influence on changes in CI than $BF_{(mean)}$. In other words, it appeared that changes in CI were driven more by the agonist activity than by the antagonist, which is reflected by the lack of significant within-set alterations in $BF_{(mean)}$ and $BF_{(peak)}$.

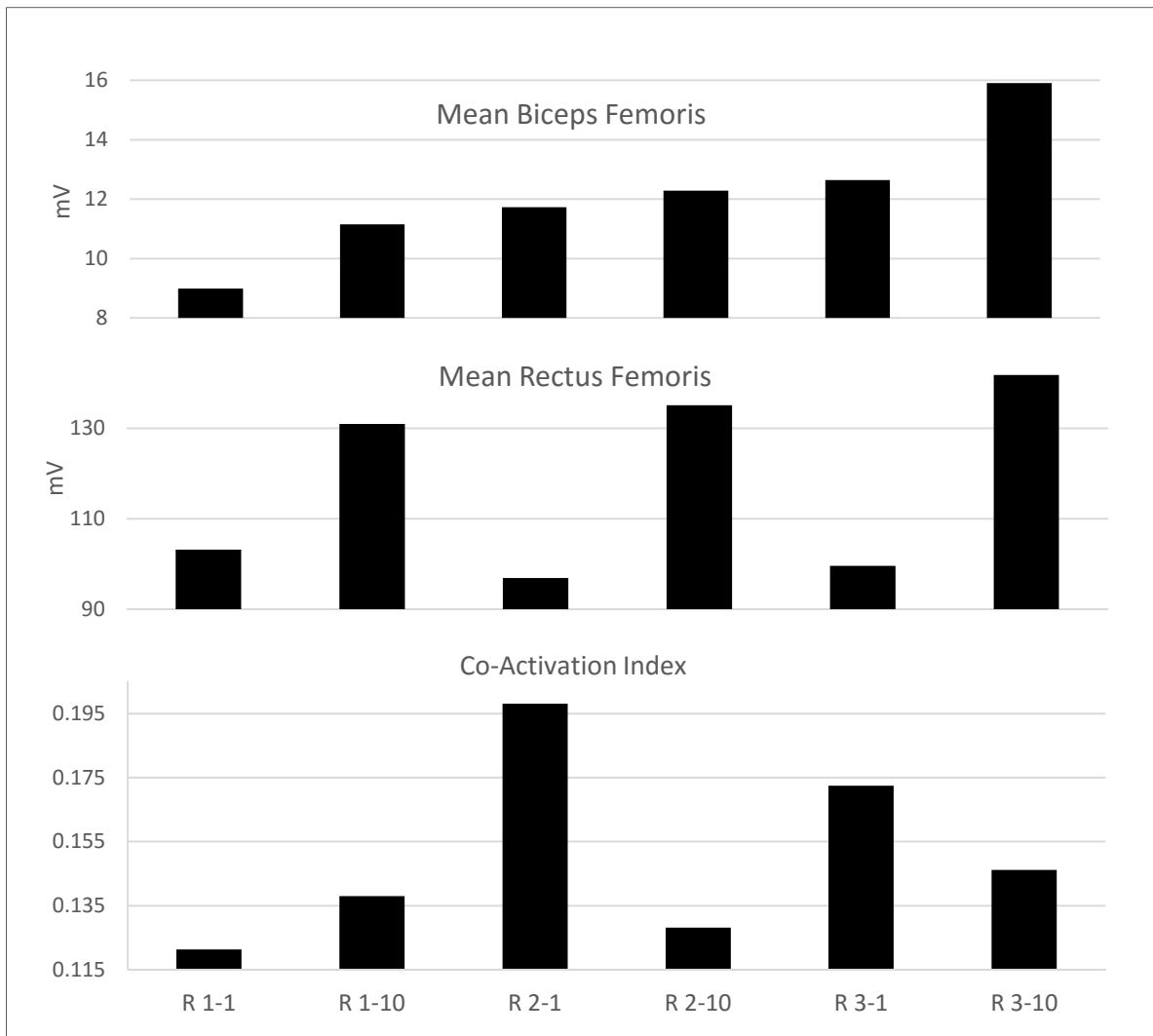


Figure 2. $BF_{(mean)}$, $RF_{(mean)}$, and CI across repetition. $n = 1$

Chapter 5

Discussion

This study investigated muscle behavior and AROM during ADS of the leg. The main finding of the present study was that HF AROM increased through performance of specific ADS targeting the musculature of the thigh, absent of alterations in antagonistic muscle activity. These findings are consistent with other studies in which muscle activity of the antagonist muscle group did not appear to be related to changes in ROM (Condon & Hutton, 1987; Moore & Hutton, 1980; Osternig et al., 1987; Osternig et al., 1990). The following sections will discuss how the current findings relate to previous research as well as the mechanisms that may explain these findings.

Hip Flexion

A repeated measures one-way ANOVA was used to assess changes in HF across repetitions. Differences between individual repetitions were analyzed using a pairwise analysis adjusted using the LSD correction. Significant increases in HF were observed in the tenth repetition compared to the first repetition in sets one and two, but not in set three. These findings are consistent with previous research in which a clear reduction in VSR has been demonstrated over a series of repeated cyclic-type stretches (Gajdosik et al., 2005; Gajdosik & Lentz et al., 2006; McNair et al., 2002; Singer et al., 2003; Taylor et al., 1990). It is likely that as the VE properties of the MTU get closer to their maximal end-point, the between-repetition alterations reduce in magnitude. This characteristic has been demonstrated in cyclic-type stretch conditions (Gajdosik et al., 2005; Gajdosik & Lentz et al., 2006; McNair et al., 2002; Singer et al., 2003; Taylor et al., 1990). It has

even been suggested that a “set point” may exist for joint motion that results in a reduced ability of the MTU to change through continued stretching (Fowles et al., 2000, pp. 1181). This “set point” theory may be evident upon examination of Figure 1. The close grouping of the final repetition of each set, while also lacking any significant differences between them, suggests that each set successfully moved HF closer to this “set point” and continued to do so despite digressing slightly during each recovery period. In summary, the results of this study displayed not only that significant increases in AROM can be accomplished through ADS, but also support the existence of an acute “set point” in AROM. It is believed that this characteristic is related to the changes in the stress-strain curve over a series of cyclic stretches (Robi et al., 2013). Although the exact mechanisms are unclear, it has been suggested that within-set alterations in tissue compliance are maximized within 10 cyclic stretches (Robi et al., 2013).

Between-Set Recovery. HF significantly reduced during the first recovery period from R_{1-10} to R_{2-1} . Despite this decrease, HF did not fully return to baseline. In contrast, the reduced HF observed from R_{2-10} to R_{3-1} was not significant. In the present study, it appeared that each set of ADS built upon the within-set alterations in HF accumulated in the sets prior. This diminishing effect is similar to that seen in the time-course of VSR (Duong, Low, Moseley, Lee, & Herbert, 2001; Gajdosik, 2006; Gajdosik et al., 2005; Gajdosik, Lentz, McFarley, Meyer, & Riggin 2006; Hufschmidt & Mauritz, 1985; Klinge, Magnusson, Simonsen, Aagaard, Klausen, & Kjaer, 1997; Magnusson, 1998; Magnusson et al., 1997; Magnusson, Aagaard, & Nielson, 2000; Magnusson, Simonsen, Aagaard, Gleim et al., 1995; Magnusson, Simonsen, Aagaard, & Kjaer, 1996; Magnusson,

Simonsen, Aagaard, Moritz, & Kjaer, 1995; Magnusson, Simonsen, Dyhre-Poulsen, et al., 1996; McHugh, Magnusson, Gleim, & Nicholas, 1992; McNair, Dombroski, Hewson, & Stanley, 2001; McNair, Hewson, Dombroski, & Stanley, 2002; Nordez, McNair, Casari, & Cornu, 2010; Ryan, Herda, Costa, Walter, & Cramer, 2012; Singer, Dunne, Singer, & Allison, 2003; Taylor, et al., 1990) and demonstrates that performing multiple sets of ADS, while eliciting progressively smaller increases in AROM, may be necessary in maintaining the acute adaptations through short recovery periods.

Several investigations have employed ADS to describe its effectiveness in preparing the body for power and speed assessments in contrast to SPST and no-stretch conditions (Faigenbaum, Bellucci, Bernieri, Bakker, & Hoorens, 2005; Fletcher & Anness, 2007; Fletcher & Jones, 2004; Little & Williams, 2006; McMillian, Moore, Hatler, & Taylor, 2006; Moran, McGrath, Marshall, & Wallace, 2008; Yapicioglu et al., 2013). A recovery period of 2 minutes has often been implemented between ADS and performance assessments (Faigenbaum et al., 2005; Little & Williams, 2006; McMillian et al., 2006). The merits of ADS in warm-up protocols prior to such assessments are clear in these investigations. It should also be noted that these studies employed multiple sets of each ADS exercise prior to performing the assessments. In the present study, the culmination of multiple sets of ADS on the within- and between-set alterations in HF suggests that set selection holds implications for the time-course of ADS on explosive-type movements.

Co-Activation

In the present study, a repeated measures one-way ANOVA was employed to assess changes in CI across repetitions. No significant alterations were observed in CI from the ADS leg kicks. The relationship between agonist-antagonist muscle activity and their effect on changes in AROM observed in the present study as well as others (Condon & Hutton, 1987; Gajdosik, 2006; Moore & Hutton, 1980; Osternig et al., 1987; Osternig et al., 1990), seem to be paradoxical. One would expect that, in order to achieve greater magnitude of movement, an increase in net force in the direction aiding the movement would be necessary. Keep in mind that although motor recruitment and force output are highly related, changes in EMG amplitude are not always representative of equal changes in force output (Konrad, 2006). The effectiveness of an EMG electrode in detecting changes in muscle activation is determined by its proximity to the motor units within the muscle. Thus, alterations in the activation of motor units that are distant from an electrode will have far less impact on the observed EMG amplitude compared to equivalent changes in activation of motor units that are closer in proximity, although both may result in equal changes in force output. (Kuriki et al., 2012). In the present study, in which a within-set and overall time-related increase in $RF_{(mean)}$ and $RF_{(peak)}$ was observed, the increase in AROM appeared to be accompanied by a compensation in the balance of such forces through increased agonist muscle activation. As discussed previously, such behavior is likely necessary to facilitate greater AROM as a greater net force aiding the movement will ultimately result in greater movement magnitude.

A compensation of this magnitude and consistency, however, was not observed in the antagonist muscle group. $BF_{(mean)}$, although displaying an upward trend of activation over time, did not show any significant alterations. The significant increase in $BF_{(peak)}$ found in R_{2-10} and R_{3-10} compared to R_{1-1} , however, demonstrates that the antagonist, rather than becoming less active to allow greater movement range, increased in the final 5 degrees of HF.

This significant increase in $BF_{(peak)}$ holds an important consideration for the identification of mechanisms involved in AROM. As mentioned previously, alterations in muscle activity do not always result in equal changes in force production. If a net change in the agonist-antagonist force relationship, favoring the agonists, is needed to generate greater movement magnitude and no significant changes were observed in CI that would indicate greater agonist force production relative to antagonist, the increase in $BF_{(peak)}$ likely did not result in changes in force production sufficient to overcome the concomitant increase in agonist forces. In other words, it may be interpreted that the increase in active resistive force did not accompany the increase in $BF_{(peak)}$. Therefore, these findings suggest that the reactive behavior of BF in response to the leg kicks failed to generate increased force at the joint. If the MTU did in fact undergo VSR during the stretching maneuver, as has been demonstrated in cyclic passive stretch conditions (Gajdosik et al., 2005; Gajdosik & Lentz et al., 2006; McNair et al., 2002; Singer et al., 2003; Taylor et al., 1990), and this VSR occurred within the SEC, as has been suggested (Lindstedt et al., 2001; Wang et al., 1993) greater activation would be necessary to maintain the effectiveness of the contractile elements of the muscle. In other words,

changes in the net torque surrounding the joint may have occurred without alterations in CI in the present study simply due to changes in the stiffness of in-series tissues. Titin, for instance, is often identified as the primary source of elasticity within the MTU (Gajdosik et al., 2005; Gajdosik, 2006; Gajdosik & Lentz et al., 2006; Lindstedt et al., 2001; Weppeler & Magnusson, 2010; Singer et al., 2003; Wang et al., 1993). As the anchor between the z-disc and the myosin filament of the sarcomere, titin is necessary in transferring force between sarcomeres. Thus, reductions in the stiffness of titin within the MTU could have an inhibiting effect on the force-producing capabilities of the muscle.

Although the lack of significant findings related to CI in the present study suggest that it is unrelated to changes in AROM, it may still have implications for performance and injury prevention. Quinzi et al. (2015) observed the presence of co-activation in the leg muscles during the round-house kick. Their study revealed an experience- or age-related increase in CI that they attributed to a training effect adopted to improve joint stability. One difference, however, between the round-house kick and the ADS leg kicks used in the present study was the final goal of performing the kick. In the study by Quinzi et al. (2015), the goal of the kick was to strike a pad with as much force as possible, creating substantial energy upon impact, whereas the goal of the present study was to kick the leg to an unknown point at which mild discomfort was experienced. First, the impact from striking a pad through a round-house kick may necessitate additional stability at the knee to prevent improper articular movement caused by the impact forces transferred up the leg, meaning that greater CI would be

favorable to long-term health of the knee and hip joints. Second, the present study lacked a visible point that participants could focus on achieving. In other words, they were unaware of their end-point goal until they reached it and experienced the associated discomfort. This uncertainty may have inspired hesitation and a concomitant increase in BF activation in order to protect the involved structures from over-stretching. This increase in volitional protection may explain why CI persisted throughout each trial as AROM increased.

Little and Williams (2006), while not assessing AROM, demonstrated that the beneficial effects from ADS related to force-production persisted through a recovery period of up to two minutes. The between-set recovery period employed in the present study was 20 seconds, well within this two minute time frame for conserving such changes. While improvements in HF AROM were largely sustained during the recovery periods, the maintenance of neurological effects from one set to the next were not as evident. While an overall increase in $RF_{(mean)}$ and $RF_{(peak)}$ was demonstrated over the entire protocol, each returned to baseline during the recovery periods. In addition, the diminishing returns observed in HF were not evident in either agonist or antagonist mean or peak activation as both continued to increase over each set.

It has been suggested that the force-inducing benefits of ADS may be the result of increased blood flow, increased signal transmission facilitated by elevated body temperature, or movement rehearsal (Herda et al., 2008; Little & Williams, 2006; McMillian et al., 2006). It is unlikely in the present study that blood flow or changes in metabolic behavior are responsible for the changes observed in the present study as a

lower-body warm-up protocol was utilized to increase heart rate and body temperature prior to stretching. The repetitive nature of the protocol used in the present study, however, may explain the significant changes observed in $RF_{(mean)}$ and $RF_{(peak)}$ in the second and third sets while failing to reveal any changes in the first. The rehearsal of the specific movement pattern may have allowed greater adaptation to occur, supporting such a mechanism in the findings of Little and Williams (2006).

Conclusions

This study demonstrated that specific ADS of the hip elicited significant increases in AROM without sacrificing co-activation of the muscles surrounding the hip and knee joints. It was clear that the stretching protocol elicited greater $RF_{(mean)}$ and $RF_{(peak)}$ EMG and that the magnitude of this within-set difference in agonist activation increased over the course of the stretching protocol. Although the purpose and mechanism is unclear, the lack of significant alterations in $BF_{(mean)}$ and minimal changes in $BF_{(peak)}$ suggested that antagonist muscle activation had little or no effect on alterations in AROM. Although the specific nature of the lack of significant changes in CI is unclear, the findings of the present study suggest that passive tension within the MTU, specifically held within tissues located in-series, declined and that those alterations were not affected by increased muscle activity.

This study was unique in that motion was analyzed in a dynamic condition during the performance of a series of specific active stretches targeting the hip musculature. The insights into the acute compensation of ROM and muscle activation to ADS

provided by the current study have largely only been assessed during SPST and static stretching with agonist contraction.

This study was limited by the frame rate of the camera utilized. A camera with a greater capture frequency would have provided a more accurate identification of eROM. In addition, a limitation exists in all dynamic muscular contraction investigations in which surface EMG is utilized due to translation of the muscle belly under the skin (Konrad, 2006). If changes in MTU length occurred during the present study, changes in muscle activity could be falsely identified as changes in motor recruitment when, in reality, they are the consequence of shifts in the muscle belly and motor units in relation to the surface electrodes. Further, it is unclear if this shift would occur in the proximal or distal direction. Keep in mind that electrodes were placed on the muscle belly while the leg was positioned in the anatomical position (Konrad, 2006). Therefore, an increase in MTU length would likely result in a translation of the muscle belly closer to the surface electrode while positioned at HF eROM.

Future research should consider analyzing each repetition within each set to find an ideal number of repetitions for application in warm-up activities in which time is limited. Much like the diminishing effect observed in the present study over the multiple sets of ADS, it has been demonstrated in passive settings that such improvements diminish within a single set of repeated stretches (Gajdosik et al., 2005; Gajdosik & Lentz et al., 2006; McNair et al., 2002; Singer et al., 2003; Taylor et al., 1990). If such an effect is present within a single set of leg kicks, identification of the number of repetitions

necessary to elicit this effect may aide health professionals designing programs to enhance AROM.

Although differences in overall flexibility may exist between males and females, there is little evidence to support an effect of sex on the magnitude of improvements that can be made through flexibility training. Although not part of the initial purpose of the present study, the researchers used a 2x6 mixed model ANOVA to identify any interaction effects between sex and HF. As expected, the results of the mixed model ANOVA ($F = 0.357$, $p = 0.716$) did not reveal any significant interaction between sex and HF. Due to the consistency of leg dominance in the sample of the present study, all indicating leg dominance in the testing limb, an analysis of the differential effects of the stretching protocol based on dominance was not possible. Although participants were not recruited based on leg dominance, nor was this variable included in the purpose of the present study, further information on the influence of leg dominance on the improvements that can be made to AROM is warranted.

APPENDIX A

PHYSICAL ACTIVITY QUESTIONNAIRE

Your participation in this research is contingent upon completion of this questionnaire. Your answers will remain confidential. Questionnaires will remain in the possession of the principle investigator and will be destroyed upon completion of the study.

Answer the first 2 questions based on the last 7 days. Include any aerobic or rhythmic physical activity performed at least 10 minutes at a time. Include resistance training that targeted the major muscle groups. Intensity of physical activity is classified as either moderate or vigorous based on your perception of the overall difficulty of the session.

In the past 7 days, how much time did you spend performing moderate intensity activity? (i.e. fairly light to somewhat hard) _____ hrs: _____ min

In the past 7 days, how much time did you spend performing vigorous intensity activity? (i.e. somewhat hard to very hard) _____ hrs: _____ min

In the past 3 months, have you taken part in any deliberate stretching of the hamstrings muscle group during which you actively flexed and extended your leg at the hip?

Yes / No (circle one)

Have you ever experienced a muscle strain in the hip flexors or extensors?

Yes / No (circle one)

Are you currently or have you, in the past 3 months, experienced lower back pain or any other pain that may prevent you from executing the study protocol?

Yes / No (circle one)

Which leg do you use to kick a ball?

Left / Right (circle one)

APPENDIX B

CONSENT FORM



Consent Form

Acute Effects of Dynamic Stretching on Flexibility and Agonist-Antagonist Muscle Activity

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Purpose and Benefits

Active range of motion is a crucial physical ability in many popular sports. This study seeks to identify factors that determine active range of motion among healthy individuals. In order to identify these factors, this investigation will monitor changes in active range of motion and muscle activity while performing dynamic stretching of the hamstrings. This information will improve understanding of active range of motion and contribute to more effective training designed to elicit improvements. The following sections will detail aspects of this study for those interested in participating.

Procedures

This investigation will require participants to perform leg kicks while recording muscle activity and motion. A familiarization session (30min) will be held during which participants will be instructed on proper leg kick technique as well as the testing procedures as follows. In order to be eligible for participation, completion of a Physical Activity Questionnaire will be required during this session. The testing session (30min) will begin by performing a moderate intensity warm-up. Once the muscles are warm, surface electrodes will be applied to the front and back of the thigh halfway between the hip and knee joints to record muscle activity. In order to maximize accuracy of measurement, the skin on which the electrodes will be applied will be shaved, lightly abraded, and cleansed. Reflective markers will then be applied to the ankle, knee, and hip to increase the accuracy of the motion analysis. Video records of participants will only be accessible by the investigators listed above. Participants' faces will be visible in the video records. Washington State law provides that private conversations may not be recorded, intercepted, or divulged without permission of the individuals involved. Participants will then lie on a yoga-type mat overlying a wood platform. A Velcro® strap will overlie the knee of the limb not being tested to minimize movement. Another Velcro® strap will overlie the pelvis to prevent rotation. Participants will then be asked to perform 10 consecutive leg kicks as instructed during the familiarization session. Participants will perform a total of 3 sets of 10 leg kicks with 20 seconds rest between each set.

Risk, Stress or Discomfort

If performed properly, the procedures employed in this study offer minimal risks to participants. During leg kicks, there is a risk of experiencing a muscle strain or other injury. In addition, participants who are uncomfortable being video recorded or having equipment applied to the thigh or hip/pelvis area are encouraged to consider their comfort with the procedures outlined previously.

Acute Effects of Dynamic Stretching on Flexibility and Agonist-Antagonist Muscle Activity

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Other Information

Due to the nature of this study, participants are asked to wear shorts and dark-colored athletic-type underwear that covers the upper thigh. During testing, participants will be required to remove shoes and socks. Participants are free to withdraw at any time without penalty. Course instructors are permitted to offer extra course credit to students for participation in this study if agreed upon beforehand. Instructors are in no way required to offer extra course credit.

Participant Statement

The study described above has been explained to me, and I voluntarily consent to participate in this study. I have had an opportunity to ask questions. I understand that by signing this form I am not waiving my legal rights. I understand that I will receive a signed copy of this form.

Signature of Participant

Date

If you have any concerns about your rights as a participant in this research or any complaints you wish to make, you may contact Ruth Galm, Human Protections Administrator (509-359-6567).

Signature of Principal Investigator

Date

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