A Dissertation

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The acute influence of static and ballistic stretching on the biomechanics and muscle activity associated with the hamstring stretch

By

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Submitted as partial fulfillment of the requirements for

the Doctor of Philosophy degree in

Exercise Science

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An Abstract of

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Stretching routines are typically integrated into exercise programs to improve flexibility and performance. Static stretching has been promoted as the safest and best method of stretching whereas the very different ballistic method of stretching has been virtually abandoned due to its associated risk of injury. The purpose of the current investigation was to examine the biomechanics and muscle activity associated with static and ballistic stretching of the hamstring muscles in order to compare the assets and liabilities of each technique. In a randomized cross-over design, 16 men and 13 women (22.5 ± 4.5 yrs) participated in both static (STA) and ballistic (BAL) conditions. Each condition required the subject to perform a pre-maximum stretch, a series of three 30-
second static or ballistic stretches, and a post-maximum stretch.

Electromyography (EMG) of the gluteus maximus, hamstrings, gastrocnemius, and rectus femoris muscles as well as joint kinematics were measured during all procedures. Data regarding maximum stretch distance and hip angle were recorded. Measurements of perceived soreness were made before and after the stretching exercise as well as at 24, 48 and 72 hours after stretching. A two-way repeated measures ANOVA was used for statistical analysis of perceived soreness, maximum stretched distance, and hip angle and t-tests were used for analysis of muscle activity. Significance was determined at the $p < 0.05$ level. Stretching exercise significantly increased maximum distance stretched and hip flexion ($p < 0.05$), however there was no difference between the stretching techniques. No significant effects for muscle activity or soreness were found between the static and ballistic conditions. In conclusion, static and ballistic stretching influence range of motion, hip angle, muscle activity, and soreness similarly and, thus, contraindications towards ballistic stretching may be unwarranted. Future research should investigate whether differences exist in the kinematics and muscle activity patterns of the actual static and ballistic stretching maneuvers.
DEDICATION

To my parents, Elizabeth Henyey and Lauren Snyder,
my brother, sister-in-law, and niece, Andrew, Jennifer, and Amelia Snyder,
to my grandparents Mr. & Mrs. A.D. Snyder and Dr. & Mrs. M.J. Ozeroff,
and to the many other family members and friends who have supported me
throughout my academic career.
Acknowledgements

Earning a doctoral degree comes down to the completion of a dissertation which validates all the studying and effort used to get to that point. The dissertation is daunting, and there are times when completion seems impossible. Fortunately, I had the guidance, support, and encouragement of many people who made accomplishing the goal possible.

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As has been said, “the key is to keep company with people who uplift you, whose presence calls forth your best” (Elizabeth Willett). All of the people in my life have made me strive to achieve. For that, I thank you all.
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CHAPTER I
INTRODUCTION

Recreational and competitive athletes have incorporated stretching exercises into pre-participation warm-ups for years. Although stretching is a common component in exercise programs, there is a discrepancy as to whether all stretching techniques provide the same benefits. Traditionally, static stretching has been advocated more strongly than ballistic stretching. This may be due to the perceived injury risk associated with ballistic movements, as well as the belief that static stretching results in greater flexibility gains \(^6, 17, 19, 41, 45, 53, 57, 59\). Interestingly, there seems to be limited evidence substantiating these beliefs. Furthermore, most of the information regarding stretching is anecdotal or based on theory and few experimental studies have actually investigated variables other than general flexibility as a means of comparing the assets and liabilities of these two stretching methods.

Stretching has been promoted as an effective way to improve flexibility, enhance performance, prevent injury and re-injury, and alleviate delayed onset muscle soreness (DOMS) \(^6, 9, 17, 18, 42, 53, 57, 59, 64, 67\). Although there are many reported reasons to stretch, choosing a stretching program is difficult because there is controversy over which stretching techniques are most beneficial. Of the
stretching methods, static techniques have been promoted as the safest\textsuperscript{17, 18, 42}. Static stretching is performed by holding a muscle in a lengthened position for a prolonged period of time, which results in steady tension placed on the muscle throughout the stretch\textsuperscript{17, 20, 38, 41, 53, 55}. Static stretching affects muscle proprioceptors by providing adequate time for muscle spindles to adapt to the stress placed on them. Additionally, it provides sufficient time for the golgi tendon organs to initiate a lengthening reaction which, in theory, allows for greater ability to stretch the muscle.

In contrast to static stretches, ballistic stretches require that the muscle be repeatedly lengthened to full range of motion in short bursts, followed by an equally short relaxation period\textsuperscript{6, 17, 53}. Ballistic stretching has been virtually abandoned because it has been reported to be associated with a high risk of injury\textsuperscript{6, 17, 19, 41, 46, 53, 57, 59}. Some authors have suggested that, accompanying the rapid motion of the ballistic stretch are high muscle forces which place greater stress on the muscle and tendon, making injury more likely than in the less stressful, static stretches. In addition, the short bursts of stretching associated with the ballistic technique appear to be inadequate to provide time for muscle spindle adaptation to the stretching stress and may be insufficient to initiate the lengthening reaction associated with the golgi tendon organs. Therefore, the ballistic technique is not thought to be as beneficial as the static method. As a result, involvement in ballistic stretching is often discouraged due to the apparent differences with static stretching in terms of the physiological mechanisms, the high forces placed on the muscle, and the risk of injury. Of interest, however, is
that it appears that the two stretching methods do not actually differ in their effect on actual flexibility and on related performance outcomes.

Often stretching is integrated into exercise programs to improve flexibility. It is thought that improved flexibility may lead to better performance and a decreased chance of injury. Previous studies have shown that stretching does increase flexibility and surprisingly that both static and ballistic stretching appear to result in equal flexibility increases. Based on the limited related research, one may conclude that, in choosing a stretching method intended to improve range of motion, either the static or ballistic method is suitable.

An alternative reason that stretching is performed is because of the belief that it may actually enhance performance. Research, however, does not always support the theory that performance improves following stretching programs. One study determined that, following three repetitions of static stretching, drop jump performance actually decreased. While the authors concluded that static stretching inhibits performance, they indicated that the same effects may not be seen with other, more dynamic stretching methods. Other investigations have reported decrements in strength following bouts of both static and ballistic stretching. A study by Evitovich et al. found that torque decreased following static stretching, and concluded that sports performance may also be negatively affected if stretching is performed immediately prior to the activity. Most of the literature regarding performance has been conducted using static techniques and shows that stretching before activity may decrease performance. However, no strong conclusions can be made regarding the effects of ballistic
stretches on athletic performance. Clearly, the results of the previous research on the effects of stretching on performance are, at best, inconclusive.

Although there do not appear to be extreme differences between static and ballistic stretching techniques in terms of the effects on flexibility, and the results are inconclusive regarding performance, there are differing views regarding the safety of the two stretches. It is generally agreed upon that ballistic stretching is associated with a higher risk of injury than other stretching techniques \(^{17, 41, 53, 55, 57, 59}\). However, there do not appear to be any studies confirming this belief. In fact, two studies have found that static stretching results in more muscle soreness than ballistic stretching \(^{44, 59}\). Unfortunately, no studies have investigated why this occurs.

Muscle injury more commonly results from eccentric, lengthening, contractions than it does from concentric, shortening, contractions \(^{2, 13, 14, 59}\). Both static and ballistic stretching maneuvers typically incorporate eccentric movements. Although the motion is relatively the same, the amount of stretch may actually be different between the two stretches. That is, people who stretch statically may stretch further than those who stretch ballistically. In addition, although more muscle force may be used to perform each eccentric contraction in the ballistic stretch, there is less total time in the eccentric position with a ballistic movement. Thus, it is possible that the factors contributing to muscle stress may be greater with the static stretch, which may make injury and perceived soreness more likely. It is possible that measurements of hip angle and muscle activity following a bout of stretching may provide information
regarding differences in the static and ballistic stretching techniques. Unfortunately, investigations into the biomechanical and muscular outcomes of static and ballistic stretches have not been made, which makes it difficult to know whether these variables provide insight into the differences in soreness found between the stretching methods.

Recently, it has been suggested that ballistic stretching incorporates movements that are more like typical sports movements which may be a greater benefit to athletes \(^{55, 59}\). However, there is still resistance to use ballistic stretching due to the associated risk of injury. A comparison of the static and ballistic stretching techniques illustrates that there are no significant differences on flexibility and performance outcomes between the two methods of stretching. The only difference is in regards to muscle soreness, with static resulting in more muscle soreness than ballistic. Interestingly, no studies have addressed why the difference in soreness occurs.

**Significance**

Commonly, athletes incorporate muscle stretching into their pre-participation warm-up activities. There are many reasons why muscle stretching is advocated, including the therapeutic effects, performance enhancements, range of motion increases, and injury prevention \(^{6, 9, 17, 42, 53, 57, 59}\). However, the current literature does not support all of these claims. Within the popular literature, it has often been stated that static stretching is associated with less chance of muscle injury than ballistic stretching. According to the limited
research literature, however, this may not be the case, as static stretching has been reported to result in more muscle soreness than ballistic. Although ballistic stretching is not commonly practiced, it is thought to incorporate motions that are more typical of sports movements than other stretching techniques. It would seem likely that stretching in a manner that is consistent with the unique motions of a particular sport may enhance athletic performance. Unfortunately, there is reluctance to use ballistic methods, due to the belief that they are associated with a higher risk of injury. Thus, research investigating the biomechanics and muscle activity associated with static and ballistic stretching exercises may help to illustrate differences in response to these two techniques, as well as provide an explanation for these differences.

**Statement of the Purpose**

The purpose of this study was to determine if selected factors related to muscle stretch were affected differentially by involvement in bouts of static and ballistic stretching exercise, through examination of the kinematics and muscle activity of a post-exercise maximum stretch.

**Hypotheses**

H1: There will be no difference in the pre maximum stretch distance between the STA and BAL stretching conditions.
H2: Post maximum stretch distance will be greater than the pre maximum stretch distance in both the STA and BAL stretching conditions.

H3: There will be no difference in the gain in maximum stretch distance between the STA and BAL stretching conditions.

H4: There will be no difference in hip angle during the pre maximum stretches for the STA and BAL stretching conditions.

H5: Hip angle during the post maximum stretch will be greater than hip angle during the pre maximum stretch in both the STA and BAL conditions.

H6: Post maximum hip angle will not differ between the STA and BAL condition.

H7: The difference in EMG activity between the pre and post maximum stretch maneuvers for the gluteus maximus, proximal, distal, medial, and lateral hamstrings, gastrocnemius, and rectus femoris muscles will be greater (larger change) in the STA condition as compared to the BAL stretching condition.

H8: Static stretching will be associated with decreased levels of EMG activity in the gluteus maximus, proximal, distal, medial, and lateral hamstrings, gastrocnemius, and rectus femoris muscles when compared to ballistic stretching.
H9: Perceived soreness will be greater in the STA condition as compared to the
BAL condition at all time points.
CHAPTER II
REVIEW OF LITERATURE

For years, stretching has been promoted as an effective warm-up prior to participation in athletic activities. Reported benefits of stretching include increased flexibility, improved performance, and prevention of injury and re-injury. Two common, but very different stretching methods often used are the static and ballistic techniques. It has become a popular belief that static stretching is superior to ballistic stretching, in part, because ballistic movements are associated with a high risk of injury. Additionally, it has been suggested that static stretching results in less post-stretching soreness. Interestingly, the literature does not confirm this, as one investigation found that static stretching actually resulted in more muscle soreness than ballistic. Regardless, it is possible that the variation in movement patterns and levels of muscle activity associated with static and ballistic stretching contribute to the differences in soreness found between the two techniques. Additionally, it is likely that these same factors may contribute to any differences in the effects of these two techniques on actually enhancing flexibility. In spite of the importance of these issues, very few studies have investigated these variables. Thus, due to the paucity of literature on the various stretching methods, it is appropriate to examine the biomechanics and muscle activity of both techniques to determine
whether these variables contribute to and may explain any observed post-stretching differences in flexibility and soreness.

**Stretching Methods**

Of the various stretching methods, two commonly contrasted techniques are static and ballistic. Static stretching is considered to be the safest, most palliative stretching method \(^{17, 18, 38, 41, 42, 48, 51, 53, 55}\). The static technique requires that a muscle is stretched to a new length and then the lengthened position is maintained for an extended period of time \(^{17, 38, 41, 53, 55}\). In contrast, ballistic stretching is believed to be unsafe and, in recent years, has been almost completely discarded by athletes and clinicians \(^{6, 17, 19, 41, 46, 49, 51, 53, 57, 59}\). Ballistic stretching is performed by rapidly stretching a muscle to its full range of motion and then immediately allowing the muscle to relax, and the alternating stretch-relax pattern is repeated throughout the duration of the stretch \(^{6, 17, 51, 53}\). The motion of ballistic stretching is thought to be jerky, inconsistent, and uncontrolled which makes it appear more dangerous than other stretching methods \(^{3, 5, 6, 41, 51}\). Furthermore, high muscle forces and tension are believed to be associated with the ballistic technique, which may stress the muscle and tendons and increase the chance of injury \(^{49, 57}\).

Recently, however, it has been suggested that ballistic motions are more typical of the movements actually used in sporting events or recreational athletics, and as such, may be beneficial for sport specific training \(^{5, 59}\). Some researchers believe that although ballistic stretching more closely mimics sport
movements, the technique is still more controlled than most athletic activities, and, therefore, is likely to be much safer than the sport itself. The discrepancy between which stretching techniques are superior to others is rooted in both the anatomy and physiology of muscle stretch and research investigations into flexibility, performance, and soreness.

**Active and Passive Components of Stretch**

Stretching a muscle, or increasing flexibility, is dependent on two distinct components, namely the joint’s range of motion and muscle flexibility. The joint’s range of motion is determined by the ability of the connective tissue to deform and the arthrokinematics of the specific joint, whereas muscle flexibility refers to the ability of the muscle to lengthen. These two components determine the maximum flexibility of a particular joint and are influenced by passive and active restraints.

**Connective Tissue**

Although joint range of motion is predominantly dictated by the joint’s arthrokinematics, connective tissue is also an important limiting structure. Of the components of connective tissue, collagen and elastin are of greatest importance when considering muscle stretch and flexibility. Collagen provides connective tissue with high tensile strength and the ability to resist mechanical forces and deformation whereas elastin helps a tissue recover from deformation. Ligaments, tendons, fascia, aponeuroses, and joint capsules are all composed
of collagen and each can contribute to limiting range of motion through passive restraint of a joint. The structural properties of collagen determine a tissue's load-bearing ability, and because of this, it should be one structure of focus when trying to improve joint range of motion and muscle flexibility through stretching techniques.

When collagen is deformed, it exhibits mechanical properties of elasticity, viscoelasticity, and plasticity in order to respond appropriately to the stresses imposed upon it. Elasticity implies that deformation, or length change, is directly proportional to the applied forces and can be illustrated by the mechanism of a typical spring. Viscoelasticity is characterized by the slow deformation and imperfect recovery that occurs when a deforming stress, such as a stretch, is removed and is time and rate change dependent. That is, the length change of the tissue is influenced by the rate and duration of the applied force. Finally, plasticity refers to the permanent change that occurs when deformation is sustained, however, in muscle, it is nearly impossible to induce a plastic change within the tissue. Although these mechanical properties characterize collagen, they are also present in most biological tissues, including muscle.

In fact, collagen and muscle are similar in that they both are viscoelastic materials, and, as a result, they exhibit the physical properties of stress relaxation, creep, hysteresis, and strain rate dependence. Stress relaxation refers to the decline in force needed to maintain a tissue at a set length over time. Creep is the continued deformation of a tissue when a constant load is applied to it, and hysteresis represents the amount of relaxation that
occurs within a tissue during one deformation-relaxation cycle $^5, 31, 55, 63$. A tissue that is strain-rate dependent incurs higher tensile stresses at faster rates of strain which means that a slower rate of strain will provide time for greater relaxation within the tissue $^{63}$.

Muscle Tissue

Although there are many tissues that can passively restrain muscle flexibility and joint range of motion, the only tissue that can actively influence flexibility is muscle $^5$. Muscle is capable of active restraint because it contains the contractile proteins actin and myosin which interact and ultimately result in shortening of the muscle fibers $^{22}$. Electromyography (EMG) is a technique that measures muscle activity and can be used to determine whether or not muscle is actively contracting, or resisting, muscle stretch. It is thought that if EMG activity is present during stretching then the muscle is not relaxed and is inhibiting flexibility gains $^{15, 42}$. Interestingly, studies show that during stretching exercises, low levels of EMG activity are detected, indicating that the muscle is not completely relaxed $^{15, 42, 43, 66}$. However, low level EMG activity does not prevent improvements in range of motion because measurements of increased flexibility have been recorded even when a muscle is actively contracting $^{42, 43}$. Therefore, muscle tissue may not be a strong active restraint to stretch and it may be that passive restraints are more responsible for limiting flexibility. Not only does skeletal muscle have contractile elements, but it contains non-contractile, passive materials as well.
The non-contractile connective tissue layers are classified as endomysium, perimysium, and epimysium. Each layer covers a different component of the muscle tissue, with endomysium covering the muscle cell, perimysium encircling the fasicle, and epimysium surrounding the entire muscle fiber. It is thought that the connective tissue associated with muscle-tendon elasticity consists of both a parallel and series elastic component, with perimysium and endomysium providing the two parts, respectively \(^{36,40}\). The role of the parallel elastic component is to distribute forces evenly over the muscle tissue and to prevent overstretching of the myofibers whereas the elastic component functions to transfer forces from the muscle’s contractile component to the tendon and finally to the bone, in series \(^{36,40}\). Because muscle contains both contractile and non-contractile elements, it is difficult to discern the contribution that each makes towards passive tension or resistance to stretch, but it does appear that the non-contractile elements limit range of motion more. However, during muscle stretch, all of the structures located in the line of elongation have the potential to be deformed, including the joint capsule, ligament, muscle, tendon, and skin, and as a result, any of the structures can limit range of motion.

**Influence of Stretching on Active and Passive Restraints**

Although the active and passive components associated with stretch are well defined, it is thought that static and ballistic stretching techniques influence them differently, and investigations into the different components of muscle have
been made. One study characterized the viscoelastic behavior of the muscle-tendon unit during static and ballistic stretching in rabbits and found interesting results. The study consisted of three experiments, each investigating a different characteristic of viscoelasticity. Experiment one showed that tension in the extensor digitorum longus muscle-tendon unit significantly decreased during the performance of ten ballistic stretches, and this decrease was greatest during the first four stretches. The authors contend that the decrease in peak tension during the stretching exercise is due to the viscoelastic property of stress relaxation which has also been found as a result of static stretching. In part one, no measure of muscle-tendon length was recorded which makes it difficult to determine whether ballistic stretching resulted in improved flexibility. Part two of the study investigated static stretching and the results indicate that after just two 30-second static stretches, the muscle had relaxed significantly and there was an increase in muscle length as well. This experiment demonstrated characteristics of creep because the muscle elongated when exposed to continued tension.

When comparing static and ballistic stretching, experiment three illustrated how the two techniques influence passive structures differently. Part three required that the muscle-tendon unit be stretched at varying rates of speed and both innervated and denervated muscles were compared. Results confirmed the viscoelastic property of the muscle-tendon unit because it was found that peak tensile force and absorbed energy were dependent on stretching rate, with faster stretching rates resulting in greater tension in the muscle-tendon unit. These
results argue against ballistic stretching because faster stretching produced greater tension which may make it more likely to overextend the tissue and sustain an injury. Another finding in the third study showed that there was no difference in the tensile forces and energy absorbed during stretching whether or not the muscle was innervated. According to this study, the behavior of stretched muscle can be attributed to the viscoelastic properties of the muscle-tendon unit and not reflex activity which contradicts popular belief.

Although some studies conclude that viscoelastic stress relaxation occurs with both ballistic and static stretching, other studies have not reported the same results. One study found that after 15 minutes of static or ballistic stretching, range of motion increased significantly. In addition, end range of motion torque was larger which lead the investigators to conclude that improvements in range of motion were not due to viscoelastic stress relaxation but were the result of an increase in the subject’s tolerance to stretching strain. It is possible that with stretching, a person becomes more accustomed to the stretching exercise and more willing to stretch the muscle to its full range of motion.

Another investigation compared static and ballistic techniques and also determined that the range of motion improvements were likely due to increased stretch tolerance as opposed to adaptations in the viscoelastic properties of the muscle-tendon unit. Subjects performed either 90 seconds of static stretching or ten ballistic stretches and both groups exhibited increases in range of motion. Although the static group exhibited a 35% viscoelastic stress relaxation during the stretch maneuver, the response was gone after just ten minutes.
Interestingly, flexibility gains remained. Similarly, the ballistic group did not show any biomechanical effects ten minutes following the exercise although the improved range of motion remained. Therefore, the authors contend that improvements in joint range of motion measured after static and ballistic stretching are attributed to an increase in stretch tolerance as opposed to alterations in the viscoelastic properties of the muscle.

Based on the few studies investigating the viscoelastic properties of the muscle-tendon unit during stretching exercise, a few conclusions may be drawn. First, the lengthening of the muscle-tendon unit is at least partially due to the viscoelastic properties of the tissues, although the response may be acute, and further ability to stretch may be due to the person’s ability to tolerate a larger stretching strain. Secondly, the rapid motions of ballistic stretching may produce greater tension which could compromise the integrity of the muscle-tendon unit. Finally, reflex activity may not play an integral role in monitoring stretching activity as it has been demonstrated that, when stretched, a denervated muscle produces the same tension as that of innervated muscle. Although there appears to be a physiological reason against ballistic stretching, an understanding of the stretch-reflex is necessary in order to determine its influence on stretching and to help establish the rationale for contraindications toward ballistic movements.
Physiology of the Stretch Reflex

The debate over whether stretching statically is a safer, more superior method of stretching when compared to ballistic stretching is largely based on the proposed role of the stretch reflex. All muscles contain various receptors which, when stimulated, send signals to the central nervous system about the state of the muscle. In general, a reflex has five components, including a sensory receptor, an afferent (sensory) path to the central nervous system (CNS), at least one synapse within the CNS, an efferent (motor) path, and an effector. The stretch reflex is the simplest type of reflex, termed monosynaptic, which means that the sensory neuron synapses directly with the motor neuron and does not involve spinal cord interneurons. Of the different types of receptors located in muscle, muscle spindles and golgi tendon organs are of predominant importance when considering muscle stretch.

Muscle Spindles

Muscle spindles are specialized sensory receptors located in muscle that contain both afferent and efferent components. The structural component of the muscle spindle consists of two to fourteen intrafusal muscle fibers that are contained within a capsule made of connective tissue, and the entire muscle spindle is surrounded by extrafusal muscle fibers. Extrafusal muscle fibers are large skeletal muscle fibers that produce tension within the muscle, and they are arranged parallel to muscle spindles. The parallel alignment of the extrafusal fibers and the muscle spindles allows the spindle apparatus to detect changes in
Intrafusal muscle fibers are small, specialized muscle fibers that do not contribute to muscle tension, however, they do control muscle spindle excitability by mechanically deforming the receptors within the muscle spindle. Intrafusal muscle fibers can be further distinguished into nuclear bag and chain fibers. The bag and chain fibers differ in their response to muscle stretch, with bag fibers being either static or dynamic and responding with slow contractions and chain fibers consisting of only static fibers and responding with fast contractions.

Different afferent axons innervate muscle spindles. The sensory portions of all nuclear bag and chain fibers are innervated by group I\textsubscript{A} axons. Static bag and all chain fibers are innervated by group II axons, as well. Type I\textsubscript{A} axons are large diameter, rapid conductors and provide information regarding rate of change in length of muscle fibers. In contrast, group II axons are sensitive to the change in length of muscle fibers as opposed to the rate of change. Three different types of motor neurons innervate the intrafusal and extrafusal fibers, including \( \gamma \) motor neurons, \( \alpha \) motor neurons, and \( \beta \) motor neurons. Gamma motor neurons innervate the contractile portion of intrafusal muscle fibers and can be either static or dynamic, meaning that they regulate the sensitivity of the muscle spindle afferents during the static or dynamic phases of stretch, respectively. Nuclear bag fibers are innervated by dynamic \( \gamma \) motor neurons whereas static bag fibers and all chain fibers are innervated by static \( \gamma \) motor neurons. Alpha motor neurons only innervate extrafusal muscle fibers and are responsible for initiating muscle contraction through stimulation of
muscle fibers. Finally, $\beta$ motor neurons innervate both intra- and extra- fusal muscle fibers, however, their involvement with human motion is not significant.

Lengthening an entire muscle, such as with muscle stretch, is one way to stimulate muscle spindles. Since intrafusal fibers and their receptors lie in series, any stretch of the muscle will result in tension throughout the length of the muscle and the production of action potentials within both the group I\textsubscript{A} and II axons. Furthermore, because muscle spindles and extrafusal fibers are arranged in parallel, stretching of the whole muscle will result in stretching and stimulation of the intrafusal fibers and their associated receptors. Stimulation of muscle spindles provides information regarding muscle length and the rate of change in length of the muscle.

**Golgi Tendon Organs**

In addition to muscle spindles, golgi tendon organs are another type of receptor that is important when discussing muscle stretch. Structurally, golgi tendon organs are slender capsules that are positioned in series with extrafusal muscle fibers. Although the name implies that golgi tendon organs are located in the tendon, it appears that they lie within the aponeurotic sheaths of muscle attachments. Extrafusal muscle fibers enter the golgi tendon organ near the muscle-tendon junction and generate bundles of collagen fibers which intertwine with group I\textsubscript{B} afferent axons. During muscle contraction, the collagen bundles straighten which compresses or squeezes the afferent nerve fibers,
resulting in firing of the axons. The created action potentials provide information regarding tension within the extrafusal muscle fibers.

A major difference between muscle spindles and golgi tendon organs is the placement of the two types of receptors. Muscle spindles lie parallel to extrafusal muscle fibers which allows them to detect changes associated with muscle length whereas golgi tendon organs are arranged in series with extrafusal muscle fibers and so are able to assess alterations in the muscle due to length change as well as active contraction. The anatomical difference in the location of the two receptors allows the state of a muscle to be monitored because, together, the receptors can determine steady-state muscle length, dynamic changes in muscle length, rate of change in muscle length, and muscle tension. Muscle stretch is one event that illustrates the relationship between muscle spindles and golgi tendon organs.

**Muscle Proprioceptors During Stretch**

When a muscle is stretched, both muscle spindles and golgi tendon organs are stimulated which sends a great deal of information to the spinal cord regarding the state of the muscle, and this information results in the initiation of the stretch-reflex. During a rapid stretch, the dynamic bag fibers in the muscle spindles are stimulated, causing an increase firing rate of I_A and group II axons. I_A axons synapse with α motor neurons innervating the homonymous, same, and heteronymous, synergistic, muscles which produce a reflex contraction in
those muscles to oppose the stretch. Group II axons also synapse with α motor neurons, although their influence on the stretch reflex is minimal.

The response of the nuclear bag and chain fibers is different depending on the amount and speed of the deforming, or stretching, stimulus. Stretching a nuclear bag fiber slowly will not result in a large amount of deformation because the bag fiber will deform and reform at relatively the same rate. Slowly deforming the bag fiber will produce little to no change in length and will not stimulate the Iₐ axons. Although there will still be stimulation of nuclear chain fibers with slow stretching, the total amount of activity in the Iₐ fibers will be less because there will be limited stimulation of the bag fibers. In contrast, fast stretching will rapidly deform the nuclear bag fiber and result in significant deformation and stimulation of Iₐ nerve fibers. However, if the stretch is sustained over time, the bag fiber will reform, activity in the Iₐ axons will decrease, and the stretch will continue with fewer inhibiting signals being sent to the spinal cord. Reformation of the bag fiber with prolonged stretching is termed intrafusal creep.

Deformation of nuclear chain fibers differs from bag fibers because chain fibers do not exhibit intrafusal creep. That is, the deformation in chain fibers remains the entire time the fiber is stretched which results in continued firing of Iₐ axons and sustained inhibition of the stretch. Based on the anatomy of the bag and chain fibers, it seems that static stretching potentially provided a more adequate environment for flexibility gains than ballistic stretching because with sustained stretching the bag fibers have time to reform and reduce the activity in
the I_A fibers. Ultimately, this will decrease the inhibitory signals sent to the muscle and provide a greater ability to stretch without restraint.

Another reason that static stretching may be superior to ballistic techniques is due to the activity of the golgi tendon organs. When a sustained stretch creates significant tension within the muscle and muscle-tendon unit, I_B axons in the golgi tendon organs are stimulated which results in inhibition of the homonymous and synergistic muscles, producing relaxation in the involved muscles. Importantly, the response of the golgi tendon organs only occurs if the deforming stimulus lasts at least six seconds. This reflex relaxation of the agonist muscle is termed autogenic inhibition, and it is theorized that the relaxation of the stretched muscle is a protective mechanism against injury.

As previously stated, ballistic stretching involves short bursts of muscle stretch and relaxation that are repeated with a bouncing or jerking type movement. During the ballistic stretch, the muscle spindles are repeatedly stimulated which produces a continued reflexive contraction of the muscle being stretched and inhibits the effectiveness of the stretch. In addition, the golgi tendon organs are only stimulated for short time periods, less than six seconds, which does not provide enough time for their activation. Therefore, not only does ballistic stretching repeatedly initiate the stretch reflex, but it also prevents autogenic inhibition and the ability to relax the muscle for further stretch.

In contrast, static stretching involves a sustained contraction of longer than six seconds which provides ample time for golgi tendon activation. Interestingly, golgi tendon organs are able to override muscle spindle activity, so
that with a sustained stretch, the golgi tendon organs can prevent reflexive contraction of the stretched muscle and induce relaxation instead. Additionally, the risk of injury associated with sustained or static stretching is less than with ballistic because during a static stretch, the muscle is not inhibited from stretching as it is with ballistic movements. Based on the physiology of the stretch reflex, it would appear that static stretching should be safer and more effective than ballistic stretching. However, when reviewing studies on flexibility and performance outcomes, the difference between static and ballistic techniques appears to be less significant than would be anticipated.

Flexibility, Performance, and Soreness

Although stretching is widely advocated as an effective warm-up before participation in recreational or competitive athletic activities, there is controversy regarding which stretching techniques are most beneficial. In general, stretching is thought to increase range of motion, enhance performance, and prevent injury, and it is generally accepted that static stretching is the safest stretching method for these improvements. A review of the anatomy and physiology of stretch reveals that there is a physiological basis that explains why static stretching techniques should be superior to ballistic techniques. However, comparisons of the two techniques in relation to flexibility and performance show that the physiological differences may not equate to significantly different performance outcomes. In actual practice, the greatest variance between the stretching
methods may be in the perception of the muscle soreness that typically follows stretching exercise.

**Flexibility**

One of the most common reasons for implementing a stretching routine into a fitness program is to improve range of motion of a particular body segment. It is believed that with increased flexibility, performance will be enhanced and the chance of injury will be decreased \(^{18, 53, 57}\). Studies do show that stretching improves flexibility \(^{4, 11, 20, 62, 65}\). An early investigation by DeVries \(^{17}\) comparing static and ballistic stretching in college aged men who trained for seven 30-minute training sessions found that static and ballistic stretching improved flexibility equally. However, the author concluded that static stretching was the preferred stretching technique because, according to the investigators, ballistic stretching may exceed the extensibility of the tissues, uses more energy than static stretching, and causes muscle soreness. However, no actual measurements of tissue extensibility, energy cost, or muscle soreness were made in the study. Recent research has confirmed the work of DeVries \(^{6, 38, 66}\), however, many questions remain.

An investigation by Wieman and Hahn \(^{66}\) compared the effect of stationary cycling, resistance training, and static or ballistic stretching on hip joint flexion. The authors concluded that three 15-second periods of static or ballistic stretching or 15-minutes of stationary cycling resulted in significant increases in hip joint range of motion of 7.8°, 8.4°, and 4°, respectively. There was no
statistical difference between the groups. It may appear that cycling is as
effective as stretching for increasing range of motion. However, another study
examined the effects of static stretching with and without a 10-minute repetitive
stair-climbing warm-up and determined that similar improvements in flexibility
were made between the groups, and the warm-up did not influence the flexibility
outcome\textsuperscript{18}.

The results of the Wiemann and Hahn\textsuperscript{66} study were confirmed by a similar
study comparing static and ballistic stretching techniques\textsuperscript{38}. These investigators
determined that ten ballistic stretches or 90 seconds of static stretching produced
equal improvements in hip range of motion. Although much research has
focused on hamstring flexibility, one study investigated the effects of static and
ballistic stretching on the soleus muscle\textsuperscript{6}. The researchers determined that
similar improvements in flexibility were measured from either 15-seconds of static
stretching or 15 ballistic stretches performed two times per weeks for five weeks.

In contrast to studies supporting the idea that static and ballistic stretching
improve range of motion, one study concluded that flexibility was not enhanced
with these stretching methods. These researchers investigated whether a six-
week stretching program consisting of either static, ballistic, or proprioceptive
neuromuscular facilitation (PNF) techniques would result in similar increases in
flexibility\textsuperscript{52}. Results demonstrated that improvements in flexibility were only
measured with the PNF style of stretching. These findings indicate that flexibility
may not be increased with the static and ballistic stretching methods.
Although there is one study which suggests that static and ballistic stretching are ineffective in increasing range of motion, the majority of studies conclude that the two stretching techniques significantly improve flexibility. In addition, there does not appear to be a difference in flexibility increases between the stretching methods. Therefore, based on flexibility, it seems that both the static and ballistic styles of stretching are equally successful in producing gains in range of motion.

Performance

Another reason exercise enthusiasts and athletes incorporate stretching programs into fitness routines is because of their perception that it may improve performance. The literature on this topic, however, has not always been in agreement with this reasoning\(^2\)\(^1\), \(^2\)\(^6\), \(^4\)\(^5\), \(^5\)\(^6\), \(^6\)\(^7\), \(^6\)\(^8\).

Several studies have looked at jumping performance following various stretching techniques\(^2\)\(^6\), \(^6\)\(^7\). One investigation into the effects of acute static and PNF stretching on jumping performance concluded that drop jump performance was 13cm/s less in subject who completed three 15-second stretches when compared to control subjects\(^6\)\(^7\). The authors speculate that it may be detrimental to warm-up with static stretching immediately before participation in quick response activities like jumping or sprinting. Although a second study investigated whether static stretching affects vertical jump technique, the results were inconclusive\(^2\)\(^6\). They found that static stretching did not affect drop jump performance although it increased countermovement jump height. The authors
conclude that stretching has little effect on jumping technique. Although no strong conclusions regarding jumping performance can be drawn, it appears that there tends to be either no change or a decrease in performance outcome following static stretching.

Recently, a study was conducted that examined the effects of both static and dynamic acute stretching on gymnasts’ speed in vaulting. Run speed on the approach to a vault is one component that determines the quality of execution of the vault. To investigate the question, eleven prepubescent boys participated in three different conditions, namely, warm-up only, warm-up and static stretching, and warm-up and dynamic stretching. The results indicated that vaulting speed significantly decreased only following the warm-up and static stretching conditions. The authors conclude that although stretching is necessary for improvements in flexibility, it is not advisable to include static stretches just prior to vaulting because it may be detrimental to performance.

Although many flexibility studies have focused on the lower body, one examination looked at the effects on elbow torque of acute static stretching of the biceps brachii muscle during fast and slow movements. The authors found that torque decreased significantly following static stretching, regardless of the speed of movement, and suggested that static stretching may be contraindicated before activities that require maximal muscle activation.

In contrast to the studies on the effects of static stretching on performance, only one study examining the relationship between ballistic stretching and performance was found. This study investigated whether both
static and ballistic stretching inhibited maximal strength performance. The authors found that both ballistic and static stretching of the knee flexor and extensor muscles significantly decreased knee flexion and extension strength. They concluded that maximal strength is inhibited following stretching, regardless of technique, and stretching should not be performed prior to events where success is determined by maximal strength output.

Even though research focusing on the influence of static and ballistic stretching on performance outcomes is somewhat limited, this research appears to show that both techniques tend to decrease performance. Therefore, it does not appear that, in terms of performance, one stretching method is better than the other. Since both flexibility and performance outcomes are similar between the static and ballistic stretching techniques, it remains unclear as to which method of stretching is superior. One area of difference may be in the perceived soreness experienced following the two stretching techniques.

**Perceived Soreness**

Although stretching is widely advocated by coaches and clinicians as a method of injury prevention, it is generally agreed upon that stretching does not prevent injury. What remains unclear is whether a novel stretching event can induce muscle soreness and, if so, whether there is a difference in perceived soreness between the stretching techniques.

One study investigated whether there was a difference in perceived muscle soreness and creatine kinase measures, a blood marker of muscle injury,
in people who exercised using either static or ballistic methods of stretching. Subjects in the study performed three identical, one minute, sets of seventeen stretches which included both upper- and lower- body exercises. The authors concluded that both groups had increased creatine kinase levels which indicates that muscle injury occurred due to the stretching exercise, regardless of stretching technique. In addition, both groups exhibited the greatest muscle soreness at 24 hours after the stretching bout. Interestingly, people who used the static method exhibited significantly higher levels of muscle soreness than those who used the ballistic method. It may be suggested that the significant level of soreness in this study was due to the large number of stretches as well as the extended time period that each stretch was held, which were both in excess of what most recreational and competitive athletes devote to stretching routines. However, these results have been confirmed by another, more realistic stretching study.

Recently, an investigation comparing the influence on perceived muscle soreness, flexibility, and vertical jump performance of various stretching techniques was conducted. Subjects in this study were required to perform five different lower body stretches targeting the quadriceps, hamstrings, gastrocnemius, and soleus muscles using one of three different methods of stretching, namely static, ballistic, and progressive velocity. Stretches were sustained for 30 seconds and repeated three times. Results indicated that more muscle soreness was reported with static than ballistic stretching. Therefore, even a typical stretching program consisting of 30 second stretches produced
significant increases in perceived muscle soreness that were greater in the static than ballistic groups.

Ballistic stretching is commonly contraindicated because it is believed to be associated with a high risk of injury. The investigations by Smith et al. 59 and Multer et al. 44 demonstrate that static stretching induces more muscle soreness than ballistic stretching and provides evidence against the contraindication of ballistic stretching. It is possible that the recommendations against ballistic stretching are unjustified, however, why differences in perceived soreness exist between the two techniques remains unknown.

**Muscle Injury**

One possible explanation for differences in soreness reported between static and ballistic stretching lies in the mechanism of muscle injury. It is generally accepted that eccentric, or lengthening, muscle contractions result in significantly more muscle damage than concentric, or shortening, muscle contractions 2, 12-14, 58. It is theorized that because eccentric contractions recruit fewer motor units than concentric contractions, there is greater tension or stress placed over a smaller cross-sectional area of muscle during eccentric as compared to concentric movements 1, 14, 60. Although tension is partly responsible for muscle injury, it is hypothesized that the amount of strain or change in length of a muscle is more directly related to the extent of injury than the amount of force generated by the muscle 32, 33. Moreover, it has been reported that muscles exercised eccentrically at long muscle lengths as opposed
to short muscle lengths result in more muscle damage which further supports the idea that strain, not force, causes damage\textsuperscript{10}.

Damaged muscle fibers are believed to have a distinct appearance. It is hypothesized that as sarcomeres are stretched through the lengthening motion of eccentric contractions, structural damage occurs within the cytoskeleton and sarcolemma of the muscle fibers\textsuperscript{14,34}. Stretched sarcomeres are described as having z-line streaming which means that the z-lines within the muscle fiber are no longer in line, and, instead, are stretched out and appear to be streaming across the sarcomere\textsuperscript{35}. Although the mechanism of z-line streaming is unknown, it is thought that the streaming may be due to damage of the cytoskeletal proteins that are responsible for maintaining the normal striated appearance of skeletal muscle\textsuperscript{34,35}.

Accompanying muscle damage and structural changes within the tissue are symptoms characteristic of muscle injury, including muscle soreness. After unaccustomed or novel exercise, the sensation of pain is felt within the involved muscles, and usually peaks between 24 and 72 hours after the exercise\textsuperscript{1,13,58,59}. This perception of pain is termed delayed onset muscle soreness (DOMS). The exact mechanism of DOMS is unknown, however, it is thought that swelling or pressure coupled with the release of chemical mediators may stimulate type III and IV pain fibers, ultimately producing the sensation of pain\textsuperscript{23,58,61}.

Interestingly, stretching a muscle involves eccentric muscle contractions which, as previously stated, are the type of contraction known to induce muscle injury and DOMS. Perhaps, alterations within muscle tissue as a result of
eccentric exercise, such as z-line streaming, are the same as the adaptations that occur within muscle that is stretched during a routine exercise program. It may be argued that stretching in order to prevent muscle soreness is irrelevant because it is quite possible that a novel stretching program could induce muscle soreness due to the eccentric motions involved with various stretching techniques.

What remains to be determined is whether different stretching methods stress muscle tissue the same and result in equal amounts of muscle damage. Ballistic stretching is contraindicated because of its inconsistent movement and the associated high forces. Interestingly, research on muscle injury due to lengthening contractions shows that muscle damage may be the result of high strain as opposed to high force, which might make the static stretch more susceptible to injury than the ballistic stretch. A possible explanation of this may be that people who stretch statically maintain the stretch at a longer length than people who stretch using ballistic methods. That is, as time progresses with a static stretch, the maximum length of stretch, or range of motion, may increase as the person becomes more comfortable with the stretching procedure. During subsequent stretches, the stretcher may become even more accustomed to the stretch and extend even further. In contrast, ballistic stretchers may not stretch to the maximum extent of the range of motion. The ballistic technique may result in a greater force due to the rapid stretch-relax pattern of the technique, but the tissue may not be strained to the same degree as with a static stretch. However,
research into the muscle activity and biomechanics of the static and ballistic stretching techniques is necessary in order to examine this theory.

Electromyography (EMG) provides insight into the activity within muscle and may help to determine whether forces within the muscle contribute to muscle injury and the perception of soreness following different stretching techniques. A few studies have investigated EMG activity associated with stretching techniques and have focused on whether or not EMG activity is present in muscle tissue during stretching exercises. In general, it has been found that low level EMG activity is present during stretching motions. However, it remains unclear as to whether a bout of stretching influences post stretching muscle activity and if the effect depends on the stretching method used. An understanding of the type of activity within the muscle following static or ballistic stretching would help to elucidate whether differences in stretching technique contribute to the varied soreness perceptions reported in previous studies. In addition, assessment of the biomechanics of a post-exercise stretching maneuver would provide insight into the range of motion at the hip which may be indicative of tissue pliability increases. Through a biomechanical assessment of the stretching motion during a post maximal stretch, it is possible to determine whether the static or ballistic stretching technique influences the biomechanics and muscle activity differently and if these differences are clinically relevant.

Over the years, ballistic stretching has been discouraged, due to its rapid motions and uncontrolled movements. However, studies have shown that static stretching results in greater perceived muscle soreness than ballistic stretching.
Possible explanations include differences in the muscle activity or range of motion associated with the different techniques, although no studies have investigated these variables. Therefore, the present study will attempt to determine whether muscle activity patterns and the kinematics of post stretching motions help to explain differences in perceived soreness reported in other investigations.

Conclusion

Popular belief maintains that static stretching is superior to ballistic stretching because it involves safer, more controlled movements. In theory, static and ballistic techniques may influence the passive and active restraints of stretch differently, with ballistic stretching producing greater tension within the muscle-tendon unit, resulting in tissue damage. In addition, it is possible that the stretch reflex may be continually activated with ballistic stretching, causing a restriction in the ability to stretch, and again, an increased risk of injury. Studies on the viscoelastic properties of the muscle-tendon unit show that increases in length are potentially the result of either the viscoelastic properties of the tissue or the subject’s ability to sustain greater levels of muscle strain.

Based on previous research, the only difference between the techniques is in the reported perceived soreness, with static stretching resulting in greater soreness than ballistic. Unfortunately, no studies have investigated why the difference in soreness is found. Muscle injury is typically the result of eccentric contractions which are the type of contraction involved with stretching.
movements. Ballistic stretching is thought to be more prone to injury because it produces high muscle forces. However, studies investigating muscle injury show that high strain rates as opposed to high forces are responsible for tissue damage which makes it more likely that a sustained static stretch would result in injury than a short ballistic stretch. In addition, the biomechanics of the static and ballistic stretch may provide insight into soreness differences observed. That is, there may be a difference between the range of motion and active strain used in the static and ballistic stretch, with static stretches incorporating a larger range of motion, and hence greater strain, than ballistic stretches. Unfortunately, the relationship between muscle activity, range of motion, perceived soreness, and static and ballistic stretching techniques has largely been overlooked. Therefore, this study provided an investigation into these relationships in an attempt to discover the mechanism responsible for differences reported in soreness perception following static and ballistic stretching techniques.
CHAPTER III

METHODOLOGY

Subjects

Thirteen men and six women (22.5 ± 4.5 yrs.) served as subjects for this study. Only healthy subjects with no history of musculoskeletal disease, preexisting inflammatory conditions, or recent lower extremity orthopedic injuries participated in the study. Subjects in the study were active individuals who had not performed regular stretching exercises in the last six months. It was required that the subjects maintain the same activity level throughout the duration of data collection. Inclusion in the study was dependent on the subject signing a written informed consent form in accordance with The University of Toledo’s guidelines for protection of human subjects (Appendix A).

Experimental Design

Each subject participated in a test of a static (STA) and a ballistic (BAL) stretching condition which was separated by a 20 minute rest period. During both of the stretching conditions, the subjects were asked to stretch the hamstring muscles for a period of 30 seconds, followed by a 30 second rest period. The hamstring stretch was repeated two times for each condition,
resulting in a total of three stretches per condition. Immediately before and after
the STA and BAL stretching conditions, subjects were asked to perform a
maximum stretch of the hamstring muscle. The STA and BAL evaluations were
conducted in the same testing session, however the stretching technique and
limb stretched differed. A randomized crossover design was used to assign both
condition, STA or BAL, and limb, right or left. Measurements of muscle activity
and joint kinematics were taken during both the stretching exercises and the pre
and post maximum stretches. Assessment of muscle soreness was made prior
to stretching as well as at five minutes, 24h, 48 h, and 72 h after stretching.

**Retroflective Marker and Electrode Placement**

Half inch retroflective markers were carefully placed, bilaterally, on the
ulnar styloid process, lateral epicondyle of the humerus, acromion process, iliac
crest, greater trochanter, lateral epicondyle of the femur, lateral malleolus, lateral
calcaneus, and the distal end of the 5th metatarsal. Noraxon Dual Electrodes
(Noraxon U.S.A., Inc, Scottsdale, AZ) were secured on selected muscles.
Specifically, the Ag/AgCl electrodes were placed on the proximal, distal, medial
and lateral hamstring muscles as well as on the medial and lateral
gastrocnemius, and the mid-belly of the gluteus maximus and rectus femoris
muscles, bilaterally. Every effort was made to position the electrodes in the
same location on both limbs of the subjects. To ensure strong marker adherence
and electrode contact, the areas for marker and electrode placement were
cleaned with alcohol and allowed to air dry prior to attachment on the body.
Experimental Protocol and Stretching Maneuvers

Prior to each stretching condition, subjects were asked to perform a five-minute warm-up consisting of riding a stationary bike at a self-selected pace. After the warm-up, retroflective markers and EMG electrodes were attached to the subject as previously described. Once the markers and electrodes were placed on the body, a visual demonstration was given to the subject showing him/her the proper technique for the stretches and, during that time, the subject was given the opportunity to practice the body position for the stretching maneuver. Correct positioning for the stretches required that the subject sit with one lower limb extended and the other lower limb flexed at the knee, with the plantar surface of the foot on the bent limb lightly touching the inner thigh of the extended limb. Knee position was controlled by placing half of a tennis ball under the subject’s knee and instructing the subject to maintain contact with the ball during all of the stretching maneuvers. No attempt was made to control for ankle position. Figures 1 (side view) and 2 (front view) show the placement of the reflective markers and the body position used during the stretch. To perform the stretch, the subject was instructed to bend forward from the hips until a slight tightness was felt in the hamstrings, but no pain was experienced. It was stressed that the subject was to maintain a straight back and to concentrate on bending only at the hips. During the stretching maneuver, subjects were encouraged to reach with extended arms for a stationary marker that was located in front of the stretching platform at a height equal to the height of the subject’s
arms. Subjects were given verbal feedback regarding correct body position throughout the stretching exercise.

Figure 1: Stretching Position and Marker Placement, Lateral View

Figure 2: Stretching Position and Marker Placement, Anterior Angle View
Although the initial body position was the same for both the STA and BAL stretching conditions, the stretching technique differed. When performing the STA stretch, the subject was instructed to hold the stretch consistently for 30 seconds. After 30 seconds, the subject was allowed to rest for 30 seconds. The stretch-rest pattern was repeated two more times. During the BAL stretch, the subject was instructed to perform an end-range bouncing movement throughout the stretch which resulted in a rapid stretch-relax pattern of motion. The stretch-relax cycle occurred rapidly at 60 bounces/minute and was repeated consistently for the duration of the 30-second stretch. Rhythm of the ballistic stretch was maintained with a metronome. As with the static condition, there was a 30-second rest period following the stretching exercise, and the BAL stretch was repeated two more times as well. Kinematic and EMG data were collected during the entire stretching exercise.

Immediately prior to and after the stretching session, subjects performed a maximum stretch using the correct stretching form. The stretch was a static stretch and allowed for measurement of maximum stretch distance and comparison of pre- and post-stretching distance changes.

Following both the STA and BAL protocols, measurements of maximum voluntary contractions (MVC) for the hamstring, quadriceps, gastrocnemius, and gluteus maximus muscles were made using manual resistance.
Kinematic and EMG Data

Kinematic data was collected using an eight camera Motion Analysis EVa Hi-Res system (Motion Analysis Corporation, Santa Rosa, CA). The EVa Hi-Res system is an integrated hardware-software system for video and analog data acquisition and processing. Sampling of kinematic data occurred at 60 Hz and the raw data was low pass filtered at 10 Hz.

Motion of the retroreflective markers placed on each subject was collected using eight Falcon High Resolution cameras (Motion Analysis Corporation, Santa Rosa, CA). Each camera produces a strobed light which illuminated the retroreflective markers and produced an image of each marker which was directly transmitted to the video processor/computer (MiDAS). MiDAS produced coordinates of each marker and sent the data to a computer which used the EVa Hi-Res software (version 6.15) to process the video data. Processing of the video data included tracking, rectification, interpolation, and smoothing of all data points. After the data was processed, the kinematic data was transferred to KinTrak (version 6.2.2) (Motion Analysis, Santa Rosa, CA) for further data analysis.

KinTrak was used to describe joint movement during the stretching exercise as well as during the pre- and post- maximum stretches. Specific variables that were measured and analyzed were hip flexion and maximum distance stretched. Hip flexion was determined by markers placed on the lateral epicondyle of the femur, greater trochanter of the femur, and acromion process of the scapula. Maximum distance stretched was calculated from the marker on
the acromion process of the scapula to a stationary marker located in front of the subject.

Electromyography data was collected using a telemetry system (Telemyo, Noraxon U.S.A, Inc., Scottsdale, AZ). The telemetry system included eight bipolar electrode leads, a transmitter and a receiver/signal processor/amplifier. The EMG data was transferred from the Telemyo system to the Eva Hi-Res system, A/D converted at 960 Hz and time-matched with the video data. Following data collection, the EMG data was imported into the MyoResearch software (Noraxon U.S.A., Inc., Scottsdale, AZ).

MyoResearch was used to analyze the data regarding muscle activity during the stretching exercises, the pre- and post- maximum stretches, and the MVC data. All EMG data from the stretching trials and the pre and post maximum stretch maneuvers was normalized by dividing the EMG value by the MVC. Thus, EMG results are expressed in units of percent of MVC. Specific analysis of the EMG data took place at the point where maximum stretched distance occurred in the pre and post maximum stretches and was assessed for a 200 millisecond time period that surrounded the time of maximum stretch.

Both the kinematic and EMG data were collected for the duration of the three 30-second stretching exercises as well as for five seconds before and after the stretch for all trials in both the STA and BAL conditions.
Measurement of Perceived Soreness

A Visual Analog Scale (VAS) was used to assess perceived muscle soreness prior to stretching as well as at five minutes post, and at 24, 48, and 72 hours after stretching. The VAS required that the subject rate his/her soreness on a 10cm line with one end of the line referring to no soreness and the other end of the line indicating extreme soreness. Subjects rated soreness separately for the right and left hamstring muscle groups.

Statistical Analysis

Comparison of both the STA and BAL maximum stretch distance and the hip angle during the pre and post maximum stretch maneuver was determined with a repeated measures analysis of variance (ANOVA). A t-test was used for statistical analysis to determine differences in EMG data during the pre and post maximum stretch maneuvers in both the STA and BAL conditions. Finally, differences in perceived soreness ratings between the two conditions were determined using a repeated measures ANOVA. An alpha level of 0.05 was used to determine the significance found. Mean scores and standard errors were calculated and reported for each variable.
CHAPTER IV
RESULTS

Measurements of the effects of static and ballistic stretching on hamstring flexibility and soreness were made in order to determine whether the two stretching techniques differed in maximum stretch distance, maximum hip angle, perceived soreness, and muscle activity. Following data collection, a power analysis was run on the difference between groups, and it was determined that with 18 subjects, the power equaled 0.94.

Maximum Stretch Distance

Maximum stretch distance was determined as the distance from the acromioclavicular (AC) joint to a fixed marker that was located in front of each subject. Results show that maximum distance of stretch significantly increased following the stretching exercise, regardless of the stretching method used (Table 1 & 2; Figure 3). Effect size was measured using the Cohen’s d and it was determined that there was a moderate effect size of 0.7. There was no main effect for stretching method nor was there an interaction between stretching method and time (Figures 4 & 5, respectively). These results indicate that maximum distance stretched did not differ between the STA and BAL groups at
any time. Figure 6 verifies that there was no difference in stretching distance between the STA and BAL groups as it graphically represents the difference in stretching distance between the pre and post stretching maximal stretches.

Table 1: Descriptive Statistics: Pre and Post Maximum Distance Stretched

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<th>Source</th>
<th>n</th>
<th>Mean and SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stretch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STA</td>
<td>17</td>
<td>398.1 ± 15.7</td>
</tr>
<tr>
<td>BAL</td>
<td>17</td>
<td>421.8 ±17.5</td>
</tr>
<tr>
<td>Time*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>17</td>
<td>387.4 ± 13.8</td>
</tr>
<tr>
<td>Post</td>
<td>17</td>
<td>432.5 ± 16.6</td>
</tr>
<tr>
<td>Stretch x Time</td>
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<td></td>
</tr>
<tr>
<td>STA Pre</td>
<td>17</td>
<td>374.4 ± 15.4</td>
</tr>
<tr>
<td>STA Post</td>
<td>17</td>
<td>421.7 ± 17.6</td>
</tr>
<tr>
<td>BAL Pre</td>
<td>17</td>
<td>400.3 ± 16.5</td>
</tr>
<tr>
<td>BAL Post</td>
<td>17</td>
<td>443.2 ± 19.2</td>
</tr>
</tbody>
</table>

* indicates significant difference p < 0.05

Table 2: ANOVA Summary Table: Maximum Distance Stretched

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>Df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stretch</td>
<td>10140.1</td>
<td>1</td>
<td>10140.1</td>
<td>2.476</td>
<td>0.13</td>
</tr>
<tr>
<td>Time</td>
<td>36675.8</td>
<td>1</td>
<td>36675.8</td>
<td>42.134</td>
<td>p &lt; 0.05*</td>
</tr>
<tr>
<td>Stretch x Time</td>
<td>90.1</td>
<td>1</td>
<td>90.1</td>
<td>0.165</td>
<td>0.69</td>
</tr>
</tbody>
</table>

* indicates statistically significant
**Figure 3:** Difference Between Pre and Post Maximum Distance Stretched Across Time (repeated measures ANOVA). Measurements were taken before and after the stretching exercise. All values are mean ± SEM, n = 18. * indicates significantly different (p<0.05) from the Pre measurement.

**Figure 4:** Stretching Distance for the STA and BAL Conditions (repeated measures ANOVA). All values are mean ± SEM, n = 18.
Figure 5: Stretching Distance for the STA and BAL Conditions Across Time (repeated measures ANOVA). Measurements were taken before and after the stretching exercise. All values are mean ± SEM, n = 18.

Figure 6: Difference from Pre to Post Maximum Stretch Distance for the STA and BAL Conditions. Measurements were taken before and after the stretching exercise. All values are mean ± SEM, n = 18.
**Hip Angle**

Hip angle was defined as the angle created by two segments, with segment one spanning from the lateral condyle of the knee to the greater trochanter of the femur and segment two connecting the greater trochanter of the femur to the acromioclavicular joint of the shoulder. The actual angle that was calculated was the posterior angle, so that an increase in hip flexion was recorded as an increase in angle size. Maximum hip angle was defined as the hip angle that corresponded to the maximum stretched distance. Recall that maximum distance stretched was calculated from the AC joint to the fixed marker. Results indicate that maximum hip angle increased from the pre to post maximum stretch maneuvers, regardless of stretching method used (Tables 3 & 4; Figure 7). Effect size was measured using the Cohen's d and it was determined that there was a small effect size of 0.35. There was no main effect for stretching method nor was there an interaction between stretching method and time (Table 4; Figures 8 & 9, respectively). These results indicate that maximum hip angle did not differ between the STA and BAL stretching groups at any time (Figures 9 & 10).
Table 3: Descriptive Statistics: Hip Angle

<table>
<thead>
<tr>
<th>Source</th>
<th>n</th>
<th>Mean ± SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stretch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STA</td>
<td>17</td>
<td>124.9 ± 2.3</td>
</tr>
<tr>
<td>BAL</td>
<td>17</td>
<td>124.2 ± 2.2</td>
</tr>
<tr>
<td>Time*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>17</td>
<td>122.9 ± 2.2</td>
</tr>
<tr>
<td>Post</td>
<td>17</td>
<td>126.2 ± 2.3</td>
</tr>
<tr>
<td>Stretch x Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STA Pre</td>
<td>17</td>
<td>122.8 ± 2.4</td>
</tr>
<tr>
<td>Post</td>
<td>17</td>
<td>126.9 ± 2.4</td>
</tr>
<tr>
<td>BAL Pre</td>
<td>17</td>
<td>123.0 ± 2.1</td>
</tr>
<tr>
<td>Post</td>
<td>17</td>
<td>125.4 ± 2.3</td>
</tr>
</tbody>
</table>

* indicates significant difference p < 0.05

Table 4: ANOVA Summary Table: Hip Angle

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stretch</td>
<td>7.3</td>
<td>1</td>
<td>7.3</td>
<td>0.527</td>
<td>0.478</td>
</tr>
<tr>
<td>Time</td>
<td>183.3</td>
<td>1</td>
<td>183.3</td>
<td>19.596</td>
<td>&lt; 0.05*</td>
</tr>
<tr>
<td>Stretch x Time</td>
<td>12.4</td>
<td>1</td>
<td>12.4</td>
<td>2.035</td>
<td>0.173</td>
</tr>
</tbody>
</table>

* indicates statistically significant
Figure 7: Hip Angle at Point of Maximal Hip Flexion During Pre and Post Maximal Stretch Maneuvers (repeated measures ANOVA). Measurements were taken before and after the stretching exercise. All values are mean ± SEM, n = 17. * indicates significantly different (p<0.05) from the Pre measurement.

Figure 8: Hip Angle and Stretching Method (repeated measures ANOVA). All values are mean ± SEM, n = 17.
Figure 9: Hip Angle for the STA and BAL Conditions Across Time (repeated measures ANOVA). Measurements were taken before and after the stretching exercise. All values are mean ± SEM, n = 17.

Figure 10: Hip Angle at Maximum Stretch for the STA and BAL Conditions During the Pre and Post Maximum Stretch Maneuvers. Measurements were taken before and after the stretching exercise. All values are means, n = 17.
EMG Activity

Muscle activity was recorded during the pre and post maximum stretch maneuvers, and the difference between the two readings was used for statistical analysis. Mean EMG refers to the muscle activity that occurred at the time of maximum stretch and is the average of two milliseconds. Results show that static and ballistic stretching did not significantly influence muscle activity in any of the muscles examined (Table 5; Figure 11). The difference in EMG activity before and after the STA or BAL conditions was relatively the same and not significantly different. Differences in subject number are due to outliers, where data was removed from analysis if the EMG value exceeded two times the standard deviation.

Table 5: Descriptive Statistics and Summary: EMG Activity

<table>
<thead>
<tr>
<th>Condition</th>
<th>Muscle</th>
<th>N</th>
<th>Mean ± SEM</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>STA</td>
<td>Glut Max</td>
<td>17</td>
<td>1.3 ± 0.60</td>
<td>1.036</td>
<td>0.316</td>
</tr>
<tr>
<td>BAL</td>
<td>Glut Max</td>
<td>17</td>
<td>0.4 ± 0.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STA</td>
<td>Prox Ham</td>
<td>15</td>
<td>-1.1 ± 0.28</td>
<td>-0.973</td>
<td>0.347</td>
</tr>
<tr>
<td>BAL</td>
<td>Prox Ham</td>
<td>15</td>
<td>-0.35 ± 0.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STA</td>
<td>Distal Ham</td>
<td>17</td>
<td>-1.76 ± 1.49</td>
<td>-0.86</td>
<td>0.402</td>
</tr>
<tr>
<td>BAL</td>
<td>Distal Ham</td>
<td>17</td>
<td>0.23 ± 1.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STA</td>
<td>Med Ham</td>
<td>17</td>
<td>-1.82 ± 1.21</td>
<td>-0.896</td>
<td>0.383</td>
</tr>
<tr>
<td>BAL</td>
<td>Med Ham</td>
<td>17</td>
<td>-0.18 ± 0.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STA</td>
<td>Lat Ham</td>
<td>16</td>
<td>-0.06 ± 1.14</td>
<td>-0.42</td>
<td>0.681</td>
</tr>
<tr>
<td>BAL</td>
<td>Lat Ham</td>
<td>16</td>
<td>0.41 ± 0.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STA</td>
<td>Med Gastroc</td>
<td>15</td>
<td>2.31 ± 3.0</td>
<td>0.50</td>
<td>0.625</td>
</tr>
<tr>
<td>BAL</td>
<td>Med Gastroc</td>
<td>15</td>
<td>1.39 ± 1.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STA</td>
<td>Rectus Femoris</td>
<td>15</td>
<td>-1.43 ± 0.96</td>
<td>-1.813</td>
<td>0.091</td>
</tr>
<tr>
<td>BAL</td>
<td>Rectus Femoris</td>
<td>15</td>
<td>1.05 ± 1.15</td>
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<td></td>
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</table>
Muscle Activity During Maximum Stretch

<table>
<thead>
<tr>
<th>Muscle</th>
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<th>BAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glut Max</td>
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<tr>
<td>Prox Ham</td>
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<td></td>
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<tr>
<td>Dist Ham</td>
<td></td>
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</tr>
<tr>
<td>Med Ham</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lat Ham</td>
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<td></td>
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<tr>
<td>Med Gastroc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rect Fem</td>
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<td></td>
</tr>
</tbody>
</table>

**Figure 11:** Change in EMG Activity During the Maximum Stretch Maneuver (t-tests). Measurements were taken before and after the stretching exercise. All values are mean ± SEM, n = 18.

**Perceived Soreness**

Values for the soreness data were calculated as difference scores from the pre measurement. Perceived soreness did not differ between the static and ballistic stretching groups at any time (Tables 6 & 7). Although not statistically significant, soreness was greater following the stretching exercise, regardless of stretching method (Figure 12). There was no main effect for stretching method nor was there an interaction between stretching method and time (Figures 13 & 14, respectively). These results indicate that perception of muscle soreness did not differ between the stretching groups. However, several trends are worth mentioning (Figure 14). Initially, as seen with the difference score from the pre to post test measurements, static stretching tends to initially produce more soreness more than ballistic stretching. In contrast, ballistic stretching seems to
increase soreness more gradually when compared to static stretching. It appears that both the STA and BAL groups experienced the greatest amount of soreness 48 h after stretching with a decrease in soreness from 48 h to 72 h post stretching exercise.

Table 6: Descriptive Statistics: Perceived Soreness

<table>
<thead>
<tr>
<th>Source</th>
<th>n</th>
<th>Mean ± SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stretch</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STA</td>
<td>16</td>
<td>6.0 ± 1.3</td>
</tr>
<tr>
<td>BAL</td>
<td>16</td>
<td>6.4 ± 2.4</td>
</tr>
<tr>
<td><strong>Time</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post</td>
<td>16</td>
<td>5.8 ± 1.7</td>
</tr>
<tr>
<td>24 h</td>
<td>16</td>
<td>5.8 ± 1.9</td>
</tr>
<tr>
<td>48 h</td>
<td>16</td>
<td>8.7 ± 3.1</td>
</tr>
<tr>
<td>72 h</td>
<td>16</td>
<td>4.6 ± 3.3</td>
</tr>
<tr>
<td><strong>Stretch x Time</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STA Post</td>
<td>16</td>
<td>6.9 ± 2.1</td>
</tr>
<tr>
<td>24 h</td>
<td>16</td>
<td>5.6 ± 1.8</td>
</tr>
<tr>
<td>48 h</td>
<td>16</td>
<td>8.1 ± 2.6</td>
</tr>
<tr>
<td>72 h</td>
<td>16</td>
<td>3.6 ± 2.3</td>
</tr>
<tr>
<td>BAL Post</td>
<td>16</td>
<td>4.7 ± 1.7</td>
</tr>
<tr>
<td>24 h</td>
<td>16</td>
<td>6.1 ± 2.1</td>
</tr>
<tr>
<td>48 h</td>
<td>16</td>
<td>9.2 ± 4.4</td>
</tr>
<tr>
<td>72 h</td>
<td>16</td>
<td>5.7 ± 4.6</td>
</tr>
</tbody>
</table>

Table 7: ANOVA Summary Table: Perceived Soreness

<table>
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<tr>
<th>Condition</th>
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<th>df</th>
<th>MS</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
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<td>5.06</td>
<td>0.05</td>
<td>0.82</td>
</tr>
<tr>
<td>Time</td>
<td>317.85</td>
<td>3</td>
<td>105.95</td>
<td>0.58</td>
<td>0.63</td>
</tr>
<tr>
<td>Stretch X Time</td>
<td>88.58</td>
<td>3</td>
<td>29.52</td>
<td>0.65</td>
<td>0.58</td>
</tr>
</tbody>
</table>
Figure 12: Perceived Soreness Over Time (repeated measures ANOVA). Measurements were taken before the stretching exercise, immediately after stretching, and at 24, 48, and 72 hours post stretching. All values are mean ± SEM, n = 16.

Figure 13: Soreness Ratings for Stretching Method (repeated measures ANOVA). All values are mean ± SEM, n = 16.
Figure 14: Soreness Ratings for the STA and BAL Conditions Over Time (repeated measures ANOVA). Measurements were taken before the stretching exercise, immediately after stretching, and at 24, 48, and 72 hours post stretching. All values are mean ± SEM, n = 16.
CHAPTER V
DISCUSSION

The purpose of this investigation was to determine whether selected factors related to muscle stretch were affected differentially by involvement in bouts of static and ballistic stretching exercise, through the examination of the kinematics and muscle activity of a post-exercise maximum stretch. Results indicated that the static and ballistic stretching techniques did not differ in their influence on a post maximum stretch nor was there a difference in the perceived soreness associated with the two stretching techniques. Therefore, it appears that static and ballistic stretching are more similar than different, which contradicts popular belief.

Maximum Stretch Distance

Maximum stretch distance was calculated in order to determine whether there was a difference in ability to stretch following static or ballistic exercises. Increases in ability to stretch reflect range of motion improvements and are potential indirect indicators of increased hamstring flexibility. It was hypothesized that the post-maximum stretch distance would be greater when compared to the pre-maximum stretch distance, regardless of type of stretching used. Results confirm this hypothesis because the maximum distance stretched following a
bout of stretching increased by nearly 1.8 inches compared to the pre measurement (Figure 3). Effect size for maximum distance stretched was 0.70 which is moderate and indicates that the increase in hip flexion is moderately clinically relevant. Therefore, stretching is a valid method of acutely influencing flexibility by producing moderate improvements in range of motion.

It was also hypothesized that the increase in stretch distance from the pre to post measurements would not differ between the STA and BAL conditions and that the two techniques would produce similar improvements in range of motion. Again, the results confirm this hypothesis as both static and ballistic stretching increased range of motion (Figure 6). Therefore, an acute bout of stretching performed using either static or ballistic techniques appears to produce similar gains in stretching distance which confirms previous research. However, although it has been established that static and ballistic stretching improve range of motion, the elucidation of what causes the increase in range of motion remains unclear. Several theories regarding flexibility and range of motion increases following stretching have been proposed, which include the stretch reflex, alterations in the viscoelastic properties of the muscle-tendon unit, and stretch tolerance.

The stretch reflex has been presented as the strongest argument against ballistic stretching. Rapid stretching motions are thought to quickly deform the nuclear bag and chain fibers which results in increased stimulation of I_A nerve fibers and, subsequently, resistance to stretch. A sustained stretch, in contrast, allows time for bag fibers to reform, which decreases the activity of I_A fibers and
limits the inhibiting signals sent to the spinal cord. Therefore, the ability to improve range of motion with a slow stretch is theoretically greater. In addition, a sustained stretch allows sufficient time for activation of golgi tendon organs and the initiation of the lengthening reaction within the stretched muscles. The combined action of fewer inhibiting signals and the initiation of golgi tendon organs makes it seems logical that a static stretch would result in greater range of motion and flexibility than a ballistic stretch.

However, in the current study there was no difference in stretching distance between the two types of stretches. Although muscle spindle and golgi tendon organ activity was not measured in this study, it does not appear that these proprioceptors had a clinically significant influence over range of motion following either static or ballistic stretching because stretching increases were similar. Therefore, even if ballistic motions stimulate more Type I_A fibers and do not activate golgi tendon organs, it does not seem like the combination of these negative influences significantly affects the ability to increase range of motion following ballistic exercise.

Another theory regarding range of motion and flexibility gains targets the viscoelastic property of muscle. Viscoelastic materials are capable of the physiological properties of stress relaxation, creep, and hysteresis. Therefore, it is theorized that when viscoelastic materials, such as muscle, are stretched the physical properties within the material are altered. In terms of stretching, the theoretical response occurs as follows. During static stretching, the muscle is thought to relax through stress relaxation and lengthen through
creep, and these alterations are thought to occur throughout the duration of the stretching exercise. It is theorized that stress relaxation and creep result in improvements in both range of motion and flexibility.

In contrast, ballistic stretching is thought to increase range of motion and flexibility through stress relaxation and hysteresis. During the deformation-relaxation cycle that occurs with one ballistic movement, the tissue is postulated to undergo stress relaxation. The repetitive bouncing motions associated with ballistic stretching produce small increases in tissue relaxation that accumulate and are thought to result in improvements in range of motion and tissue flexibility. Therefore, through the viscoelastic properties of muscle tissue, the static and ballistic stretching techniques can alter flexibility. One study did support the belief that improvements in range of motion following passive static stretching were due to viscoelastic stress relaxation, based on the observation that during the stretch there was no visible EMG activity. However, it is generally believed that viscoelastic stress relaxation through stretching is short lived and the more predominant influence on improved flexibility and range of motion is increased stretch tolerance.

In contrast to the immediate effects of stretching, more long-term changes in range of motion and flexibility have been attributed to increases in stretch tolerance. Stretch tolerance refers to the ability of a person stretching to tolerate the strain of the muscle stretch. As a person stretches, he/she becomes accustomed to the feeling of the stretch and is able to tolerate higher levels of strain which ultimately results in improved range of motion.
One study found that although three 45 second static stretches resulted in 20% viscoelastic stretch relaxation, the absolute resistance in the three stretches was similar\(^{37}\). Thus, a 45 second stretch did not influence the resistance to stretch in subsequent stretches. The authors concluded that improvements in range of motion were due to increases in stretch tolerance as opposed to changes in the viscoelastic property of the muscle tissue.

In the current study it is thought that the acute increases in stretching distance are attributed to increased stretch tolerance as opposed to the stretch reflex or alterations in the viscoelastic properties of the muscle tissue.

**Hip Angle**

Hip flexion angle was measured in order to confirm that stretching distance is primarily a function of this motion, as opposed to the motion of other segments that could contribute to this measure. It was hypothesized that post maximum hip angle would be greater when compared to pre maximum hip angle, regardless of stretching method used. In this study, a larger hip angle corresponded to an increase in hip flexion. Results support the hypothesis as hip angle did significantly increase by 3.3 degrees following the stretching exercises (Figure 7). In addition, the hypothesis that hip angle would not differ between the STA and BAL conditions was also supported which follows consistently with the data regarding maximum distance stretched. From the results, it does not appear that method of stretching significantly influences hip angle as similar changes in hip angle were found with static and ballistic stretching. In addition,
since both hip angle and stretching distance increased following stretching exercise, it is likely that part of the improvement in stretching distance is due to greater hip flexion.

Although there was a significant increase in hip flexion following a bout of stretching, the effect size was relatively small, 0.35. The small effect size indicates that the increase in hip flexion is important but does not hold strong clinical relevance. Therefore, there is likely some other mechanism in addition to hip angle that is producing the increase in range of motion.

Possible explanations for greater hip flexion include an increase in the flexibility of the muscle due to alterations in the viscoelastic properties of the tissue or an increase tolerance to the stretch itself. Based on the previous explanation, it is thought that the increased range of motion of the hip is attributed to greater tolerance towards the strain of the stretch as opposed to any significant change within the muscle tissue.

EMG Activity

Muscle activity of the gluteus maximus, hamstrings, gastrocnemius, and rectus femoris was measured in order to determine whether stretching exercise would affect activity of the muscles during a post-exercise maximal stretch. It has often been discussed that reflexive activation of the muscles being stretched ballistically might result in residual activation during a post-maximum stretch that would influence flexibility. Unlike with maximum stretch distance and hip angle,
results of the EMG activity of the various muscles did not support the original hypotheses.

It was hypothesized that static stretching would result in decreased EMG levels of the stretched and antagonistic muscles. In contrast, it was thought that ballistic stretching would not diminish EMG activity and that ballistic stretching may even increase the activity in the antagonistic muscles. Results indicate that there was no significant difference in EMG activity between the two stretching conditions in any of the muscles tested (Fig. 11). Therefore, in this study, an acute bout of static or ballistic stretching had little to no influence over muscle activity within the muscles being stretched or those opposing the stretch. Results from previous studies regarding EMG and stretching have had varied findings which makes it difficult to determine the relationship between EMG activity and stretching.

One study found that following bouts of static and ballistic stretching, EMG activity significantly decreased. It was postulated that following the stretching protocol in the current study, a similar decrease in EMG activity would be found with the static stretching but that ballistic stretching would retain a significant amount of muscle activity in the muscle being stretched and opposing the stretch. However, this was not the case as the stretching protocols in the present investigation did not result in altered EMG activity. One difference may be that in the study by Wiemann and Hahn, the subjects stretched for 15 consecutive minutes which is much longer than the 1.5 minutes of stretching conducted in the current investigation and typical of normal stretching routines.
Prolonged stretching may produce different responses within the muscle than short stretching bouts.

Another explanation as to why there was no difference in EMG activity between the stretching techniques is in regards to the increase in stretching distance and hip angle that resulted from the two stretching protocols. Since there was an increase in range of motion following the stretching exercises, it may be that the new angle of stretch produced a similar level of muscle activity as the pre-measurement angle\textsuperscript{39}. That is, if the post-stretching angle was different than the pre-stretching angle, the level of muscle activity could be altered, and, in this case, increased. Therefore, the new hip angle that results from the stretching exercise places the muscle at a new length which elicits a similar muscular response as the pre-measurement angle.

However, it is not completely surprising that neither the static nor the ballistic protocols influenced EMG activity in the present study. Previous investigations have found that during stretching exercises using static, ballistic, and proprioceptive neuromuscular facilitation techniques there is a constant low level of EMG activity throughout the stretch that is not changed with time\textsuperscript{15, 39, 42, 43}. In addition, some of the largest improvements in range of motion have occurred in muscles that are experiencing the greatest amount of muscle activity\textsuperscript{43}. Muscle activity may be a sign of resistance to stretch, but in these studies where EMG activity is present, significant increases in range of motion are still found and the level of muscle activity does not appear to be strong enough to
inhibit range of motion gains. These findings have led some investigators to question what is being stretched when a person engages in flexibility exercises.

The presence of low level EMG activity is generally expected and present during a muscle stretch that does not stress the connective tissue surrounding the muscle beyond the physiological limit. If a stretch is strong and risks the integrity of the connective tissue, a larger muscle response is required to protect the muscle from injury. A significant response by the muscle would produce stronger EMG activity. During typical stretching protocols, the person stretching is instructed to obtain a position that stretches the desired muscle but does not produce pain, and if pain is experienced the stretcher is instructed to reduce the amount of stretch in order to avoid muscle injury. Interestingly, in one study the stretching position that produced the greatest perceived stretch still only recorded low levels of EMG activity. These authors suggest that the traditionally accepted “muscle stretch” is really a connective tissue stretch because increasing levels of EMG activity were not recorded with higher intensity stretches.

Suggestion has been made that the parallel, or perimysium, and series, or endomysium, elastic components of the muscle-tendon unit are what is being stretched and, therefore, adapting to the stretch through viscoelastic stress relaxation. The perimysium may relax in order to acutely adapt to the increased tension by lowering the strain throughout the muscle-tendon unit. However, there is not a clear consensus that improvements in range of motion are due to viscoelastic stress relaxation. Furthermore, it is still possible that
stretching exercises do stretch muscle tissue, but the stretch does not produce
enough tension within the muscle fibers to induce a protective muscle contraction
that results in significantly more muscle activity 42.

Although no strong conclusion regarding the relationship between muscle
activity and stretching can be drawn, it does appear that stretching, either
statically or ballistically, may have little influence over muscle activity.

**Perceived Soreness**

Perceived soreness was measured to determine whether there was a
difference in soreness levels between the static and ballistic stretching
techniques. Based on previous studies, it was hypothesized that perceived
soreness would be greater with the STA condition for all time points when
compared to the BAL condition 44, 59. The results show that there was no
difference in perceived soreness between the groups in this study (Figure 13).
Although not significant, there was a tendency for soreness to increase over
time, regardless of stretching technique used, which indicates that a typical bout
of stretching of one muscle group has the potential to produce muscle soreness.

The results of this study contradict those of previous investigations 44, 59.
In the studies by Smith et al. 59 and Multer et al. 44, the ballistic groups
experienced more muscle soreness than the static groups. However, differences
in the stretching protocols may explain the contradictory findings in the present
investigation. Specifically, the study by Smith et al. 59 required the subjects to
perform three identical sets of seventeen stretches that targeted specific muscle
groups in the upper and lower body. The duration of each stretch was 60 seconds with the total stretching protocol lasting nearly 90 minutes. Similarly, the study by Multer et al. incorporated five different lower body stretching exercises that were maintained for 30 seconds and were repeated three times. In contrast, the current study required just three 30-second stretches of the hamstring muscle group which resulted in a total stretching time of 1.5 minutes.

The differing results between the previous studies and the present examination are likely attributed to the inconsistencies in the total duration of the stretching protocols. In the present investigation, one objective was to make the stretching protocol as practical and clinically relevant as possible, and constructing a stretching routine that is typically performed by recreational and competitive athletes was an important component of the project. Stretching for durations as long as 30 and 90 minutes is somewhat unrealistic for the everyday athlete. Interestingly, one and a half minutes of stretching was almost enough to induce significant levels of muscle soreness.

Although a series of three static or ballistic stretches did not produce significant levels of muscle soreness, there were some interesting tendencies worth mentioning (Figure 14). First, it appears that with static stretching, there is an immediate rise in soreness from the pre to post measurements, followed by a more gradual increase. In contrast, ballistic stretching seems to slowly rise over the days following the stretching exercise. Therefore, there appears to be a difference in the immediate sensation of soreness following the two techniques. The constant strain applied to the muscle-tendon unit during static stretching may
result in increased muscle soreness that is heightened immediately post exercise. In contrast, perception of muscle soreness following ballistic exercise may not be as strong because the ballistic technique does not require sustained strain of the muscle. Instead, ballistic stretching uses short bounces coupled with periods of relaxation. It is possible that the severity or degree of muscle injury is determined by the amount of strain as opposed to the amount of force required in the stretch which makes the static stretch more susceptible to immediate increases in muscle soreness. However, these ideas are only speculation.

Another interesting finding in regards to perceived soreness is that the peak soreness for both stretching conditions occurred at 48 hours after the stretching exercise. Typically, soreness following muscle injury is greatest at 24 to 48 hours post-exercise, and the results from the current investigation follow this trend. Therefore, although there was a difference in the appearance in perceived soreness between the stretching techniques, both of the methods exhibited the greatest soreness levels at the same time point. Although neither the static nor the ballistic stretching methods produced significant levels of soreness, there does appear to be a difference in the initial perception of pain immediately following the stretching exercise, and this difference warrants further investigation.
Conclusion

Stretching, regardless of method, produced an acute increase in maximum distance stretched which is partially explained by an increase in hip flexion. However, it is unlikely that muscle activity is influenced greatly by a single session of static or ballistic stretching, and it does not appear to contribute to improvements in range of motion. Interestingly, although it has been found in other studies that static stretching results in more muscle soreness than ballistic stretching, it does not appear that muscle soreness occurs following a typical static or ballistic stretching routine of a single muscle group. Differences in the initial perception of pain following ballistic and static stretching may occur, however, but further investigation is necessary.

Future examinations should expand on the current research by investigating the mechanics of the static and ballistic stretching techniques through the use of videography and electromyography. Examination of the forces associated with ballistic and static stretching will help to elucidate whether force or strain of the stretching exercise contributes to muscle soreness perception. In addition, more long term studies are necessary to determine whether the static and ballistic stretching techniques result in altered biomechanics or muscle activity that is acquired over time as opposed to immediately following a stretching event.

In conclusion, large differences related to the outcome measures of stretching distance, hip angle, muscle activity, and soreness were not found between the static and ballistic stretching methods. Instead, the outcome of the
two methods was quite similar which contradicts popular belief. Recently it has been suggested that ballistic motions incorporate movements that are more typical of sports maneuvers and may be of more benefit to athletes than stationary, static exercises. Based on the present study, there does not appear to be a reason why ballistic stretching should be contraindicated for exercise programs targeted towards increasing flexibility.
References


Appendix A

Informed Consent
Project Title: Comparison of the muscle activity and joint kinematics of two different stretching techniques

You are invited to participate in an experiment investigating the differences in the static and ballistic stretching maneuvers. If you wish to participate, you will be asked to: 1) report to the University of Toledo’s Applied Biomechanics Laboratory, 2) jog for five minutes at a self selected pace, 3) allow for electromyography electrodes and video system markers to be placed on your skin, 4) perform both static and ballistic hamstring stretches, 5) allow for muscle activation and joint kinematic data to be recorded during the stretching sessions, 6) provide muscle soreness ratings for 3 days, and 7) abstain from any additional physical activity or stretching during the 3 day testing period.

As a participant in the study, you will be required to perform hamstring stretches using the static (sustained) and ballistic (bouncing) stretching techniques. Measurements of muscle activity and joint motions will be taken during the stretching exercises. Muscle soreness for each leg will be measured before and after the stretching exercise as well as 24 and 48 hours post stretching.

Stretching Exercise. All subjects will perform both static and ballistic modified hurdler hamstring stretches. To complete the stretch, you will be asked to keep one leg straight and place the other foot on the inner thigh of the straightened leg. The static and ballistic stretches use the same body position, however, the technique differs. For the static stretch, you will be asked to stretch your hamstring by reaching for your toes until you feel tightness, but no pain, in the hamstring (back of the thigh) area. You will be required to hold the stretch for 30 seconds. During the ballistic stretch, you will be asked to reach for your toes in the same manner used for the static stretch, but instead of holding the stretch you will perform a 30 second bounding motion in sync with a metronome. You will be verbally instructed on proper technique and form during all of the stretching maneuvers.

Testing. The testing session will begin with an assessment of any soreness in your right and left legs using a visual analogue scale. Next, you will be asked to jog for 5-minutes at a pace that you choose. The purpose of the 5-minute jog is to provide a warm-up before stretching. The jog will be followed by the application of electrodes and video system markers to your skin. Once the markers have been attached to your skin, you will be instructed on the static and ballistic stretching maneuvers. Testing will require that you perform a set of 3 static or ballistic stretches on one of your legs. Following the first set of stretches, you will rest for 20 minutes. After the 20 minute rest period, you will perform another set of three stretches (static or ballistic) using the opposite leg. Another assessment of muscle soreness in each leg will be made following each set of stretches. The testing session will take approximately one hour. You will be required to assess your muscle soreness in each leg 24 and 48 hours following the initial testing.

Risks/Discomforts. Risks associated with the stretching program are loss of strength and range of motion, inflammation, and muscle soreness in the lower extremities. In addition, the electrodes and markers could result in skin irritation. To reduce the risks of injury, you will be instructed on correct positioning for the stretching. In addition, if skin irritation occurs, the markers will be removed from your skin immediately. Finally, trained personnel from the Exercise Physiology Laboratory and Applied Biomechanics Laboratory will be present during all testing which will decrease the risks associated with participation. In an effort to reduce your risk, you will be asked to complete a health history questionnaire. If there is any question as to whether you have a pre-disposing risk factor for injury during this study, the study investigator will discuss it with you, and you may be excluded from participation.
Benefits. The benefits to you for participating in this study are minimal. You may experience increased range of motion in the hip joint, however, the increases will be small since you will only be performing one bout of stretching. Your own personal results will be made available to you upon your request at the completion of the study.

Please understand that you have the right to withdraw from the study at any time during the investigation.

At the conclusion of the study, the data obtained from your participation will be made available to you. The results will be kept confidential.

I, _____________________, hereby give my consent to participate in the research study entitled “Comparison of the muscle activity and joint kinematics of two different stretching techniques,” the details of which have been provided to me on the attached page, including anticipated benefits, risks, and potential complications.

I fully understand that I may withdraw from this research project at any time without prejudice or effect on my standing with The University of Toledo or with the study investigators. I also understand that I am free to ask questions about any techniques or procedures that will be undertaken.

I understand that in the unlikely event of physical injury resulting from research procedures that medical treatment will be arranged. The cost of the treatment will be my responsibility since The University of Toledo will not provide financial compensation.

Finally, I understand that the information about me obtained during the course of this study will be kept confidential.

___________________________
Participants Signature

I hereby certify that I have given an explanation to the above individual of the contemplated study and its risks and potential complications.

___________________________
Principal Investigator

I, _________________________, certify that I was present at the time the explanation was given and in my opinion the subject understood the factors involved. I also witnessed the signatures of both parties above.

___________________________
Witness

___________________________
Date
Appendix B

Medical History Questionnaire
Date___________________ Subject # ___

University of Toledo
Applied Biomechanics Laboratory
Health Appraisal Questionnaire
** Confidential**

Name: ____________________________ Sex:  F  M  Date of Birth___________
Address_____________________________________________________________________
Phone:__________________________________ Email:___________________________

Medical History: Check if Applicable, give further explanation if necessary:

- Heart Disease/Heart Attack/Heart Surgery
- Pacemaker
- High Blood Pressure
- Diabetes
- Varicose Veins
- Muscle Disease
- Asthma
- Back Problems
- Brain Injury
- Fractures (indicate location)

- Upper Extremity Injury
- Lower Extremity Injury
- Back Problems
- Arthritis
- Stroke
- Rheumatic Fever
- Cancer
- Lung Disease
- Neurological Disease
- Surgery (indicate type)

○ YES  ○ NO ............. I do not participate in a regular hamstring stretching program
○ YES  ○ NO ............. I have no lower extremity injury and have not for the past six months

Explain any above that have been marked:

Family History: Indicate which (if any) of your blood relatives have had any of the following conditions:

- Asthma
- Diabetes
- Cancer
- Heart Attack
- Heart Operation

Your Current Health Status: Indicate if you have any of the following symptoms

- Chest Pain/Pressure
- Dizziness with exercise/exertion
- Shortness of breath
- Pregnant or recent childbirth
- Skipped or irregular heart beats
- Joint Pain during exercise

Other:
Medications:
○ YES ○ NO ............ I am currently taking medication
  Type of Medication:  Prescription______ Non-prescription______
  Name of Medication(s):_____________________
  __________ Purpose of Medication:_____________________

Health Habits:
○ YES ○ NO ............ I currently smoke cigarettes
  Amount smoked per day______
  If you used to smoke, how long ago did you quit? _____ years.

○ YES ○ NO ............ I am currently overweight

○ YES ○ NO ............ I am currently on a weight reduction program
  If YES, briefly describe the program______________________________

○ YES ○ NO ............ I currently engage in sports and/or fitness activities
  If YES, briefly describe the types of activities________________________
  How frequently do you exercise? Day per week____
  Minutes per day____
Appendix C

Stretching Data Collection Sheet
Stretching Data Collection Sheet

Name: ___________________ Date: _______ Age: _______ DOB: _______

Address: __________________________________________
(Street) (City) (State) (Zip)

E-mail: __________________________________________ Phone #: ___________________

Height: _______ Subject #: ___________________ Folder Name: ___________________

Weight: _______ Cube Calibration File Name: ___________________

Wing Span: _______ Input Range (V) for Trials: _______

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<th>Left</th>
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<td>MVC File Names: (5 seconds)</td>
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<td></td>
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<tr>
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<td>Glut Max ___________________</td>
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<tr>
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<td>Hamstrings ___________________</td>
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<tr>
<td>Trial 2 File Name: ___________________ (40 Seconds)</td>
<td>Rectus Fem ___________________</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trial 3 File Name: ___________________ (40 Seconds)</td>
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<td>Input Range (V): __________</td>
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<td>MVC File Names: (5 seconds)</td>
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</tr>
<tr>
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<td>Trial 3 File Name: ___________________ (40 Seconds)</td>
<td>Gastroc ___________________</td>
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<tr>
<td>Post-Max Stretch File Name: ___________________ (5 Seconds)</td>
<td>Input Range (V): __________</td>
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Appendix D

Randomization of Trials
## Randomization of Trials

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Appendix E

MVC Data Sheet
Subject ____________________________

**MVC Data (mV)**

<table>
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<th>Trial 1</th>
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<tr>
<td>MVCglut 1</td>
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<tr>
<td>MVCham1</td>
<td>MVCham2</td>
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<tr>
<td>MVCgastroc1</td>
<td>MVCgastroc2</td>
</tr>
<tr>
<td>MVCrectus 1</td>
<td>MVCrectus 2</td>
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</tbody>
</table>

MVCham1 (prox)  
MVCham2 (prox)  
MVCham1 (dist)  
MVCham2 (dist)  
MVCham1 (med)  
MVCham2 (med)  
MVCham1 (lat)  
MVCham2 (lat)  
MVCgastroc1 (med)  
MVCgastroc2 (med)  
MVCgastroc1 (lat)  
MVCgastroc2 (lat)  
MVCrectus 1  
MVCrectus 2  


Appendix F

Visual Analogue Scale
RIGHT LEG

Pre-stretch post  Post-stretch  24 h post  48 h post  72 h post

Directions: Draw one line on the scale below that represents how much muscle soreness you are feeling in your leg at this time. Please use only one line.

No Soreness  Extreme Soreness

LEFT LEG

Pre-stretch post  Post-stretch  24 h post  48 h post  72 h post

Directions: Draw one line on the scale below that represents how much muscle soreness you are feeling in your leg at this time. Please use only one line.

No Soreness  Extreme Soreness