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The acute effects of stretching on pennation angle and force production

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THE ACUTE EFFECTS OF STRETCHING ON PENNATION ANGLE AND FORCE PRODUCTION

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ABSTRACT

PURPOSE: This study was designed to investigate the acute effects of stretching on pennation angle of the Medial Gastrocnemius and maximal voluntary isotonic plantar flexion. METHODS: 24 healthy college age subjects (14 female, 10 male, age 19-30) completed four trials using a randomized crossover design. Trials consisted of assessing the maximal voluntary isotonic contraction (MVC) and pennation angle (PA) before and after each treatment. Treatments consisted of either stretching (S) or mock stretching (MS). The S treatment involved four 30 second periods of stretching with 15 seconds of rest in between. During the MS treatment subjects were maintained in the same relative position as the S treatment, but were not stretched. RESULTS: There were no significant changes observed in PA from pre to post measurements, though during stretch PA was significantly reduced ($p \leq 0.05$). MVC was significantly reduced in the S treatments ($p \leq 0.01$). CONCLUSIONS: Stretching had little lasting effect on PA, while MVC was significantly reduced. This finding indicates PA is likely not strongly linked to the MVC reductions observed following stretching.

CHAPTER 1: INTRODUCTION

It is not uncommon for both recreational exercisers, and athletes to stretch prior to exercising or competing. The rational for doing so is typically related to injury prevention, and reduction of "tightness" of one's muscles (1). Though many still practice this pre-workout regimen, studies indicate that stretching confers little injury prevention benefit, and can actually cause a decrease in force production (2, 3). Though the scientific community has determined that stretching can reduce force production, the acute physiological changes which occur post stretching have yet to be determined. There are several theories which attempt to explain this phenomenon, though none has conclusively been proven to account for this decrease in force production.

The Golgi tendon reflex has been highlighted as a potential neural inhibitory explanation of why muscles lose force following a stretch. The Golgi tendon reflex is triggered when the Golgi Tendon Organ in the myotendinous junction is subjected to large forces combined with lengthening. Once this force-lengthening event occurs the Golgi Tendon Organ sends a signal to the central nervous system to inhibit action potentials, and thus decreases the force of contraction (4, 5). This reflex could potentially be triggered by a stretching program, and can account for a loss of force production, though this effect is typically short lived (6). As this reflex is usually not long lasting it is unlikely that it would account for more than a momentary reduction in force production.

Another theory is that pain secondary to stretching results in neural inhibition. During intense stretching some discomfort is generally felt, and this could cause the mechanoreceptors within that muscle to respond by sending feedback to the neurological system of the muscle, with the end result being a reduction of muscle activation (7, 8). Though this effect is also short lived,

it might also explain some of the deficit of force production directly following a bout of stretching (9).

From the standpoint of muscle architecture there are also theories which can help to explain force production loss after stretching. When a muscle tendon unit is stretched an increased range of motion is typically observed about one or more of its accompanying joints. To accomplish this range of motion increase, the muscle tendon unit must lengthen (10). The degree to which the lengthening of either tendon or muscle may contribute to a decrease in force production has yet to be determined.

Some researchers have explored the effects of stretching on tendon length and its properties. Research has shown that a sufficiently rigorous stretching program can induce alterations of a tendon's viscoelastic properties (4, 11, 12). The rigidity of tendons plays an important role in the transfer of kinetic energy from the muscle fiber's contraction to the bones. When a tendon's viscoelastic properties change from being rigid to more pliable, the fibers of the accompanying muscle may be contracting with their usual force, but they are only transferring a portion of that force to the bones; and ultimately the external force production (13).

Other research has examined the effects of stretching upon the muscle, namely the fibers and fascicle lengths. It has been found that stretching can cause an increase in fascicle pliability and length (14). If the fascicle is lengthened then the fibers which accompany the fascicle will also be lengthened. According to the length-tension relationship of the sliding filament theory there is an ideal length at which muscle fibers contract with greatest force. If a muscle fiber's sarcomeres are moved beyond their optimal length, or are shortened, these sarcomeres will produce less than peak force (15). Therefore, depending upon the muscle's structure and the

amount of stretch it experiences, there may be a loss of force due to a change in the resting length (or length before contraction is initiated) within its sarcomeres.

Pennation angle alteration is another possible explanation for force reduction following stretching. Pennated muscle is a type of muscle whose fibers join with its aponeuroses at angles which form a feather-like arrangement; this type of muscle is found throughout the human body (16). In pennated muscles the angle formed by the fascicles/muscle fibers and its deep aponeurosis is referred to as its pennation angle. The angle of pennation may play an important role in force transfer (17). From a mathematical standpoint, the lower the pennation angle (closer to zero), the more force should be transferred from each fiber to the line of action, or deep aponeurosis (Figure 1). When a pennated muscle is stretched, depending upon which structures of the muscle-tendon unit architecture are most affected, there could be residual changes in its pennation angle; which will in turn affects the muscle's ability to transfer force to its line of action.

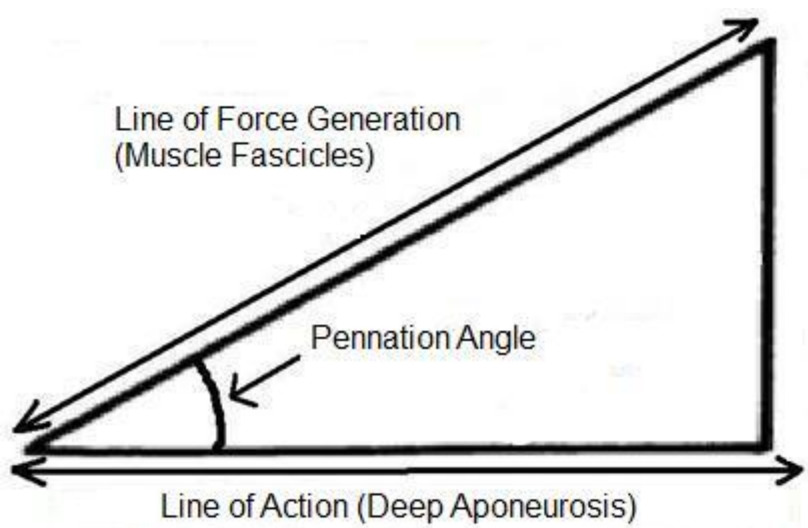

Figure 1: Graphical representation of the relationship between the fascicle/muscle fibers and aponeurosis in pennated muscle.

If stretching induces significant alterations in tendon viscoelastic properties or deforms the tendon, than there may be a resulting increase in the pennation angle of its accompanying

muscle. This increase in pennation angle would be a result of the viscoelastic nature of the tendon (18). Thus, should the tendon become lengthened, or more pliable, muscle fibers will 'take up the slack,' this will result in an increase in pennation angle. Conversely, should the muscle fibers be more affected by stretching and not the tendon, than the result would be a decrease in pennation angle, as the increase in pliability secondary to stretching may induce increased laxity of the muscle fiber. Should the muscle fiber's sarcomeres become more pliable and without changes in tendon viscoelasticity than the result would be a decrease in pennation angle. Previous studies have shown that pennation angle is reduced during a stretch, which suggests that a persisting pennation angle change may be possible (11). While, Morse et al. (14) found that pennation angle was increased following a stretching protocol. The observed increase in pennation angle by Morse et al. (14) was found while the muscle was contracted, so the persisting alterations secondary to stretching in non-contracted muscle may differ.

Should pennation angle be increased following stretching, there should be a reduction in force production (17). This is due to the reduction in relative force each fiber contributes to the deep aponeurosis, or line of action. Figure 2 illustrates the change in pennation angle that may result from stretching. These simple triangles explain the relationship between pennation angle and force production. Assume the hypotenuse for the triangle to be a muscle fiber, the adjacent side is the deep aponeurosis, and the opposite side if the distance from deep to superficial aponeurosis, which depending upon the muscle may represent its physiological cross sectional area. When the hypotenuse is lengthened the cosine of the angle is decrease, whereas when the hypotenuse is shortened the cosine is increased. The cosine of this angle is representative of the pennation angle, and is inversely related to how much force each muscle fiber exerts on the deep aponeurosis. Therefore, when the muscle fiber is lengthened more force should be exerted on

the deep aponeurosis, and when shortened the opposite should be true. While mathematically, there should be a strong relationship between pennation angle and force production, the physiological alterations to the muscle fibers are not taken into account in this model. With the well-established drop in force production from changes in length-tension in muscle fibers, the result of either an increase or a decrease in pennation may be a drop in force production (15). If the muscle fiber has a persisting increase in length following a stretch than it will be beyond its ideal length-tension, and the result will be a reduction force production; if the muscle fiber is shortened, than it will be below its ideal length-tension, and the same result should be true.

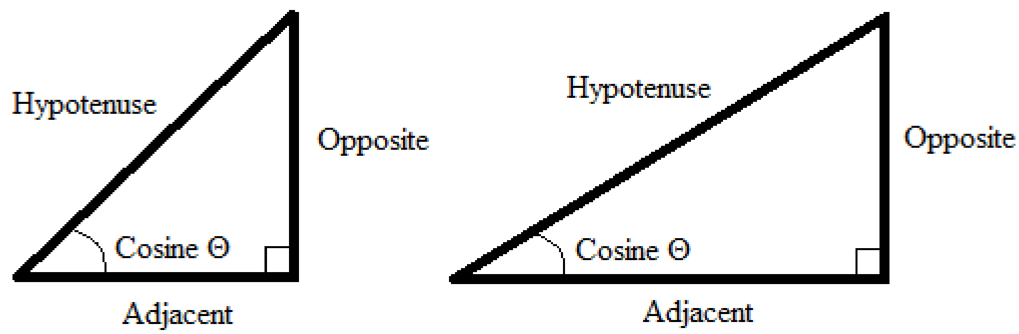

Figure 2: Diagram of pennation angle alterations. Hypotenuse represents muscle fibers/fascicles; the adjacent side represents the line of action, or deep aponeurosis. The opposite side represents the distance from deep to superficial aponeurosis. Cosine Θ is the pennation angle.

Although figures 1 and 2 illustrates the relationship between muscle fiber contraction and the accompanied force generation in respect to the line of action, it may also be indicative of the lengthening characteristics of pennated muscle during stretch. It is expected that muscle fibers will lengthen when stretched, which could cause a decrease in pennation angle (19), and concomitant increase in force. Given that it is possible that pennation angle could increase or decrease with stretching, it is clear that the lasting effects of stretching on muscle architecture are not fully understood. In order to gain more understanding of this issue it is the purpose of this

study to investigate the acute changes in pennation angle, and the accompanying change in force production, following a stretch protocol.

Problem Statement

It is the purpose of this study to examine the effects of stretching on pennation angle and its relationship to force production.

Hypothesis 1

It is hypothesized that following an acute stretching regimen there would be a persisting increase in pennation angle.

Hypothesis 2

An increase of pennation angle will result in a decreased force production.

Limitations of the Study Design

Flexibility and Muscle Length/Tendon Length Ratios: Each individual naturally has differing levels of flexibility and muscle length/tendon length ratios about the dorsiflexion range of motion. This is a limitation because with the equipment utilized there was no means of quantifying these differences. Therefore, people with different anthropomorphics may have differing responses to the stretch treatment. Additionally, individuals who are more flexible may have responded differently than those who are less flexible.

Pain Tolerance: The stretching imposed upon the subjects entails some discomfort. The individual pain tolerance level may vary between subjects, which may vary the amount that each subject's triceps surae was stretched. All subjects may not have been stretched to the same degree as each individual was only stretched till they acknowledged that they had reached their pain threshold.

Other Muscles of the Triceps Surae: There are multiple muscles which act to plantar flex the foot (Gastrocnemius, Plantaris, and Soleus), and within the Gastrocnemius there are two heads. The only head of the aforementioned muscle assessed with ultrasound was the Medial Gastrocnemius, while the combined force production of all three of these muscles was assessed. This limitation has more to do with the possible interpretations which can be drawn from the results of this study, as there may be significant differences in maximum force production between both heads of the Gastrocnemius, Plantaris, and the Soleus. Any possible differences in force production may or may not be reflective of the changes in the differences in pennation angle which was assessed.

Other Muscle Architectural Structures: This study only assessed the pennation angle of the Medial Gastrocnemius which allowed the researcher to gauge some of the structural changes occurring as a result of the stretch in that particular aspect. There are also other structures which may or may not be impacted by the stretch protocol which were not assessed due mainly to the limitations of the equipment utilized. The tendon, fascicle, and aponeuroses lengths were not assessed, which limits the overall observations which can be obtained from this study.

Voluntary Muscle Contraction: When subjects performed their maximal isotonic plantar flexion tests they were instructed to push as hard as they could. Force production is as related to the muscle mechanics as it is to the neural input; so it is possible that variations in the subjects' neural activation could account for some of the variability in maximal force production results.

Delimitations

Medial Gastrocnemius: The only muscle studied was the Medial Gastrocnemius; a bipennate muscle of the lower leg. Though the results of this study are strictly applicable to this muscle, there can perhaps be some insight gained into the workings of other muscles throughout the body.

Joint Angles: The Medial Gastrocnemius was assessed with the ankle at approximately 90 degree angle, and the knee at approximately 180 degree angle. This insured that the muscle-tendon unit was held at approximately the same tension during each assessment. Maintaining the relevant joints in the same position through pennation angle assessment also helped with ensuring that the point being assessed was constant throughout the experiment.

Muscle's Contraction State: The subjects were instructed to relax their calves during the ultrasound assessments. The pennation angle changes between a state of rest and contraction even if there is no motion about the joint. In an effort to minimize any inadvertent flexing of the calf muscles during ultrasound assessment subjects were lying on their back; this removed the need for balance related contraction of the lower leg.

CHAPTER 2: METHODS

Subjects

Twenty-four college age students, 10 male and 14 female (age range = 19-30), were recruited to participate in the project. All subjects completed the Physical Activity Readiness Questionnaire (PAR-Q) before being included in the study. Only those individuals who answered “no” to all questions were included as research subjects. In addition, each person’s history of injury was reviewed to reduce the possibility of undue harm or discomfort. Informed consent was reviewed and signed before subjects underwent any testing.

Experimental Overview

A randomized crossover design was used to test the acute effects of stretching on pennation angle of the Medial Gastrocnemius. Each participant underwent four trials, two of each treatment; stretching and mock stretching, with a minimum of 48 hours between trials. Pennation angle was assessed before, during, and after each treatment. Maximal voluntary isotonic plantar flexion was measured before and after each treatment. All testing was conducted with the subjects lying down in a supine orientation. Subjects were not moved from their supine orientation during any of the testing procedures. The time line for each trial was as follows in Figure 3:

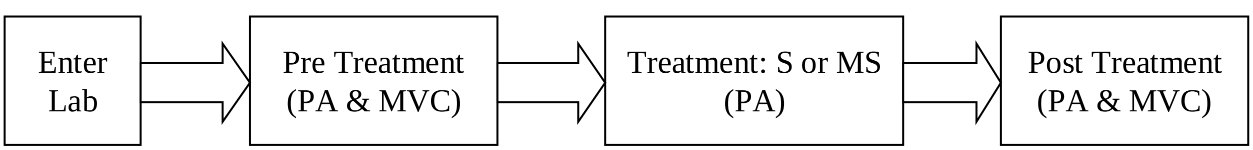

Figure 3: Graphical representation of the order of events during each trial. Pennation angle (PA) and maximal voluntary contraction (MVC) were tested before and after each treatment. Treatments consisted of either a stretch (S) or mock stretch (MS) protocol.

Additionally, subjects did not engage in heavy physical activity which might have affected the lower leg for a period of 48 hours before each trial. This was in an effort to reduce

variability that may be introduced by having fatigued or damaged muscles. If their muscles had been fatigued then their maximal force production might have been compromised. Had their lower legs been sore, the localized edema associated with delayed onset muscle soreness may have influenced pennation angle measurements.

Stretching Protocol

The stretching treatment consisted of four passive (assisted) static stretches on the right leg. The stretches were performed while the participants were lying on their back. From this position, the foot was moved in to a position of dorsiflexion, which stretched the triceps surae. The foot was moved until the participant verbally acknowledged that stretch was felt in the muscle. The experimenter maintained the subject's foot in this position for 30 seconds. Then, the tension was removed for 15 seconds. This cycle of stretching and relaxing was performed a total of four times. Stretches of this duration have been shown by Winchester et al. (20) to significantly decrease force production in as little as a single 30 second stretch to pain tolerance. For mock stretching, the leg was maintained in the same relative position it would have been in had it been stretched, but no force was applied; this condition was maintained for approximately three minutes (the same as the total stretch/relax time).

Maximal Voluntary Isotonic Plantar Flexion

Maximal force production was tested using a single repetition maximal voluntary isotonic contraction protocol. In order to determine the success of each repetition the subjects' range of motion had to be established. The range of motion involved in plantar flexion is fairly small. A system of determining successful repetitions versus failed repetitions was therefore essential. This system involved first having the subject push the apparatus as far as they were capable; this maximal range of motion was marked, and used for the end range of each of their repetitions.

Once their range of motion was established they were given five “warm up” contractions, which served to familiarize them with the motion, and prepare them for the single repetition testing. In order to reduce the subject’s ability to “cheat” on the maximal voluntary isotonic contraction testing, a strap was placed over their hips which reduced their ability to move the hip. While this was somewhat of a novel task requiring isolation of a single joint a hip strap was used as a means of reducing the subjects’ ability to recruit other muscle groups to aid in the plantar flexion testing.

Once in place and familiarized with the apparatus; subjects began their maximal single repetition testing. The single repetition maximal testing was accomplished by first loading the individual with a weight they were able to fairly easily move through the full range of motion. The load was then progressively increased until they were either unable to complete a full range of motion repetition, or their lifting form was compromised. Subjects were given a period of two minutes between each attempt in an effort to reduce the possibility of muscle fatigue influencing the results.

Pennation Angle Measurement

Pennation angles of the Medial Gastrocnemius were assessed with ultrasonography, which functions by passing sound waves through the muscle and digitally recording the resultant image. The measurements were made around the area of greatest circumference of the calf, while supine with a knee and ankle joint angle of ~180°. Within the calf the researcher located a point where the ultrasound image was of high quality with regard to the fascicle and aponeurosis. Once this point was located it was marked and recorded as a measure from the medial Malleolus to the point. This point was then used for all future measures of pennation angle.

While pennation angle was assessed, subjects were instructed not to contract the muscles of their calf. When muscles contract the architecture of the muscle is altered; for uniformity, all subjects were assessed while not contracted. For this reason, and to maintain the normal structure of the Medial Gastrocnemius during ultrasound assessment, subjects were supine throughout testing.

Before any assessments were performed each subject was maintained in a supine position, with the leg to be assessed placed on foam blocks for a period of 20 minutes prior to any measures being taken. This rest period was a precaution meant to reduce variability of the pennation angle measurements. This precaution was put in place to allow the body to accomplish a more homeostatic state before measurements were obtained. The foam blocks were placed under the hamstring and Calcaneus to prevent any possible variations in pennation angle due to pressure being put on either the proximal or distal tendons.

Image Analysis

Images procured during ultrasound assessment were selected based on the clarity of fascicle and aponeuroses. Images were then analyzed using Image-Pro Plus 4.0 (Media Cybernetics, Silver Springs, MD). Images were analyzed by tracing the fascicles, which are hyperechoic, and thus produce a light appearance which contrasts with the darker muscle fibers that surround the fascicles (Figure 4). The lines traced over the fascicles were then compared with a line traced about the deep aponeurosis. The angle made by intersecting these lines represents the pennation angle of the muscle.

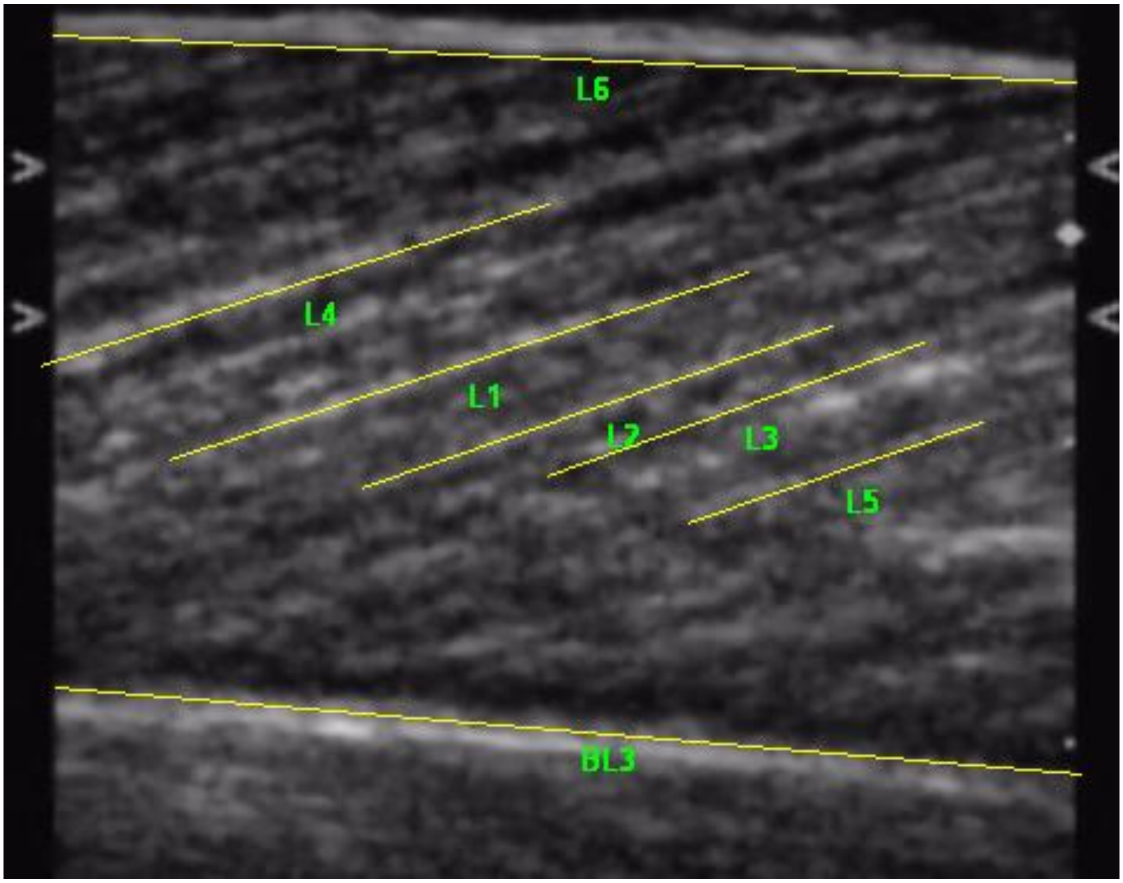

Figure 4: The medial Gastrocnemius, with lines traced over muscle fascicles, and both deep and superficial aponeuroses.

Statistical Analysis

All statistics were performed with the aid of SPSS version 20 for windows (IBM, Armonk, New York). Paired T-tests were utilized to assess the differences between pennation angle and maximal voluntary contraction measures. As there were two trials of each condition, both trials were averaged together. For reliability testing, Pearson's correlations and Cronbach's Alpha testing were used. One-way ANOVAs were used to assess the relationship between gender and both pennation angle change and maximal voluntary contraction force. The relationship between pennation angle change and maximal voluntary contraction change was also analyzed using a One-way ANOVA.

CHAPTER 3: RESULTS

Population

Twenty-four college ages subjects (14 female, 10 male, age 19-30) completed this study. The subjects' pretreatment pennation angle averaged 20.7±3° and their average baseline maximal voluntary isotonic contraction was 46.05±10.86kg.

Reliability

The reliability of pretreatment pennation angle measurements had an interclass correlation of $r = 0.78$, and a Cronbach's alpha score of $\alpha = 0.93$. The pennation angle scores assessed during the stretch treatment had an interclass correlation of $r = 0.84$, and a Cronbach's alpha score of $\alpha = 0.90$. Following the stretch treatment the pennation angle measurements had a correlation of $r = 0.72$, and a Cronbach's $\alpha = 0.83$. The pennation angle scores following the mock stretch protocol had a interclass correlation of $r =0.82$, and a Cronbach's score of $\alpha = 0.90$.

The pretreatment reliability of maximal voluntary contraction had an interclass correlation of $r = 0.93$, and a Cronbach's alpha score of $\alpha = 0.98$. Following the stretch treatment maximal voluntary contraction scores had an interclass correlation of $r = 0.93$, and a Cronbach's alpha score of $\alpha = 0.97$. The maximal voluntary contraction scores following the mock stretch protocol had an interclass correlation of $r = 0.92$, and a Cronbach's $\alpha = 0.96$.

Change in Pennation Angle

When subjects underwent the stretch treatment their pennation angle had an average increase of 0.31±1.33° when compared pre to post measures ($p = 0.27$). When subjects were not stretched their pennation angle had an average increase of 0.41±1.12° ($p = 0.09$). The pennation angle changes from pre to post treatment across all trials are depicted in Figure 5. When the pre stretch treatment measures were compared to the measures recorded during the stretch, there was

an average decrease of 3.06±2.60° ($p < 0.01$). The change in pennation angle between all three time points is depicted in Figure 6.

Maximal Voluntary Contraction Change

When comparing pre stretch to post stretch measures, the change in the subjects' maximal voluntary isotonic contraction was found to average -5.30±2.40kgs ($p < 0.01$). When subjects were not stretched, an average increase of 0.52±0.26kgs was observed ($p = 0.06$). Figure 7 depicts the changes in force production observed during each trial. When the change in pennation angle was analyzed to determine its relationship to change in maximal force production the interaction was found to be insignificant ($p = 0.95$).

Gender Differences

Pretreatment pennation angle scores were significantly different between genders; with males having an average of 22.47±3.26°, while females were measured at 19.39±2.41° ($p = 0.01$). Males scored an average of 55.91±8.82kg, while females averaged 39.00±5.73kg on their pretreatment maximal voluntary contraction testing ($p < 0.01$). The gender based differences in several other analyses are displayed in Table 1.

Table 1: The gender based differences in the change scores (Δ) of pennation angle (PA) measured in degrees (°) and maximal voluntary contraction (MVC) measured in kilograms (kg). The change scores for pre to post treatment (Pre-Post) are presented for the stretch treatment (S) and for the mock stretch treatment (MS). Pre to during treatment (Pre-During) assessments are presented for stretch treatment. Scores are listed as the average followed standard deviation in parentheses, significance was determined using One-way ANOVA ($p \leq 0.05$).

Category	Male	Female	Significance
Δ PA Pre-Post (S) °	+0.82(1.89)	-0.18(1.85)	0.093
Δ PA Pre-Post (MS) °	-0.12(1.43)	+0.79(1.42)	0.040
Δ PA Pre-During (S) °	-2.75(2.93)	-3.60(2.87)	0.379
Δ MVC Pre-Post (S) kg	-6.36(3.51)	-4.55(2.31)	0.888
Δ MVC Pre-Post (MS) kg	+1.25(1.73)	+0.01(1.52)	0.033

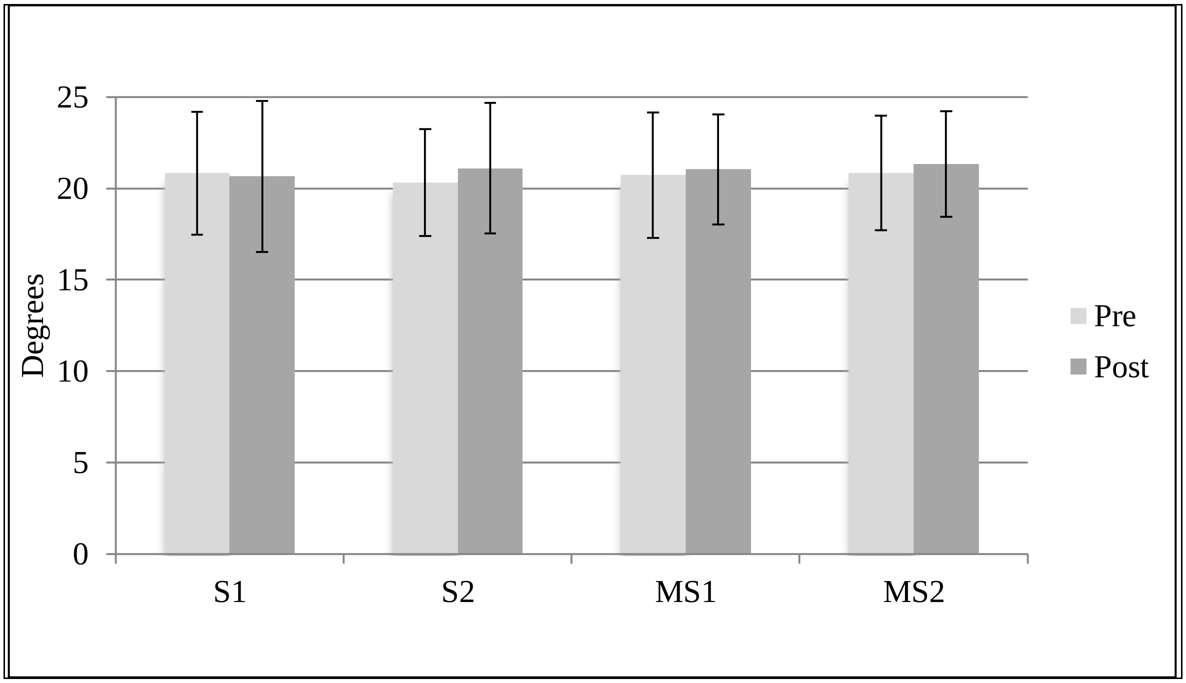

Figure 5: The bars represent the averaged pennation angle scores of each trial; with the subject either being stretched (S) or mock stretched (MS). The angles presented are representative of the pennation angle observed within the Medial Gastrocnemius at time points either pre condition, or post, and are portrayed in degrees. Error bars represent ±1 standard deviation.

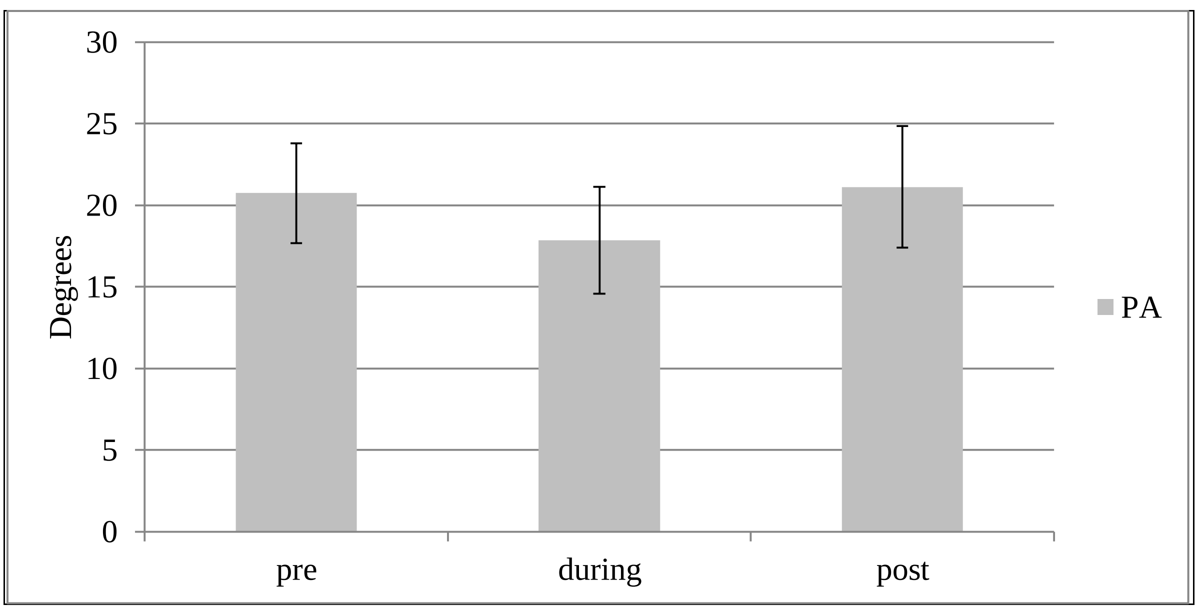

Figure 6: The bars represent the averages of pennation angle (PA) measures, represented in degrees, taken on the medial gastrocnemius pre stretch, during stretch, and post stretch. Error bars represent ±1 standard deviation.

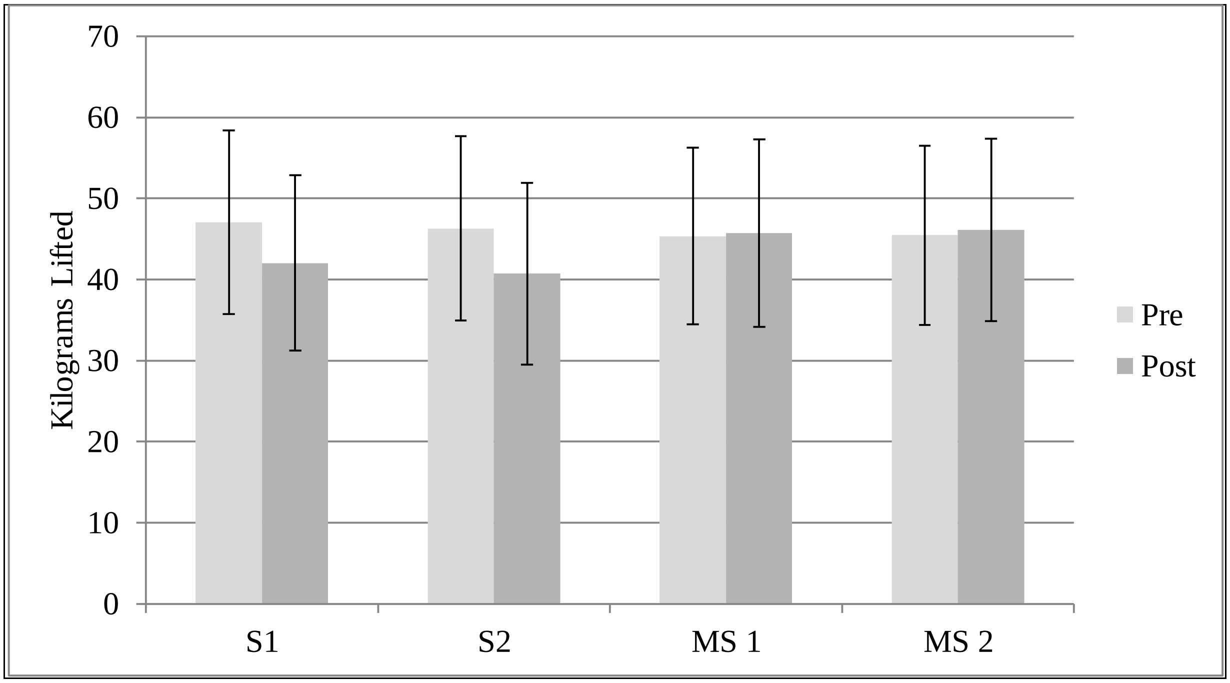

Figure 7: Bars represent the averaged maximal voluntary force subjects were able to produce both pre and post treatment, in kilograms lifted. Subjects were either stretched (S) or mock stretched (MS) each trial. Error bars represent ±1 standard deviation.

CHAPTER 4: DISCUSSION

While it is understood that stretching will acutely reduce maximal force production, the mechanisms which contribute to this phenomenon have yet to be uncovered. This study aimed to examine how significant a pennation angle change would be to the acute force reduction observed following stretching. In this experiment a significant force production deficit was observed, while no significant lasting alterations in pennation angle were found. These results suggest that the force production deficits observed following stretching are not related to persisting pennation angle increases.

While there may not have been significant alterations in pennation angle from pretreatment to post treatment, there were significant reductions in pennation angle while the stretch treatment was administered. Similar findings were also observed by Kasuyama et al (21), who found a 2.9° decrease in pennation during stretch. Morse et al. (14) also observed an average decrease of 2.9° in pennation angle from pre stretch to during stretch ultrasound assessments. This reduction in pennation angle verifies that stretching affects muscle architecture, though any lasting alternations were not apparent in the present study.

The stretch protocol of the present study resulted in no significant alteration in pennation angle post stretch treatment. While the present study found no difference, Morse et al. (14) observed a significant change in pennation angle following a stretch of five minutes. While these results are seemingly in opposition to those of the present study, the differences in may be a function of study design. Morse et al. (14) stretched their subjects approximately two and a half times longer than the stretch treatment from the present study. This suggests that for a lasting difference in pennation angle to be observed the stretch may need to be administered for a larger period of time. This theory is supported by Samukawa et al. (22), who observed no

significant change in pennation angle following a three and a half minute stretch protocol. Therefore, had the stretching protocol in this study been of greater duration it is perhaps more likely that a lasting change in pennation angle might have been observed.

The lack of observed change in pennation angle may also be attributable to the methodology of pennation angle assessment. Tendons are viscoelastic; they have the tendency to both deform for a period when stretched, and have the tendency to rebound to their original shape. Additionally, when tendons are stretched their viscoelastic properties can be altered such that they become more pliable (4, 11). This change in viscoelasticity was not well addressed in the present experiment due to the pennation angle measurements being taken while the subjects' muscles were not contracted. This also would explain the difference in findings between Morse et al. (14), and the present study, as their measurements were all assessed under maximal voluntary isometric contraction. Therefore, had the pennation angle measurements been assessed under a similar state of contraction there may have been similar alterations.

Pennation angle may have not been significantly impacted by the stretching treatment in this present study, but force production was. There was an 11.7% reduction in force production following the two minute stretch protocol. These results are similar to those observed by Winchester et al. (20) who observed a 5.4% reduction in maximal force production following a single 30 seconds stretch, while three minutes of stretching resulted in a 12.4% reduction. These findings suggest that that there is a dose response between stretching and force reduction.

While the relationship between stretching and force production may be fairly well understood, the underlying mechanisms at play are not. The stretch related reduction in maximal force production has been attributed to several possible mechanisms; in this study pennation angle's role in force change was investigated. The statistical analysis showed no relationship

between the changes in force production and pennation angle. This finding was shared by Tilp et al. (19), who likewise found pennation angle to have little effect on the maximal force production of the tibialis anterior at various joint angles. These results are somewhat in contrast to those of Earp et al. (23), who found that pennation angle was a predictor for rates of force development, which might suggest that although maximal force is not necessarily affected, that it may have a relationship to the characteristics of its production.

While the present study displayed a lack of relationship between pennation angle and force production, there are theories which suggest that a relationship does exist. According to Zajac (13), the angle formed by muscle fibers attaching with the deep aponeurosis should be indicative of how much force the muscle exerts. This is to say that mathematically, there should be an effect of altering pennation angle. Though the present study failed to observe a relationship, Kawakami et al. (17) has speculated that there may be a sort of diminishing return with increasing pennation angle. Increasing muscle fiber diameter, or hypertrophying muscle, is positively associated with the amount of force that each individual muscle fiber can exert. While hypertrophying muscle fibers does increase its force production, it also has been shown to increase pennation angle. If the muscle fibers were exerting force in the exact same line as the deep aponeurosis than there should be a100% force transfer to the line of action. When increasing pennation angle the force production in moved away from the line of action, which in turn means there is a smaller percentage of force acting on the line of action. Thus, while hypertrophying muscle fibers may increase the force production capabilities of individual fibers the increase in pennation angle imposes a diminished return (17). It is possible that this diminished return was not an important factor in this experiment as the pennation angles assessed were fairly small.

It is also possible that the decrease in pennation observed while under stretch might have produced some lasting effect on the sarcomeres of muscle fibers. It is understood that there is a strong relationship between the length/tension of a muscle fiber and its ability to produce force (15). Perhaps when sarcomeres are stretched to a great enough extent there is some prolonged effect on their ability to produce force. If there were a lasting change in the sarcomeres as a result of the stretch condition it may explain the reduction in force production observed.

The lack of persisting change in pennation angle relative to change in strength observed in the present study may be indicative of some combination of neural response mechanisms working to reduce force production. Cornwell et al. (24) found that following a similar stretch protocol there was a reduction in electro-myograph (EMG) activity. This reduction in neural activity was thought to have contributed to the observed reduction in performance. Likewise, Behm et al. (25) observed static stretching to reduce force production regardless of flexibility, which they attributed to neural inhibition due to mechanoreceptor related pain reflexes. The findings of these previous studies suggest that the reduction in force production observed may be linked to neural factors. Neural inhibitory mechanisms were not evaluated in this experiment therefore no conclusions about their role can be made. Had EMG been employed, there may have been more compelling evidence as to the role of neural inhibition on the observed reduction in force production in this study.

Population Differences

The subject's baseline pennation angle and maximal voluntary contractions were significantly different between genders. Males on average had larger pennation angle and greater maximal force production than did their female counterparts. Similar results were observed by Manal et al. (26), who found that males had an average medial Gastrocnemius

pennation angle of 18.7±3°, while females had an average of 15.95±1.95°. While the gender differences between those observed in the present study and in Manal et al. (26) are approximately equal it should be noted that the baseline values are approximately 3° greater. The subjects in Manal et al. (26) were older than those of the present study, which according to Kubo et al. (27) may account for the differing baseline pennation measures. In this study Kubo et al. (27) found that pennation angle was greater in males and young subjects, and that their muscle mass as proportionally greater than their counterparts. This finding supports those of Kawakami et al. (17), as the same relationship was displayed in both works.

The measures of pennation angle change between genders suggest that there were significant differences in the results of the mock stretch treatment. These differences in gender response may suggest that the baseline differences could have influenced the subjects' responses to the force production testing. Though the reasons as to why only the mock stretch would produce significantly different pennation angle and maximal voluntary contraction scores on as basis of gender are unknown.

Hypothesis 1

The first hypothesis postulated that when a stretching condition was applied there would be a persisting increase in post stretch pennation angle. While there was an increase in pennation angle during stretch, there were not persisting increases in pennation angle observed. Since no significant increase in pennation angle was observed as a result of the stretch condition, hypothesis 1 must be rejected.

Hypothesis 2

The second hypothesis was that an alteration in pennation angle would decrease force production. This experiment failed to produce a significant alteration in pennation angle, thus the second hypothesis cannot be either accepted or rejected.

Implications

The significant reduction in force production implies that some mechanism influenced the muscle tendon unit. The only mechanism investigated in this study was pennation angle, which was not significantly altered. The change in force production independent of change in pennation angle suggests that pennation angle did not significantly impact force production. Therefore, we can infer from this study is that pennation angle does not affect the acute force reduction following stretching.

Future Research

The results of this experiment indicate a need to research the role other mechanisms which relate to the reductions in force production secondary to stretching. The potential inhibition of nervous system activity at either a peripheral or central level may have contributed to the reduction of maximal voluntary isotonic contraction force observed (7, 8, 9). For this reason further research should be undertaken to explore the possible mechanisms related to neural inhibition, and to what degree those mechanisms contribute to the observed reduction in force production. In addition to investigating these neural mechanisms action, work should also be undertaken to gain an understanding of the lasting effects of such mechanisms.

Additionally, more testing must be done on muscle in different states of contraction, after having been exposed to a stretch condition. It is possible that potential muscle architecture differences may not arise until the muscle is activated, as the viscoelastic properties of the

muscle tendon unit may be altered (4, 11). A change in the viscoelastic properties of the tendon will change how compliant it is, and how well it transfers force form the muscle to the bones. Thus, having not applied any forces to the muscle tendon unit while the pennation angle was assessed, the potential differences in viscoelastic properties of the tendon were not addressed in this study as well they could have been. This indicates that future research of muscle architecture may be more successful while assessing contracted muscle, rather than relaxed muscle.

Further research should also examine the relationship between the medial gastrocnemius and the other muscles of the triceps surae, to determine how much of each muscle contributes to maximal production of force during plantar flexion. While Cresswell et al. (28) examined the relationship between the Soleus and the Gastrocnemius with the use of eletro-myography and determined that the Soleus accounted for approximately 40% of the total force produced. There are few studies examining the differences in the force production of the individual muscles in the triceps surae. Muscle fiber type may also play an important role in determining which muscles are most effected by stretching as the myotendinous junctions differs based on fiber type (29, 30). Trotter et al. (30) has found that the myotendinous junction of fast twitch fibers has a significantly greater surface area than slow twitch fibers. This difference in myotendinous junction may have implications for the passive resistance that each fiber type exerts when exposed to a stretching condition. Fast twitch fibers produce more power than do slow twitch fibers, so this increased surface area of myotendinous junction is intuitively logical as there is more force being exerted on this point (31). This increase in myotendinous junction rigidity serves to better resist sheer forces produced through high power productions, but in turn may also resist stretching. If slow and fast twitch fibers do indeed have differing passive resistance to

stretching, than the changes in muscle architecture observed following a stretch protocol may also differ. This potential difference, and the lack of research directly examining it, indicates the need for more study of the subject. This may be especially significant to the results of the present study as the medial gastrocnemius is comprised of a greater percentage of fast twitch fibers than the soleus (32). This may suggest that there were differing results pennation angle between the two muscles as a result of the stretch treatment; though the soleus was not assessed so any of these potential changes were not observed. Further research would help future investigation into determining how appropriate each of the muscles comprising the triceps surae are for examining force production of the entire muscle group.

Also, to gain more insight into the physiological properties of muscle it is essential that other muscles tendon units around the body be examined. The ratio of muscle to tendon may be an important fact when examining the results of stretching. The tendon's viscoelasticity is altered with stretching, so should a muscle have a long tendon and short muscle the degree of pennation angle change will be more exacerbated than if the muscle were long and tendon short (4, 14). This potential difference of the effects of stretching on muscle tendon units of differing length ratios would suggest that stretching could have differing results on muscles around the body; as there are a great variety of muscle tendon ratios found around the body. Investigating other muscles will increase our understanding of how different muscle tendon unit's force productions properties are influenced by their composition and construction. Additionally, further research into the effects of large pennation angles on the diminishing returns of muscle fiber hypertrophy will increase our understanding of how muscles function.

When selecting subjects in the future perhaps a more comprehensive methodology should be utilized for inclusion into such a project as the present study. Research has shown that

individuals with differing passive torques have differing responses to stretching (33). Therefore, it is possible that the subjects in this study may have had such differing levels of passive torque that when their results were assessed together there was no observed difference, when in actuality there may have been. Therefore grouping subjects by passive torque levels may serve as more precise means of determining the effects of stretching treatments.

Conclusion

Ultimately, this experiment has demonstrated that following a relatively short duration stretch protocol, there was no significant lasting alteration on pennation angle, while there was a significant decrease in force production. The results indicate that pennation angle did not prove to be a major player affecting force production following stretch. Additionally, the difference observed between genders suggests that there may be some factor unaccounted for between genders which contributed to their differing results.

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VITA

Ryan Miskowiec was born in March on the 26^{th} of 1984 in southern California, where he lived for the first decade of his life. He then moved to Covington, Louisiana, where he attended Saint Paul's School. There he discovered a taste for knowledge, and acquired many life skills. Following high school Ryan attended Southeastern Louisiana University for two years, before finally moving to Baton Rouge, and attending Louisiana State University, where he received a bachelor's of science degree in kinesiology. Following undergraduate career he was accepted into the US Navy Officer Candidate School, where he decided that family was his greatest priority. After leaving the Navy he married his fiancé, and began work at a local YMCA as an assistant fitness director. After a couple years working at the YMCA he worked as an emergency medical technician as he began his graduate school studies. Throughout his graduate schooling he has grown fond of both teaching and research. With the birth of his first child, he now has a family to provide for.

His future plans include the completion of his master's degree followed by working toward an eventual doctorate. Following graduate school he intends to pursue a career in academia.