The Biomechanics of Stretching

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Abstract

This narrative review examined the biomechanical effect of stretching exercises on skeletal muscles. While there is a long history of clinical research on the effect of stretching on flexibility, there have only been a few years of research on the acute and chronic effects of stretching on the biomechanical parameters of muscle function. The acute effect of stretching appears to be a significant increase in range of motion primarily due to increased stretch tolerance and significant reductions in most all forms of muscular performance. Stretching also creates significant acute reductions in passive tension (stress-relaxation) in the muscle, but does not appear to affect its stiffness/elasticity. Stretch training significantly increases range of motion, but it also tends to increase the passive tension and stiffness of the musculature. Future research of human muscle *in vivo* during stretching and normal movement using ultrasound promises to help clarify the effects of stretching on the active and passive components of muscle and the many biomechanical variables of muscular performance.

Key Words: **Elasticity, Flexibility, Muscle, Stiffness, Tendon, Viscoelastic**

Introduction

Stretching is an important therapeutic and exercise training modality for increasing joint range of motion. There has been extensive research on the effects of various stretching programs that have documented the clinical effectiveness of these techniques in modifying flexibility *(Knudson et al. 2000; Harvey et al., 2002; Shrier, 2004; Decoster et al., 2005)*. Improvements in soft tissue imaging and force measurement technology have only recently begun to allow biomechanical studies to document the mechanisms of the effect of stretching on the muscle-tendon unit and muscular performance. This review will summarize the biomechanical research on the effects of stretching on the muscle-tendon unit. These studies provide important basic science evidence that compliments clinical studies to help guide professionals in prescribing stretching exercises.

Biomechanics of Muscle Tension

The tension created by skeletal muscle can be classified as originating from two mechanical sources, active and passive. Active tension represents the contractile effects or the force generated by the interaction of actin and myosin filaments. Passive tension arises from the connective tissue components of skeletal muscle when elongated beyond their resting length. Active and passive tension cannot be considered separate structural elements of muscle because the connective tissue matrix of muscle is quite complex (within muscle and between muscles in anatomical compartments) and actin cross-bridges have elastic properties *(Proske and Morgan, 1999)*. Many readers will be familiar with the electro-mechanical delay and hyperbolic force-velocity properties of muscle (*Hill, 1938)* that also complicate the production of muscle force. Most biomechanical models of muscle use a Hill model that includes a series-elastic component to account for passive tension interacting with active tension. This review will focus on the muscle length-dependent properties of muscle since this is the mechanical property most strongly related to stretching exercises. The force and moment of force about a joint axis created by a particular muscle or muscle group is a result of both active and passive components of muscle tension.

Biomechanics has typically described the active and passive components of muscle as the length-tension relationship of muscle. The active tension of skeletal muscle is said to have three regions or limbs (ascending, plateau, and descending), while passive tension increases in an exponential fashion (Figure 1). While most of these studies have been based on tissue preparations from animal models *(e.g. Taylor et al. 1997; Davis et al., 2003),* several in vivo studies of human muscle groups have recently reported similar patterns of active and passive tensile resistance, especially in the plantar flexors *(Maganaris, 2001; Gajdosik, 2002; Hoang et al., 2005).* There is considerable normative data on the rise in passive torque provide by passive tension of the plantar flexors *(Gajdosik et al., 1999; Moseley et al., 2001).*

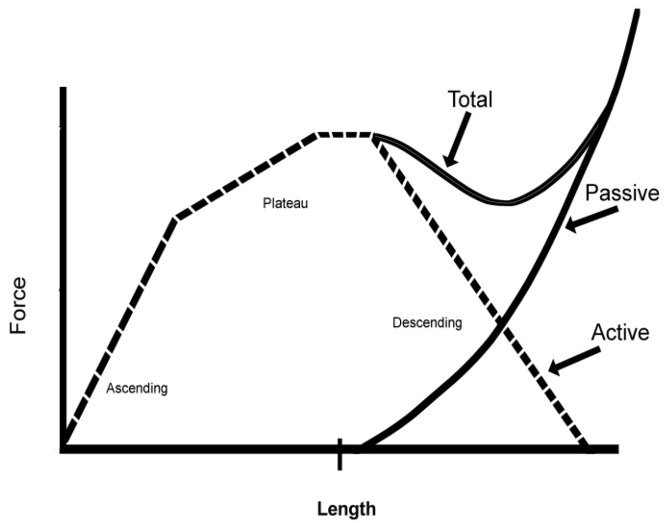

Figure1. The force-length relationship of muscle reflects the sum of the active (—— —) and passive tension (———) sources of force. The active tension curve is typically classified as having an ascending, plateau, and descending limbs. Adapted with permission from Knudson (2003).

When connective tissues like ligament and tendon samples are stretched to failure in materials testing machines, a variety of variables can be calculated documenting their mechanical response. Variables like peak forces, energy absorbed, elongation, and stiffness (elasticity) have all been measured for a variety of these tissues. For example, whole rabbit muscle preparations have been stretched to failure to document the effect of warm-up *(Safran et al., 1988)* or cadaver tissues tested to document the mechanical strength of the various bundles of the human medial collateral ligament *(Robinson et al., 2005).*

While the tension of muscle can be easily understood as arising from active of passive sources, the interaction of these two sources is very complex. The interaction of these two components of tension implies that exercise interventions, like stretching, may have complex effects on skeletal muscle depending on the interaction of the tissues and the nature of the training stimulus.

Acute Effects of Stretching

When a muscle or muscle group is passively stretched using techniques like in static, dynamic, or proprioceptive-neuromuscular facilitation (PNF) stretching there may be some short-term changes in the muscle. Acute or short-term effects of stretching on muscle relate to the initial performance changes in the first few hours after stretching. This section will look at factors affecting the acute response of muscle to stretching. The acute effect following stretching then depends on the biomechanical performance variable of interest. Some biomechanical variables (like range of motion) have been shown to improve following stretching, while some appear to be unaffected (stiffness) and others are significantly reduced (strength).

An important factor in the acute effect of stretching is that the passive tension in a muscle depends on the rate of stretch. This rate dependency means that the tensile resistance in a muscle strongly depends on the timing of the stretch. This property is called viscoelasticity. The faster the stretch the higher will be the stiffness of the muscle (Figure 2). Stiffness is the measure of elasticity of a material and is defined as the slope of the stress/strain or load/deformation curve <u>in the elastic region of the curve</u>. The load-deformation curves of viscoelastic materials (like Figure 2) are complex and have several regions. The "toe" region is the initial quick elongation with minimal force rise). There is a highly nonlinear region followed the "elastic" region where the curve begins to approximate a straight line. If these tissues were pulled to failure the curve would show a "plastic" region where the curve flattens out as permanent damage is done to the tissue. During normal activities most ligament and tendon strain is typically between 2 and 5 percent strain so they occur in the toe and just before the elastic regions of the curve *(Carlstedt and Nordin, 1989).* The viscoelastic response of muscles, tendons, and ligaments means that a slow stretch will create less passive tension than a faster stretch to the same length.

The acute effect of stretching on flexibility is pretty clear. Stretching creates an acute increase in joint range of motion that tends to persist for 60 to 90 minutes *(Moeller et al., 1985; Kirsch et al., 1995; Zito et al., 1997).* Much of this short-term increase in static flexibility is related to an increase in stretch tolerance *(Wiemann and Hahn, 1997; Magnusson, 1998).* In other words, the increased range of motion may be related to an analgesic effect that allows the person to tolerate higher levels of passive tension required to stretch the muscle farther than it was before. Stretch tolerance has also been observed to be higher in flexible persons than "tight" persons, so greater range of motion in most persons is achieved with higher passive tensions *(Magnusson et al., 2000a).*

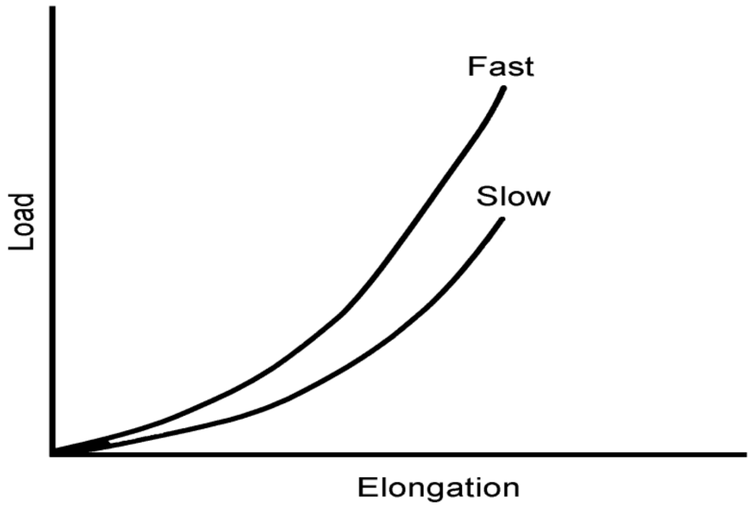

Figure 2. Typical force-elongation curves for slow and fast stretches of a muscle, tendon, or ligament. The visocoelastic response of these tissues means that faster stretches make the tissue stiffer, resulting in greater force for a given elongation. Adapted with permission from Knudson (2003).

Another related factor is that stretching decreases the passive tension in the muscle at a given length. This decrease in passive tension in the muscle at a particular joint angle is due to stress relaxation (Figure 3). Stress relaxation is the decrease in stress (force per unit area) in a material elongated and held at a constant length. Holding stretches for 20 to 30 seconds is a good standard because most of the stress relaxation in passive stretches occurs in the first 20 seconds *(McHugh et al., 1992; Magnusson, 1998; McNair et al., 2000; Duong et al., 2001).* Patients can feel this decrease in muscle tension when they hold a static stretch. Stress relaxation following stretching provides an acute 10 – 30% decrease in passive tension *(Magnusson et al., 1995; Magnusson et al., 2000b; McNair et al., 2000),* but this stress relaxation lasts only about one hour *(Magnusson et al., 1996b).*

This lower tension early in range of motion should not be confused with the stiffness or elasticity of the muscle. While a patient might feel stretching makes their muscles feel less "stiff" *(Reisman et al. 2005),* this is not correct in the true sense of the word. What patients are often feeling following stretching or mild movement following inactivity are "thixotropic" or history dependent (length and contraction) effects *(Hutton, 1993; Magnusson et al., 1995).* An everyday example would be when a person is sitting in a constrained position for a long time; they will find their back muscles feel inextensible or 'stiff' until they move around for a few seconds. This change in passive tension very early in the toe region of a muscle has been called "short-range stiffness," but is not the true stiffness of the tissue if it were to be stretched near injury-producing levels.

Many studies have measured the torque/angle curves immediately following stretching as estimates of the load/elongation behavior and passive stiffness of stretched muscle groups *(e.g.*

Rosenbaum and Hennig, 1995; Halbertsma et al. 1996, 1999; Magnusson, 1998; Magnusson et al., 1996b; 1998; 2000,). These studies are conducted at very slow speeds (1 to 5 degrees per second) for ethical (safety) and neuromuscular (minimal reflex activation) reasons. There are many problems in accurately measuring muscle group/joint stiffness *(Latash and Zatsiorsky, 1993)* and comparisons are difficult. There are conflicting results from these studies, different experimental protocols (dynamometers, set-ups, test speeds) and incorrect definitions of stiffness (slope not calculated in the elastic region of the torque/angle curve). This latter issue is a problem because the torque/angle slopes in various regions of the curve are not strongly correlated to each other *(Gadjosik & Williams, 2002).* Other studies estimate muscle group stiffness from damped vibration during activation, but there also is a very low correlation between passive and active muscle stiffness *(Blackburn et al., 2004).* Most strong studies of passive stiffness observe results like in Figure 3, where the slope of the torque/angle curve does not change following multiple bouts of stretching. The only conclusion is that there is no clear evidence that stretching creates an acute decrease in muscle stiffness.

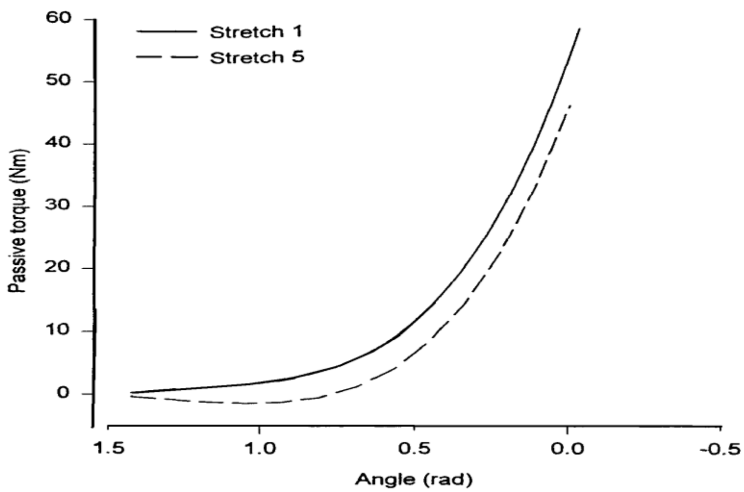

Figure 3. Torque/angle curves for the hamstring muscles for the first and fifth stretches. Note the lower resistance at each joint angle from stress relaxation, but also notice the slope of the curve in the elastic (linear) region does not change so the stiffness of the muscle group is similar. Reproduced with permission from Magnusson et al., (1996a).

It is likely that the stiffness of a muscle group is more dependent on warm-up than stretching. One of the most effective methods to decrease muscle stiffness is to increase muscle temperature with warm-up activities, this also increases the maximum strain and stress the muscle can endure before injury *(Safran et al., 1989; Noonan et al., 1994).* Studies in humans that have examined both stretching and active warm-up in combination have shown that the decrease in muscle stiffness is mainly a result of increased temperature from warm-up and not the effects of stretching (*Rosenbaum & Hennig, 1995; McNair & Stanley, 1996)*. One study found that continuous passive motion significantly reduced the stiffness of the plantar flexors while stretching did not *(McNair et al., 2000).*

One of the latest areas of research on the acute effects of stretching uses bright mode ultrasound to examine the responses of the various components of muscle (fibers, aponeurosis, and tendon). *Kubo et al. (2002b)* studied the acute effect of stretching and contractions on the stiffness of the human Achilles tendon. The acute effect of stretching was to significantly decrease tendon stiffness (8%), but the largest effect of stretching was a 29% reduction in hysteresis. Hysteresis is the energy lost when a viscoelastic material is stretched and returns to its normal length. This is a promising area of research since ultrasound studies have also begun to document the interaction of length changes of fibers, aponeurosis, and tendons during a variety of contractions of human skeletal muscle *(e.g. Fukunaga et al., 1997; Kubo et al., 2000).*

Another factor in the acute effect of stretching involves the changes in muscle force following stretching. Stretching of muscle results in an exponential rise in passive tension in the muscle and research on animal models has shown that the force which can damage (weaken) muscle can be as low as 16 to 30% of maximum failure force or at lengthening as small as 16 to 25% (*Noonan et al., 1994; Sun et al., 1998; Tsuang et al., 1998).* Research in the last decade on humans has conclusively confirmed that an acute effect of stretching is a decrease in the static and dynamic expressions of muscular strength *(for reviews see: Knudson et al., 2000; Shrier, 2004; Weerapong et al., 2004).* A decrease between 4 and 30 percent has been observed in maximal strength tests *(e.g. Kokkonen et al., 1998; Avela et al., 1999; Nelson and Kokkonen, 2001; Marek et al., 2005),* jumping *(Church et al., 2001; Cornwell et al., 2001; McNeal and Sands, 2003: Young and Behm, 2003),* sprinting *(Fletcher and Jones, 2004; Nelson et al. 2005a),* muscular endurance *(Nelson et al., 2005b),* and throwing *(Noffal et al., 2004).* Stretch-induced decrements in muscular performance seem to be about equally related to neuromuscular inhibition and decreased contractile force *(Avela et al., 1999)* and can last up an hour *(Fowles et al., 2000)*. The effect is similar in males and females, with a curvilinear dose-response and 20 to 40 seconds of static stretching resulting in significant reductions in isometric strength *(Knudson and Noffal, 2005).*

It is clear that from the standpoint of maximizing muscular performance, stretching creates an acute decrease in performance, therefore stretching should not normally be recommended prior to exercise with apparently healthy individuals, but be programmed during the cool-down after exercise training *(Knudson, 1999; Knudson et al., 2000).* The other line of evidence that supports this conclusion is that the largest, prospective studies of stretching show no effect of stretching on injury rates *(Pope et al., 1998, 2000; Amako et al., 2003).*

Chronic Effects of Stretching

The chronic or training effects of stretching have also been studied extensively, but surprisingly these effects have often differed from the acute effects of stretching. Reviews of research on stretching a variety of muscle groups report significant improvements (5 – 31% or 6 to

12 degrees) in range of motion with 3 to 6 weeks of training *(Knudson et al., 2000; Harvey et al. 2002; Guissard and Duchateau, 2004; Decoster et al. 2005)*. The long-term extensibility of muscles due to stretching or physical activity are believed to be due to a myogenic response of sarcomeres and its clinical implications fairly well understood *(DeDeyne, 2001; Gajdosik, 2001)*. The effects of stretch training on muscular strength and the mechanical properties of the muscle-tendon unit, however, are less clear.

A common belief in many circles is that stretch training will decrease muscle stiffness, possibly even decrease the increases in muscular stiffness that results from strength training. Like the acute effects of stretching, this belief about the chronic effect of stretching is not likely correct. The combination of stretching with isometric training does not prevent the increase in muscle group stiffness *(Klinge et al., 1997)*. Other studies of stretch training alone show no effect on stiffness *(Halbertsma and Goeken, 1994; Magnusson et al. 1996b&c)* or increases in muscle stiffness *(Reid and McNair, 2004)*. *Kubo et al. (2002a)* found no change in the stiffness of the Achilles tendon following three weeks of stretch training. When studies report decreases in passive muscle stiffness following stretch training it is often because they do not use correct definitions of stiffness, taking torque/angle slopes at standardized points in the range of motion before the linear region *(e.g. Guissard and Duchateau, 2004)*. The research is fairly consistent that stretch training will not likely significantly decrease muscle stiffness, rather it may have no effect or increase muscle stiffness.

If future research were to confirm that stretching has a chronic effect of increasing muscle stiffness, it is unclear if this would be beneficial. The predominant hypothesis is that a stiff muscle may be better adapted for force transmission in concentric muscle actions, while a more compliant muscle may be better for shock absorption, stretch-shortening cycle muscle actions, and reducing risk of injury *(Wilson et al., 1991, 1994; Walshe et al., 1996)*. There is very little training or basic science research to confirm or refute these hypotheses *(Owen et al. 2005)*. It is unknown if a more compliant tendon that absorbs small, rapid stretches allowing the muscle fibers to remain in concentric or an isometric state would be better or worse than a stiff muscle that can absorb more energy but may force the fibers into eccentric action. The complexity of the active and passive components of muscle tension mentioned earlier and the variety of movements makes it difficult to predict what changes in stiffness in what muscle-tendon components would do to muscular performance.

It is likely that the addition of stretching following strength training bouts is effective not only in maintaining normal range of motion, but also as an additional overload stimulus that tends to increase strength adaptations *(Shrier, 2004)*. The research does not support the belief that stretch training decreases muscle stiffness, but there is preliminary evidence that it may increase stiffness and decrease energy lost in recovery from stretch *(Kubo et al. 2002a)*. The relationship between any muscle mechanical adaptations to stretch training and muscular performance is likely to be complex. This will be a fertile area for future research on stretching.

Conclusion

Recent research with dynamometers and ultrasound imaging has cast new light on the biomechanical mechanisms and effects of stretching. The acute effect of stretching appears to be a significant increase in range of motion mostly due to increased stretch tolerance and a significant reduction in most all forms of muscular performance. Stretching also results in significant acute stress-relaxation in the muscle, but does not appear to affect muscle stiffness/elasticity. Stretch training has a chronic effect of increasing range of motion, but also tends to increase the passive tension and stiffness of the musculature at the limits of motion. Future research of human muscle during stretching and contraction using ultrasound *in vivo* promises to help clarify the effects of stretching on active and passive components of muscle and on the many biomechanical variables of muscular performance.

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