

## Increasing Muscle Extensibility: A Matter of Increasing Length or Modifying Sensation?

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Various theories have been proposed to explain increases in muscle extensibility observed after intermittent stretching. Most of these theories advocate a mechanical increase in length of the stretched muscle. More recently, a sensory theory has been proposed suggesting instead that increases in muscle extensibility are due to a modification of sensation only. Studies that evaluated the biomechanical effect of stretching showed that muscle length does increase during stretch application due to the viscoelastic properties of muscle. However, this length increase is transient, its magnitude and duration being dependent upon the duration and type of stretching applied. Most of these studies suggest that increases in muscle extensibility observed after a single stretching session and after short-term (3- to 8-week) stretching programs are due to modified sensation. The biomechanical effects of long-term (>8 weeks) and chronic stretching programs have not yet been evaluated. The purposes of this article are to review each of these proposed theories and to discuss the implications for research and clinical practice.



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Various theories have been proposed to explain increases in muscle extensibility observed after intermittent stretching. Most of these theories suggest a mechanical increase in length of the stretched muscle. The mechanical theories include viscoelastic deformation, plastic deformation, increased sarcomeres in series, and neuromuscular relaxation. More recently, a sensory theory has been proposed suggesting instead that increases in muscle extensibility are due to a modification of sensation only. The purposes of this article are to review each of these theories and to discuss the implications for research and clinical practice.

## Muscle Length, Length Measurements, and Muscle Extensibility

According to the science of biomechanics, *muscle length* is multidimensional.<sup>1</sup> *Length measurements* are only one dimension of muscle length. When more than one dimension is included in muscle length assessment, important biomechanical properties of the muscle can be determined. These additional dimensions include tension, cross-sectional area, and time. From these added dimensions, the biomechanical properties of stiffness, compliance, energy, hysteresis, stress, viscoelastic stress relaxation (VESR), and creep can be derived (Table).<sup>1,2</sup>

Because muscle comprises deformable material, its length measurement at a given moment in time is always dependent upon the amount of tensile force (force that pulls the specimen in the direction of elongation) applied.<sup>1</sup> *Tension* is the passive resistance of the muscle being stretched and is equal to the applied tensile force. The relationship between length and tension can be described by a passive length/tension curve on which multiple individual

length measurements are plotted according to the amount of passive tension required to reach each measurement.<sup>1,2</sup>

Human muscle length measurements are, with few exceptions, measurements of joint angles, and the tensile force is applied in a rotational manner (ie, a torque). For this reason, length/tension curves are commonly presented as torque/angle curves in human studies. Physical therapy texts describe techniques for measuring muscle length in human subjects. However, this is traditionally presented as a one-dimensional concept of muscle length, describing only the measurement of end-range joint angles, and does not clearly distinguish between the single and multi-dimensional concepts of muscle length. Throughout this perspective article, one-dimensional measurement of muscle length will be referred to as “muscle extensibility.” The term “muscle length” will be reserved to refer to the multidimensional concept of length as a function of tension.

For the purposes of this article, *muscle extensibility* is defined as the ability of a muscle to extend to a predetermined endpoint. The endpoint of stretch varies depending on the intent of the study. In human research, this endpoint is most often subject sensation. For this reason, when referring to human studies throughout this article, the term “extensibility” assumes an endpoint of subject sensation unless otherwise noted.

Skeletal muscles comprise contractile tissue intricately woven together by fibrous connective tissue that gradually blends into tendons. The tendons are made of fibrous connective tissue and attach the muscle to bone.<sup>3</sup> Although the contractile tissue and tendons are sometimes evaluated separately for research purposes, they cannot be separated

during routine clinical testing and stretching procedures, nor during functional activity. Both the muscular contractile tissue and tendon exhibit changes in biomechanical properties and cross-sectional area in response to exercise, disuse and aging.<sup>4</sup> For these reasons, the term “muscle” is used in this article to indicate the entire skeletal muscle, including the contractile tissue and tendon components.

Animal studies of muscle length are able to purely test the mechanical properties of the muscle-tendon unit (MTU) as other overlying and adjoining tissues—skin, connective tissue, muscles, and neurovascular structures—can be surgically reflected. These tissues remain fully intact during human muscle length testing, so the passive resistance and extensibility measured may not be attributable solely to the tested muscles.<sup>5–11</sup> When assessing muscles that cross at least 2 joints in human subjects, each joint can be tested separately to ensure that a joint restriction is not responsible for motion limitations and end-range passive resistance. With appropriate joint positioning, the stretched muscle can be placed under maximal stretch,<sup>12</sup> ensuring that the passive resistance to stretch is due primarily to the muscle being stretched and conjoining soft tissues. However, when testing muscles that cross only one joint, it may not be possible to determine to what degree the joint itself and its capsular structures contribute to extensibility limitations and passive resistance.<sup>7</sup>



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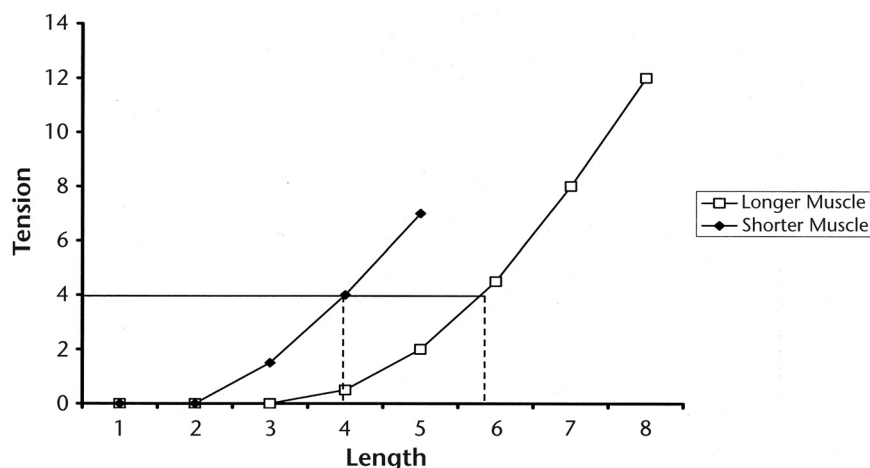
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## Increasing Muscle Extensibility

**Table.**

Muscle Length Dimensions and Biomechanical Properties That Can Be Derived From Each Added Dimension

Muscle Length Dimension	Biomechanical Property
Length measurement	Muscle extensibility: ability of a muscle to extend to a predetermined endpoint. When referring to human studies, "extensibility" assumes an endpoint of subject sensation unless otherwise noted.
Tension	Stiffness: change in tension per unit change in length Compliance: change in length per unit change in tension Energy: area under the length/tension curve Hysteresis: energy dissipated during the unloading phase
Cross-sectional area	Stress: tension per unit of cross-sectional area Stiffness, compliance, energy, and hysteresis normalized for muscle thickness
Time	Viscoelastic stress relaxation: decrease in resistance that occurs during a passively applied static stretch, the percentage difference between peak and final torque Creep: increase in muscle length as applied force is held constant



**Figure 1.**

Model of shifting length/tension curve. When a change in muscle length occurs, there is a shift in the entire passive length/tension curve. When "shortening" occurs, the curve shifts to the left, reflecting shorter muscle length measurements at a given passive tensile force. When lengthening occurs, the curve shifts to the right, reflecting a longer muscle length measurement at a given passive tensile force. Note: Number values are absolute; curve is a theoretical illustration.

## Increasing Muscle Extensibility

Increases in human muscle extensibility are demonstrated by an increase in end-range joint angles. When an increase in muscle extensibility is observed, it is possible that the increase is due to a simple decrease in muscle stiffness or an increase in muscle length. A simple

decrease in muscle stiffness is demonstrated by a decrease in the slope of the torque/angle curve. Increases in muscle length are reflected on the torque/angle curve by a shift to the right of the entire curve.<sup>1,2,12,13</sup> This right shift results in decreased stiffness and an increased length measurement (joint angle) for any given tension (Fig. 1). Muscle extensibility

also can increase—without a change in muscle length or stiffness—due to a simple increase in applied tension, which causes the muscle to stretch further (Fig. 2). Without information about applied tension, there is no way to differentiate between these possibilities.<sup>14,15</sup>

## Mechanical Theories for Increasing Muscle Extensibility

The rehabilitation literature often suggests that increases in muscle extensibility observed after intermittent stretching involve an increased mechanical length of the stretched muscle. These mechanical theories include viscoelastic deformation, plastic deformation, increased sarcomeres in series, and neuromuscular relaxation.

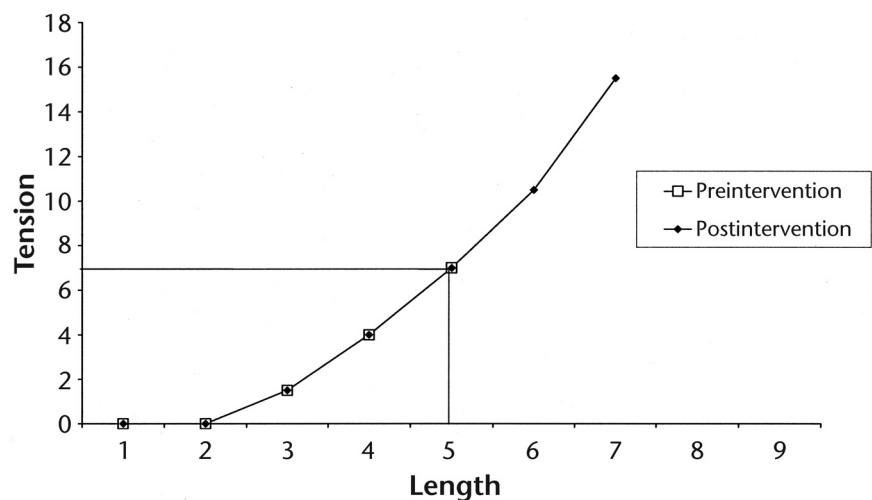
### Viscoelastic Deformation

Many human studies<sup>11,16–18</sup> suggest that increases in muscle extensibility observed immediately after stretching are due to a lasting viscoelastic deformation. Skeletal muscles are considered to be *viscoelastic*. Like solid materials, they demonstrate *elasticity* by resuming their original length once tensile force is removed. Yet, like liquids, they also behave *viscously* because their response to tensile force is rate and time dependent.<sup>1,14</sup> An immediate increase in muscle length can occur due to the viscous behavior of muscles whenever they undergo stretch of sufficient magnitude and duration or frequency. This increased length is a *viscoelastic deformation* because its magnitude and duration are limited by muscles' inherent elasticity.<sup>1</sup> Viscoelastic deformation has been tested in research using various stretching methods such as "static" (constant joint angle) stretches,<sup>19–23</sup> constant load,<sup>24</sup> contract/relax,<sup>25</sup> and repeated cyclic stretches.<sup>23,26</sup> Static stretching can be used to evaluate the property of viscoelastic

stress relaxation. When stretch is applied to a muscle and the muscle is held in the stretched position for a period of time, as is the case with normal static stretching techniques, the muscle's resistance to stretch gradually declines (Fig. 3).<sup>1,2,14,27</sup> This decline in resistance to stretch is called *viscoelastic stress relaxation* and is expressed as a percentage of the initial resistance.<sup>14,19,20</sup> Constant load stretching, such as stretching that uses a fixed torque, can be used to evaluate the property of *creep*. Creep occurs when mechanical length gradually increases in response to a constant stretching force.<sup>1,2,23</sup>

The study most commonly used to support the theory that viscoelastic deformation is responsible for increases in human muscle extensibility is an animal study by Taylor et al.<sup>23</sup> The results of this study showed an immediate increase in MTU length induced by repeated cyclic and static stretches. The authors suggested that the observed length increases should be lasting due to the viscous properties of the MTU.<sup>23</sup> However, no further testing was performed to determine the duration and residual magnitude of these length increases.<sup>23</sup>

In human studies, viscoelastic deformation and recovery have been tested on hamstring and ankle plantar-flexor muscles.<sup>20–22,24,28</sup> The results refute viscoelastic deformation as a mechanism for lasting increases in muscle length and extensibility. These studies showed that the magnitude and duration of the length increases vary depending on the duration of the stretch and the type of stretching applied. All of these studies consistently showed viscoelastic deformation of human muscle to be transient in nature. With stretch application typical of that practiced in rehabilitation and sports, the biomechanical effect of



**Figure 2.**

No shift in passive length/tension curve model. When there is no mechanical change in muscle length after an intervention, there is no shift in passive length/tension curves, and tension required to achieve the preintervention muscle length measurement remains unchanged. In human studies, if the endpoint of the stretch is determined by subject sensation, the increased measurements may be attributed to sensory modification. Note: Number values are absolute; curve is a theoretical illustration.

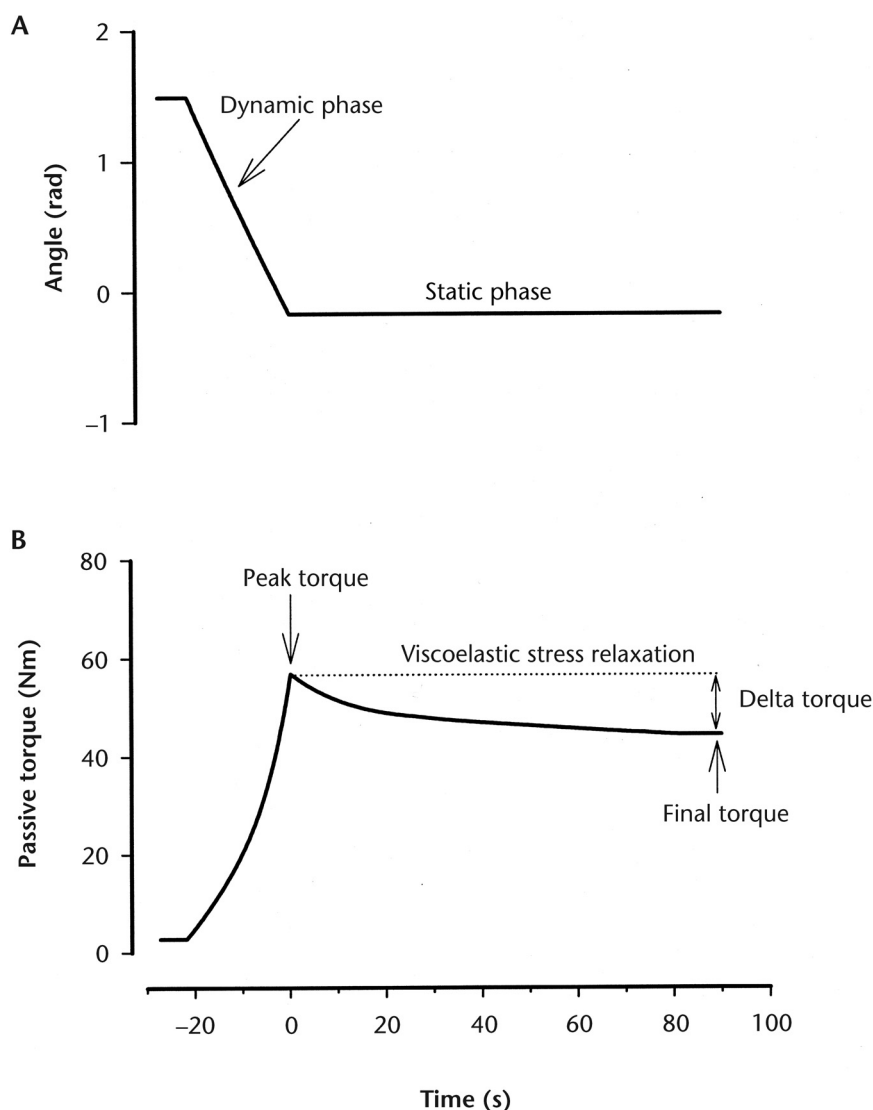
viscoelastic deformation can be quite minimal and so short-lived that it may have no influence on subsequent stretches. In one hamstring muscle study, a static stretch of 45 seconds' duration was found to have no significant effect on the next stretch performed 30 seconds later.<sup>28</sup> With 3 consecutive 45-second static stretches (30-second rest intervals between stretches), each stretch showed VESR of 20% during the static holding phase. However, the muscles had already recovered from the relaxation by the next stretch.<sup>28</sup> Similar results were demonstrated in a study of ankle plantar-flexor muscles.<sup>21</sup> There was no change in stiffness of the ankle plantar-flexor muscles that underwent static stretches of: (1) 4 sets of 15 seconds' duration and (2) 2 sets of 30 seconds' duration (10-second rest intervals between stretches).<sup>21</sup>

### Plastic Deformation of Connective Tissue

Another popular theory suggests that increases in human muscle extensibility observed immediately af-

ter stretching are due to "plastic,"<sup>17,29–32</sup> or "permanent"<sup>17,30–36</sup> deformation of connective tissue.<sup>37</sup> The classical model of plastic deformation would require a stretch intensity sufficient to pull connective tissue within the muscle past the elastic limit and into the plastic region of the torque/angle curve so that once the stretching force is removed, the muscle would not return to its original length but would remain permanently in a lengthened state (Fig. 4).<sup>1,2</sup> In 10 studies<sup>17,29–37</sup> that suggested plastic, permanent, or lasting deformation of connective tissue as a factor for increased muscle extensibility, none of the cited evidence was found to support this classic model of plastic deformation. The term "plastic deformation" often was considered only to be a synonym for deformation that is permanent in nature.<sup>31,32</sup>

The evidence cited<sup>29–31,33–35,37</sup> in support of this theory can be traced almost entirely to a study by Warren et al.<sup>38</sup> performed on rat tail tendons and a review article by Sapega et al.<sup>32</sup>



**Figure 3.**

Viscoelastic stress relaxation during static stretch. Peak torque occurs when muscle first reaches the final stretch position. Final torque is measured at the end of the static stretch holding phase. Viscoelastic stress relaxation (delta torque) is the decrease in torque and can be expressed as a percentage of peak torque:  $(\text{peak torque} - \text{final torque}) \div \text{peak torque}$ . Reprinted with permission of Wiley-Blackwell from: Magnusson SP. Passive properties of human skeletal muscle during stretch maneuvers: a review. *Scand J Med Sci Sports*. 1998;8:65–77.

Neither of these works recommended the classical model of plastic deformation, which requires high stretching loads, but instead suggested viscoelastic deformation: using lower stretching loads with prolonged stretch duration in order to facilitate “viscous flow” within the connective tissue.

Although model passive length/tension curves that include a plastic deformation phase may be applicable for some types of biological tissue, studies of muscle demonstrate a markedly different typical curve. A plastic deformation phase would be reflected on the passive length/tension curve by a decrease in its slope.<sup>2</sup>

There was no evidence of a classic plastic deformation phase occurring in any of the cited studies.

### Increased Sarcomeres in Series

Animal studies have demonstrated that the number of sarcomeres in series of a muscle can be changed by prolonged immobilization in extreme positions. That is, when muscles are immobilized in fully extended positions, there is an increase in the number of sarcomeres in series. Although often reported otherwise, these muscles demonstrated no overall change in muscle length because increases in the number of sarcomeres in series were offset by a concurrent decrease in sarcomere length.<sup>39–41</sup> When muscles are immobilized in shortened positions, there is a decrease in the number of sarcomeres in series and a concurrent decrease in muscle length.<sup>39–41</sup> Sarcomere number and muscle length in the shortened muscles have been found to increase to normal levels after recovery from immobilization.<sup>39,40</sup> These animal studies suggest that muscles adapt to new functional lengths by changing the number and length of sarcomeres in series in order to optimize force production at the new functional length.<sup>39,41</sup> Despite substantial differences between muscle immobilization and intermittent stretching, this research has been generalized to suggest that short-term (3- to 8-week) human stretching regimens cause similar increases in sarcomeres in series and a concurrent increase in length of the stretched muscles.<sup>7,11,12,17,31,42–45</sup>

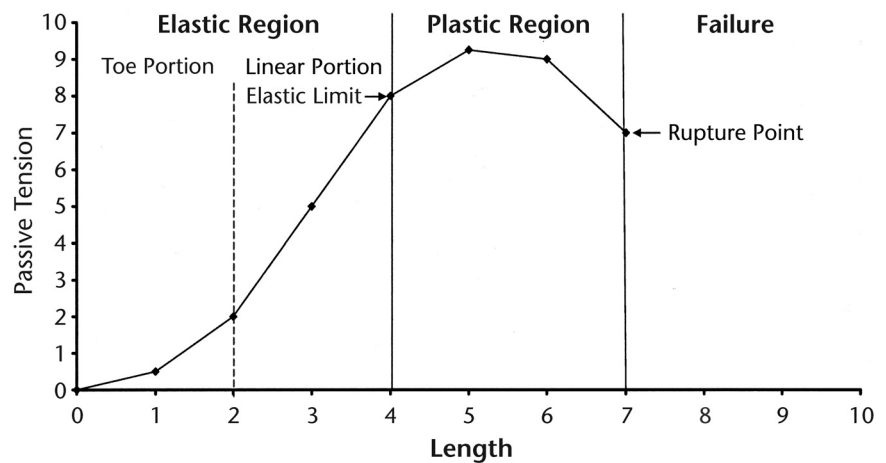
For obvious practical and ethical reasons, there are no human stretching studies that evaluated on a histological level whether the number of sarcomeres in series changes due to therapeutic intervention. Perhaps with development of imaging techniques, this will someday be a possibility.



### Neuromuscular Relaxation

The rehabilitation literature often suggests that involuntary contraction of muscles due to a neuromuscular “stretch reflex” can limit muscle elongation during static stretching procedures.<sup>16,33,34,46–50</sup> In order to increase muscle extensibility, it often has been proposed that slowly applied static stretch (used alone or in combination with therapeutic techniques associated with proprioceptive neuromuscular facilitation) stimulates neuromuscular reflexes that induce relaxation of muscles undergoing static stretch.<sup>16,17,34,36,46,47,49–53</sup> Some authors,<sup>34,53</sup> furthermore, have suggested that neuromuscular reflexes adapt to repeated stretch over time, which enhances the stretched muscles’ ability to relax and results in increased muscle extensibility.

Experimental evidence does not support any of these assertions.<sup>13,14,54,55</sup> Stretch reflexes have been shown to activate during very rapid and short stretches of muscles that are in a mid-range position, producing a muscle contraction of short duration.<sup>54</sup> However, most studies of subjects who were asymptomatic and whose muscles were subjected to a long, slow, passive stretch into end-range positions did not demonstrate significant activation of stretched muscles.<sup>14,54,56,57</sup> Even studies that simulated ballistic (cyclic and high-velocity) stretching demonstrated no evidence of significant stretch reflex activation of muscles both in human<sup>26</sup> and animal<sup>23</sup> models. In a study that evaluated the effects of a single “contract-relax” stretch<sup>25</sup> and in short-term (3 and 6 weeks’ duration) stretching studies,<sup>45,58</sup> no significant electromyographic activity of the stretched muscles was found and no shift of passive torque/angle curves was observed. The increase in end-range joint angles, therefore, could not be attributed to neuromuscular relaxation.<sup>14,25,45,58</sup>



**Figure 4.**

Model passive length/tension curve for biological tissue. The elastic region begins at the initial length and ends at the elastic limit. Increases in the length measurement due to applied tensile force are temporary. When tensile force is removed, the specimen will resume its original length. In the plastic region, with application of tensile force beyond the elastic limit, permanent deformation of the specimen will occur. In this case, once the tensile force is removed, the specimen will not return to its original length. Failure or rupture point is the last point on the curve. The length attained at the rupture point is the maximum length of the specimen. Note: Number values are absolute; curve is a theoretical illustration.

### Sensory Theory for Increasing Muscle Extensibility

In the early 1990s, several researchers put these mechanical theories to the test by assessing the biomechanical effects of stretching. By including the dimension of tension in muscle length evaluation, they were able to construct torque/angle curves and assess biomechanical properties of the muscles before and after stretching. If the increases in muscle extensibility observed after stretching were due to an increase in length of the muscles caused by any of these mechanical explanations, there should have been a lasting right shift in passive torque/angle curves (Fig. 1). Instead, the only change observed in passive torque/angle curves was an increase in end-range joint angles and applied torque (Fig. 2).<sup>15,25,58,59</sup> Because the end-point of these stretches was subject sensation (pain onset,<sup>15,25,26,58</sup> maximum stretch,<sup>59</sup> or maximum pain tolerated<sup>15</sup>), the only observable expla-

nation for these results was that subjects’ perception of the selected sensation occurred later in stretch application.

These studies suggest that increases in muscle extensibility observed immediately after stretching and after short-term (3- to 8-week) stretching programs are due to an alteration of sensation only and not to an increase in muscle length.<sup>15,25,53,59</sup> This theory is referred to as the *sensory theory* throughout this article because the change in subjects’ perception of sensation is the only current explanation for these results. To what extent this adaptation is a peripheral or central phenomenon or a combination thereof remains to be established.

It is possible that psychological factors also play a role in the observed increases in muscle extensibility. Because there is no way to keep subjects from knowing that they are participating in a stretching study,

subjects may demonstrate an increase in extensibility because they expect this to be the result of stretching. Increased extensibility then may be due to a psychological alteration in sensory perception or to a willingness of subjects to tolerate greater torque application.<sup>16,19,42,47</sup>

### Single Stretching Session

A modification in sensation that occurs immediately after a single stretching session was first reported in 1996 in a study by Magnusson et al<sup>25</sup> (using a passive knee extension test involving a Kin-Com dynamometer\* with a modified thigh pad) that investigated the effects of a 10-second static hold versus a single contract/relax stretch on human hamstring muscles. Halbertsma et al,<sup>59</sup> using an instrumented passive straight-leg raise method, tested subjects just prior to and immediately following a 10-minute hamstring muscle stretching session. In both of these studies, there was no shift of passive torque/angle curves (Fig. 1), but an increase in applied torque and increased end-range joint angles were observed (Fig. 2). Subsequent studies showed that sensory perception in response to stretching of human hamstring muscles is acutely modified by assuming a stooped versus an upright trunk position<sup>60</sup> and is similarly modified by a single 90-second static stretch and 10 repeated cyclic ("ballistic") stretches.<sup>26</sup>

### Short-Term (3- to 8-Week) Stretching Programs

In a study investigating the biomechanical effects of a 4-week hamstring muscle stretching program, Halbertsma and Göeken<sup>15</sup> (using an instrumented passive straight-leg raise test) found that sensations of pain onset and pain or stretch tolerance occurred at increased torques, resulting in increases in hamstring

muscle extensibility (pain onset: mean increase = 10°, 95% confidence interval = 5°–14°; pain or stretch tolerance: mean increase = 5°, 95% confidence interval = 1°–9°). Concurrently, no shift of passive torque/angle curves was observed. Magnusson et al<sup>58</sup> reported similar results in a 3-week hamstring muscle stretching study that induced a 17-degree mean increase in end-range joint angles using an endpoint of pain onset. These results—no shift in passive torque/angle curves accompanied by increases in end-range joint angles—have been supported repeatedly in studies involving hamstring muscles and using various stretching and testing methods.<sup>17,42,43,45,61,62</sup> Modification of subjects' sensory response to stretch after short-term stretching programs also has been demonstrated in the rectus femoris muscle<sup>63</sup> and in ankle plantar-flexor muscles.<sup>44,64</sup> Studies involving subjects with spinal cord injuries showed no evidence of a shift in torque/angle curves after 4-week programs of sustained 30-minute daily stretching of hamstring<sup>65</sup> and ankle plantar-flexor<sup>66</sup> muscles, further supporting the notion that short-term stretching does not alter torque/angle relationships.

### Long-Term (>8 Weeks) and Chronic Stretching Programs

The effect of longer-term stretching programs (>8 weeks) and rigorous chronic stretching regimens on passive torque/angle curves has not yet been evaluated.<sup>14</sup>

### Conflicts in Research Conflicting Terminology

Throughout the rehabilitation literature regarding the effects of stretching, confusion arises due to inconsistent use of terminology among studies. Some of the above-cited studies confirmed that increases in muscle extensibility occurred after stretching, whereas others claimed that muscle extensibility did not in-

crease. On the surface, it appears that these studies had conflicting results, but the difference merely resides in the definition of muscle extensibility. The studies reporting increases in muscle extensibility used a sensory endpoint, which indicates that the selected sensation had onset later during stretch application, allowing increases in end-range joint angles.<sup>15,59</sup> The studies reporting no increases in muscle extensibility used an endpoint of standardized torque, which gives some evidence that there was no shift of the torque/angle curves or change in muscle stiffness.<sup>61,62,65</sup> Taken together, the findings of all of these studies support the sensory theory to explain increases in end-range joint angles.

### Conflicting Interpretations

Although the results of many of the supporting studies were similar, not all of these studies attributed the findings to a change in sensory perception.<sup>43–45,64</sup> Some studies<sup>43–45</sup> suggest instead that because there is increased applied torque, a longer torque/angle curve, and increased end-range joint angles, the stretching program has induced structural changes within the muscle, such as increased sarcomeres in series and a mechanical increase in muscle length. If an increase in the number of serial sarcomeres is accompanied by an increase in length of the muscle, there should be an observable right shift in the entire passive torque/angle curve similar to the shift in passive length/tension curves shown in the animal studies (Fig. 1).<sup>39,40,67</sup> Without a concurrent right shift in passive torque/angle curves, there is no evidence of an increase in muscle length. The theory of structural adaptation occurring after a short-term stretching program also does not explain similar increases seen immediately after a single stretching session that occur

\* Isokinetic International, 6426 Morning Glory Dr, Harrison, TN 37341.

without a regimented stretching program.<sup>14,25,59,60</sup>

### Conflicting Results

Although there is growing evidence to support the theory that increases in muscle extensibility observed after stretching are due to modified sensation only, there are a few conflicting reports. In a study of ankle plantar-flexor muscles, Guissard and Duchateau<sup>68</sup> observed a right shift of torque/angle curves that occurred over a 6-week training period. This result may have been due to the vigorous design of the stretching program, which was performed 5 days per week and took 20 minutes to complete. This stretching dosage for a single muscle group on a single limb is well in excess of the 15 to 150 seconds<sup>29,44,64,69,70</sup> of daily stretch typically used in sports and research but may be applicable in rehabilitation settings. Thirty days after the stretching program ended, increases in extensibility and muscle length were partially maintained. More research is needed to determine: (1) whether increases in muscle length are an appropriate and desirable outcome of treatment and (2) the most efficient therapeutic intervention and dosage to induce and maintain length increases.

### A Multidimensional Approach to Evaluating Muscle Length

The sensory theory of increasing muscle extensibility demonstrates how multidimensional muscle length testing can enhance basic knowledge about muscle adaptation. Evaluation techniques that include multiple dimensions of muscle length (eg, extensibility measurements, torque and cross-sectional area) provide tools to better assess muscle status and the effect of therapeutic interventions.

### Muscle Extensibility

Muscle extensibility is a critical dimension of muscle length. Tests of extensibility (traditionally called “muscle length tests”) were developed with the idea that there is a “normal” or ideal range of muscle extensibility that promotes optimal kinematics, resulting in efficient motion, enhancing the ability to adapt to imposed stresses, and potentially decreasing the risk of injury.<sup>71,72</sup> It is suggested that when a particular muscle or muscle group demonstrates insufficient extensibility (appearing to be “short”), motion between joint surfaces that the muscle crosses may be limited, resulting in restricted joint motion. When the muscle or muscle group demonstrates excessive extensibility (appearing to be “long”), motion between the joint surfaces also may be excessive, resulting in excessive joint motion.

Whether insufficient or excessive, a deviation from optimal extensibility is thought to precipitate unusual wear patterns on capsular structures and articular surfaces of involved joints. It is suggested that deviations from optimal extensibility contribute to muscle imbalances, faulty posture, and dysfunctional movement.<sup>71,73</sup> Although guidelines for what constitutes insufficient, optimal, and excessive extensibility measurements are based on the science of kinematics, their clinical validity has rarely been studied.

Although kinematic analysis is concerned with the motion that occurs at the joint and can identify the clinical extensibility measurements that are theoretically optimal, it is not concerned with analyzing the forces causing the motion.<sup>1,72</sup> Except in cases where bony approximation is the limiting factor, this type of analysis does not clearly define what should constitute the endpoint of stretch application. Perhaps this is

the reason that stretch endpoints often are poorly defined and inconsistent among texts and research studies and in clinical practice.

An endpoint of the examiner’s perception of “(firm) resistance” is suggested in some texts<sup>72,74</sup> and often is used in research, although many studies did not measure the amount of applied torque required to reach this point.<sup>35,49,53,69,70</sup> The validity and reliability of this endpoint are highly questionable because without quantitative measurement, there is no way to be certain that torque is being applied consistently.<sup>75</sup> There also is evidence that the amount of torque applied by trained therapists can vary markedly—as much as 40-fold for a single subject.<sup>76</sup> Even if torque were standardized, how would the most clinically relevant torque be determined?

The importance of subject sensation as an endpoint has largely been overlooked. To date, endpoints of subject sensation are widely used in research, but basic texts describing muscle extensibility assessment have not clearly and unequivocally made this recommendation. Is passive muscle stiffness necessary to stop joint motion, or is it possible that just the subject’s sensory perception of stiffness or perception of moderate stretch can be a limiting factor? Studies evaluating the biomechanical effects of stretching reveal that in controlled clinical settings under the condition of slowly applied passive stretch, it is subject sensation—not the degree of stiffness—that limits joint motion. Researchers have been able to apply passive torque up to the sensory endpoint of pain<sup>25,58</sup> or stretch tolerance<sup>15,59</sup> without being limited by stiffness. It seems reasonable that subject sensation could both alter and reflect the way the tested muscle is routinely used in function. Further research is needed to determine whether subject sensation



tion is a significant factor in limiting joint motion during functional motion and whether muscle extensibility measurements are truly a reflection of the way muscles are used during function.

Although subject sensation is the most frequently used endpoint in human stretching research, there is little consensus regarding which sensation is most relevant clinically. A wide range of sensations has been used in research, from the subject's perception of a "pull,"<sup>47</sup> to varying degrees of:

- "resistance"<sup>16,37</sup>
- "stretch"<sup>15,17,19,20,22,42,44,45,59,63</sup>
- "discomfort"<sup>7,29,33,69-71</sup>
- "tightness"<sup>25,26,28,58,69,70,77</sup>
- "stiffness"<sup>78</sup>
- "pain"<sup>7,15,18,25,26,58,60,64,79</sup>

A change in endpoints from detection of the "first sensation of pain" to pain or stretch tolerance can result in a change in end-range joint angles that varies markedly among subjects.<sup>15</sup> This has been demonstrated in the hamstring musculature of otherwise "normal" subjects assessed with "short" hamstring muscles to range anywhere from no change at all to a 20-degree increase in end-range joint angle values.<sup>15</sup> Further research is needed to assess which sensation is most clinically relevant.

Subject sensation is—at the very least—an important endpoint of the torque/angle curve and may give information regarding how the muscle is routinely used during functional activity. However, extensibility measurements alone are only one dimension of muscle length and may not accurately reflect the actual length of the muscle. This has been demonstrated repeatedly in studies that included evaluation of torque<sup>80</sup> and cross-sectional area.<sup>81,82</sup> Torque and cross-sectional area measurements provide critical information that allows a more precise muscle length assessment.

### Torque

When the dimension of tension is included in muscle length evaluation, a passive torque/angle curve can be constructed. This curve shows the relationship between individual extensibility measurements and the torque required to attain each measurement (the torque/angle relationship). Using this curve, important biomechanical properties such as stiffness, compliance, energy, and hysteresis can be assessed.<sup>2</sup> This information allows evaluation of an individual's muscle for comparison before and after an intervention, thus showing the effect of the intervention on the tested muscle's biomechanical properties. Use of this type of testing led to the development of the sensory theory.<sup>15,25,58,59</sup>

Torque/angle curves, however, may not fully reflect actual muscle length. Torque measurements quantify a muscle's resistance to passive stretch, and this resistance is partly determined by thickness of the muscle. Other factors being equal, a thicker muscle demonstrates increased stiffness at a given joint angle, which causes the muscle to appear shorter on a torque/angle curve. A thinner muscle, other factors being equal, demonstrates decreased stiffness at a given joint angle, causing the muscle to appear longer on a torque/angle curve. In order to evaluate the contribution of muscle thickness to passive resistance, measurement of cross-sectional area is required.

### Cross-Sectional Area

Measurement of cross-sectional area is, by itself, valuable. Changes in cross-sectional area indicate an intervention effect of muscle hypertrophy (when increased) and atrophy (when decreased).

When assessment of muscle cross-sectional area is combined with

torque and joint angle, the biomechanical properties of muscles of different thicknesses can be compared.<sup>1,81,82</sup> Measurements of stress (tension/cross-sectional area), as well as normalized stiffness, compliance, energy, and hysteresis values, can be derived. These normalized values allow researchers to determine to what degree muscle cross-sectional area contributes to observed passive resistance and biomechanical properties.

### Implications for Research and Clinical Practice

Despite its fundamental role in rehabilitation, as well as sports and fitness, very little is actually known about muscle length: what constitutes optimal extensibility, torque/angle parameters, and cross-sectional area. Future research is needed to address which biomechanical properties and measures (or combination thereof) reflect an optimal muscle length. An optimal muscle length would allow not only an optimal range of muscle extensibility and joint motion but also optimal tendon length, overlap of contractile tissue filaments, and overall muscle thickness so that the muscle can generate the amount of passive and active tension required during function. Further research could address the extensibility, torque/angle relationship, and cross-sectional area considered optimal and how these parameters vary among individuals, between the sexes, over the lifespan, and for various muscles and subject groups. With continued research, muscle length disorders may someday be more precisely assessed, allowing selection of the intervention that will best address the specific disorder. This research also has relevance in developing general fitness guidelines.

For example, a muscle that is too short is operating in a range that is left of optimal torque/angle curves.

Clinically, this would be considered to be a “contracture.” Whether a muscle exhibits decreased extensibility or if it is truly shortened cannot be determined by extensibility measures alone. Two studies on ankle plantar-flexor muscles compared different subject groups (elderly women<sup>7</sup> and subjects diagnosed with diabetes mellitus and peripheral neuropathies<sup>80</sup>) with control subjects and found that the test groups exhibited decreased extensibility but that torque/angle curves, besides being shorter, were not significantly different. These findings would suggest that the test subjects’ muscles were not actually shortened (torque/angle curves were not shifted left) but were lacking in extensibility. The commonly prescribed treatment of stretching would address this clinical problem by increasing extensibility without shifting torque/angle curves. Neither of these studies assessed cross-sectional area of the tested muscles, however, so it is not known to what extent muscle thickness contributed to passive resistance. For example, it is possible that shortened muscles combined with decreased cross-sectional area could have confounded the results.<sup>80</sup>

Another study involving male endurance athletes found that subjects whose hamstring muscles were classified as “tight” did have passive torque/angle curves that were shifted left compared with control subjects’ hamstring muscles.<sup>82</sup> Both groups were similar in age, height, weight, training history, and hamstring muscle cross-sectional area. Decreased hamstring muscle extensibility also has been associated with a left shift in active torque/angle curves.<sup>83</sup> Does this left shift in torque/angle curves predispose the subjects to be less efficient in functional motion or more prone to musculoskeletal pain syndromes and injury? Does the change in biome-

chanical properties that accompanied the shorter muscles enhance or detract from functional performance? It appears that standard dosage stretching regimens do not change the torque/angle relationship in the short term, and 8 of 10 of the athletes with “tight” hamstring muscles were already performing regular stretching exercises. If the left shifted position was found to be detrimental, the challenge would be to find a therapeutic intervention that would induce a lasting right shift of these subjects’ torque/angle curves.

A study involving subjects diagnosed with benign joint hypermobility syndrome (BJHS) suggests that hamstring muscles attaining greater than “normal” extensibility may not actually be longer than those of “normal” control subjects.<sup>81</sup> Both groups were matched for age and sex and were similar in hamstring muscle cross-sectional area. The biomechanical properties (VESR and passive energy absorption [area under the stress/angle curve] at mutual joint angles) of the subjects with BJHS were not significantly different from those of “normal” controls.<sup>1,81</sup> The excessive range of muscle extensibility in the subjects diagnosed with BJHS was attributed to altered sensation and not to mechanically longer muscles.<sup>81</sup> Using just the end-range joint angles as a guide, the typical treatment recommendation would be strengthening of the muscles and avoiding stretched positions.<sup>71</sup> In this case, the biomechanical analysis suggests that the primary problem is sensory in nature—a late onset of sensation in response to stretch. Strengthening has been shown to affect torque/angle curves by increasing passive stiffness<sup>84</sup> but would not address the sensory problem. Instead, perhaps treatment should focus primarily on avoidance of overstretching the muscle. It is not known whether the sensory perception of stretch could return to an

optimal range over time with appropriate treatment and adherence to kinematic guidelines.

These examples suggest 3 different potential muscle length disorders and how treatment can be specifically directed to address them. As research continues, there are likely to be more disorders of muscle length (involving different combinations of altered extensibility, torque/angle curves, and cross-sectional area) discovered that may be able to explain clinical anomalies. One possible example could be an athletic subject with a history of recurrent hamstring muscle strains who stretches regularly and demonstrates an optimal range of extensibility. Perhaps the root of the problem is a torque/angle curve that is left of optimal. The challenge, once again, would be to find an intervention that can induce a lasting shift in the torque/angle curve toward an optimal range.

Multidimensional muscle length testing also can be important in developing fitness guidelines. There is a growing popularity of various exercise regimens that encourage stretching to a degree considered excessive by kinematic analysis. Little is known about the short- and long-term effects of this type of stretching and what accounts for the increased extensibility it induces. Are the adaptations sensory in nature, as was suggested by the study of subjects diagnosed with BJHS, or is there a long-term increase in muscle length or a change in other biomechanical properties? Are these adaptations reversible once this type of stretching is stopped? Are these adaptations desirable, despite kinematic evidence to the contrary?

## Conclusion

Traditionally, rehabilitation literature has attributed increases in muscle extensibility observed after stretching to a mechanical increase in muscle length. A growing body of re-

search refutes these mechanical theories, suggesting instead that in subjects who are asymptomatic, increases in muscle extensibility observed immediately after a single stretching session and after short-term (3- to 8-week) stretching regimens are predominantly due to modification in subjects' sensation. This research brings to light the importance of using sensory endpoints when assessing muscle extensibility, the value of multidimensional muscle length assessment, and the need for basic research in this field. Multidimensional evaluation of muscle length can lead to a more comprehensive and effective approach to addressing disorders of muscle length and has application in developing fitness guidelines.

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## References

- Özkaya N, Nordin M. *Fundamentals of Biomechanics: Equilibrium, Motion, and Deformation*. 2nd ed. New York, NY: Springer; 1999.
- Enoka RM. *Neuromechanics of Human Movement*. 3rd ed. Champaign, IL: Human Kinetics Publishers; 2002.
- Hollinshead WH, Rosse CM. *Textbook of Anatomy*. 4th ed. Baltimore, MD: Lippincott Williams & Wilkins; 1985.
- Magnusson SP, Narici MV, Maganaris CN, Kjaer M. Human tendon behaviour and adaptation, in vivo. *J Physiol (Lond)*. 2008;586:71-81.
- Gajdosik RL, Rieck MA, Sullivan DK, Wightman SE. Comparison of four clinical tests for assessing hamstring muscle length. *J Orthop Sports Phys Ther*. 1993;18:614-618.
- Gajdosik RL, Lusin G. Hamstring muscle tightness: reliability of an active-knee-extension test. *Phys Ther*. 1983;63:1085-1090.
- Gajdosik RL, Vander Linden DW, Williams AK. Influence of age on length and passive elastic stiffness characteristics of the calf muscle-tendon unit of women. *Phys Ther*. 1999;79:827-838.
- Johnson EK, Chiarello CM. The slump test: the effects of head and lower extremity position on knee extension. *J Orthop Sports Phys Ther*. 1997;26:310-317.
- Kornberg C, Lew P. The effect of stretching neural structures on grade one hamstring injuries. *J Orthop Sports Phys Ther*. 1989;10:481-487.
- Turl SE, George KP. Adverse neural tension: a factor in repetitive hamstring strain? *J Orthop Sports Phys Ther*. 1998;27:16-21.
- Webright WG, Randolph BJ, Perrin DH. Comparison of nonballistic active knee extension in neural slump position and static stretch techniques on hamstring flexibility. *J Orthop Sports Phys Ther*. 1997;26:7-13.
- Gajdosik RL. Passive extensibility of skeletal muscle: review of the literature with clinical implications. *Clin Biomech (Bristol, Avon)*. 2001;16:87-101.
- Liebesman J, Cafarelli E. Physiology of range of motion in human joints: a critical review. *Crit Rev Phys Rehabil Med*. 1994;6:131-160.
- Magnusson SP. Passive properties of human skeletal muscle during stretch maneuvers: a review. *Scand J Med Sci Sports*. 1998;8:65-77.
- Halbertsma JP, Göeken LN. Stretching exercises: effect on passive extensibility and stiffness in short hamstrings of healthy subjects. *Arch Phys Med Rehabil*. 1994;75:976-981.
- de Weijer VC, Gorniak GC, Shamus E. The effect of static stretch and warm-up exercise on hamstring length over the course of 24 hours. *J Orthop Sports Phys Ther*. 2003;33:727-733.
- Chan SP, Hong Y, Robinson PD. Flexibility and passive resistance of the hamstrings of young adults using two different static stretching protocols. *Scand J Med Sci Sports*. 2001;11:81-86.
- Willy RW, Kyle BA, Moore SA, Chleboun GS. Effect of cessation and resumption of static hamstring muscle stretching on joint range of motion. *J Orthop Sports Phys Ther*. 2001;31:138-144.
- Magnusson SP, Simonsen EB, Aagaard P, et al. Viscoelastic response to repeated static stretching in the human hamstring muscle. *Scand J Med Sci Sports*. 1995;5:342-347.
- Magnusson SP, Simonsen EB, Aagaard P, Kjaer M. Biomechanical responses to repeated stretches in human hamstring muscle in vivo. *Am J Sports Med*. 1996;24:622-628.
- McNair PJ, Dombroski EW, Hewson DJ, Stanley SN. Stretching at the ankle joint: viscoelastic responses to holds and continuous passive motion. *Med Sci Sports Exerc*. 2001;33:354-358.
- Duong B, Low M, Moseley AM, et al. Time course of stress relaxation and recovery in human ankles. *Clin Biomech (Bristol, Avon)*. 2001;16:601-607.
- Taylor DC, Dalton JD, Seaber AV, Garrett WE. Viscoelastic properties of muscle-tendon units: the biomechanical effects of stretching. *Am J Sports Med*. 1990;18:300-309.
- Ryan ED, Beck TW, Herda TJ, et al. The time course of musculotendinous stiffness responses following different durations of passive stretching. *J Orthop Sports Phys Ther*. 2008;38:632-639.
- Magnusson SP, Simonsen EB, Aagaard P, et al. Mechanical and physical responses to stretching with and without pre-isometric contraction in human skeletal muscle. *Arch Phys Med Rehabil*. 1996;77:373-378.
- Magnusson SP, Aagaard P, Simonsen E, Bojsen-Møller F. A biomechanical evaluation of cyclic and static stretch in human skeletal muscle. *Int J Sports Med*. 1998;19:310-316.
- De Deyne PG. Application of passive stretch and its implications for muscle fibers. *Phys Ther*. 2001;81:819-827.
- Magnusson SP, Aagaard P, Nielson JJ. Passive energy return after repeated stretches of the hamstring muscle-tendon unit. *Med Sci Sports Exerc*. 2000;32:1160-1164.
- Feland JB, Myrer JW, Schulthies SS, et al. The effect of duration of stretching of the hamstring muscle group for increasing range of motion in people aged 65 years or older. *Phys Ther*. 2001;81:1110-1107.
- Draper DO, Castro JL, Feland B, et al. Shortwave diathermy and prolonged stretching increase hamstring flexibility more than prolonged stretching alone. *J Orthop Sports Phys Ther*. 2004;34:13-20.
- Wessling KC, DeVane DA, Hylton CR. Effects of static stretch versus static stretch and ultrasound combined on triceps surae muscle extensibility in healthy women. *Phys Ther*. 1987;67:674-679.
- Sapega AA, Quedenfeld TC, Moyer RA, Butler RA. Biophysical factors in range-of-motion exercise. *Phys Sportsmed*. 1981;9:57-65.
- Zito M, Driver D, Parker C, Bohannon RL. Lasting effects of one bout of two 15-second passive stretches on ankle dorsiflexion range of motion. *J Orthop Sports Phys Ther*. 1997;26:214-221.
- Hortobágyi T, Faludi J, Tihanyi J, Merkely B. Effects of intense "stretching"-flexibility training on the mechanical profile of the knee extensors and on the range of motion of the hip joint. *Int J Sports Med*. 1985;6:3173-3121.
- Knight CA, Rutledge CR, Cox ME, et al. Effect of superficial heat, deep heat, and active exercise warm-up on the extensibility of the plantar flexors. *Phys Ther*. 2001;81:1206-1214.
- Smith CA. The warm-up procedure: to stretch or not to stretch: a brief review. *J Orthop Sports Phys Ther*. 1994;19:12-17.
- Taylor BF, Waring CA, Brashear TA. The effects of therapeutic application of heat or cold followed by static stretch on hamstring muscle length. *J Orthop Sports Phys Ther*. 1995;21:283-286.



- 38 Warren CG, Lehmann JF, Koblanski JN. Elongation of rat tail tendon: effect of load and temperature. *Arch Phys Med Rehabil*. 1971;52:465-474.
- 39 Tabary JC, Tabary C, Tardieu C, et al. Physiological and structural changes in the cat's soleus muscle due to immobilization at different lengths by plaster casts. *J Physiol*. 1972;224:231-244.
- 40 Goldspink G, Tabary C, Tabary JC, et al. Effect of denervation on the adaptation of sarcomere number and muscle extensibility to the functional length of the muscle. *J Physiol*. 1974;236:733-742.
- 41 Williams PE, Goldspink G. Changes in sarcomere length and physiological properties in immobilized muscle. *J Anat*. 1978;127(pt 3):459-468.
- 42 Folpp H, Deall S, Harvey LA, Gwinn T. Can apparent increases in muscle extensibility with regular stretch be explained by changes in tolerance to stretch? *Aust J Physiother*. 2006;52:45-50.
- 43 Gajdosik RL. Effects of static stretching on the maximal length and resistance to passive stretch of short hamstring muscles. *J Orthop Sports Phys Ther*. 1991;14:250-255.
- 44 Gajdosik RL, Vander Linden DW, McNair PJ, et al. Effects of an eight-week stretching program on the passive-elastic properties and function of the calf muscles of older women. *Clin Biomech (Bristol, Avon)*. 2005;20:973-983.
- 45 Reid DA, McNair PJ. Passive force, angle, and stiffness changes after stretching of hamstring muscles. *Med Sci Sports Exerc*. 2004;36:1944-1918.
- 46 Spennoga SG, Uhl TL, Arnold BL, Gansseder BM. Duration of maintained hamstring flexibility after a one-time, modified hold-relax stretching protocol. *J Athl Train*. 2001;36:44-48.
- 47 Tanigawa MC. Comparison of the hold-relax procedure and passive mobilization on increasing muscle length. *Phys Ther*. 1972;52:725-735.
- 48 Alter MJ. *Science of Flexibility*. 3rd ed. Champaign, IL: Human Kinetics Publishers; 2004.
- 49 Bandy WD, Irion JM, Briggler M. The effect of static stretch and dynamic range of motion training on the flexibility of the hamstring muscles. *J Orthop Sports Phys Ther*. 1998;27:295-300.
- 50 Etnyre BR, Lee EJ. Comments on proprioceptive neuromuscular facilitation stretching techniques. *Res Q Exerc Sport*. 1987;58:184-188.
- 51 Depino GM, Webright WG, Arnold BL. Duration of maintained hamstring flexibility after cessation of an acute static stretching protocol. *J Athl Train*. 2000;35:56-59.
- 52 Winters MV, Blake CG, Trost JS, et al. Passive versus active stretching of hip flexor muscles in subjects with limited hip extension: a randomized clinical trial. *Phys Ther*. 2004;84:800-807.
- 53 Nelson RT, Bandy WD. Eccentric Training and static stretching improve hamstring flexibility of high school males. *J Athl Train*. 2004;39:254-258.
- 54 Chalmers G. Re-examination of the possible role of Golgi tendon organ and muscle spindle reflexes in proprioceptive neuromuscular facilitation muscle stretching. *Sports Biomech*. 2004;3:159-183.
- 55 Sharman MJ, Cresswell AG, Riek S. Proprioceptive neuromuscular facilitation stretching: mechanisms and clinical implications. *Sports Med*. 2006;36:929-939.
- 56 Moore MA, Hutton RS. Electromyographic investigation of muscle stretching techniques. *Med Sci Sports Exerc*. 1980;12:322-329.
- 57 McHugh MP, Kremenich IJ, Fox MB, Gleim GW. The role of mechanical and neural restraints to joint range of motion during passive stretch. *Med Sci Sports Exerc*. 1998;30:928-932.
- 58 Magnusson SP, Simonsen EB, Aagaard P, et al. A mechanism for altered flexibility in human skeletal muscle. *J Physiol*. 1996;497(pt 1):291-298.
- 59 Halbertsma JP, van Bolhuis AI, Göeken LN. Sport stretching: effect on passive muscle stiffness of short hamstrings. *Arch Phys Med Rehabil*. 1996;77:688-692.
- 60 Laessøe U, Voigt M. Modification of stretch tolerance in a stooping position. *Scand J Med Sci Sports*. 2004;14:239-244.
- 61 Ben M, Harvey LA. Regular stretch does not increase muscle extensibility: a randomized controlled trial. *Scand J Med Sci Sports*. 2009 May 28. [Epub ahead of print]
- 62 Law RYW, Harvey LA, Nicholas MK, et al. Stretch exercises increase tolerance to stretch in patients with chronic musculoskeletal pain: a randomized controlled trial. *Phys Ther*. 2009;89:1016-1026.
- 63 Björklund M, Hamberg J, Crenshaw AG. Sensory adaptation after a 2-week stretching regimen of the rectus femoris muscle. *Arch Phys Med Rehabil*. 2001;82:1245-1250.
- 64 Gajdosik RL, Allred JD, Gabbert HL, Sonsteng BA. A stretching program increases the dynamic passive length and passive resistive properties of the calf muscle-tendon unit of unconditioned younger women. *Eur J Appl Physiol*. 2007;99:449-454.
- 65 Harvey LA, Byak AJ, Ostrovskaya M, et al. Randomised trial of the effects of four weeks of daily stretch on extensibility of hamstring muscles in people with spinal cord injuries. *Aust J Physiother*. 2003;49:176-181.
- 66 Harvey LA, Batty J, Crosbie J, et al. A randomized trial assessing the effects of 4 weeks of daily stretching on ankle mobility in patients with spinal cord injuries. *Arch Phys Med Rehabil*. 2000;81:1340-1347.
- 67 Williams P, Simpson H, Kyberd P, et al. Effect of rate of distraction on loss of range of joint movement, muscle stiffness, and intramuscular connective tissue content during surgical limb-lengthening: a study in the rabbit. *Anat Rec*. 1999;255:78-83.
- 68 Guissard N, Duchateau J. Effect of static stretch training on neural and mechanical properties of the human plantar-flexor muscles. *Muscle Nerve*. 2004;29:248-255.
- 69 Bandy WD, Irion JM. The effect of time on static stretch on the flexibility of the hamstring muscles. *Phys Ther*. 1994;74:845-850; discussion 850-852.
- 70 Bandy WD, Irion JM, Briggler M. The effect of time and frequency of static stretching on flexibility of the hamstring muscles. *Phys Ther*. 1997;77:1090-1096.
- 71 McCreary EK, Provance PG, Rodgers MM, Romani WA. *Muscles: Testing and Function, With Posture and Pain*. 5th ed. Baltimore, MD: Lippincott Williams & Wilkins; 2005.
- 72 Reese NB, Bandy WD. *Joint Range of Motion and Muscle Length Test*. Philadelphia, PA: Saunders; 2002.
- 73 Sahrmann S. *Diagnosis and Treatment of Movement Impairment Syndromes*. St Louis, MO: Mosby; 2002.
- 74 Norkin CC, White DJ. *Measurement of Joint Motion: A Guide to Goniometry*. 3rd ed. Philadelphia, PA: FA Davis Co; 2003.
- 75 Bohannon RL. Commentary on "Hamstring Muscle Tightness." *Phys Ther*. 1983;63:1088-1089.
- 76 Harvey LA, McQuade L, Hawthorne S, Byak A. Quantifying the magnitude of torque physiotherapists apply when stretching the hamstring muscles of people with spinal cord injury. *Arch Phys Med Rehabil*. 2003;84:1072-1075.
- 77 Magnusson SP, Simonsen EB, Aagaard P, et al. Contraction specific changes in passive torque in human skeletal muscle. *Acta Physiol Scand*. 1995;155:377-386.
- 78 Stephens J, Davidson J, Derosa J, et al. Lengthening the hamstring muscles without stretching using "awareness through movement". *Phys Ther*. 2006;86:1641-1650.
- 79 Halbertsma JP, Göeken LN, Hof AL, et al. Extensibility and stiffness of the hamstrings in patients with nonspecific low back pain. *Arch Phys Med Rehabil*. 2001;82:232-238.
- 80 Salsich GB, Mueller MJ, Sahrmann SA. Passive ankle stiffness in subjects with diabetes and peripheral neuropathy versus an age-matched comparison group. *Phys Ther*. 2000;80:352-362.
- 81 Magnusson SP, Julsgaard C, Aagaard P, et al. Viscoelastic properties and flexibility of the human muscle-tendon unit in benign joint hypermobility syndrome. *J Rheumatol*. 2001;28:2720-2725.
- 82 Magnusson SP, Simonsen EB, Aagaard P, et al. Determinants of musculoskeletal flexibility: viscoelastic properties, cross-sectional area, EMG and stretch tolerance. *Scand J Med Sci Sports*. 1997;7:195-202.
- 83 Alonso J, McHugh MP, Mullaney MJ, Tyler TF. Effect of hamstring flexibility on isometric knee flexion angle-torque relationship. *Scand J Med Sci Sports*. 2009;19:252-256.
- 84 Klinge K, Magnusson SP, Simonsen EB, et al. The effect of strength and flexibility training on skeletal muscle electromyographic activity, stiffness, and viscoelastic stress relaxation response. *Am J Sports Med*. 1997;25:710-716.