Warm-up and Flexibility

DUANE V. KNUDSON

Introduction

Athletes looking to improve sport performance or lengthen their athletic careers by modifying the risk of injury—as well as the exercising public—often focus on warm-up and flexibility routines in their training. Considerable research has been conducted on both of these issues and a surprising picture is emerging. The bulk of the current research is supportive of training and injury-prevention beliefs related to warm-up. Common beliefs about flexibility and stretching, however, are changing. This chapter summarizes what is known about the performance and injury-prevention benefits of warm-up and flexibility, since the two have complex relationships to performance and the risk of musculoskeletal injury. The chapter concludes with general recommendations for prescribing stretching exercises and programs.

WARM-UP

It is important to realize that warm-up and stretching are two different activities. Warm-up is designed to elevate core body temperature and stretching is primarily performed to increase the range of motion (ROM) at a joint or group of joints. It is well accepted that generalized warm-up movements are important to maximizing sport performance and reducing injury risk in physical activity. **Warm-up** consists of active or passive warming of body tissues in preparation for physical activity. **Active warm-up** consists of low-intensity movements that are effective in elevating body temperature, warming tissue, and producing a variety of improvements in physiological function. **Passive warm-up** includes external heat sources like heating pads, whirlpools, or ultrasound. Prior to vigorous exertion, athletes should perform several minutes of general body movements (**general warm-up**) of progressively increasing intensity. These movements should emulate the actual movements of the sport or exercise to follow. Low-intensity movement specific to the sport or activity of interest is called **specific warm-up**.

Warm-up benefits performance through thermal, neuromuscular, and psychological effects (9,10,22,46,87,89). In some people, warm-up may also decrease the occurrence of dangerous cardiac responses from sudden strenuous exercise (5). Active warm-up activities mobilize metabolic resources and increase tissue temperature. Much of the benefit of warm-up comes from the increased body temperature (22). Moderate-intensity active warm-up (general movements) and passive warm-up (e.g., diathermy, heating pads, whirlpool) can increase muscular performance between 3 and 9% (9,10). Large-muscle-group motor tasks benefit from warm-up more than fine motor tasks (22).

Another reason for warm-up is to prepare the tissues for the greater stresses of vigorous physical activity and thus to lower the risk of muscle-tendon injury. Biomechanical evidence supports this "injury-protective" hypothesis, since warmed-up muscle in animal models has been found to elongate more before failure (28,80,86,91). This, combined with prospective studies of warm-up (19), suggests that general warm-up prior to vigorous activity may decrease the risk of musculo-tendinous injury compared to no warm-up. More direct evidence of this relationship would be helpful, but it is not possible to design studies that put subjects at risk of injury.

> *Warm-up activities are necessary to prepare the body for vigorous physical activity because they increase performance and decrease the risk of muscular injury.*

Athletes and other exercisers should therefore warm up prior to competition, practice, and physical conditioning. Recommendations for effective warm-up routines vary depending on the nature and duration of the exercise to be performed (10). In general, warm-up routines should use general, whole-body movements up to 40% to 60% of aerobic capacity for 5 to 10 minutes followed by 5 minutes of recovery (10). The American College of Sports Medicine recommends 5 to 10 minutes of calisthenic-type exercises and 5 to 10 minutes of progressive aerobic activity in warm-up (5). For example, tennis players may perform 5 minutes of light jogging, followed by the traditional 5-minute warm-up of ground strokes and serves prior to a match. Movement and muscular contractions commonly used in active warm-up also create decreases in passive tension (76,94) and increases in ROM as large as or larger than those due to passive stretching (40,77).

Most warm-up sessions should begin with general body movements of gradually increasing intensity, focusing on the muscles and joints to be used in training or competition. Static stretching currently is not recommended during warm-up routines (51). The reasons for this change from traditional practice are explored in the following sections on flexibility and stretching.

FLEXIBILITY

Flexibility is an important component of fitness and physical performance. Inconsistent use of terminology related to the term *flexibility* by a variety of health and exercise science professionals has led to confusion. There is a distinct difference between flexibility and joint laxity. **Flexibility** is "the intrinsic property of body tissues which determines the range of motion achievable without injury at a joint or series of joints" (37). The ability to move a joint without causing injury usually refers to the major anatomical rotations at joints rather than the joint laxity or accessory motion tests that orthopedists,

physical therapists, and athletic trainers often evaluate to test joint and/or ligament integrity. Flexibility can be measured a variety of ways, and several variables of interest have emerged.

One variable is the common clinical measure of the limits of rotation through a ROM referred to as **static flexibility**. This is estimated by linear or angular measurements of the limits of motion in a joint or joint complex. For example, it might be of clinical interest to know the static flexibility of areas of the body that tend to lose ROM with inactivity, like the lower (lumbar region) back or hamstring muscle group. Many professionals employ a sit-and-reach test (Fig. 9.1), using a linear measurement that provides a good field measure of hamstring static flexibility (34). These tests are limited by the rise in passive tension as the muscle and connective tissue are stretched.

Tests of static flexibility, although easy to administer, have several limitations. A major weakness of these tests is that the measures obtained are subjective and largely related to the subject's stretch tolerance (28,32,68,70), as well as the way in which the endpoint of the ROM is determined. Accurate measurements also depend on testing methodology. Variations in instruments, body positioning, instructions, or the protocol used all heavily influence results. Another problem is the variety of conditions in which the measurements are made. For example, physical therapy uses both active ROM (unassisted) and passive ROM (therapist-assisted) tests (81). The ROM achievable with the assistance of the tester (passive) is usually greater than that obtained with unassisted ROM. A great deal of information must be known about testing conditions to interpret data on static flexibility.

In a research setting, we now have the ability to measure mechanical properties of the body in addition to the clinical measurements of ROM. Research laboratory measurements of flexibility using computerized dynamometers have allowed the measurement of new biomechanical variables related to the mechanical properties of muscle and tendon. Two of these variables that may be related to performance and injury risk are stiffness and hysteresis. These terms are used in physics to describe properties of materials. Since the human body is composed of materials that react to external forces in exactly the same as other materials, the terms are also applicable to the human body.

The term **stiffness**, sometimes also known as dynamic flexibility, refers to how quickly tissue resistance rises during a movement that requires the muscle-tendon unit to stretch. With passive stretching, the stiffness of the muscle-tendon unit measures how quickly the passive tension rises right before damage occurs. Studies show that dynamic flexibility accounts for only about 44% to 66% of the variance of static flexibility (70,74). Therefore, these variables are related but probably represent different functional properties of the musculature.

Figure 9.2 illustrates a schematic of a torque-angle curve of the elongation phase of repeated
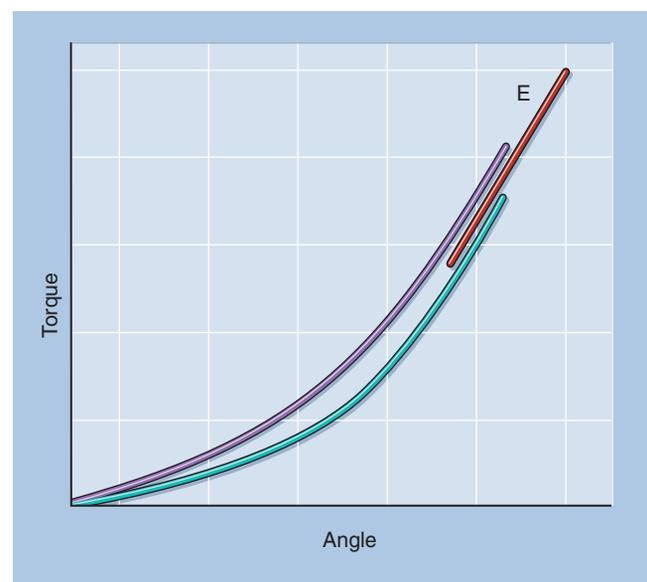

FIGURE 9.1 Since its development in the 1950s, the sit-and-reach test and several variations have become popular field tests of hamstring static flexibility.

FIGURE 9.2 Schematic of a torque-joint angle plot during repeated passive stretches of a muscle group. Stress relaxation makes the passive torque at a given joint angle in subsequent stretches (blue line) less than in the first stretch (purple line). The stiffness (E) of the muscle group in these stretches, however, is not different.

passive stretches of a muscle group. These angular variables approximate well the load-deformation (linear) curve of the muscle (67) and provide an in vivo (in the living animal) functional estimate of the passive stiffness of muscle groups (25,70,74). Scientists normally use linear measurements of load and deformation to define the mechanical properties of materials. Note that in the graph, the torque (and also tension) in the muscle rises in a complex fashion, slowly and then rapidly as the muscle gets longer.

Biological tissues have other complex behaviors that influence their function. The muscle-tendon unit is considered to be **viscoelastic**. This means that the muscle-tendon unit can extend immediately when a tensile stress is applied and that it also continues to elongate with continued application of the stress. A faster stretch would have a similar shape but a higher stiffness because of this viscoelastic behavior. The tension developed during a stretch depends on the degree of elongation and the rate of the stretch. Also note in Figure 9.2 that the stiffness (E) of the muscle group does not change with repeated static stretching. Preliminary evidence suggests that although stretching does not affect muscle stiffness, passive motion does create significant reductions in muscle stiffness (76).

One problem in discussing the stiffness of muscles is the difference in the scientific and lay meaning of *stiffness* and *elasticity.* In biomechanics, stiffness and **elasticity** are synonymous, so a muscle with a quick rise in tension during stretch will tend to recover rapidly when the stretch is released. This conflicts with the colloquial meaning of the term *elasticity,* which refers to low resistance to elongation.

Although the application of materials science to the human body may seem complex, it is important to realize that the human body is a material that responds to stress in a predictable manner. Materials science defines stiffness as the slope of the stress-strain curve in the elastic (linear) region, which is how quickly the tension rises late in elongation before the elastic limit. The elastic limit is the point on the graph depicting the lengthening of the muscle-tendon unit just before the material begins to fail or the beginning of permanent damage. Beyond the elastic limit is the plastic region, so called because this is where the deformation is not immediately recoverable. Fortunately, small stretches beyond the elastic limit may be repaired by the body if it is given enough rest, but a very severe

elongation can cause rupture or complete failure of the tissue. Materials scientists call the maximum force or energy absorbed before complete failure the **mechanical strength** of the material.

When a muscle is stretched, but not beyond its elastic limit, it will return to resting length and recover some of the energy stored in it as it was stretched. Some of the energy, however, is lost as heat. The energy lost in the return to normal length from a deformed material is termed **hysteresis**. This represents the energy lost and can be visualized as the area (loop) between the loading (elongation) and unloading (restitution) phases in Figure 9.3. This figure illustrates a schematic of a torque-angle curve of the elongation phase (purple line) and the restitution phase (blue line) of a static stretch.

From Figure 9.3, note that in static stretching, 40% to 50% of the energy stored in the stretch is lost as the muscle returns to normal length (64). Much of this energy loss is in the contractile and connective tissue components within the muscle. To the contrary, studies of long tendons in normal activity show that they recover most (80% to 90%) of the energy stored in them in cyclic stretch-shortening actions (2,55).

Measuring energy may be better for examining the effect of stretching on muscle, as opposed to stiffness, because muscle tissue does not reach the elastic region of the stress/strain curve in typical
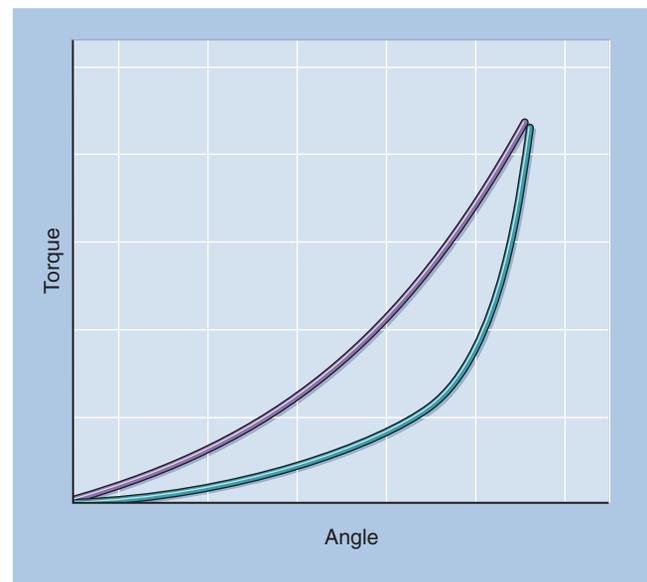
FIGURE 9.3 Schematic of a torque-joint angle plot of the elongation (purple) and restitution (blue) phases of a passive stretch of a muscle group. The energy lost (hysteresis) is the area of the loop between the loading and unloading phases.
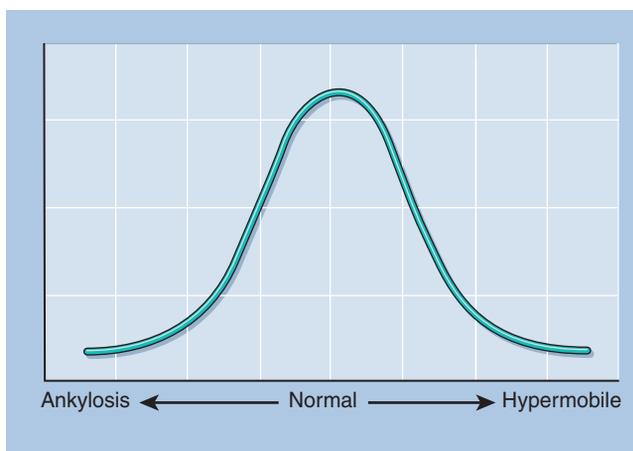
hamstring stretches (67). Stretching has a greater effect on hysteresis than on the stiffness of muscle. This is important because it gives direction to where we should be performing research in the future if that research is going to be practical and meaningful in terms of improving performance.

> *The ability to move the joints of the body freely without injury is known as flexibility, and several mechanical properties can be used to document aspects of flexibility.*

Normal Static Flexibility

The wealth of research on static flexibility measurements provides a general picture of what is normal static flexibility for most joints and populations. Normal static flexibility is the typical joint movement allowed between two extremes (Fig. 9.4): ankylosis and hypermobility (85,93). **Ankylosis** is pathological loss of ROM, while **hypermobility** is excessive ROM. Static flexibility is not a whole-body characteristic but, like fitness, is specific to joints and directions of movement (33,39). People may tend to have low static flexibility in one part of the body and normal or high flexibility in another. It is also clear that females have greater static flexibility than males (33), and some of these differences are related to anthropometric differences (13).

Fitness professionals can access data on normal ranges of static flexibility for most joints from several professional sources (4–6,27). Several recent reviews of flexibility have been published (1,23,42, 51,64,59) and provide more information on static flexibility. It is unclear however, whether an "optimal" level of static flexibility for muscle groups or areas of the body exists. If this is the case, it is likely that different sports would require different optimal levels of static flexibility. Future research studies should be designed to focus on determining "normative" static ranges of motion at joints in athletes participating in specific sports, as well as documenting anomalies in athletes and active people who are outside of this normative range. It is too early to make a definitive statement, but it is possible that an athlete or active person whose muscles are too tight is more prone to *muscle* injuries and that one whose muscles are too loose is more prone to *joint* injuries as well as decreased performance in strength and power activities.

Common deviations from normal static flexibility are present in many joint(s). Some people lose ROM from physical inactivity. People may also lose static flexibility from workplace or sport-specific positions and/or repetitive movements. For example, the repetitive motion in several sports with overhead throwing patterns (baseball, tennis, etc.) without specific stretching intervention (47) can result in glenohumeral internal rotation deficit (GIRD). Persistent wearing of high heels can decrease ankle dorsiflexion ROM (Fig. 9.5).

> *Several resources provide normative data on the typical static flexibility of most major joints of the body, but current research does not identify an optimal level of static flexibility.*

Flexibility and Injury Risk

What appears to be desirable, based on data on the incidence of injury, is to avoid the extremes in static

FIGURE 9.4 Schematic of a continuum of static flexibility. There is considerable research documenting the normal limits of static flexibility but little prospective research that links specific levels of static flexibility to increased risk of injury at either extreme.

FIGURE 9.5 Repetitive work or body positions (like wearing high heels) can create tight muscles and decrease ankle static flexibility.

flexibility. Athletes and exercisers at both extremes of static flexibility may be at a higher risk for musculoskeletal injuries (45,48). The literature on clinical and basic science provides a very different view of the role of flexibility in injury risk and performance than what is commonly believed and practiced. This section focuses on the association between flexibility and injury risk: the sections on stretching, further on, discuss the association between stretching and changes in muscular performance and injury risk.

Low levels of hamstring flexibility have been related to a higher risk of muscular injury in soccer (103). The common belief that greater static flexibility will always decrease the risk of muscular injury, however, appears not to be valid. This may be explained by the stability-mobility paradox. The mechanical stability and ROM at a joint or joints are inversely related (14,59,93). It is possible that as static flexibility increases beyond the normal range, the potential benefits of greater motion and less tissue resistance are offset by the greater instability of the joint. More research is needed to begin to define the ranges of motion for various joints, so that the best compromise of stability and mobility may be provided, along with a lower risk of injury.

A good example of the lack of an association between high levels of static flexibility and lower injury risk is provided by low back fitness testing. Although it seems logical that less flexible back or hamstring muscles would be related to the incidence of low back pain, little evidence supports this association. A review of the literature found limited support (mixed results) for an association between lumbar/hamstring flexibility and the occurrence of low back pain (82). More recently, a large prospective study found no relationship between static flexibility and subsequent low back pain in adults (43). Therefore, the field tests of hamstring static flexibility commonly used in fitness test batteries may not be useful in predicting future low back injury.

People also commonly believe that less "stiff" muscles result in greater flexibility and a lower risk of injury. Unfortunately, little research is available on the association between dynamic flexibility and injury risk. Less stiff muscles may be less susceptible to muscle strain injury (102), but only one study has been conducted in this area (73). It appears that muscle with greater stiffness is more susceptible to eccentrically induced muscle damage. Currently, the evidence is insufficient to conclude that decreased dynamic flexibility will provide an injury-protective benefit. Combined with the unclear nature of the exact levels of static flexibility that decrease injury risk, this means that strength and conditioning professionals must educate athletes on the complexity of flexibility and injury risk.

A complex relationship exists between static flexibility and risk of muscular injury. Higher injury rates appear to be related to very flexible or very inflexible muscles.

Assessing Flexibility

Exercise prescriptions to modify flexibility should be based on valid measurements using standardized testing procedures. Static flexibility tests are based on both linear and angular measurements of the motion of a joint or group of joints. These tests can focus on single joints or compound movements of many body segments and joints.

Single-joint static flexibility tests are commonly used clinically in the medical professions (4,6,24, 27,81); they often involve angular measurements (with goniometers or inclinometers) rather than linear measurements. Single-joint tests are considered better measurements of static flexibility than compound tests because they better isolate specific muscles and are less affected by anthropometric differences (15,58). The straight-leg-raise (30) and

REAL-WORLD APPLICATION
The Stability-Mobility Paradox

Static flexibility is like exercise in that more is not always better. Joint motion (mobility) is inversely proportional to the stability of the joint (93). Decreasing muscle passive tension around a joint increases the joint's ROM but also makes it easier for the joint to be pulled out of normal position. This presents the fitness professional with a paradox. What is the right amount of static flexibility? How much motion is necessary for normal and safe movement without adversely affecting the joint or ligaments? It is not possible to give easy answers to these questions. The amount of motion depends on the joint, the requirements of the sport/activity a person engages in, and other factors. Given that the lowest injury rates seem to correspond to normal flexibility and higher injury rates with the extremes in flexibility (inflexible and hypermobile), maintenance of normal or moderate amounts of static flexibility should be the goal for most people. Unless a person participates in an activity requiring extreme flexibility (dance, gymnastics, diving), most exercise prescriptions should focus on maintaining normal levels of static flexibility.

active-knee-extension (26) tests are the common hamstring flexibility tests used in physical therapy. The many variations of the sit-and-reach test (31, 36,38) are compound tests and are often validated with the straight leg raise or active knee extension.

Sit-and-reach scores are associated with hamstring flexibility but not with low back flexibility (72). Although the sit-and-reach test has been shown to be a moderately valid measure of hamstring flexibility which is only slightly affected by anthropometric variations (41,72), the prescriptive value of these measurements is limited. One study showed that 6% of children falsely passed and 12% falsely failed the sit-and-reach test relative to the straight-leg-raise test (15). If these data are consistent across all ages, people failing the sit-and-reach test should be retested with the straight-leg-raise or active-knee-extension test to make sure that they have limited hamstring static flexibility.

Current health-related norms for sit-and-reach or other static flexibility tests should be used only to identify individuals at the extremes who may be at higher risk for muscle injuries. Not enough data are available to provide specific static flexibility goals beyond the maintenance of normal flexibility. Fitness professionals must also remember that in measuring flexibility, exacting attention to testing details is necessary. Static flexibility scores are subjective and highly dependent on the subject's tolerance of the high muscle tension (discomfort) during testing. The clinical measurement of dynamic flexibility is not ordinarily practicable; it is limited to research settings because of problems related to expensive equipment, insufficient standardization, and the lack of normative data.

recommended for most people because of their often limited physical activity and also because regular participation in some activities is associated with sport-specific flexibility imbalances. In general, stretching recommendations should be limited to the maintenance of normal levels of static flexibility because of the complex nature of flexibility and the lack of data linking specific levels of flexibility to lower injury risk. This section concludes with recent evidence on the effect of stretching on muscular performance, which has implications for the placement of stretching in the training cycle.

Stretching exercises are usually classified into four types: passive, static, ballistic (dynamic), and **proprioceptive neuromuscular facilitation, or PNF** (8). **Passive stretching** uses an external force, usually another person, to stretch muscle groups (Fig. 9.6). **Static stretching** involves a slow increase in muscle group length and holding the stretched position at that length for a short time (usually 15 to 30 seconds). **Ballistic stretching** traditionally has meant fast, momentum-assisted, and bouncing stretching movements. These stretches are generally avoided because of the viscoelastic nature of muscle. For a given elongation, a fast stretch results in a higher force in the tissue and a greater risk of injury (61,88,95). Some refer to the active warm-up movements mentioned earlier as **dynamic stretching**. These stretches may be acceptable if they are performed in a relatively slow manner to create muscle elongation without imposing high levels of force on the tissue. This is probably how regular physical activity can maintain static flexibility.

The last group of stretching exercises focuses on PNF. PNF stretch routines use a specific series of

DEVELOPMENT OF FLEXIBILITY

Normal levels of flexibility can be maintained by regular physical activity and through specific programs of stretching and strengthening exercises. Kinesiology professionals should assess a client's flexibility, and based on these data and the client's history, develop a program to improve flexibility. Although poor flexibility can be treated with a combination of stretching and strengthening exercises (1), this section focuses on general recommendations for stretching in mass exercise prescription. Regular stretching exercises are usually

FIGURE 9.6 Passive stretching often uses external force from another person to produce a greater stretch of a muscle group.

movements and contractions to use neuromuscular reflexes to relax the muscles being stretched. PNF stretches can be performed with or without assistance. A simple PNF procedure is a "contract-relax" stretch where a person performs an isometric contraction of a muscle to be stretched, which is immediately followed by a static stretch of that muscle. This strategy takes advantage of the inhibitory effects of **Golgi tendon organs** as the muscle is slowly stretched. Assisted stretching procedures like PNF should be performed with care by trained subjects or sports medicine personnel. The practice of having athletes passively stretch partners should be used with caution until the athletes have been carefully trained in correct procedures and understand the risks of incorrect or high-force stretches.

The recommendations for stretching procedures are based on reviews of the basic science studies of the viscoelastic response of muscle to stretching (49,50). These recommendations (Table 9.1) are designed for group exercise prescription with normal subjects. Static or PNF stretching should be performed at least three times per week, preferably daily and after moderate or vigorous physical activity (in the cool-down phase of training). Exacting technique in stretching is recommended to safely focus tension on a muscle group or groups without systematic stress on other joint stability structures (ligaments, joint capsules, cartilage). Some experts have hypothesized, based on functional anatomy, that some stretching exercises are contraindicated because of potentially dangerous ligament and tissue loading (60,62,63).

Stretching programs should include up to four or five stretches for each major muscle group, with each stretch held for 15 to 30 seconds. The intensity (force) of each stretch should be minimized, slowly elongating and holding the stretched position just before the point of discomfort. The American College of Sports Medicine recommends holding static stretches "to a position of mild discomfort" (5). Slow elongation of muscles creates less reflex contraction through the action of **muscle spindles**. These sense muscle length and are responsible for the contraction of a stretched muscle (myotatic reflex). This reflex contraction is most sensitive to fast stretches, so slow muscle elongation in stretching exercises helps maintain relaxation in the muscle groups being stretched.

Static stretching will create a short-term increase in ROM and a decrease in passive tension in the muscle at a particular joint angle due to **stress relaxation**, which is the gradual decrease in stress (force per unit area) in a material stretched and held at a constant length. Most people can feel the decrease in passive tension in a muscle group held in a stretched position. This stress relaxation following stretching provides an immediate 10% to 30% decrease in passive tension (65,71,76), but the effect will have dissipated after about an hour (69). Holding stretches for 20 seconds is a good guideline, because most of the stress relaxation in passive stretches occurs in the first 20 seconds (64,75,95).

Stretching to increase static flexibility in a muscle group should normally use four to five static stretches held for 15 to 30 seconds.

TABLE 9.1	STRETCHING RECOMMENDATIONS FOR GROUP EXERCISE PRESCRIPTION
FITNESS VARIABLE	**RECOMMENDATION**
Frequency	At least three times per week, preferable daily and after moderate or vigorous physical activity
Intensity	Slowly elongate muscle and hold with low level of force
Time	Up to four to five stretches held from 15 to 30 seconds. Stretch normally during the cool-down phase. Be sure to stretch only muscles that have been thoroughly warmed up from physical activity. Warning: Stretching in the warm-up prior to physical activity may weaken muscles and decrease performance
Type	Static or PNF stretches for all major muscle groups

Source: Reproduced with permission from Knudson D, Magnusson P, McHugh M. Current issues in flexibility fitness. PCPFS Res Digest 2000;3(10):1–8 (51).

Q & A from the Field

Q Our high school track-and-field athletes routinely stretch before, during, and after their events. I know that flexibility is an important component of performance, but I have heard rumblings in the running community for years that stretching before a sprint is a bad idea. Is it true that stretching prior to high-intensity track-and-field events is a bad idea?

—high school track coach

A Athletes stretch in the warm-up for track events because they believe that it decreases their risk of injury and improves their performance. Unfortunately, research has shown that this practice is probably not justified for most athletes. Unless an athlete has a major deficit in ROM, stretching prior to vigorous exertion actually decreases most forms of maximal muscular performance for about an hour. Stretching prior to vigorous activity has also been shown to have no effect on the risk of muscular injury. The most important thing a coach can do is teach athletes that proper warm-up is essential for maximum performance and decreasing the risk of injury. Focus their precompetition routine around a progressive and specific warm-up. Most athletes with normal flexibility should perform their stretching routines after practice or competition.

Stretching should be performed during the cool-down period because of three important factors:

1. Warmed-up tissues are less likely to be injured.
2. The placement of stretching within the workout does not affect gains in static flexibility (16).
3. There can be performance decrements following stretching.

Programming static stretching during the cool-down period is also logical because stretching tends to relax or inhibit muscle activation (7,96). For example, static stretching is commonly used for the acute relief from muscle cramps or delayed-onset muscle soreness (DOMS). The former is indicated, but research on the latter indicates no effect of stretching before (44,99) or after activity (11,99) on the DOMS that occurs after unaccustomed exercise. Static stretching routines in the cool-down period primarily serve to help maintain normal levels of static flexibility.

Biomechanical Effects of Stretching

Stretching exercises are prescribed routinely to increase static flexibility. Research has shown that stretching can provide increases in static flexibility of 5% to 20%, but short-term and over the course of several weeks (50). Less well known are the facts that stretching has minimal effect on the stiffness of muscle (see Fig. 9.2), decreases muscular performance, and modifies the energy recovery of stretched muscle.

Passive stretching can create large tensile loads in the muscle, so it is possible to weaken and injure muscle with vigorous stretching programs. Stretching exercise is like any other training stimulus in that it results in temporary weakening before the body recovers and supercompensates for that activity. This decreased muscular performance following stretching has been documented by the growing consensus of many studies. Decreased performance of 4% to 30% has been observed in maximal strength tests (7,52,78,79) and jumping (12,17,35,104). Stretch-induced decrements in muscular performance appear to be equally related to neuromuscular inhibition and decreased contractile force (16) and can last up to an hour (21). This is why most stretching should be performed in the cool-down phase of training and avoided in the warm-up period for athletic competition. Only athletes who require extreme static flexibility for performance (dancers, gymnasts, divers) might need to stretch at the end of the warm-up phase.

Stretching should normally be performed in the cool-down phase of conditioning because stretching prior to activity decreases muscular performance.

We saw earlier that stretching does not create a short-term decrease in muscle stiffness, but several studies have also shown that stretch training *over time* does not decrease muscle stiffness (51). This is difficult for people to understand because they can feel the lower passive tension in the muscle group at a certain joint angle. Some researchers have also incorrectly defined stiffness as the change in tension over the change in angle from the beginning of the stretch, not as the true mechanical stiffness of the tissue (the slope in the linear region). Strength and conditioning professionals should instruct athletes and other exercisers that the primary benefits of stretching are maintenance of ROM and a decrease in the passive tension in the muscle. The stiffness or elasticity of muscle and tendon is a complex mechanical variable that is not easily understood or experienced.

Another performance-related mechanical variable of interest following stretching is hysteresis. Recall that hysteresis is the energy lost (see Fig. 9.3) when a viscoelastic material returns to its normal shape following a stretch. Only recently have studies begun to examine the effect of stretching on the hysteresis of muscle groups. Although stretching has minimal effect on the passive stiffness of muscle and tendon, it has a significant effect on hysteresis since the loss of recovery energy decreases from 17% to 37% after stretching (53,54,66). This appears to be a promising new area of research on the effects of stretching. Unfortunately, it is not clear whether short- or long-term stretching will increase muscular performance through reductions in hysteresis.

The relationship between muscle mechanical variables, like static and dynamic flexibility and performance, is quite complex. For example, lower levels of static flexibility have been associated with better running economy (18,29), but less stiff musculature is more effective in utilizing elastic energy in stretch-shortening cycle movements (56,57,97,100,101). It is likely that the effects of stretching and flexibility on muscular performance are complex and activity-specific (28).

Prophylactic Effects of Stretching

The other traditional rationale for prescribing pre-activity stretching is a hypothesized reduction in the risk of injury. The logic was that if there were greater static flexibility from stretching, the chance that stretching the muscle beyond this point might lead to injury would be reduced. In the case of flexibility, this logic has not been supported by scientific evidence. Muscle strains (pulls) usually occur in eccentric muscle actions rather than passive elongation (87).

The larger and better-designed prospective studies have shown little or no effect of stretching on injury rate (3,83,84,98). The studies with larger samples and better controls (83,84) support the conclusion that flexibility and stretching may be unrelated to injury risk. Currently the data are insufficient to support the common prescription of stretching programs to modify flexibility based on the hypothesis of reducing the risk of muscle injury. Much more research on the effects of stretching and the associations between various flexibility levels and injury rates are needed before specific guidelines on stretching will be available.

Research has not confirmed the belief that stretching decreases the risk of muscular injury, so general stretching prior to physical activity probably confers no protective effect.

SUMMARY

Both active and passive warm-up are common preparatory activities before exercise and athletic competition. Several lines of research have supported the beneficial effects of warm-up on improving performance and reducing injury risk. Typical warm-up should consist of general movements of gradually increasing intensity. The intensity of warm-up should be moderate (up to 40% to 60% of aerobic capacity) and sustained (5 to 10 minutes) to increase the tissue temperature. Flexibility is an important property of the musculoskeletal system that determines the ROM and resistance to motion at a joint or group of joints. This property can be examined by measuring the limits of the achievable motion (static flexibility) or the stiffness of passively stretched muscle group (dynamic flexibility). Normal ranges of static flexibility are well documented for most joints through a variety of tests. There is some evidence that extremes in static flexibility (top or bottom 20% of the distribution) may be associated with a higher incidence of muscle injury.

Sport science research and prospective studies of flexibility and stretching suggest that stretching should not be performed in warm-ups. Stretching prior to physical activity decreases muscular performance and does not reduce the risk of musculoskeletal injury. Currently, little scientific evidence is available on which to base precise, individualized prescriptions of stretching development beyond the maintenance of normal levels of static flexibility. Static or proprioceptive neuromuscular facilitation (PNF) stretching should normally be performed during the cool-down phase of physical activity. Stretches should slowly elongate and hold muscles with low levels of force for 15 to 30 seconds. Four to five stretches per muscle group or area of the body are usually recommended.

MAXING OUT

1. Dancer—A dancer/cheerleader requests your help in increasing hip flexion and abduction ROM to facilitate the split position for a variety of stunts. What stretching program would you recommend?
2. Personal training client—A manager seeks relief from neck and shoulder pain from long days on an office computer. What stretching and strengthening exercises would you recommend?
3. Athlete—An athlete who has undergone acute rehab wants to return to play and increase plantarflexion ROM following an ankle sprain. What assessments would you use to document progress and what stretching program would you employ?

CASE EXAMPLE
Postmatch Flexibility Routine in Tennis

BACKGROUND

You are a strength coach working with the university medical staff and a 20-year-old male collegiate tennis player. The player has limited internal shoulder rotation ROM in the dominant shoulder, which is common in repetitive overarm sports like tennis.

RECOMMENDATIONS/CONSIDERATIONS

Following matches, practice, and conditioning sessions, the cool-down phase will consist of a static stretching routine. This will be a typical whole-body routine but will focus extra stretching on sport-specific imbalances common in tennis players: reduced shoulder internal rotation and flexibility of the lower back and hamstrings.

IMPLEMENTATION

Three 20-second wrist flexor and extensor stretches
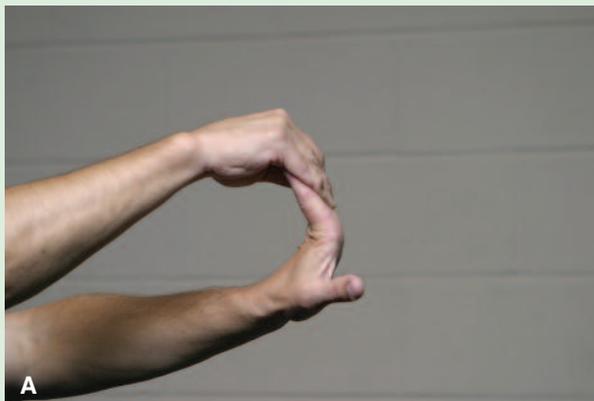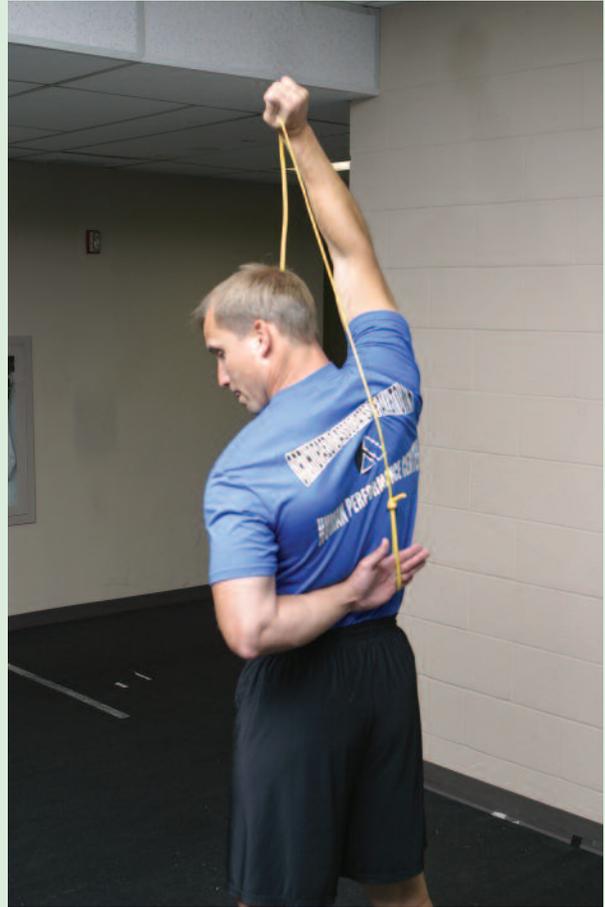
Wrist flexor and extensor stretches.

Four 20-second standing pectoralis major stretches

Standing pectoralis major stretch.

Four 20-second shoulder internal rotation stretches

Shoulder internal rotation stretch.

Four 20-second knees to chest low back stretches

Knees to chest low back stretch.

Three 20-second trunk twists both directions
Three 20-second butterfly hip internal rotator stretches

Butterfly hip internal rotators stretch.

(continued)

Four 20-second seated hamstring stretches

Seated hamstring stretch.

Three 20-second seated calf stretches

Seated calf stretch.

Three 20-second seated dorsiflexor stretches

Seated dorsiflexor stretch.

RESULTS

Results before and after (a 10-week flexibility program) indicate an improvement in ROM over the period of the training program in specific movements. Tests included shoulder internal rotation ROM, hip flexion ROM, and sit and reach.

Shoulder internal rotation ROM
Initial: dominant, 33 degrees; nondominant, 66 degrees
Posttraining: dominant, 48 degrees; nondominant, 70 degrees.

As is typical with overhead throwing athletes, shoulder internal rotation was decreased in the dominant extremity. The prescribed program caused a change in the ROM of the dominant arm in internal rotation in the direction of normal. Because of the demands of the sport, it is unlikely that the dominant arm would ever reach the same ROM as the nondominant arm.

Hip flexion ROM with knee extended
Initial: dominant, 40 degrees; nondominant, 39 degrees
Posttraining: dominant, 49 degrees; nondominant 49 degrees

In hip flexion, a dominant-to-nondominant difference is not as pronounced as it is in the upper extremity. Both extremities demonstrated a small increase in ROM due to the prescribed flexibility program.

Sit-and-reach flexibility
Initial: + 1 cm
Posttraining: + 3 cm

The flexibility program resulted in a slight increase in ROM in trunk flexion.

Theoretically, these increases in ROM would indicate a reduction in injury risk to the shoulder, hamstrings, and lower back. The effect on performance (power, explosiveness) is undetermined at this time.

REFERENCES

1. Alter MJ. Science of Flexibility. 3rd ed. Champaign, IL: Human Kinetics, 2004.
2. Alexander RM. Tendon elasticity and muscle function. Comp Biochem Physiol Part A 2002; 133:1001–1011.
3. Amako M, Oda T, Masuoka K, et al. Effect of static stretching on prevention of injuries for military recruits. Mil Med 2003;168:442–446.
4. American Academy of Orthopaedic Surgeons. Joint motion: method of measuring and recording. Chicago, IL: AAOS, 1965.
5. American College of Sports Medicine. ACSM's Guidelines for Exercise Testing and Prescription, 7th ed. Philadelphia: Lippincott Williams & Wilkins, 2005.
6. American Medical Association. Guides to the Evaluation of Permanent Impairment. Chicago: AMA, 1988.
7. Avela J, Kyrolainen H, Komi PV. Altered reflex sensitivity after repeated and prolonged passive muscle stretching. J Appl Physiol 1999;86:1283–1291.
8. Beaulieu JE. Developing a stretching program. Phys Sportsmed 1981;9(11):59–66.
9. Bishop D. Warm up I: potential mechanisms and the effects of passive warm up on exercise performance. Sports Med 2003a;33:439–454.
10. Bishop D. Warm up II: performance changes following active warm up and how to structure the warm up. Sports Med 2003b;33:483–498.
11. Buroker KC, Schwane JA. Does postexercise static stretching alleviate delayed muscle soreness? Phys Sportsmed 1989;17 (6):65–83.
12. Church JB, Wiggins MS, Moode EM, et al. Effect of warm-up and flexibility treatments on vertical jump performance. J Strength Cond Res 2001;15:332–336.
13. Corbin CB. Flexibility. Clin Sports Med 1984;3:101–117.
14. Corbin CB, Noble L. Flexibility: a major component of physical fitness. J Phys Ed Rec 1980; 51(6),23–24,57–60.
15. Cornbleet SL, Woolsey NB. Assessment of hamstring muscle length in school-aged children using the sit-and-reach test and the inclinometer measure of hip joint angle. Phys Ther 1996;76:850–855.
16. Cornelius W, Hagemann RW, Jackson AW. A study on placement of stretching within a workout. J Sports Med Phys Fit 1988;28:234–236.
17. Cornwell A. Nelson AG, Heise GD, et al. Acute effects of passive muscle stretching on vertical jump performance. J Hum Mov Stud 2001;40:307–324.
18. Craib MW, Mitchell VA. The association between flexibility and running economy in sub-elite male distance runners. Med Sci Sports Exerc 1996;28:737–743.
19. Eckstrand J, Gillquist J, Liljedahl S. Prevention of soccer injuries: supervision by doctor and physiotherapist. Am J Sports Med 1983;11:116–120.
20. Fitness and Lifestyle Research Institute. Fitness and Lifestyle in Canada. Ottawa: Fitness and Lifestyle Research Institute, 1983.
21. Fowles JR, Sale DG, MacDougall JD. Reduced strength after passive stretch of the human plantar flexors. J Appl Physiol 2000;89:1179–1188.
22. Franks DB. Physical warm-up. In: Williams M H, ed. Ergogenic Aids in Sport. Champaign, IL: Human Kinetics, 1983:340–375.
23. Gajdosik RL. Passive extensibility of skeletal muscle: review of the literature with clinical implications. Clin Biomech 2001;16:87–101.
24. Gajdosik RL, Bohannon RW. Clinical measurement of range of motion: review of goniometry emphasizing reliability and validity. Phys Ther 1987;67:1867–1872.
25. Gajdosik RL, Guiliani CA, Bohannon RW. Passive compliance and length of the hamstring muscles of healthy men and women. Clin Biomech 1990;5:23–29.
26. Gajdosik R, Lusin G. Hamstring muscle tightness: reliability of an active-knee extension test. Phys Ther 1983;63:1085–1088.
27. Gerhardt JJ, Russe OA. International SFTR Method of Measuring and Recording Joint Motion. Bern: Hans Huber, 1975.
28. Gleim GW, McHugh MP. Flexibility and its effects on sports injury and performance. Sports Med 1997;24:289–299.
29. Gleim GW, Stachenfeld NS, Nicholas JA. The influence of flexibility on the economy of walking and jogging. J Orthop Res 1990;8:814–823.
30. Goeken LN, Holf AL. Instrumental straight-leg raising: results in healthy subjects. Arch Phys Med Rehabil 1993;74:194–203.
31. Golding LA. Flexibility, stretching, and flexibility testing. ACSM Health Fit J 1997;1(2):17–20,37–38.
32. Halbertsma JPK, Goeken LNH. Stretching exercises: effect on passive extensibility and stiffness in short hamstrings of healthy subjects. Arch Phys Med Rehabil 1994;75:976–981.
33. Harris ML. Flexibility. Phys Ther 1969;49:591–601.
34. Hartman JG, Looney M. Norm-referenced and criterion-referenced reliability and validity of the back-saver sit-and-reach. Meas Phys Ed Exerc Sci 2003:7:71–87.
35. Hennig EM, Podzielny S. The effects of stretch and warming-up exercises on the vertical jump performance [German]. Dtsch Zeitschr Sportmed 1994;45:253–260.
36. Hoeger WW, Hopkins, DR. A comparison of the sit and reach and the modified sit and reach in the measurement of flexibility in women. Res Q Exerc Sport 1992; 63:191–195.
37. Holt J, Holt LE, Pelham TW. Flexibility redefined. In: Bauer T, ed. Biomechanics in Sports XIII. Thunder Bay, Ontario: Lakehead University, 1996:170–174.
38. Holt LE, Pelham TW, Burke DG. Modifications to the standard sit-and-reach flexibility protocol. J Athlet Train 1999;34:43–47.
39. Hoshizaki TB, Bell RD. Factor analysis of seventeen joint flexibility measures. J Sports Sci 1984;2:97–103.
40. Hubley CL, Kozey JW, Stanish WD. The effects of static stretching exercises and stationary cycling on range of motion at the hip joint. J Orthop Sports Phys Ther 1984; 6:104–109.
41. Hui SC, Yuen PY, Morrow JR, et al. Comparison of the criterion-related validity of sit-and-reach tests with and without limb length adjustment in Asian adults. Res Q Exerc Sport 1999;70:401–406.
42. Hutton RS. Neuromuscular basis of stretching exercise. In: Komi P, ed. Strength and Power in Sports. Oxford, UK: Blackwell, 1993:29–38.

43. Jackson AW, Morrow JR, Brill PA, et al. Relation of sit-up and sit-and-reach tests to lower back pain in adults. J Orthop Sports Phys Ther 1998;27:22–26.

44. Johansson PH, Lindstrom L, Sundelin G, et al. The effects of preexercise stretching on muscular soreness, tenderness and force loss following heavy eccentric exercise. Scand J Med Sci Sports 1999;9:219–225.

45. Jones BH, Knapik JJ. Physical training and exercise-related injuries. Sports Med 1999;27:111–125.

46. Karvonen J. Importance of warm-up and cool down on exercise performance. In: Karvonen, J, Lemon P, Iliev I, eds. Medicine in Sports Training and Coaching. Basel: Karger, 1992:189–214.

47. Kibler WB, Chandler TJ. Range of motion in junior tennis players participating in an injury risk modification program. J Sci Med Sport 2003:6:51–62.

48. Knapik JJ, Jones BH, Bauman CL, et al. Strength, flexibility, and athletic injuries. Sports Med 1992:14:277–288.

49. Knudson D. Stretching: science to practice. J Phys Ed Rec Dance 1998;69(3):38–42.

50. Knudson D. Stretching during warm-up: do we have enough evidence? J Phys Ed Rec Dance 1999;70 (7): 24–27,51.

51. Knudson D, Magnusson P, McHugh M. Current issues in flexibility fitness. PCPFS Res Dig 2000;3(10):1–8.

52. Kokkonen J, Nelson AG, Cornwell A. Acute muscle stretching inhibits maximal strength performance. Res Q Exerc Sport 1998;69:411–415.

53. Kubo K, Kanehisa H, Fukunaga T. Effect of stretching on the viscoelastic properties of human tendon structures in vivo. J Appl Physiol 2002a;92:595–601.

54. Kubo K, Kanehisa H, Fukunaga T. Effect of transient muscle contractions and stretching on the tendon structures in vivo. Acta Physiol Scand 2002b;175:157–164.

55. Kubo K, Kanehisa H, Fukunaga T. Gender differences in the viscoelastic properties of tendon structures. Eur J Appl Physiol 2003;88:520–526.

56. Kubo K, Kanehisa H, Kawakami Y, et al. Elastic properties of muscle-tendon complex in long-distance runners. Eur J Appl Physiol 2000;81:181–187.

57. Kubo K, Kawakami Y, Fukunaga T. Influence of elastic properties of tendon structures on jump performance in humans. J Appl Physiol 1999;87:2090–2096.

58. Leighton JR A simple objective and reliable measure of flexibility. Res Q 1942;13:205–216.

59. Liebesman J, Cafarelli E. Physiology of range of motion in human joints: a critical review. Crit Rev Phys Rehabil Med 1994;6:131–160.

60. Liemohn W, Haydu T, Phillips D. Questionable exercises. PCPFS Res Digest 1999;3(8):1–8.

61. Lin RM, Chang GL, Chang LT. Biomechanical properties of muscle-tendon unit under high-speed passive stretch. Clin Biomech 1999;14:412–417.

62. Lindsey R, Corbin C. Questionable exercises—some safer alternatives. J Phys Ed Rec Dance 1989;60(8):26–32.

63. Lubell A. Potentially dangerous exercises: are they harmful to all? Phys Sportsmed 1989;17(1):187–192.

64. Magnusson SP. Passive properties of human skeletal muscle during stretch maneuvers: a review. Scand J Med Sci Sports 1998;8:65–77.

65. Magnusson SP, Aagaard P, Nielson JJ. Passive energy return after repeated stretches of the hamstring muscle-tendon unit. Med Sci Sports Exerc 2000a;32:1160–1164.

66. Magnusson SP, Aagard P, Simonsen E, et al. A biomechanical evaluation of cyclic and static stretch in human skeletal muscle. Int J Sports Med 1998;19:310–316.

67. Magnusson SP, Aagaard P, Simonsen EB, et al. Passive tensile stress and energy of the human hamstring muscles in vivo. Scand J Med Sci Sports 2000;10:351–359.

68. Magnusson SP, Simonsen EB, Aagaard P, et al. A mechanism for altered flexibility in human skeletal muscle. J Physiol 1996;487:291–298.

69. Magnusson SP, Simonsen EB, Aagaard P, et al. Biomechanical responses to repeated stretches in human hamstring muscle in vivo. Am J Sports Med 1996b;24:622–628.

70. 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.

71. Magnusson SP, Simonsen EB, Aagaard P, et al. Visocoelastic response to repeated static stretching in human skeletal muscle. Scand J Med Sci Sport 1995;5:342–347.

72. Martin SB, Jackson AW, Morrow JR, et al. The rationale for the sit and reach test revisited. Meas Phys Ed Exerc Sci 1998;2:85–92.

73. McHugh MP, Connolly DAJ, Eston RG, et al. The role of passive muscle stiffness in symptoms of exercise-induced muscle damage. Am J Sports Med 1999;27:594–599.

74. McHugh MP, Kremenic IJ, Fox MB, et al. The role of mechanical and neural restrains to joint range of motion during passive stretch. Med Sci Sports Exerc 1998;30:928–932.

75. McHugh MP, Magnusson SP, Gleim GW, et al. Viscoelastic stress relaxation in human skeletal muscle. Med Sci Sports Exerc 1992;24:1375–1382.

76. McNair PJ, Dombroski EW, Hewson DJ, et al. Stretching at the ankle joint: viscoelastic responses to holds and continuous passive motion. Med Sci Sports Exerc 2000;33:354–358.

77. Medeiros JM, Smidt GL, Burmeister LF, et al. The influence of isometric exercise and passive stretch on hip joint motion. Phys Ther 1977;57:518–523.

78. Nelson AG, Guillory IK, Cornwell A, et al. Inhibition of maximal voluntary isokinetic torque production following stretching is velocity specific. J Strength Cond Res 2001;15:241–246.

79. Nelson AG, Kokkonen J. Acute ballistic muscle stretching inhibits maximal strength performance. Res Q Exerc Sport 2001;72:415–419.

80. Noonan TJ, Best TM, Seaber AV, et al. Thermal effects on skeletal muscle tensile behavior. Am J Sports Med 1993;21:517–522.

81. Norkin CC, White DJ. Measurement of Joint Motion: A Guide to Goniometry. 3rd ed. Philadelphia: Davis, 2003.

82. Plowman SA. Physical activity, physical fitness, and low-back pain. Exerc Sport Sci Rev 1992;20:221–242.

83. Pope RP, Herbert RD, Kirwan JD. Effects of flexibility and stretching on injury risk in army recruits. Aust J Physiother 1998;44:165–172.

84. Pope RP, Herbert RD, Kirwan JD, et al. A randomized trial of preexercise stretching for prevention of lower-limb injury. Med Sci Sports Exerc 2000;32:271–277.

85. Russek LN. Hypermobility syndrome. Phys Ther 1999; 79:591–599.

86. Safran MR, Garrett WE, Seaber AV, et al. The role of warm-up in muscular injury prevention. Am J Sports Med 1988;16:123–129.

87. Safran MR, Seaber A, Garrett, WE Warm-up and muscular injury prevention: an update. Sports Med 1989;8: 239–249.

88. Sapega AA, Quedenfeld TC, Moyer R, et al. Biophysical factors in range-of-motion exercise. Phys Sportsmed 1981;12(9):57–65.

89. Shellock FG, Prentice WE. Warming-up and stretching for improved physical performance and prevention of sports-related injuries. Sports Med 1985;2:267–278.

90. Shephard RJ, Berrirdge M, Montelpare W. ON the generality of the "sit and reach" test: an analysis of flexibility data for an aging population. Res Q Exerc Sport 1990; 61:326–330.

91. Strickler T, Malone T, Garrett WE. The effects of passive warming on muscle injury. Am J Sports Med 1990;18: 141–145.

92. Suni JH, Miilunpalo SI, Asikainen A, et al. Safety and feasibility of a health-related fitness test battery for adults. Phys Ther 1998;78:134–148.

93. Surburg PR. Flexibility exercise re-examined. Athl Train 1983; 18:37–40.

94. Taylor DC, Brooks DE, Ryan JB. Viscoelastic characteristics of muscle: passive stretching versus muscular contractions. Med Sci Sports Exerc 1997;29:1619–1624.

95. Taylor DC, Dalton JD, Seaber AV, et al. Visoelastic properties of muscle-tendon units. Am J Sports Med 1990; 18:300–309.

96. Vujnovich AL, Dawson NJ. The effect of therapeutic muscle stretch on neural processing. J Orthop Sports Phys Ther 1994;20:145–153.

97. Walshe AD, Wilson GJ, Murphy AJ. The validity and reliability of a test of lower body musculotendinous stiffness. Eur J Appl Physiol 1996;73:332–339.

98. Weldon SM, Hill RH. The efficacy of stretching for prevention of exercise-related injury: a systematic review of the literature. Manual Ther 2003;8:141–150.

99. Wessel J. Wan A. Effect of stretching on the intensity of delayed-onset muscle soreness. Clin J Sports Med 1994; 4:83–87.

100. Wilson GJ, Elliott BC, Wood GA. Stretch shorten cycle performance enhancement through flexibility training. Med Sci Sports Exerc 1992;24:116–123.

101. Wilson GJ, Wood GA, Elliott BC. Optimal stiffness of series elastic component in a stretch-shorten cycle activity. J Appl Physiol 1991;70:825–833.

102. Wilson GJ, Wood GA, Elliott BC. The relationship between stiffness of the musculature and static flexibility: an alternative explanation for the occurrence of muscular injury. Int J Sports Med 1991;12:403–407.

103. Witvrouw E, Danneels L, Asselman P, et al. Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players: a prospective study. Am J Sports Med 2003;31:41–46.

104. Young W, Elliot S. Acute effects of static stretching, proprioceptive neuromuscular facilitation stretching, and maximum voluntary contractions on explosive force production and jumping performance. Res Q Exerc Sport 2001;72:273–279.