Critical Review


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Objective: To evaluate the clinical and basic science evidence surrounding the hypothesis that stretching immediately before exercise prevents injury.

Data Sources and Selection: MEDLINE was searched using MEDLINE subject headings (MeSH) and textwords for English- and French-language articles related to stretching and muscle injury. Additional references were reviewed from the bibliographies, and from citation searches on key articles. All articles related to stretching and injury or pathophysiology of muscle injury were reviewed. Clinical articles without a control group were excluded.

Results: Three (all prospective) of the four clinical articles that suggested stretching was beneficial included a covariate of warm-up. The fourth study (cross-sectional) found stretching was associated with less groin/thigh problems in cyclists, but only in women. There were five studies suggesting no difference in injury rates between stretchers and non-stretchers (3 prospective, 2 cross-sectional) and three suggesting stretching was detrimental (all cross-sectional). The review of the basic science literature suggested five reasons why stretching before exercise would not prevent injuries. First, in animates, immobilization or heating-induced increases in muscle compliance cause tissues to rupture more easily. Second, stretching before exercise should have no effect on force in which excessive muscle length is not an issue (e.g., jogging). Third, stretching won't affect muscle compliance during eccentric activity, when most strains are believed to occur. Fourth, stretching can produce damage at the cytoskeleton level. Fifth, stretching appears to mask muscle pain in humans.

Conclusion: The basic science literature supports the epidemiologic evidence that stretching before exercise does not reduce the risk of injury.

Key Words: Injuries, prevention—Muscles, stretching, wounds and injuries—Sports injuries, prevention.


Many clinicians and authors currently advise that stretching before exercise, with or without warm-up, prevents injury.1-4 However, these authors often fail to cite the appropriate studies to support their recommendations. Those that do cite appropriate references appeal to cite or emphasize only those studies that support their recommendations. Therefore, the objective of this study was to determine whether the clinical and basic science evidence supports the hypothesis that stretching before exercise prevents injury.

This review is limited to a discussion of stretching before exercise. It does not discuss injury prevention with flexibility exercises performed at other times, or the effects of stretching on performance in sport.

MATERIALS AND METHODS

This study involved one MEDLINE search strategy for clinical articles and another for basic science articles (Table 1). The purpose of the first search was to identify all clinical articles related to injury and stretching. Because results of the clinical articles did not support the use of stretching before exercise, a second search of the basic science literature was performed. There were no basic science articles that directly examined the effect of stretching on injury. Therefore, the objective of this search was to find basic science articles that directly discussed muscle-tendon injury mechanisms. All pertinent articles from the bibliographies of these papers were reviewed. A citation search was performed on the key articles found in each search. In addition, papers discussing tendinal issues, such as cytoskeleton structures, eccentric contractions, etc., were reviewed.

RESULTS

Clinical Evidence

Of the 138 articles retrieved from the clinical search, only 12 used a control group to analyze whether stretching before exercise prevents injury; all of these were included in this analysis. Of these 12 articles, four suggested stretching before exercise is beneficial (Table 2); 7 three suggested it is detrimental (Table 3); and five suggested no difference (Table 3).
TABLE 1. MEDLINE search strategy using a combination of MEDLINE subject headings (MeSH) and textwords (tw)

<table>
<thead>
<tr>
<th>Item</th>
<th>Search</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clinical search</td>
<td></td>
<td>3,814</td>
</tr>
<tr>
<td>1</td>
<td>stretch(tw)</td>
<td>1,204</td>
</tr>
<tr>
<td>2</td>
<td>&quot;sprain and strains&quot; (MeSH) or strain (tw) or injury (tw) or sport(tw) or adolescent (tw) or &quot;anterior injuries&quot;</td>
<td>38</td>
</tr>
<tr>
<td>Basic science search</td>
<td></td>
<td>25,302</td>
</tr>
<tr>
<td>1</td>
<td>Skeletal muscle (MeSH) or &quot;skeletal muscle&quot; (tw)</td>
<td>12,316</td>
</tr>
<tr>
<td>2</td>
<td>Flexibility (tw) or stretch(tw) or &quot;range of motion&quot; (tw) or &quot;range of motion&quot; (MeSH) or &quot;wound and injuries&quot; (MeSH) or injury(tw) or &quot;spain and strains&quot; (MeSH) or strain(tw)</td>
<td>137,363</td>
</tr>
<tr>
<td>3</td>
<td>1 and 2</td>
<td>194</td>
</tr>
</tbody>
</table>

* Textword strategy will retrieve any article which includes the word in the title or abstract (if abstract is included in MEDLINE). The symbol "S" in textword searches acts as a wildcard for any text.

A closer examination of these studies suggests that the clinical evidence does not support the hypothesis that stretching before exercise prevents injury. Figure 1 summarizes the relative risks or odds ratios (OR) for all the prospective studies.

Studies with Positive Results
When grouped together, three of the four studies that showed a positive effect actually evaluated a complete program that included many cointerventions in addition to stretching. For example, Ekstrand et al. found that elite soccer teams that were part of an experimental group (preexercise warm-up, leg guards, special shoes, taping ankles, controlled rehabilitation, education, and close supervision) had 75% fewer injuries compared with a control group of soccer teams. However, it is impossible to determine which of the interventions might be responsible for the decrease in injury rates.

TABLE 2. Brief summary of the clinical studies that suggest stretching before exercise may prevent injury

<table>
<thead>
<tr>
<th>Study (ref.)</th>
<th>Population</th>
<th>Study Design</th>
<th>Study Results*</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ekstrand et al. (6)</td>
<td>180 elite male soccer players</td>
<td>RCT intervention of warm-up, stretch, leg guards, prophylactic ankle taping, controlled rehabilitation, information, supervision</td>
<td>the group that received the combined interventions had a RR of 0.18 (9.6 injuries versus 2.6 injuries)</td>
<td>if an intervention came too late, time might be considered as part of the &quot;control&quot; data; no numbers are given for changes in exposure; with increased exposure and consistent risk, frequency of injuries is expected to increase, therefore, risk cannot be calculated.</td>
</tr>
<tr>
<td>Bieler and Jones (7)</td>
<td>5 high school football teams</td>
<td>prospective RCT intervention of half-time stretching and warm-up</td>
<td>intervention group had 0.3 injuries/game vs. 0.8 injuries/game for control group</td>
<td>no real analysis of stretching before exercise</td>
</tr>
<tr>
<td>Ekstrand et al. (7)</td>
<td>180 elite male soccer players</td>
<td>1-year prospective cohort study</td>
<td>all seven quadriceps strain affected players on teams in which stretching at the goal occurred before warm-up (p &lt; 0.05), stretching strains were more common in teams using special flexibility exercises (2.1 vs. 0.7)</td>
<td>response rate = 51/8250; the association between stretching and injuries to other body parts (e.g., knees, back) was not reported, even though data were available; not clear if people stretched before injury, or because of injury</td>
</tr>
<tr>
<td>Wilber et al. (4)</td>
<td>518 recreational cyclists</td>
<td>survey of overuse injuries and other related factors</td>
<td>only results available are &quot;preventing fatigue cycling (1 vs. 2 min, p &lt; 0.007); had a significant effect on those female cyclists who sought medical treatment for groin/buttock strain&quot;</td>
<td></td>
</tr>
</tbody>
</table>

* For the relative risk (RR) or odds ratios (OR), a value above 1 means a higher rate of injury in people who stretch. BCT = randomized controlled trial.
STRETCHING BEFORE EXERCISE DOES NOT PREVENT MUSCLE INJURY

<table>
<thead>
<tr>
<th>Study (ref)</th>
<th>Population</th>
<th>Study Design</th>
<th>Results*</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>van Mechelen et al. (15)</td>
<td>421 male recreational runners</td>
<td>16-wk RCT matched on age and weekly running distance</td>
<td>RR = 1.12</td>
<td>intervention was warm-up and preexercise stretching; there was a lot of noncompliance in each group</td>
</tr>
<tr>
<td>Mancini et al. (12)</td>
<td>583 habitual runners</td>
<td>1-yr prospective cohort</td>
<td>OR for men = 1.1, for women = 1.6</td>
<td>stretching data was only collected for age; stretching was not included in the multiple regression analysis because it was insignificant in the univariate analysis</td>
</tr>
<tr>
<td>Walter et al. (13)</td>
<td>1,880 community road race runners</td>
<td>1-yr prospective cohort</td>
<td>comparison group was people who always stretch; RR for never stretched = 1.15-1.18, for sometimes stretch = 0.55-0.64, for usually stretch = 1.00-1.23</td>
<td>to be consistent with other articles, the RR was computed so that the numbers reflect the risk of people who always stretch; these numbers are controlled for running distance and frequency, type of runners, use of warm-up, injuries in past year</td>
</tr>
<tr>
<td>Howell (8)</td>
<td>17 elite women rowers</td>
<td>Cross-sectional</td>
<td>stretching associated with injury</td>
<td>not clear if people stretched before injury, or because of injury</td>
</tr>
<tr>
<td>Brunet et al. (14)</td>
<td>1,303 road race recreational and competitive runners</td>
<td>survey of past injuries and other related factors</td>
<td>similar frequency of injuries among people who stretch and those who don’t</td>
<td>response rate unknown; cross-sectional study design but injury profile was “any injury” and not recent injury; non clear if people stretched before injury, or because of injury</td>
</tr>
<tr>
<td>Blair et al. (15)</td>
<td>436 habitual runners</td>
<td>survey of past injuries and other related factors</td>
<td>only results available are “frequency of stretching...” worth not associated with running injuries</td>
<td>response rate = 438/726; this article comprises these studies, only the cross-sectional sample directly looked at stretching habits; not clear if people stretched before injury, or because of injury</td>
</tr>
<tr>
<td>Kerner and D’Amico (10)</td>
<td>540 people buying running shoes</td>
<td>survey of past injuries and other related factors</td>
<td>only results available are “a comparison of subjects who warmed up before running (87.7%) and those who did not (66%) revealed a higher frequency of pain in the former”</td>
<td>response rate = 540/600. No data available to determine clinical relevance. Not clear if people stretched before injury, or because of injury</td>
</tr>
<tr>
<td>Jacobs and Berne (9)</td>
<td>451 10-km race participants</td>
<td>survey of past injuries and related factors</td>
<td>90% of injured people stretched, compared with 80% of uninjured people</td>
<td>response rate = 451/550. Not clear how 550 were chosen from potential 1,600; univariate analysis only; not clear if people stretched before injury, or because of injury</td>
</tr>
</tbody>
</table>

* For the relative risk (RR) or odds ratio (OR), a value above 1 means a higher rate of injury in people who stretch. RCT = randomized controlled trial.

In a similar study completed 1 year earlier, Ekstrand et al. found less hamstring and quadriceps strains in elite soccer players who performed warm-up, skill, and stretching exercises before playing soccer.

In the remaining multiple-intervention group, high school football teams were assigned in pseudorandom fashion to stretching and warm-up during half-time. The hypothesis was that athletes become stiff during half-time, and that stretching at half-time would decrease third-quarter injury rates. Along with problems of randomization and multiple interventions, if an intervention team did not stretch at half-time, injuries during that game were considered as part of the control group. Therefore, it is not possible to determine the denominator for the calculation of risk, and one is left only with frequencies.

The remaining study supporting stretching before exercise was cross-sectional and examined cyclists. These authors found that female cyclists who stretched before exercise had less groin and buttock pain. The effect was not observed in male cyclists.

Although there are some strong studies about stretching before exercise, the presence of probable effective counterinterventions prevents us from making any conclusions about the effects of stretching before exercise itself.

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Studies with Negative Results

There have been three studies (all cross-sectional) that suggested stretching before exercise may increase the risk of injury. However, it is unclear whether these athletes became injured because they were stretching, or stretched because they were injured.

In the two other cross-sectional studies that showed stretching might increase injury rates, the authors did not control for any other factor, such as training distance, experience, etc. Conclusions based on these studies should be guarded.

Studies with Equivocal Results

There have been five studies (1 randomized controlled trials, 2 prospective, 2 cross-sectional) that found no difference in injury rates between people who stretch before exercise and those who don't.

van Mechelen and colleagues assigned 421 persons in randomized fashion to an intervention group that included 6 minutes of warm-up and 15 minutes of stretching. The risk for injury for those in the intervention group was 1.12 compared with controls. Of note, only 47% of those in the intervention program actually stretched according to the instructions outlined in the study. In addition, many of the runners in the control group also performed some type of stretching before exercise. This type of noncompliance (or "misclassification") would be expected to "bias toward the null" and minimize the OR obtained. However, it should not reverse the direction of the OR, which was actually greater than one. Although one could reanalyze the data according to whether the actual intervention was performed, most statistical consultants believe the intention-to-treat analysis (as was done in the paper) is more appropriate.

In a prospective study by Walter et al., the authors found that stretching was unrelated to injury after controlling for previous injuries and for mileage. Macera et al. found that stretching before exercise increased the risk of injury, but the difference was not statistically significant (OR 1.1 for men, 1.6 for women). Although these studies were not randomized controlled trials, they had few limitations.

Finally, two cross-sectional studies showed no protective effect of stretching before exercise. In fact, Houset et al. reported that nonstretchers had fewer injuries even though they had higher mileage per week and fewer previous injuries. The cross-sectional design limits the conclusions that can be drawn from these studies.

Summary of Clinical Evidence

Overall, the only studies to suggest that stretching before exercise has no benefit or may be detrimental. Thus, even day by day should not adopt an inappropriate randomized controlled trials on the subject, the clinical evidence available contradicts the hypothesis that stretching before exercise prevents injury. Therefore, the basic science literature was reviewed to see whether there was any underlying support for the hypothesis.

Basic Science Evidence

Most of the basic science information on acute muscle injuries has been published by Garrett et al. Their studies were performed on rabbit anterior tibialis and extensor digitorum muscles. The authors fixed the femur in place with a wire, clamped the Achilles tendon, and applied a force so that the muscle-tendon unit lengthened. The authors recorded the length, force, and energy absorbed at the rupture, and found that muscles always rupture near the musculotendinous junction, with some muscle fibers always attached to the tendon. Other authors have found ruptures within the muscle itself. No model exists in which a healthy ten-
tions. Therefore, the results from this review apply only to muscle strains, and not to ruptured tendons.

The length at which a muscle ruptures is independent of muscle activity, 15 or rate of stretch. 16 Recent studies on single frog muscle fibers suggest that muscle injury occurs when the actin and myosin filaments are stretched beyond overlap. 17 In these experiments, the sarcomeres attached to the tendon stretch the least (i.e., lowest compliance as obtained from a force-length relationship) and remain undamaged, but adjacent sarcomeres are stretched beyond actin-myosin overlap and become injured. 18-23 These results are consistent with the results of whole muscle studies by Garrett et al., in which some sarcomeres always remained attached to the tendon at the time of rupture. 26 Note that the damaged sarcomeres are less compliant (i.e., they do not stretch as much).

Based on a review of the basic science evidence, there are five theoretical arguments why stretching before exercise would not prevent injury. First, is compliance an important physical characteristic vis-à-vis injury? Although a balloon will stretch before it bursts (high compliance), a steel sphere never stretches (low compliance) but will withstand extremely high pressure (Note: compliance for a sphere is determined by the volume-pressure relationship, and compliance for planar tissue is determined by the length-force relationship). Further, a contracting muscle is less compliant than a muscle at rest, 27,28 but absorbs more energy. 29,30 Therefore, compliance refers to the length change that occurs when a force is applied but is not necessarily related to a tissue’s resistance to injury.

The basic science evidence suggests that an increase in compliance is associated with a decrease in the ability of the tissue to absorb energy. For example, if muscle compliance is increased with warming from 25°C to 40°C, the muscle ruptures at a longer length. 28 Although this may appear to be beneficial, the muscle actually ruptures under less force, and absorbed less energy. 28 The same is true for ligaments that have been immobilized. 22 The lower amount of energy absorbed with an increase in compliance suggests that as increased compliance may increase the risk of injury during an eccentric load (i.e., high force).

Second, does an injury occur because the muscle reaches a certain length or because a certain force is applied? Garrett et al. 24-26 and others 15 hypothesize that the most important variable with respect to muscle injury is the energy absorbed by the muscle. For example, a hamstring strain would occur during eccentric activity if the muscle is unable to prevent excessive sarcomere lengthening caused by the force of the leg swinging forward. When sarcomeres are stretched so that the actin and myosin filaments no longer overlap, the force is transmitted to the cytoskeleton of the muscle fiber and muscle fiber damage occurs. Note that the joint is usually still within its normal range of motion. This is because sarcomere length within the muscle is heterogeneous; some sarcomeres lengthen during the contraction at the same time others are shortening. 27,28,30 Therefore, it appears that is the sarcomere length that is related to most exercise-related muscle strains rather than total muscle length. Under this hypothesis, an increase in total muscle compliance (i.e., pre-activity stretch) would decrease injury.

Third, does stretching increase the compliance of active muscle? Because injuries are believed to occur when the muscle is active (i.e., during eccentric contractions), 29 compliance during activity should be more important than compliance at rest. However, these two compliances are unrelated, because compliance of resting muscle is almost exclusively due to the muscle cytoskeleton 27 whereas compliance of active muscle is directly dependent on the number of active actin-myosin cross-bridges. 32,33,34 Further, active muscle has a much lower compliance than resting muscle 27,28 but absorbs significantly more energy. 22 These data again support the argument that an increase in compliance does not mean a decreased risk of injury.

Fourth, over-stretching a muscle can certainly produce damage. However, even strains as little as 20% beyond resting fiber length, as one would expect to occur with correct stretching techniques, can produce damage in isolated muscle preparations. 35 Therefore, the basic science evidence suggests that correct stretching techniques may be more difficult to define than previously thought.

Fifth, the increased range of motion that occurs with stretching may be partly due to masking of pain (i.e., an increase in stretch tolerance). For example, proprioceptive neuromuscular facilitation (PNF) stretching has been known to increase range of motion for more than 20 years. 15 Although the original hypothesis predicted that PNF stretching would decrease EMG activity of the muscle 15,16 PNF activity is actually increases when measured. 37-40 In addition, there is no change in the compliance of the tissue (i.e., the length-force relationship) despite a marked increase in the range of motion before the subject feels discomfort. 39,40 Therefore, these authors hypothesized that stretching increases range of motion because of an increase in stretch tolerance. This altered stretch perception is also true for static stretch. 15 The hypothesis that range of motion is determined mostly by pain rather than tissue compliance is also supported by the finding that incising (decreases compliance) produces approximately the same increased range of motion when associated with stretching in healthy muscle as does warming, even though they have opposite effects on compliance.

Finally, and surprisingly, the increased range of motion observed with stretching over 3 to 4 weeks is also due to an increased stretch tolerance. In the only two studies that properly evaluated the question of changes in tissue compliance with long-term stretching, 35,40 both found the increased range of motion occurred because the subjects felt less pain; there was no change in actual tissue compliance. If stretching masks the protective mechanisms of pain, then it may predispose to injury if performed immediately before exercise.

DISCUSSION

A review of the clinical and basic science literature suggests that stretching before exercise would not reduce

the risk of injury; increases in resting muscle compliance are associated with a decrease in resistance to injury in resting animal muscle. Because this experiment is clearly impossible in humans, we have no basis on animal studies; there is no reason to believe it would behave differently than human muscle. Further, if stretching is done improperly so that the actin and myosin filaments are pulled beyond overlap in even some sarcomeres, focal muscle damage will occur. It does not seem prudent to then engage in physical activity with muscle that has less energy-absorbing capacity, and may have even been recently damaged. It must be stressed that this review does not address the question of performance effects on performance are likely to depend on the sport.66,67

In this study, we were not able to review all of the studies of eccentric contraction-induced mild injury in depth. Although muscles clearly become damaged before fully rupturing,48,49 the outcome used6 in mild-injury studies is peak contractile force.49,50 The results are difficult to interpret because the injury-induced decrease in force cannot be separated from the fatigue-induced decrease in force. Therefore, these studies were generally omitted from the review.

Although both the basic and clinical science suggest that stretching before exercise does not prevent local muscle injury, stretching outside of activity periods may have some positive effects. For instance, some studies suggest that stretching can induce hyper trophy.6,43 These studies all used cast-immobilization51-53 or weights to continuously stretch the muscle over a period of 3 to 30 days,52 which is very different from human stretching programs. However, if normal stretching programs performed over months also cause hypertrophy, then one would expect the muscle to be able to absorb more force and energy before rupture. In support of this hypothesis, a recent study using two companies of military recruits during basic training found that the group who stretched three times per day in addition to their normal preexercise stretching regimen had fewer injuries than a control group who stretched only before exercise.62 Although there were problems with baseline comparisons and lack of control for previous injuries, fitness levels, etc., the study represents a good beginning. This is an area that requires further research.

This review has not discussed tendon injuries. In an isolated tendon preparation, passive warming increased the force absorbed and length to rupture21 in tendons. However, there is no muscle-tendon-bone animal model that produces tendon ruptures or injuries. The clinical evidence does not suggest that stretching before exercise reduces tendon injuries. More research is needed in this area.

Some clinicians argue that one has to warm-up before stretching. Indeed, the clinical evidence reviewed in this article suggests that warm-up may be beneficial. However, although warm-up exercises before stretching allow the muscle to become more compliant compared with stretching alone,64 it has other effects as well. For example, Cosmetan et al.77 found that a single isometric contraction before fovea application allows the muscle to absorb more energy before failure. Therefore, warm-up may be beneficial for reasons other than compliance, and may even counteract the potential detrimental effects of stretching before exercise. However, the amount of warm-up is critical because too much could cause muscle fatigue, which itself is also associated with increased injury.66

**CONCLUSION**

**Clinical evidence**
- The only prospective studies that showed beneficial effects of stretching before exercise used multiple interventions.
- All prospective studies that investigated stretching before exercise alone found no significant difference in injury rates; in fact, the trend in those studies was actually toward a higher injury rate in people who stretch.

**Basic science evidence**
- An increase in compliance decreases the amount of energy that can be absorbed.
- Heterogeneous sarcomere lengths mean that muscles can become injured during eccentric activity even though they are not being stretched beyond their normal length.
- Even mild stretching can cause damage at the cytoskeleton level.
- Stretching masks muscle pain.

Although many of the studies in our review did not control for the most important variables, e.g., previous injury, mileage, etc., the basic science and clinical evidence today suggest that stretching before exercise is more likely to cause injury than to prevent it. Further, if stretching induces changes in muscle flexibility and strength through muscle damage (an in-jet unproven hypothesis), it does not seem prudent to advise people to potentially damage tissue immediately before exercising. More research into the long-term effects of stretching also is needed to determine whether stretching after or outside of activity periods helps prevent injury. The relative efficacy of beginning stretching exercises early in the period of rehabilitation, versus beginning strengthening exercises early in the rehabilitation period, should also be evaluated more closely.

**REFERENCES**