CHAPTER 3
Does stretching help prevent injuries?

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Since the first edition of this book, several other authors have performed systematic reviews on this topic and reached the same conclusions: stretching prior to exercise does not prevent injury.[1–3] This concept is now also being promoted to a wider audience than simply sports-medicine clinicians.[4,5] However, practicing evidence-based medicine means that everything constitutes work in progress, and it is important to update the knowledge base on any question continuously. With respect to original clinical research, two recent studies are added to this review.[6,7] Two tangential studies have not been included: Malliaropoulos *et al.*[8] studied the effects of stretching once per day versus four times per day, but did not include a no-stretch control group. Sherry and Best[9] compared stretching and isolated hamstring strengthening versus progressive agility and trunk stabilization. Although these studies are valid, they did not address the question with which this chapter is concerned and are not included in the analysis.

Introduction

Over the past 30 years, sports-medicine professionals have promoted stretching as a way to decrease the risk of injury.[10–15] Two potential mechanisms are often proposed by which stretching could decrease injury: a direct decrease in muscle stiffness via changes in passive viscoelastic properties, or an indirect decrease in muscle stiffness via reflex muscle inhibition and consequent changes in viscoelastic properties due to decreased actin–myosin cross-bridges. These changes in muscle stiffness would allow for an increased ROM (ROM) around a joint (within this paper, I will use the term flexibility as a synonym for range of motion (ROM) because that is the common use of the term by clinicians even though it may have other meanings in other domains), which is believed to decrease the risk of injury. However, there are several important points the reader must consider.

First, both the muscle–tendon unit and the joint capsule may limit ROM. Flexibility is usually considered the ROM limited by muscle–tendon, and mobility is usually considered the ROM limited by capsule/ligament. These differences should be taken into account when reading the literature.

Second, stretching must be differentiated from ROM. There are many individuals who have excellent ROM but never stretch, and many individuals who stretch but continue to have limited ROM. Therefore, different injury rates in people with different ROMs may not be related to the effect of stretching, but rather to the underlying interindividual variations in tissue properties (e.g., strength), anatomy, etc. To understand the specific effect of stretching, one should limit the review to studies that directly look at the intervention of stretching.

Third, stretching immediately before exercise may have different effects than stretching at other times and should be considered as a separate intervention. Whereas there is a considerable amount of clinical data on stretching immediately before exercise, there is much less data on stretching at other times.

Fourth, some people claim that negative results in some studies are due to improper stretching technique. Because the effects of stretching are believed to occur through changes in stiffness and ROM, an "improper" technique implies that the ROM is not increased. If ROM is increased without causing an immediate injury, then by definition the stretches were done properly.

Fifth, warm-up is not synonymous with stretching. In the colloquial sense, warm-up means any activity performed before participating in sport. Used in this sense, stretching is only one component of warm-up, and if stretching is included in the pre-exercise activity, I explicitly state that stretching was used. The other component of warm-up is participating in an activity that requires active muscle contractions. This type of warm-up can be divided into general or sport-specific warm-up. In a general warm-up, the objective is to increase body temperature. As such, the muscles used are either not the muscles required in the activity (e.g., a pitcher jogs before a game), or do not reflect the type of activity in sport (e.g., jumping jacks prior to sprinting). In sport-specific warm-up, the activity is the same but performed at a lower intensity (e.g., jogging slowly before starting a running race). Whether warm-up itself prevents injury or improves performance is beyond the scope of this chapter. However, if it does, the reader should be aware that the mechanism of action (e.g., temperature, muscle fiber energetics, central programming of muscle contractions, proprioception) will dictate whether one type of warm-up is superior to another. In this chapter, I will use warm-up to mean performing an activity prior to sport and specify if it was general or sport-specific where possible.

Sixth, the term "dynamic stretching" is currently used differently by different people, but in essence it refers to the stretching of a muscle by contracting and relaxing the antagonist muscle. For example, if a subject uses the hip abductor muscles to swing the lower limb laterally until the adductor muscles are stretched and then relaxes the abductors and contracts the adductors to swing the lower limb medially, and repeats this several times, some would consider this a dynamic stretch of the adductor and abductor muscles. There is some preliminary evidence that dynamic stretching is less effective than static stretching at improving range of motion (ROM: 4.3° vs. 11.4°).[16] There is no research on injury rates with this type of stretching, and therefore all claims are conjectural. One should note that dynamic stretching includes both classical stretching and warm-up at the same time. Because dynamic stretching requires the muscles to contract, other possible mechanisms include central programming of muscle contraction/coordination and decreased fatigue through increased warm-up activity. Those who promote dynamic stretching as a method to prevent injury should provide some evidence that supports their claim. Further, if they want to demonstrate that it is the stretch that is important as opposed to the general warm-up that also occurs, then the control group intervention should include warm-up activity.

In this chapter, I will first review new findings that have changed our understanding of what stretching actually does to muscle. This will include changes at the level of the whole muscle (e.g., compliance) and at the level of the myofiber. Next, I will review the clinical evidence surrounding the protective effect of stretching both immediately before exercise, and at other times. Finally, I will review the basic science evidence to see whether it supports or contradicts the clinical evidence. The use of stretching as performance enhancement has been discussed elsewhere.[17]

Physiology of stretching

Immediate effects

Stretching is believed to increase the ROM around a joint through decreases in viscoelasticity and increases in the compliance of muscle. What are compliance and viscoelasticity? Compliance is the reciprocal of stiffness, and mathematically it is equal to the length change that occurs in a tissue divided by the force applied to achieve the change in length. A tissue that is easy to stretch is compliant because it lengthens with very little force. Viscoelasticity refers to the presence of both elastic behavior and viscous behavior. An elastic substance will exhibit a change in length for a given force, and will return to its original length immediately on release (e.g., a regular store-bought elastic). The effect is not dependent on time. However, a viscous substance exhibits flow and movement (e.g., molasses), which is dependent on time.[18] Experimentally, viscous behavior produces "creep" if the force is held constant (i.e., the length continues to increase slowly even though the applied force is constant) or "stretch relaxation" if the length is held constant (i.e., the force on the tissue decreases if the tissue is stretched and then held at a fixed length). When the force is removed, the substance slowly returns to its original length. This is different from plastic deformation, in which the material remains permanently elongated even after the force is removed (e.g., a plastic bag[18]). The reader should note that stretching affects tendons and other connective tissue in addition to muscle. However, within the context of normal stretching, the stiffness of a muscle–tendon unit is mostly related to the least stiff section (i.e., resting muscle) and is minimally affected by the stiffness of tendons.

Stretching appears to affect the viscoelastic behavior of muscle and tendon, but the duration of the effect appears short. In one study, canine gastrocnemius muscle was repeatedly stretched to a fixed length and the force was measured. The force required to produce the length change declined over 10 repetitions and was fairly stable after four stretches.[19] The authors did not measure how long the effect lasted. In humans, Magnusson originally found that increased ROM was lost by 60 min if the subjects remained at rest after stretching. Because they did not take measurements at intervals, the effect could have lasted anywhere from 1 to 60 min.[20] In a later study designed to further narrow the interval for the effect, the same group found that the increased ROM lasted less than 30 min even if the person warmed up prior to the stretch and continued to exercise.[21] More studies are needed to see exactly how long the effect does last—e.g., 1 min, 5 min, 15 min, etc.

As one observes people, it becomes clear that some are naturally flexible even though they never stretch, whereas others remain inflexible no matter what they do. The effect of stretching also appears to be specific to individuals and also muscle-specific. For instance, within every study, some individuals have large increases in ROM with stretching whereas others do not, both in animal studies[19] and human studies.[22,23] In addition, stretching appears less effective in increasing hip external rotation and abduction in comparison with hip flexion.[24] Finally, the effects of stretching for 60 s versus 30 s were found to be greater in the elderly[25] but not in younger populations.[26] If true, the optimal duration and frequency for stretching may be different for different muscle groups or individuals. This appears logical, given that different muscles have different temperatures (superficial muscles are colder than deep muscles) and different amounts of pennation (i.e., the angle of sarcomeres to the direction of force when the muscle contracts—e.g., gastrocnemius muscle), and different subjects have different baseline muscle compliances. More research is needed on which variables are responsible (and to what degree) for the variation observed in response to stretching protocols.

Stretching also appears to increase the pain threshold during a muscle stretch—i.e., it acts like an analgesic.[27–29] In these series of studies, subjects' muscles were stretched until they felt pain, and the stretch stopped. After the subjects stretched, the expected increased ROM before pain was felt was associated with both an increased length and force across the muscle. Had the increased ROM been limited to viscoelastic changes, the muscle length would have increased, but the force applied would have been less or unchanged. The only explanation for an increase in force before pain is felt is that stretching acts like an analgesic. Finally, the analgesia is at least partially due to the effects at the spinal cord or cerebral level, because during unilateral proprioceptive neuromuscular facilitatory (PNF) stretching, the ROM in the unstretched leg also increases.[30]

PNF stretching is also an interesting example of the way in which myths can be propagated within the medical literature. When they were first proposed in the early 1970s, PNF techniques were based on the basic science finding that stretching/activity of the antagonist muscle creates reciprocal inhibition of the agonist muscle.[31] When tested, PNF techniques were indeed shown to increase ROM more than static stretching. However, these initial studies did not measure muscle activity, so the reason for the increased ROM was not known. In fact, when electromyographic findings were recorded in 1979, the reciprocal inhibition theory was disproved.[30,32] Although these results have been confirmed more recently,[28,33,34] the myth of reciprocal inhibition continues to be promoted in textbooks and the medical literature. In fact, muscles are electrically silent during normal stretches until the end ROM is approached. Surprisingly, PNF techniques actually increase the electrical activity of the muscle during the stretch,[30,32,33] even though the ROM is increased.[28,32,34,35] This suggests firstly, that PNF stretching is associated with a more pronounced analgesic effect, and secondly that the muscle is actually undergoing an eccentric contraction during a "PNF stretch."

Although stretching may affect the viscoelastic properties of resting muscle, it does not affect the compliance of *active* muscle. Compliance of resting muscle is almost exclusively due to the muscle cytoskeleton,[36,37] whereas compliance of active muscle is directly dependent on the number of active actin–myosin cross-bridges.[38–41] Because injuries are believed to occur when the muscle is active (i.e., during eccentric contractions),[42] compliance during activity should be more important than compliance at rest.

In summary, stretching decreases viscoelasticity of muscle for less than 30 min, and the increased ROM is at least partially due to an analgesic effect mediated at the level of the spinal cord or higher.

Long-term effects

Although the immediate effects of a single stretching session produce a decrease in viscoelasticity and an increase in stretch tolerance, the effect of stretching over 3–4 weeks appears to affect only stretch tolerance, with no change in viscoelasticity.[35,43] In this case, a second explanation for the increased stretch tolerance besides an analgesic effect is possible; regular stretching may induce muscle hypertrophy.

Animal research has shown that muscles that are stretched for 24 h per day for several days will actually increase in cross-sectional area (or decrease in cross-sectional area less than if casted without stretch), even though they are not contracting.[44–46] This is known as stretch-induced hypertrophy. These studies all used cast-immobilization[44,46] or weights to stretch the muscle continuously 24 h/day over 3–30 days.[45] This is of course very different from human stretching programs, which involve stretching for only 30–60 s/day for any particular muscle group. In this connection, Black and Stevens[47] recently found that 2 min stretching of the mouse extensor digitorum longus muscle per day for 12 days did not reduce the force or work deficit created by an acute eccentric-induced injury. However, it must be remembered that stretch-induced hypertrophy may be affected by the presence of injury, and that the stretching period was only 12 days. Therefore, the possibility remains that some hypertrophy will occur in healthy muscle or if muscles are stretched over a longer period of time.

There is some supporting evidence for stretch-induced hypertrophy in humans. If hypertrophy occurred, one would expect force to increase with an isolated stretching program. In a recent review, I showed that stretching regularly over weeks not prior to exercise improves results on tests of maximal voluntary contraction, jumping height and possibly running speed.[17] However, there is an alternative hypothesis as well—a reduction in central neuromuscular inhibition. In most subjects, an electrically-stimulated muscle produces more force than a maximal voluntary contraction, and this means that the central nervous system is unable to fully activate the muscle.[48] If regular stretching reduced this central inhibition, a greater force would occur. Although neuromuscular adaptation is known to be the prime reason for an increase in untrained individuals, its role is thought to be minimal in the type of trained individuals participating in the studies cited in the review. The differentiation between these two theories (hypertrophy and reduction of inhibition) is theoretically simple: getting trained people to stretch regularly for several weeks and measure cross-sectional muscle area with magnetic resonance imaging and neuromuscular inhibition with twitch interpolation. This study remains to be done.

Finally, if stretch-induced hypertrophy does occur, it should be associated with an increase in stiffness, because of the increased muscle cross-sectional area. For example, the stiffness of an elastic band doubles when the cross-section of an elastic band is doubled (e.g., by folding it over itself), even though the elastic itself has not changed. Therefore, a thicker muscle should also be stiffer. However, the stiffness of human muscles does not change over time with stretching.[35,43] Therefore, if stretch-induced hypertrophy is occurring in this situation, then there must be associated changes in the viscoelastic properties of the individual muscle fibers to explain the lack of increase in whole-muscle viscoelasticity. This would only be observable through isolated fiber studies and could not be done *in vivo*.

Does stretching prevent injury?

Methods

The MEDLINE and EMBASE databases were searched for all clinical articles related to stretching and injury, using the strategy outlined in Table 3.1. All titles were scanned, and

Table 3.1 MEDLINE (PubMed search engine) and EMBASE search strategies, searching all fields, including MEDLINE Subject Headings (MeSH) and text words between 1996 and September 2003. The text-word strategy retrieves any article that includes the word in the title or abstract (if the abstract is included in MEDLINE). The symbol "*" in the search acts as a wildcard for any text

Item	Search	MEDLINE	EMBASE
1	Stretch*	30731	12795
2	Sprain OR strain OR injur*	682286	339533
3	Sport OR athlet* OR activ*	2223441	997212
4	1 AND 2 AND 3 (limited to human studies)	554	474

the abstracts of any potentially relevant articles were retrieved for review. All studies that used stretching as an intervention, included a comparison group, and had some form of injury risk as an outcome were included for this analysis. In addition, all pertinent articles from the bibliographies of these papers were also reviewed. Finally, a citation search was carried out on the key articles. Forrest plots were generated using Cochrane Review Manager version 4.2.7.

Results

Every study has limitations. This does not usually invalidate the research, but only limits the interpretation of the study. This chapter summarizes the main weaknesses of the studies and illustrates how the data can still be interpreted for clinical usefulness.

Does pre-exercise stretching prevent injuries?

Only 17 of the articles retrieved from the search strategy used a control group to analyze whether pre-exercise stretching prevents injury and all were included in this analysis. Of these, seven articles suggested it is beneficial (Table 3.2),[6,7,49–53] three articles suggested it is detrimental (Table 3.3),[54–56] and seven articles suggested no difference (Table 3.3).[57–63]

Figure 3.1 shows the relative risks or odds ratios or hazard ratios (with 95% confidence intervals) for all the prospective studies. A close examination of these studies suggests that the clinical evidence does not support the hypothesis that stretching before exercise prevents injury. Because the methodology differed greatly between the studies, an overall summary statistic is inappropriate. The values shown in the figures are for qualitative purposes only and are used to show the effect of stretching before versus not before exercise, and the inclusion/exclusion of certain studies.

Positive studies. When grouped together, four of the seven studies that showed a positive effect actually evaluated a complete program that included many co-interventions in addition to stretching prior to exercise. First, Ekstrand *et al.* found that elite soccer teams that were part of an experimental group (pre-exercise warm-up, leg guards, special shoes, taping ankles, controlled rehabilitation, education, and close supervision) had 75% fewer injuries in comparison with the control group of soccer teams.[52] However, it is impossible to determine which of the interventions might be responsible for the decrease in injury rates. Second, in a similar study completed a year earlier, Ekstrand *et al.* found less

Table 3.2 Brief summary of the clinical studies that suggest stretching immediately before exercise may prevent injury. For the relative risk (RR) or odds ratios (OR), a value above 1 means a higher rate of injury in people who stretch

Reference	Population	Study design	Results	Comments
Ekstrand *et al.*[52]	180 elite male soccer players	RCT intervention of warm-up, stretch, leg guards, prophylactic ankle taping, controlled rehabilitation, information, supervision	The group that received the combined intervention had a RR of 0.18 (0.6 injuries/month versus 2.6 injuries per month)	The multiple interventions prevent one from concluding that pre-exercise stretching is beneficial
Bixler & Jones[51]	5 high-school football teams	Pseudo-RCT intervention of half-time stretching and warm-up	Intervention group had 0.3 injuries per game vs. 0.8 injuries per game for control group	If an intervention team did not stretch at half-time, they were considered as part of the "control data." No numbers given for changes in exposure. With increased exposure and constant risk, frequency of injuries is expected to increase. Therefore, risks cannot be calculated. Also, there was a co-intervention of warm-up
Ekstrand *et al.*[64]	180 elite male soccer players	1-year prospective cohort study	"All seven quadriceps strain affected players of teams in which shooting at the goal occurred before warm-up ($P < 0.058$)" "Hamstring strains were most common in teams not using special flexibility exercises ($t = 2.1$)"	No real analysis of stretching before exercise. Multiple co-interventions

Wilber *et al.*[50]	518 recreational cyclists	Survey of overuse injuries and other related factors	Only results available are "stretching before cycling (1 vs. 2 minutes, $P < 0.007$) . . . had a significant effect on those female cyclists who sought medical treatment for groin/buttock conditions"	Response rate of 518/2500. The association between stretching and injuries to other body parts (e.g., knees, back) was not reported, even though data available. Not clear if people stretched before injury, or because of injury. Effect only in women and not in men
Cross *et al.*[49]	195 Division III college football players	Chart review, pre–post stretching intervention using historical controls. Stretching immediately before exercise	43/195 injuries pre-intervention, and 21/195 post-intervention ($P < 0.05$)	Use of historical controls is poor design. Likely to have had high rate of injuries and decided to introduce stretching. If true, results are likely by chance due to regression towards the mean
Amako *et al.*[6]	901 military recruits	Prospective, exposure decided by company commander. Intervention 4 upper extremity stretches, 7 lower extremity stretches, 7 trunk stretches. Static stretch for 30 s pre- and post-exercise	Risk of injury 11.2% in stretching group and 14.1% in control group ($P = 0.12$)	The company commander chose whether their group would be exposed to the intervention, and groups may train differently. Further, non-stretch group was not prevented from stretching. Finally, group also stretched after activity, so not purely pre-exercise stretch intervention
McKay *et al.*[7]	Elite and recreational, male and female basketball players	Observational study during competitions	OR_{adj}: 0.38 (95% CI, 0.16 to 0.92)	Note that there was a coding error in OR in the article; this is corrected here and the OR represents the odds of injury with stretching versus the odds of injury without stretching. This study examined basketball, but there was no adjustment for position or ankle taping

Table 3.3 Brief summary of the clinical studies that suggest stretching immediately before exercise does not prevent injury. For the relative risk (RR), odds ratio (OR) or hazard ratio (HR), a value above 1 means a higher rate of injury in people who stretch

Reference	Population	Study Design	Results	Comments
Pope *et al.*[62]	1538 male military recruits	12-week RCT	Univariate HR 0.95 (95% CI, 0.77 to 1.18) Multivariate HR 1.04 (95% CI, 0.82 to 1.33)	Large sample size. Military recruits do not perform same activities as elite athletes, but the activity is probably very similar to recreational athletes. Compliance and follow-up is easy in this group
Pope *et al.*[63]	1093 male military recruits	12-week RCT stretch calves	HR 0.92 (95% CI, 0.52 to 1.61)	Although stretching didn't reduce risk, there was a 5-fold increased ankle injury if ankle ROM only 34° ($P < 0.01$)
Van Mechelen *et al.*[61]	421 male recreational runners	16-week RCT matched on age and weekly running distance	RR 1.12	Intervention was warm-up and pre-exercise stretching. There was a lot of "noncompliance" in each group
Macera *et al.*[58]	583 habitual runners	1-year prospective cohort	OR for men 1.1, for women 1.6	Response rate 966/1576. Stretching data was only controlled for age. Stretching was not included in the multiple regression analysis because it was insignificant in the univariate analysis
Walter *et al.*[59]	1680 community road race runners	1-year prospective cohort	Comparison group was people who always stretch. RR: Never stretched: 1.15, 1.18; sometimes stretch: 0.56, 0.64; usually stretch: 1.05, 1.25	To be consistent with other articles, the RR was converted so that the numbers reflect the risk of people who always stretch. These numbers are controlled for running distance and frequency, type of runner, use of warm-up, injuries in past year

Howell[54]	17 elite women rowers	Cross-sectional	Stretching associated with injuries	Not clear if people stretched before injury, or because of injury
Brunet *et al.*[60]	1505 road race recreational and competitive runners	Survey of past injuries and other related factors	Similar frequencies of injuries among those who stretch and those who don't	Response rate unknown. Cross-sectional study design, but injury profile was "any injury" and not recent injury. Not clear if people stretched before injury, or because of injury
Blair *et al.*[57]	438 habitual runners	Survey of past injuries and other related factors	Only results available are "frequency of stretching . . . were not associated with running injuries"	Response rate 438/720. This article comprises three studies. Only the cross-sectional study directly looked at stretching habits. Not clear if people stretched before injury, or because of injury
Kerner[56]	540 people buying running shoes	Survey of past injuries and other Related factors	Only results available are "A comparison of subjects who warmed up prior to running (87.7%) and those who did not (66%) revealed a higher frequency of pain in the former"	Response rate 540/800. No data available to determine clinical relevance. Not clear if people stretched before injury, or because of injury
Jacobs[55]	451 10-km race participants	Survey of past injuries and related factors	~90% of injured people stretched, compared to ~80% of non-injured people	Response rate 451/550. Not clear how 550 were chosen from potential 1620. Univariate analysis only. Not clear if people stretched before injury, or because of injury

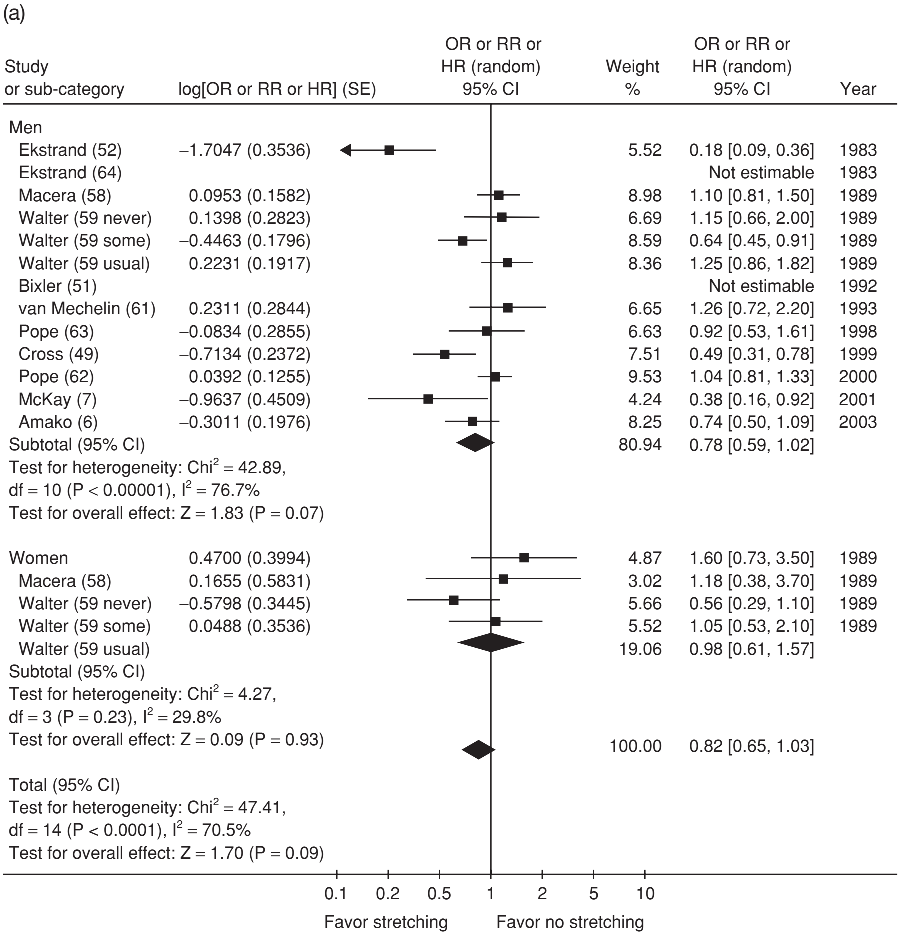

Figure 3.1 In (**a**), the relative risks or odds ratios or hazards ratio (±95% confidence intervals) are plotted for all randomized controlled trials and cohort studies grouped by men or women. (Note that the McKay study included both women and men in the same analysis, but is grouped with men). A value greater than 1 means an increased risk for people who stretch before exercise, and a value below 1 means a decreased risk of injury for people who stretch before exercise. There were two studies[51,64] in which there were insufficient data in the article to calculate the relative risk or odds ratio. The study by Ekstrand *et al.*[52] was calculated for strains and sprains only, and as if each person was only injured once. The study by Walter *et al.*[59] compared several groups with "Always stretched before exercise" (a relative risk above 1 means the "always" group had a higher injury rate). The test of heterogeneity suggests that the results are very heterogeneous. In this situation, sources of heterogeneity should be sought out. In (**b**), the same data are shown, but I have omitted the studies in which stretching may very well not have been the reason for the differences between groups. The more likely reasons in these studies are co-interventions[6,52] and regression to the mean.[49] The test of heterogeneity still suggests some heterogeneity (most likely due to the study by McKay on basketball injuries), but much less. Qualitatively, the overall effect of stretching before exercise suggests no clinically relevant benefit.

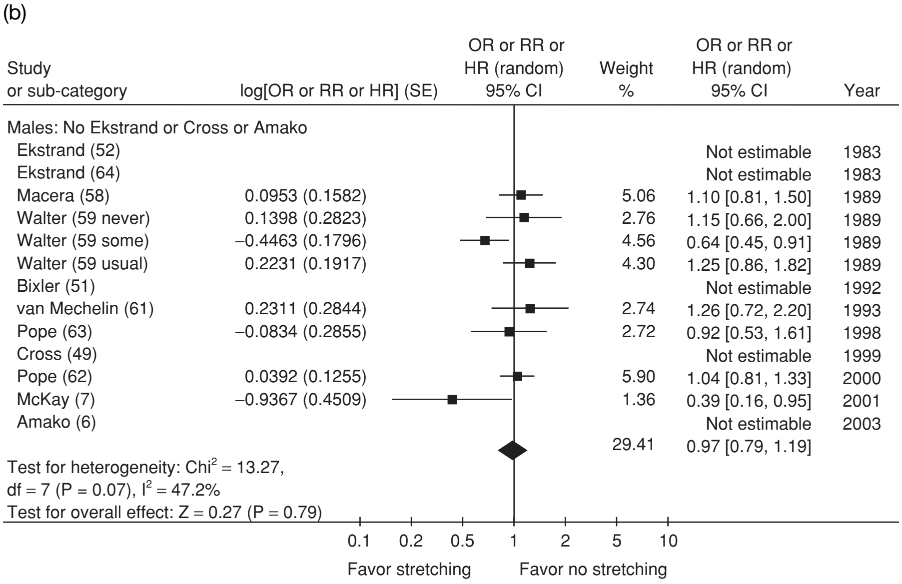

Figure 3.1 (*Continued*)

hamstring and quadriceps strains in elite soccer players who performed warm-up, skill exercises, and stretching exercises before soccer.[64] In a third study,[51] high-school football teams were pseudorandomized to either stretching or warm-up during half-time. The hypothesis was that athletes become stiff during half-time and that stretching at half-time might decrease third quarter injuries. In addition to the co-intervention, this study had problems with randomization and compliance, and did not use the recommended "intention-to-treat" analysis. Finally, the intervention in the Amako *et al.* study was stretching both before and after exercise,[6] and there is some evidence that regular stretching not prior to exercise is beneficial (see the section on "Does stretching after or outside periods of exercise prevent injuries?" below).

Of the remaining three studies, the methodology was weak in two. First, Cross *et al.* used a cohort design with historical controls and found that pre-exercise stretching decreased injuries.[49] Historical controls are only appropriate if certain assumptions are met. For instance, if there were an unusually high injury rate one year by chance, one would expect the injury rate to return to normal the following year. If the medical staff had introduced an intervention to decrease injuries after the high injury rate year, they would mistakenly attribute the decrease in injuries to their intervention. Statistically, this is called regression towards the mean. Studies using historical controls only provide strong evidence when the rates are stable over a number of years, and then fall (or rise) for a few years following the introduction of an intervention. Therefore, without knowing the rates of injury for several seasons before and after the intervention, nor the reason why the intervention was applied during that particular year, the most likely reason for the drop in injury rates in the Cross *et al.* study is regression towards the mean. Second, in a cross-sectional study, women cyclists who stretched before exercise had less groin and buttock pain, but the effect was not observed in men.[50] Because the physiological effect of stretching is similar in both groups, these results are difficult to interpret.

The remaining study examined ankle injuries in basketball players.[7] This was the only study to look at higher intensity exercise and showed a mild protective effect, but did not adjust for position of play or presence of ankle taping. With respect to the basic science evidence, strain rates (analogous to high-intensity vs. low-intensity exercise) did not affect the relationship between compliance and length/energy absorbed before failure.[65] Therefore, intensity is unlikely to modify the effect of stretching and injury, and more research is needed before stretching should be recommended in high-intensity sports.

In summary, although there are some strong studies for which pre-exercise stretching was associated with a reduction in injury rates, the presence of probable effective co-interventions or other limitations suggests that whatever evidence is in favor is weak.

Negative studies. There have been three studies (all cross-sectional) that suggested stretching before exercise may increase the risk of injury.[54–56]

In a cross-sectional study, Howell found that 13 of 13 elite rowers who stretched had back pain, and only one of four athletes who did not stretch had back pain.[54] Interestingly, of the study subjects with hyperflexibility of the lumbar spine, the only two who did not have back pain did not stretch. However, it is again 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 that stretching might increase injury rates,[55,56] the authors did not control for any other factor such as training distance, experience, etc. In summary, recommendations based on these studies should be very guarded.

Equivocal studies. There have been seven studies—three randomized controlled trials (RCTs), two prospective studies, and two cross-sectional studies—that found no difference in injury rates between people who stretch before exercise and those who do not.[57–62,66]

In the most recent large RCT, Pope and colleagues randomly assigned 1538 military recruits to either warm-up and then stretch immediately before exercise, or simply warm-up and exercise.[62] The hazard ratio (equivalent to an odds ratio, but taking into account different follow-up times) after adjusting for height, weight, day of enlistment, age, and 20-m shuttle run test score, suggested no benefit. This study was consistent with a previous study by the same authors that used only calf stretching immediately before exercise.[63] With respect to sports injury prevention, the main limitation of this study is that it occurred in military recruits, who may not be doing the same type of activity as recreational or elite athletes, and may experience a sudden increase in activity that is not typical of recreational or elite athletes.

Van Mechelen randomly assigned 421 persons to an intervention group that included 6 min of warm-up and 10 min of stretching.[61] The relative risk for injury for those in the intervention group was 1.12 in comparison with controls. Notably, 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 pre-exercise stretching. This type of non-compliance (or "misclassification") would be expected to "bias towards the null" and minimize the odds ratio obtained. However, it should not reverse the direction of the odds ratio, which showed more injuries in the group randomized to stretch. 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 cohort study by Walter *et al.*,[59] the authors found that stretching was unrelated to injury after adjusting for previous injuries and mileage. Macera *et al.*[66] found that stretching before exercise increased the risk of injury, but the differences were not statistically significant. Although not RCTs, these were good studies with few limitations.

Finally, two cross-sectional studies showed no protective effect of pre-exercise stretching.[57,60] In fact, Brunet *et al.* reported that non-stretchers had fewer injuries, even though they had higher mileage per week and fewer previous injuries.[60] The cross-sectional design limits the conclusions that can be drawn from these studies.

Summary of clinical evidence

Even though the studies have very different methodologies, one can perform a meta-analysis for qualitative purposes. In this case, the overall effect is estimated at 0.82 (95% CI, 0.65 to 1.03). However, if one omits the studies that included other interventions besides stretching immediately before exercise,[6,52,64] the overall effect is estimated at 0.97 (95% CI, 0.79 to 1.19). Thus, the clinical evidence available does not support the hypothesis that pre-exercise stretching prevents injury.

Does stretching after or outside periods of exercise prevent injuries?

There have only been two studies that isolated the effect of stretching after or outside periods of exercise on injury risk. Both studies suggested a clinically relevant decrease in injury risk, but the results did not reach statistical significance in one. A third study, previously mentioned, examined stretching before and after exercise and also found a non-statistically significant but clinically relevant decrease in risk.[6] More research is needed in this area before definitive conclusions can be drawn.

Positive studies (Fig. 3.2, Table 3.4). In support of the hypothesis that regular stretching prevents injury, a recent study using basic training for military recruits found that the companies of soldiers who stretched three times per day besides their normal pre-exercise stretching regimen had fewer injuries than a control group who stretched only before exercise.[67] However, there were problems with baseline comparisons and there was no adjustment for previous injuries, fitness levels, etc.

Hilyer *et al.* randomly assigned firefighters from two of four fire districts to perform 12 daily stretches for 6 months, while the firemen from the other two districts were instructed not to stretch (total 469 firemen).[68] Although the change in flexibility was greater in the experimental group, this was due to loss of flexibility in the control group and not a gain in flexibility in the experimental group, even though exercise physiologists visited the various stations during the first month to correct improper technique. Although the number of injuries was not statistically different between groups, there was a clinically relevant decrease in risk for the group that stretched (relative risk 0.82; 95% CI, 0.59 to 1.13). Further, the costs due to lost time from work were also less in the group that stretched ($950/injury vs. $2828/injury).

Finally, Amako *et al.* randomly assigned subjects to stretching before and after exercise or a control group and found an overall relative risk of injury of 0.77 (95% CI, 0.54 to 1.08)

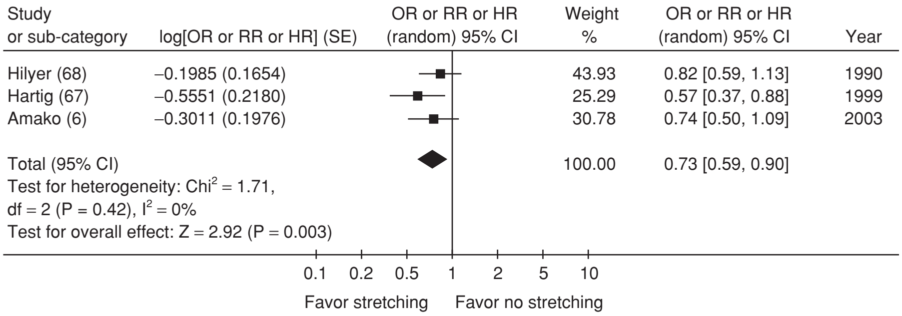

Figure 3.2 A Forrest plot of the relative risks or odds ratios (±95% confidence intervals) from three studies that examined the intervention of stretching regularly not immediately prior to exercise. The test of heterogeneity suggests the studies show similar magnitudes of effect.

for the intervention group.[6] There were some limitations to this study, the most important being that allocation to the stretch or non-stretch group was carried out by the company commander, and different companies may train at different intensities, different levels of fatigue, etc.

Although all three studies have limitations and only one has statistically significant results, they all show clinically relevant decreases in injury risk. In addition, if stretch-induced hypertrophy occurs, as suggested by the basic science evidence,[44–46] one would expect a benefit from regular stretching. These results represent a good beginning, and the area requires further research.

Discussion

A review of the clinical evidence strongly suggests that pre-exercise stretching does not prevent injury, and that the evidence on stretching at other times suggests that it may be beneficial but is too limited to make definitive recommendations at this time. Considering that these results are contrary to many people’s beliefs, it seems prudent to review why some people ever believed stretching before exercise was so beneficial. There appear to be six general arguments that have been proposed in the past.

First, paraphrasing an old Chinese saying, “that which does not bend, breaks.” However, when a tree bends, the force (i.e., the wind) changes from a perpendicular force to a longitudinal force; it is much easier to break a stick by applying a perpendicular force to the middle in comparison with longitudinal forces at the end. In stretching a muscle prior to activity, we do not alter the direction of force at the time of injury, and the analogy is inappropriate.

Second, 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. For example, even though a balloon will stretch before it bursts (high compliance), a sphere made of metal with the same thickness as the balloon might never stretch (low compliance) and still withstand extremely high pressures.

Table 3.4 Brief summary of the clinical studies that suggest stretching not immediately before exercise may prevent injury. For the relative risk (RR) or odds ratios (OR), a value above 1 means a higher rate of injury in people who stretch

Reference	Population	Study Design	Results	Comments
Hilyer *et al.*[68]	469 firefighters	Cluster randomization by fire district. Stretching at work; obviously not possible immediately before fire	48/251 injuries in stretching group and 52/218 injuries in control group (RR 0.82, 95% CI, 0.57 to 1.14). \$950 per injury for lost time in stretching group and \$2838 in control group ($P = 0.026$)	Reviewed exercises with subjects but not clear how closely. Medical cost difference also greater in control group, but not significantly ($P = 0.19$) Because medical costs more similar than lost time costs, total cost not significantly different (0.56)
Hartig *et al.*[67]	298 basic training recruits	Cluster randomization by company	25/150 injuries in stretching group and 43/148 in control group (RR 0.57, 95% CI, 0.37 to 0.88)	Stretching group more flexible prior to training and not controlled for in analysis. Almost twice the no. lost to follow-up in stretch group, which means less people available to be injured. This would make stretching appear more effective
Amako *et al.*[6] (study also included in Table 3.2)	901 military recruits	Prospective, exposure decided by company commander. Intervention: 4 upper extremity stretches, 7 lower extremity stretches, 7 trunk stretches. Static stretch for 30 s pre- and post-exercise	Risk of injury 11.2% in stretching group and 14.1% in control group ($P = 0.12$)	The company commanders chose whether their group would be exposed to the intervention, and groups may train differently. Further, non-stretch group was not prevented from stretching. Finally, group also stretched before activity, so not purely post-exercise stretch intervention

Third, if muscle compliance is increased with warming from 25 °C to 40 °C, the muscle ruptures at a longer length but absorbs less energy.[69] Which is more important, length or energy absorbed? Although muscles are sometimes injured when stretched beyond their normal length of motion, most authors believe that the majority of injuries occur within the normal ROM during eccentric activity, and that the most important variable with respect to muscle injury is the energy absorbed by the muscle.[65,70,71] For example, the hamstring muscle contracts to slow the forward movement of the lower leg during the swing phase of gait (i.e., as the leg moves forward). If the energy is not absorbed, the leg will continue to move forward in the presence of a compliant tissue until it exceeds the tissue's maximum length, whatever that maximum length happens to be. If the muscle absorbs the energy, the lower leg is stopped from extending and the maximum length is never reached. Finally, the reader must remember that the damage occurs at the level of the sarcomere and not the whole muscle.[72] Therefore, if there is excessive sarcomere lengthening so that the actin and myosin filaments no longer overlap, the force is transmitted to the cytoskeleton of the muscle fiber, and damage occurs. This occurs within the normal ROM, because sarcomere length within the muscle is heterogeneous; some sarcomeres lengthen during a contraction at the same time as others are shortening.[72–76] Therefore, it appears that it is the sarcomere length that is related to most exercise-related muscle strains, rather than the total muscle length. Under this hypothesis, an increase in total muscle compliance is irrelevant.

In support of the above argument, ligaments that have been immobilized are also more compliant but absorb less energy.[77] In addition, resting muscle is more compliant than a contracting muscle,[40,41] but again absorbs less energy.[70,78] Finally, sarcomeres directly attached to the tendon are the least compliant and remain undamaged, but adjacent sarcomeres are stretched beyond actin–myosin overlap and become injured.[75,76,79] These results are consistent with Garrett's whole-muscle studies, in which the sarcomeres attached to the tendon remained intact, but the more compliant adjacent sarcomeres ruptured.[70] Taken together, this evidence suggests that increased compliance is associated with an inability to absorb as much energy, which may increase the risk of injury during an eccentric load.

Fourth, overstretching a muscle can certainly produce damage. However, even strains as little as 20% beyond resting fiber length, as one would expect with "correct" stretching techniques, can produce damage in isolated muscle preparations.[71] Therefore, the basic science evidence suggests that "correct" stretching techniques may be more difficult to define than previously thought.

Fifth, we have seen that the increased ROM with stretching is partly due to an analgesic effect.[28,29,32,35] This may explain some preliminary findings that muscle aches and pains are reduced in pre–post testing,[80–82] but does not mean that the risk of injury is decreased. Nor does it mean that stretching shortens rehabilitation time and prevents re-injury following an injury. In two clinical studies comparing stretching with strengthening after injury,[83,84] both found that a strengthening program was superior to stretching. In one study,[83] 23 of 34 male athletes with more than 2 months of groin pain who participated in a strengthening program returned to pre-activity levels within 4 months, in comparison with only four of 34 of athletes who participated in a stretching program (OR_{adj} 12.7; 95% CI, 3.4 to 47.2). Neither study examined acute injuries, nor the potential benefit/harm of adding stretching to a strengthening program; these remain to be determined.

Sixth, some argue that stretching may prevent tendon or other injuries, even though there is no effect on total injuries. First, in the Australian military, tendon injuries occurred in 20 of 735 subjects (2.7%) who stretched and 16 of 803 (2.0%) who did not stretch.[62] Others have suggested that stretching one area reduces the risk of injury in a different area (e.g., stretch the hamstrings to reduce stress on the back), but have not put forth any data. Finally, even if stretching does prevent one specific type of injury, because overall injury rates among stretchers and non-stretchers are not different, any protection against one type of injury would mean an increased risk of other types of injuries in order to balance the equation. It would therefore only be appropriate to generally advise stretching prior to activity if the severity and long-term consequences were greater for the injury that has a decreased risk with stretching in comparison with the injury that has an increased risk with stretching.

In conclusion, the clinical evidence is consistent with the basic science evidence and theoretical arguments; stretching before exercise does not reduce the risk of injury and stretching at other times may be beneficial. Future research should evaluate high-intensity sports and the effects of stretching on recovery following injury.

Key messages

- Stretching immediately before exercise is different from stretching at other times.
- Stretching immediately before exercise does not appear to prevent injury.
- Regular stretching that is not done immediately before exercise may prevent injury.

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Sample examination questions

Multiple-choice questions (answers on page 602)

1 The original study by Ekstrand *et al.*[52] suggested that stretching immediately prior to exercise is associated with a decrease in injuries. Which of the following interventions that are likely to prevent injury were also included in the experimental group as co-interventions?
A Shin guards
B Supervised rehabilitation
C Warm-up
D Education
E All or none of the above

2 With regard to the number of studies examining whether stretching outside periods of exercise prevent injury or minimize the severity of injury:
A 3 found it does and 3 found it does not
B 0 found it does and 3 found it does not
C 3 found it does and 0 found it does not
D All studies used a cohort design
E All or none of the above

3 Theoretical reasons why stretching prior to exercise would not decrease injuries include all of the following *except*:
   A Tissues that are more compliant are associated with a decreased ability to absorb energy
   B The compliance of active muscle is related to the compliance of muscle during normal stretches
   C Most injuries occur during eccentric activity of the muscle, within its normal range of motion
   D Overstretching a muscle is known to be a cause of muscle injury
   E All or none of the above

Essay questions

1 Discuss the evidence for and against the use of stretching immediately prior to exercise as an intervention to prevent injuries.
2 Explain the theoretical reasons why stretching immediately prior to exercise was thought to prevent injuries, and why they do not apply to regular exercise such as jogging.
3 Describe how stretching increases range of motion.

Summarizing the evidence

Comparison	Results	Level of evidence*
Does stretching before exercise prevent injury?	5 RCTs, 4 prospective cohorts, 1 historical cohort, 6 cross-sectional studies. Conflicting results are explained in Tables 3.2 and 3.3. *Overall, stretching before exercise does not prevent injury.* There was an additional prospective cohort study, but it used an intervention of pre- and post-exercise stretching. Note that most studies done on recreational athletes or military personnel. According to the basic science of injury, there is no reason why elite athletes would be expected to have different results. The only study examining high intensity sport was a cohort study on ankle injuries in basketball and suggested a protective effect	A1
Does stretching outside periods of exercise prevent injury?	2 RCTs ($n = 300-470$) with weaknesses in follow-up and differences in baseline characteristics. *One study suggested a decreased injury rate and the other only decreased severity of injury.* There was an additional prospective cohort study, but it used an intervention of pre- and post-exercise stretching	A1

* A1: evidence from large randomized controlled trials (RCTs) or systematic review (including meta-analysis).†
A2: evidence from at least one high-quality cohort.
A3: evidence from at least one moderate-sized RCT or systematic review.†
A4: evidence from at least one RCT.
B: evidence from at least one high-quality study of nonrandomized cohorts.
C: expert opinions.
† Arbitrarily, the following cut-off points have been used: large study size: ≥ 100 patients per intervention group; moderate study size ≥ 50 patients per intervention group.

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