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Review

To stretch or not to stretch: the role of stretching in injury prevention and performance

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Stretching is commonly practiced before sports participation; however, effects on subsequent performance and injury prevention are not well understood. There is an abundance of literature demonstrating that a single bout of stretching acutely impairs muscle strength, with a lesser effect on power. The extent to which these effects are apparent when stretching is combined with other aspects of a pre-participation warm-up, such as practice drills and low intensity dynamic exercises, is not known. With respect to the effect of pre-participation stretching on injury prevention a limited number of studies of varying quality have shown mixed results. A general consensus is that stretching in addition to warm-up does not affect the incidence of overuse injuries. There is evidence that pre-participation stretching reduces the incidence of muscle strains but there is clearly a need for further work. Future prospective randomized studies should use stretching interventions that are effective at decreasing passive resistance to stretch and assess effects on subsequent injury incidence in sports with a high prevalence of muscle strains.

The purpose of this review is to examine the literature on the effects of stretching on sports injury and performance. The specific focus will be on stretching and not flexibility, where stretching is an extrinsic factor potentially affecting sports injury and performance, while flexibility would be an intrinsic factor. The focus will also be on pre-participation stretching as opposed to habitual stretching, i.e. the type of stretching athletes typically do before undertaking an athletic performance. Finally, the focus will be on stretching, not warm-up, with the understanding that stretching is usually practiced as a component of a general pre-participation warm-up. In assessing the effects of stretching on injury, special attention will be given to the intensity, frequency and duration of the stretching interventions used in specific studies. However, potential differences between different stretching techniques, such as static stretching, ballistic stretching or proprioceptive neuromuscular facilitation stretching, will not be addressed. While there is an abundance of literature comparing these techniques in terms of changes in range of motion, there is insufficient data on the effects of different stretching techniques on injury.

The intended purposes of stretching before an athletic event are: (1) to ensure that the individual has sufficient range of motion in his or her joints to perform the athletic activity optimally and (2) to decrease muscle stiffness or increase muscle compliance thereby theoretically decreasing injury risk. Stretching is therefore intended to affect both performance and injury risk. With respect to performance, stretching might improve performance, have no effect on performance or impair performance. Similarly with respect to injury risk, stretching might decrease injury risk, have no effect on injury risk or increase injury risk. Therefore, when one considers the potential effects of stretching on performance and injury risk, there are nine possible combined effects. Optimally stretching would improve performance and decrease injury risk and the most detrimental effect would be that stretching impairs performance and increases injury risk. This range of possibilities must be considered in an overall assessment of the efficacy of pre-participation stretching.

Acute viscoelastic and neural effects of stretching

Acute effects of stretching have been extensively studied. These effects can be categorized into viscoelastic effects and neural effects. In terms of viscoelastic effects, changes in range of motion and resistance to stretch after an acute bout of stretching can be described in terms of stress relaxation, creep and hysteresis (Taylor et al., 1990; McHugh et al.,

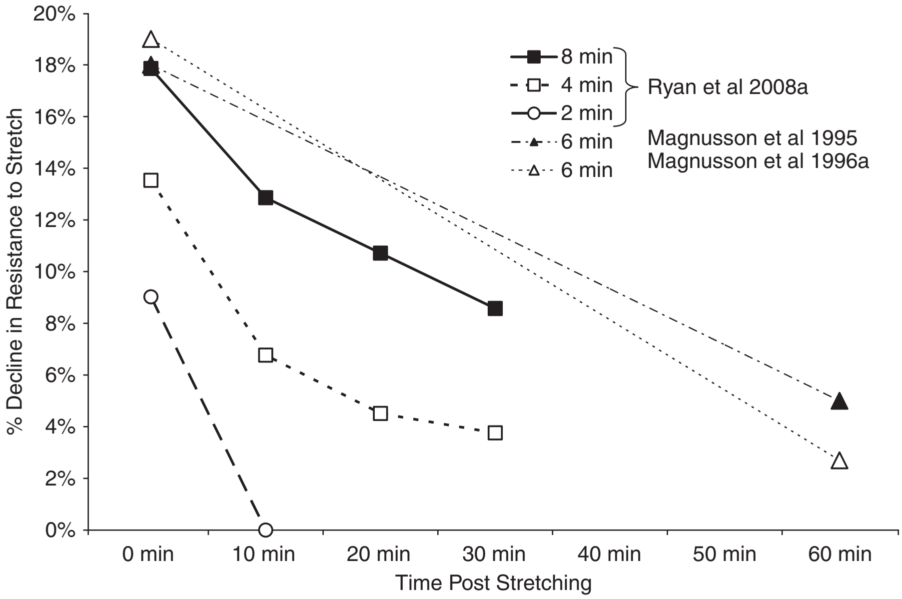

Fig. 1. Effect of duration of stretch on passive resistance to stretch. The data from Ryan et al. (2008a) are for the plantar flexors and the data from Magnusson et al. (1995, 1996a) are for the knee flexors. Ryan et al. (2008a) reported stiffness values while Magnusson et al. (1995, 1996a) reported passive resistive torque. Magnusson et al. (1995, 1996a) performed five consecutive stretches lasting 90 s with a sixth stretch performed after a 1-h break. Percent decline in resistance to stretch shown on graph at 0 min is the difference in resistance at the start of the first stretch vs the start of the fifth stretch (i.e. after total stretch time of 6 min). Percent decline in resistance to stretch at 60 min is the difference in resistance at the start of the first stretch vs the start of the sixth stretch (i.e. after total stretch time of 7.5 min). Immediate and prolonged effects are dependent on total stretch duration. For Ryan et al. (2008a) percent change in resistance to stretch was calculated from the reported absolute changes in terminal stiffness. These data indicate that a total stretch duration of 2 min has no prolonged effect, approximately 50% of the effect of a 4-min stretch duration is lost in 10 min, and approximately 50% of the effect of an 8-min stretch duration is lost in 30 min.

1992, 1998; Magnusson et al., 1998). With respect to neural effects of stretching, it is apparent that when slow passive stretches are applied to skeletal muscle of healthy individuals, there is minimal active contractile activity in response to the stretch (Magnusson et al., 1995, 1996b; McHugh et al., 1998; Ryan et al., 2008a) and indices of motor neuron excitability are decreased (Guissard et al., 1988, 2001; Avela et al., 1999). Interestingly, stretch-induced strength loss (discussed in the following section) is, in part, attributable to a prolonged inhibitory effect of stretching (Avela et al., 1999).

Studies examining the viscoelastic effects of stretching have clearly shown that increases in joint range of motion are associated with decreases in passive resistance to stretch such that after several stretches of a given duration, resistance to stretch at the same range of motion will be decreased (Magnusson et al., 1995, 1996a; McHugh & Nesse, 2008; Ryan et al., 2008a). This decrease in resistance can be referred to as a decrease in muscle stiffness or an increase in muscle compliance. An important goal of stretching before sports performance is to increase range of motion and to decrease resistance to stretch, allowing a freer movement pattern. This is particularly true in activities requiring a large range of motion in multiple joints. An extreme example of which would be ballet dance where the combination of warm-up and stretching accounts for approximately 25% of the total practice time (Reid et al., 1987).

Optimal stretching prescription with respect to intensity, frequency and duration for reducing passive muscle stiffness, has received little attention in literature pertaining to effects of stretching on injury prevention and performance. Stretching intensity is typically controlled by subjective assessment of the discomfort of the stretch with study participants tolerating stretches that are somewhere below a painful threshold but providing some degree of discomfort. With respect to the duration and frequency of stretching, Magnusson et al. (1995, 1996a) showed that 4 × 90 s static stretches of the hamstring muscle group progressively decreased passive resistance to stretch by approximately 18–19% (Fig. 1). Of note, this effect was reversed within 1 h. More recently McHugh and Nesse (2008) demonstrated 5 × 90 s hamstring stretches reduced passive resistance to stretch by 8.3%. Interestingly, in the same study, reduction in resistance to stretch was similar (9%) when the stretch duration was decreased to 60 s (five repetitions) but stretch intensity was significantly increased. In another study (Magnusson et al., 2000b), 2 × 45 s static hamstring stretches had no significant effect on resistance to passive stretch. Similarly, 4 × 30 s stretches of the plantar flexors did not affect resistance to stretch (Muir et al., 1999). By contrast, more recently, Ryan et al. (2008a) demonstrated a 12% reduction in passive stiffness of the plantar flexors with 4 × 30 s stretches, but this effect lasted <10 min. Longer duration stretches clearly have more prolonged effects (Fig. 1). Taking these studies together provides some insight into the total duration of stretches required to provide a prolonged decrease in passive resistance to stretch acutely; 4 × 30 s (2 min) and 2 × 45 s (1.5 min) appear to be insufficient while 5 × 60 s (5 min) and 4 × 90 s (6 min) appear to be effective. The effects of a 4-min stretch duration were still apparent after 10 min (Ryan et al., 2008a) and this may be the minimal stretch duration required to provide a prolonged effect using static stretches.

If a total stretch duration approximating 5 min is required to make a meaningful change in passive resistance to stretch in a single muscle group with static stretching, it would take in the region of 20 min to effectively stretch both the agonist and antagonist muscle groups bilaterally. If two or three sets of agonists and antagonists are to be stretched, as would be typical in preparation for a sports activity involving numerous different joints and body parts, total stretch durations would be in the region of 40–60 min if the goal is to decrease passive resistance to stretch in those target muscle groups. This amount of time is clearly well in excess of typical pre-participation stretching practices with the possible exception of elite ballet dancers. Pre-participation stretching protocols that include individual stretches involving more than one muscle group can reduce the total time for an effective protocol. For example, performing a straight leg raise hamstring stretch with the non-stretched leg held in neutral hip flexion means that the hip flexors of the non-stretched leg are being stretched at the same time as the contralateral hamstrings. Additionally, a combined stretch of the plantar flexors, hamstrings and lumbar spine can be achieved in toe touch stretch. However, a limitation of these types of combined stretches is that stretch intensity to a particular muscle group will vary and some muscle groups may be stretched more effectively than others.

It might be possible to more readily achieve reductions in passive muscle tension utilizing stretching techniques other than static stretching. Toft et al. (1989) demonstrated a 6% reduction in passive resistance of the plantar flexors 1 h following a contract–relax stretching protocol that involved only 2 min of total stretch time (including contraction time). Effects of differing durations of ballistic or cyclic stretching on passive resistance to stretch are not known. Additionally, the efficacy of dynamic stretching for decreasing passive muscle stiffness remains to be determined. Similarly, the effect of a combination of stretching and active warm-up on passive resistance to stretch has not been studied extensively. In one study, 10 min of jogging did not decrease passive resistance to stretch in the hamstring muscle group, but the addition of three 90-s stretches after 10-min jogging did decrease passive resistance (Magnusson et al., 2000a). However, this effect was not maintained after an additional 30 min of running. Of note, passive resistance to stretch was still 8% lower than baseline after 30 min of running preceded by three stretches. With only eight subjects this did not reach statistical significance. Furthermore, the hamstring muscle group operates at relatively short muscle lengths during sub-maximal running (75% VO_{2max}) and some reversal of a stretching effect may be expected.

Effect of stretching on performance

It has been well established that applying a series of stretches to a relaxed muscle leads to an acute loss of strength after the stretching has been completed. This effect has been referred to as the stretch-induced strength loss and has been primarily examined in the knee flexors, knee extensors and plantar flexors. Decreased amplitude of the surface EMG signal during maximal voluntary contractions after stretching provides evidence that stretch-induced strength loss is a neural effect (Avela et al., 1999, 2004). Additional evidence that stretch-induced strength loss is due to a neural effect is that stretch-induced strength loss has been demonstrated in the contralateral non-stretched limb (Cramer et al., 2005). Importantly, some studies (Kokkonen et al., 1998; Nelson et al., 2005a, b; Sekir et al., 2009) that have shown stretch-induced strength loss have utilized stretching protocols with <4-min total stretch duration (Table 1) and therefore, the stretching was probably not sufficient to decrease passive muscle stiffness. It may be easier to initiate a neural affect (stretch-induced strength loss) than a viscoelastic effect (decreased passive resistance to stretch).

In practical terms, the effects of stretching on measures of performance are more important than the effects of stretching on measures of muscle strength. It is notable that stretch-induced decrements in performance measures are generally smaller than decrements in strength measures (Table 1). For example, stretch-induced decrements in vertical jump performance averaged approximately 3–4% (range 0–8%) with decrements in sprint performance ranging from 0% to 2% approximately (Table 1). By

Table 1. Studies examining effects of stretching on muscle strength and power

References	Subjects	Muscle group(s) stretched	Stretch time (min)	Stretch technique	Stretch intensity	Strength loss*	Strength measure	Power loss*	Power measure
Avela et al. (2004)	Recreational male athletes	Plantar flexors	60	Cyclic	10° dorsiflexion	14%	Isometric	Not tested	NA
Avela et al. (1999)	Unspecified Male	Plantar flexors	60	Cyclic	10° dorsiflexion	23%	Isometric	Not tested	NA
Behm and Kibele (2007)	Unspecified	Three lower extremity stretches	2 min per stretch	Static	≤ Point of discomfort	Not tested	NA	2–8%[†]	Vertical jump
Cè et al. (2008)	Non-athletes	Two lower extremity stretches	2 min per stretch	Static	"Onset of soreness"	Not tested	NA	0%	Vertical jump
Cornwell et al. (2002)	Unspecified male	Plantar flexors	3	Static	Maximum tolerance	Not tested	NA	7%	Vertical jump
Costa et al. (2009)	Recreational female athletes	Knee extensors and flexors	8	Static	"Mild discomfort"	9%	Isokinetic 60–300°/s	Not tested	NA
Cramer et al. (2004)	Recreational female athletes	Knee extensors	8	Static	"Mild discomfort"	5%	Isokinetic 60 and 240°/s	Not reported	NA
Cramer et al. (2005)	Not specified	Knee extensors	8	Static	"Mild discomfort"	4%	Isokinetic 60 and 240°/s	8%	Isokinetic 60 and 240°/s
Cramer et al. (2006)	Recreational female athletes	Knee extensors	8	Static	"Mild discomfort"	6%	Isokinetic 60 and 180°/s	Not tested	NA
Cramer et al. (2007b)	Recreational male athletes	Knee extensors	8	Static	"Mild discomfort"	3% (eccentric)	Isokinetic 60 and 180°/s	3% (eccentric)	Isokinetic 60 and 180°/s
Cramer et al. (2007a)	Recreational athletes	Knee extensors	8	Static	"Mild discomfort"	6%	Isokinetic 60 and 300°/s	Not reported	NA
Egan et al. (2006)	Female basketball	Knee extensors	8	Static	"Mild discomfort"	3%	Isokinetic 60 and 300°/s	6%	Isokinetic 60 and 300°/s
Fowles et al. (2000)	Recreational athletes	Plantar flexors	30	Static	Maximum tolerance	28%	Isometric	Not reported	NA
Herda et al. (2008)	Recreational athletes	Knee flexors	6 6	Static Dynamic	"Point of discomfort"	14% 4%	Isometric	Not reported	NA
Herda et al. (2009)	Recreational athletes	Plantar flexors	20	Static	"Point of discomfort"	10%	Isometric	Not tested	NA
Knudson et al. (2004)	Tennis players	Seven upper and lower body stretches	0.5 min per stretch	Static	"Point of discomfort"	Not tested	NA	0%	Velocity of tennis serve
Kokkonen et al. (1998)	Recreational athletes	Knee flexors Knee extensors	3[‡] 3[‡]	Static	Not specified	7% 8%	Isotonic	Not tested	NA
Manoel et al. (2008)	Recreational female athletes	Knee extensors	1.5 1 1.5	Static PNF Dynamic	"Mild discomfort"	Not reported	NA	4% 2% +9%	Isokinetic 60 and 180°/s
Marek et al. (2005)	Recreational athletes	Knee extensors	8	Static PNF	"Point of discomfort"	2% 5%	Isokinetic 60&300°/s	3% 4%	Isokinetic 60 and 300°/s
McBride et al. (2007)	Recreational athletes	Knee extensors	4.5	Static	Not specified	19%	Isometric	Not tested	NA

McHugh and Nesse (2008)	Not specified	Knee Flexors	9	Static	Maximum tolerance	16%	Isometric	Not tested	NA
Nelson and Kokkonen (2001)	Recreational athletes	Knee flexors Knee extensors	3‡ 3‡	Ballistic	To "pain threshold"	7% 5%	Isotonic	Not tested	NA
Nelson et al. (2005a)	Male athletes	Three lower extremity stretches	2 min per stretch	Static	Point of discomfort	Not Tested	NA	2%	Sprint time
Nelson et al. (2001)	Recreational athletes	Knee extensors	4	Static	To "pain threshold"	10%	Isometric	Not tested	NA
Nelson et al. (2005b)	Recreational athletes	Knee flexors Knee extensors	3‡ 3‡	Static	"Tolerable pain"	3% 6%	Isotonic	Not tested	NA
O'Connor et al. (2006)	Not specified	Lower extremity	3.7§	Static	Not specified	Not tested	NA	+7%	Cycling power
Power et al. (2004)	Not specified	Knee extensors Plantar flexors	4.5 4.5	Static	"Onset of pain"	10% 0%	Isometric	6%	Vertical jump
Robbins & Scheuermann (2008)	Male athletes	Three lower extremity stretches	2 min per stretch	Static	<Onset of pain	Not tested	NA	3%	Vertical jump
Ryan et al. (2008b)	Recreational athletes	Plantar flexors	8	Static	Not specified	6%	Isometric	Not tested	NA
Sekir et al. (2009)	Female athletes	Knee extensors Knee flexors	1.3 1.3	Static Dynamic	"Mild discomfort"	14% +15%	Isokinetic 60&180°/s	Not tested	NA
Torres et al. (2008)	Elite athletes	Seven upper body stretches	0.5 min per stretch	Static Dynamic Both	Not specified	Not tested	NA	+2% 0% 0%	Bench press 30% 1RM
Unick et al. (2005)	Female athletes	Four lower extremity stretches	0.75 min per stretch	Static Ballistic	"Just before discomfort"	Not tested	NA	1% 3%	Vertical jump
Vetter (2007)	Recreational athletes	Four lower extremity stretches	0.5–1 min per stretch	Static Dynamic	Not specified	Not tested	NA	$\leq$ 1% <1%	Vertical jump Sprint time
Winchester et al. (2008)	Elite athletes	Four lower extremity stretches	1.5 min per stretch	Static	Point of discomfort	Not tested	NA	2%	Sprint time
Yamaguchi et al. (2006)	Recreational male athletes	Knee extensors	12	Static	Point of discomfort	Not tested	NA	12%	Knee extension
Yamaguchi et al. (2007)	Recreational male athletes	Knee extensors	8	Dynamic	Not specified	Not tested	NA	+9%	Knee extension

*Highest value reported if effects for different conditions are reported, e.g. strength loss at different angles. Percentage change reported regardless whether effect reached statistical significance.

†Several different types of jumps analyzed.

‡Five different stretches were performed for a total stretch time of 7.5 min but only two stretches directly or indirectly targeted the knee flexors and only two targeted the knee extensors.

§Eleven different lower extremity stretches were performed (2 $\times$ 10 s for each stretch).

contrast stretch-induced decrements in strength averaged 22% for 30–60-min total stretch duration (range 14–28%) and ranged from 2% to 19% for shorter total stretch duration (average approximately 8%).

Stretch-induced strength loss is dependent on the stretching technique applied, the contraction type used for measuring strength loss and the muscle length at which strength is measured. With respect to stretching technique, it has been shown that there is no stretch-induced strength loss with dynamic stretching (Herda et al., 2008; Hough et al., 2009). With respect to contraction type, stretch-induced strength loss was not apparent with eccentric contractions in one study (Cramer et al., 2006) but was apparent in another (Sekir et al., 2009). With respect to muscle length, stretch-induced strength loss has been shown not to occur at longer muscle lengths (Nelson et al., 2001; Herda et al., 2008; McHugh & Nesse, 2008). These length-dependent effects can be explained in terms of the length–tension relationship. Stretching makes the muscle–tendon unit more compliant, which allows greater muscle shortening when muscle contractions are initiated at longer muscle lengths. This allows greater cross-bridge formation and is reflected by a change in the joint angle at which peak torque occurs (longer muscle length) and by a shift in the angle–torque relationship (decreased torque production at short muscle lengths and increased torque production at long muscle lengths).

Because stretch-induced strength and power loss are, in part, due to neural effects, it is important to consider that other neural inputs to the muscle will typically occur before an athletic performance where stretching is combined with other warm-up activities and practice drills. Additionally, the psychological stress that often manifests immediately before a competitive event likely alters the excitatory and inhibitory inputs to muscles to an extent that cannot be replicated in a laboratory experiment. These confounding factors limit the generalizability of laboratory findings to on field performance.

Effect of stretching on injury risk

Several studies have examined the association between pre-participation stretching and injury risk (Ekstrand et al., 1983; Bixler & Jones, 1992; van Mechelen et al., 1993; Pope et al., 1998, 2000; Amako et al., 2003; Hadala & Barrios, 2009). The rationale for these studies is that stretching is universally practiced before participation in a wide range of physical activities. However, little attention has been given to the question of why stretching theoretically could impact injury risk. Stretching before performance may impact on some types of injuries but not impact on other injuries. For example, there is a good rationale for why stretching could impact the risk of sustaining a muscle strain injury, but the effect of stretching on muscle strain injuries has not been adequately researched in sports with a high incidence of muscle strains. A plausible theory is that (1) stretching makes the muscle–tendon unit more compliant (Toft et al., 1989; Magnusson et al., 1996a; McHugh & Nesse, 2008), (2) increased compliance shifts the angle–torque relationship to allow greater relative force production at longer muscle lengths (Herda et al., 2008; McHugh & Nesse, 2008), and (3) subsequently the enhanced ability to resist excessive muscle elongation may decrease the susceptibility to a muscle strain injury. This theoretical rationale for why pre-participation muscle stretching might decrease the risk of subsequent muscle strain injuries is a testable hypothesis that has not been adequately addressed in the literature. Indeed, a counter hypothesis could be that enhanced contractile force production when a muscle is in a lengthened position could increase the likelihood of injury. Importantly, this rationale does not apply to the risk of other injuries such as ligament injuries, fractures or overuse injuries, such as tendinopathies.

Studies showing no efficacy for stretching reducing injury risk

Several randomized (or quasi-randomized) controlled interventions have been published showing no effect of pre-participation stretching on injury risk (van Mechelen et al., 1993; Pope et al., 1998, 2000;Table 2). Subjects in these studies were military recruits in a "boot camp" training environment (Pope et al., 1998, 2000) and recreational runners (van Mechelen et al., 1993). The stretching interventions involved three 10-s stretches to various muscle groups (van Mechelen et al., 1993), one 20-s stretch to various muscle groups (Pope et al., 2000) and four 20-s stretches to one muscle group (plantar flexors) (Pope et al., 1998). In each study static stretches were employed. Based on the available literature (Magnusson et al., 1996a, 2000b; Muir et al., 1999; McHugh & Nesse, 2008; Ryan et al., 2008a), it is highly unlikely that any of these three stretching protocols decreased passive resistance to stretch in the target muscles.

With respect to compliance with the stretching and control interventions, it is easier to achieve compliance with a military study group (Pope et al., 1998, 2000) vs lay volunteers (van Mechelen et al., 1993). For example, in the study by van Mechelen et al. (1993), which examined the combination of warm-up and stretching, only 47% of the stretching group actually complied with the stretching intervention

Table 2. Studies examining effects of stretching on injury risk

References	Study design	Subjects	Sample size	Intervention	Effect on all injuries	% muscle strains	Effect on muscle strains
van Mechelen et al. (1993)	Randomized trial	Recreational runners	167 control 159 intervention	10-min stretching+warm-up vs. neither	No effect	Low (not specified)	Not specified
Pope et al. (1998)	Randomized trial	Military recruits	544 control 549 intervention	Warm-up+Stretching (4 × 20 s gastroc and soleus) vs. Warm-up+Upper extremity stretching	No effect	Low (not specified)	Not specified
Pope et al. (2000)	Randomized trial	Military recruits	803 control 735 intervention	Warm-up+Stretching (1 × 20-s stretch six different muscle groups) vs. Warm-up only	No effect	7.5% of	Not specified*
Ekstrand et al. (1983)	Randomized trial	Soccer Players	Six teams control Six teams intervention	Multi-component intervention (including 10-min stretching) vs. no intervention	Control: 93 injuries Intervention: 23 injuries $P<0.001$	25%	Control: 23 injuries Intervention: six injuries $P<0.001$
Bixler and Jones (1992)	Randomized trial	American Football	Two teams control Three teams intervention	3-min stretching+warm-up vs. no intervention	No effect	Sprains and strains 38%	Control: 13 injuries† Intervention: one injury† $P<0.05$
Amako et al. (2003)	Randomized trial	Military Recruits	383 control 518 intervention	20-min supervised stretching (18 × 30-s stretches) vs.10-min unsupervised stretching	No effect	20%‡	Control: 16 injuries‡ Intervention: seven injury‡ $P<0.05$
Hadala and Barrios (2009)	Longitudinal study	Yachting Crew	28 per season	30-min stretching (12 stretches 1 or 2 × 20–30 s stretches) vs. no intervention	Control: 33 injuries§ Intervention:14 injuries§ $P<0.05$	67%	Control: 22 injuries§ Intervention: four injury§ $P<0.01$

*Prevalence of thigh strains was 1.2% in the control group (10 strains in 803 subjects) vs. 0.3% in the stretching group (two in 735 subjects), $P=0.04$, but not alluded to in paper.

†Strains and sprains were grouped together for analysis.

‡Muscle strains and low back muscle strains combined.

§Four-year study with stretching introduced in second year and additional interventions the following 2 years. The overall effect was analyzed for all 4 years. The effect of stretching in first year was extracted from the reported data.

while 5% of the control sample, who should not have been stretching, were in fact stretching. Compliance with the warm-up portion of the intervention was a little better with 68% of the intervention group doing their proposed warm-up; however, not surprisingly, 21% of the control group that were not supposed to be doing the warm-up actually did a warm-up. These compliance values simply highlight the difficulty of doing a proper controlled intervention in athletes who have engrained pre-participation practices, regardless of the knowledge of the efficacy of those practices.

The most prevalent injuries in military recruits and recreational runners would be expected to be overuse injuries and in fact that was what was found in all three studies. The prevalence of muscle strains was either low or not cited. A consistent finding in the three studies was that pre-participation stretching in addition to a formal warm-up did not affect injury risk compared with a control group performing a warm-up without stretching (Pope et al., 1998, 2000) or no warm-up and no stretching (van Mechelen et al., 1993). Since most of the injuries were overuse injuries, the firm conclusion can be that the addition of stretching to a formal warm-up does not decrease the risk of overuse injuries. Interestingly in the largest of these studies Pope et al. (2000), with 1538 male military recruits, 7.5% of injuries were muscle strains. There were 35 muscle strains in the study, 21 of which occurred in the control group and 14 of which occurred in the stretching group. The most striking difference was the occurrence of 10 thigh strains in the control group vs two thigh strains in the stretching group. These injuries amount to a 1.2% prevalence in the control group (10 strains in 803 subjects) vs a 0.3% prevalence in the stretching group (two strains in 735 subjects), which is statistically significant ($P<0.05$). The authors did not perform any analyses with respect to muscle strains and did not refer to this apparent difference. While this possible effect of stretching has a high risk of a type 1 error, the observation warrants some mention here given the lack of research on the effect of stretching on muscle strains. However, considering that the stretching intervention was probably inadequate to decrease passive resistance to stretch and that there was not a high prevalence of muscle strains it is difficult to make any firm conclusions from these data.

Studies showing some efficacy for stretching reducing injury risk

Several randomized (or quasi-randomized) controlled interventions have been published showing an effect of pre-participation stretching on injury risk (Ekstrand et al., 1983; Bixler & Jones, 1992; Amako et al., 2003;Table 2). Additionally, a non-randomized study also showed a beneficial effect of pre-participation stretching (Hadala & Barrios, 2009).

These studies involved military recruits (Amako et al., 2003), adolescent American football players (Bixler & Jones, 1992), soccer players (Ekstrand et al., 1983) and elite competitive sailors (Hadala & Barrios, 2009). The stretching interventions involved one 30-s static stretch for each of four different upper extremity stretches, seven trunk stretches, seven lower extremity stretches (Amako et al., 2003), three 25-s static stretches to three different muscle groups (Bixler & Jones, 1992), an unspecified number of contract–relax stretches to various lower extremity muscle groups (total time for stretch intervention was 10 min) (Ekstrand et al., 1983) and 12 stretches (PNF and static) with two warm-up exercise lasting 30 min (Hadala & Barrios, 2009). In the one study involving soccer players (Ekstrand et al., 1983), the stretching was part of a multi-component intervention consisting of (1) no shooting before warm-up, (2) 10-min warm-up ball exercises, (3) 10-min stretching, (4) prophylactic ankle taping, (5) controlled rehab for new and previous injuries, (6) exclusion of players with knee instability, (7) instruction on fair play and injury risk and (8) medical coverage for all games.

The difficulty in controlling the stretching and control interventions in these types of studies is highlighted in the study by Amako et al. (2003), where the control group performed 5–10 min of unsupervised dynamic stretching before each training session. This dynamic stretching was presumably analogous to an active warm-up. The stretching group performed a 20-min supervised stretching so there was still a marked difference in what was performed before training. Compliance was not specified in these studies (Ekstrand et al., 1983; Bixler & Jones, 1992; Amako et al., 2003; Hadala & Barrios, 2009).

As would be expected for a military training study, Amako et al. (2003) found that most injuries were overuse injuries (36%), but muscle strains accounted for 10% of injuries and low back injury accounted for 13% of injuries. In this study, low back injury was categorized as "disc herniation," "disc degeneration," or "muscle/unknown." Twelve of the 15 low back injuries were categorized as "muscle/unknown." Bixler and Jones (1992) grouped muscle strains with ligament sprains and these accounted for 38% of all injuries. Most notably, Ekstrand et al. (1983) found that muscle strains accounted for 25% of all injuries in their sample of soccer players and Hadala and Barrios (2009) found that muscle injuries accounted for 67% of all injuries during the control period in their study of sailors.

Bixler and Jones (1992) studied the effect of a half-time stretching and warm-up intervention on injuries in high-school football. Five teams were studied, three in an intervention group and two in a control group, in a quasi-random fashion. The intervention was extremely limited with only 3 min devoted to the stretching and warm-up. Injuries occurring in the third-quarter of the games were analyzed. For analysis, ligament sprains and muscle strains were grouped together. One sprain/strain occurred in the intervention group and 13 occurred in the control group, showing a significant effect of the intervention ($P<0.05$). Given that the intervention was only 3 min and the injuries were only studied in the third-quarter, the results may be due to a type 1 error and should be viewed with skepticism.

Amako et al. (2003) examined the effect of pre-exercise stretching on 901 male military recruits (518 in the stretch group and 383 in the control group) in a quasi-random fashion. While only 10% of the injuries were muscle strains and only 13% were low back injuries, given a study sample of 901 recruits, this amounted to a large number of muscle strains and low back injuries. For analysis, muscle strains were combined with tendon injuries. The prevalence of muscle/tendon injury was 2.5% in the intervention group and 6.9% in the control group ($P<0.05$). The prevalence of low back injury was 1% in the intervention group and 3.5% in the control group ($P<0.05$). In total, there were 11 lower extremity muscle strains and 12 low back muscle injuries. Of these 23 injuries, seven occurred in the stretching group (1.4% prevalence) vs 16 in the control group (4.2% prevalence). While this breakdown of injuries was not performed in the study it represents a significantly lower occurrence of injury in the stretching group ($P<0.05$). Taking the low back and muscle injuries together, the intervention resulted in a 66% reduction in musculotendinous injuries when compared with the control group. The intervention resulted in a 67% reduction in muscle strains and low back muscle injuries combined. This significant effect of stretching on muscle and low back injuries was apparent despite the fact that the control group actually did perform some unsupervised stretching. The important component of this study was that the complete stretching intervention was 20 min, which is longer than most interventions. A negative factor is that only one 30-s stretch was used for each of 18 stretches. However, six of these stretches involved the quadriceps and hip flexors combined and three involved the low back and hamstrings.

In the study by Ekstrand et al. (1983), six teams were placed on the intervention and six teams served as controls in a quasi-random fashion. The intervention was effective in reducing all types of injuries. With respect to muscle strains, there were six in the intervention group and 23 in the control group ($P<0.001$), representing a 74% reduction in muscle strains. Because the intervention involved multiple components, the key question is what role stretching played in the dramatic reduction in muscle strains. While the stretching intervention was only 10 min, stretching plus warm-up accounted for 20 min and were possibly complimentary. Other components of the intervention, such as prophylactic ankle taping, rehabilitation of previous injuries and instruction on fair play and injury risk, are less likely to have significantly impacted the risk of sustaining a muscle strain. However, as with any multi-component intervention it is not possible to attribute any observed effect to one particular component of the intervention.

Hadala and Barrios (2009) studied injuries in an elite yachting crew during four consecutive seasons. The first season served as a control period and the subsequent seasons involved a progression of interventions aimed at reducing injuries. Of particular interest is the first year of intervention, which involved a 30-min stretching intervention (12 different stretches for upper and lower extremities and two low back warm-up exercises/stretches). The stretching was performed before competition and involved one to two repetitions lasting 20–30 s. In the pre-intervention season, there were 22 muscle injuries in 9 days of competition compared with only four muscle injuries in 9 days of competition the following season. This represents an 82% reduction in muscle injuries. Despite the fact that this was not a randomized controlled trial, the data are noteworthy for the marked beneficial effect of stretching. Of note, 30-min total stretch duration is longer than stretching interventions employed in other studies (Ekstrand et al., 1983; Bixler & Jones, 1992; van Mechelen et al., 1993; Pope et al., 1998, 2000; Amako et al., 2003).

Summary of effect of stretching on injury risk

Of the seven studies cited in Table 2, the three showing no effect of stretching had a low prevalence of muscle strains (van Mechelen et al., 1993; Pope et al., 1998, 2000) while the four studies showing some effect of stretching had a high prevalence of muscle strains (Ekstrand et al., 1983; Bixler & Jones, 1992; Amako et al., 2003; Hadala & Barrios, 2009). A common limitation among these studies is the difficulty in isolating the effect of stretching. The ideal randomized trial would include four groups: (1) a group performing stretching alone, (2) a group performing warm-up alone, (3) a group performing stretching plus warm-up and (4) a group performing neither. The stretching intervention should be of sufficient intensity, frequency and duration to decrease passive resistance to stretch and the study population should be involved in a sport with a high prevalence of muscle strains. However, it is questionable if it would be possible, or practical, to carry out such a study in a group of athletes playing a sport known to have a high incidence of muscle strains.

In conclusion, despite the previously mentioned limitations there is evidence that pre-participation stretching is beneficial for reducing muscle strains (Ekstrand et al., 1983; Bixler & Jones, 1992; Amako et al., 2003; Hadala & Barrios, 2009). However, there is clearly a need for larger controlled trials.

Risk factors for muscle strains: where does stretching fit in?

Injury risk in sports is multi-factorial and, in general, is sport specific. There may be intrinsic risk factors for specific injuries in a particular sport, such as age, strength and flexibility, as well as extrinsic risk factors, such as stretching, warm-up, training errors, protective equipment and rules. With respect to studies on military recruits, the primary risk factor for injury is likely overuse or what might be referred to as training errors. Military recruits are subjected to a massive increase in training volume involving many activities to which they have not previously been exposed. Specific risk factors for muscle strains have been previously identified; increasing age (Emery & Meeuwisse, 2001; Orchard, 2001; Verrall et al., 2001; Arnason et al., 2008), having sustained a previous muscle strain (Seward et al., 1993; Emery & Meeuwisse, 2001; Verrall et al., 2001; Arnason et al., 2008) and muscle weakness relative to the antagonist or the contralateral side (Orchard et al., 1997; Tyler et al., 2001) are the strongest intrinsic risk factors for sustaining a muscle strain. Several studies have shown that flexibility is not a significant intrinsic risk factor for muscle strain in various sports (Dvorak et al., 2000; Orchard, 2001; Tyler et al., 2001; Verrall et al., 2001), but this is not synonymous with concluding that stretching does not prevent muscle strains. While flexibility is an intrinsic factor inherent to the individual, stretching is an extrinsic factor that is either practiced or not. The acute effects of a pre-participation stretching intervention on injury risk may be very different from the chronic effects of habitual regular stretching.

Stretching, flexibility and functional range of motion

Some sports such as long-distance running require much less range of motion in the major joints of propulsion compared with other activities such as ballet dance or gymnastics. In practical terms, the athlete must have a sufficient range of motion in his or her joints before performing in order to perform their particular sport adequately. A period of warm-up, with or without stretching, will generally be required to achieve this range of motion. A hurdler must have sufficient hip range of motion to flex the lead hip with the knee fully extended and extend and abduct the trailing leg to clear each hurdle. The gymnast or ballet dancer may need to perform bilateral hip abduction to 90° to meet the aesthetic demands of their activity. While dancers, gymnastics and to a lesser extent hurdlers may be inherently more flexible in the hip joints than athletes from other sports involving smaller changes in joint range of motion, these athletes will still spend a lot of time in warm-up and stretching to maximize joint range of motion before participation.

The functional range of motion for a particular joint can be assessed by examining the joint angle–torque relationship for muscle contractions of agonist muscle groups for a particular joint. The angle–torque relationship is analogous to the length–tension relationship. Flexibility has been shown to affect the functional range of motion measured by the angle–torque relationship. Specifically, hamstring flexibility has recently been shown to affect the angle–torque relationship for the knee flexors (Alonso et al., 2009). In subjects with tight vs normal hamstring flexibility, peak torque occurred at a joint angle corresponding with a shorter muscle length. Additionally, while at muscle lengths shorter than optimal, subjects with tight hamstrings could produce more torque than subjects with normal hamstring flexibility, while at muscle lengths greater than optimal, subjects with tight hamstrings produced less torque than subjects with normal hamstring flexibility (Alonso et al., 2009). The clinically relevant question is whether acutely increasing flexibility by stretching also produces a shift in the angle–torque relationship such that torque production at long muscle lengths is augmented at the expense of torque production at short muscle lengths. It is more difficult to answer this question because acute stretching has a neural inhibitory effect on strength (as discussed previously). However, several studies have shown that stretch-induced strength loss, while apparent at short muscle lengths is not apparent at lengths beyond optimal (Nelson et al., 2001; Herda et al., 2008; McHugh & Nesse, 2008). These findings imply that acute stretching does shift the angle–torque relationship thereby counteracting stretch-induced strength loss at longer muscle lengths. Since muscle strains are thought to occur with muscles in a relatively stretched position, this effect may be advantageous for counteracting potentially injurious muscle elongations. In practical terms, such a hypothesis would be difficult to examine with respect to muscle strains. However, the effect of a stretching-induced change in the angle–torque relationship and symptoms of exercise-induced muscle damage has been examined (McHugh & Nesse, 2008). In general, the stretching intervention, which was sufficient to change the viscoelastic properties of the muscle, did not affect subsequent strength loss and pain after the eccentric exercise. However, when tested with a muscle in a lengthened position, strength loss was apparent in the non-stretched leg over 3 days after the eccentric exercise, with no strength loss apparent in the leg that was stretched before eccentric exercise. Why this effect occurred at the longer muscle length but not at shorter muscle lengths was not readily explained. While the data provide some experimental evidence of a protective effect of stretching, it is important to note that exercise-induced muscle damage and muscle strain injury are different clinical entities.

Brockett et al. (2004) showed that a previous muscle strain can alter the length-dependent characteristics of muscle contraction and increase susceptibility to eccentric contraction-induced muscle damage. Athletes with previous hamstring strains generated peak knee flexion torque at a shorter muscle length compared with the contralateral side and compared with a group with no prior history of hamstring injury. Furthermore, the previously injured hamstring muscles were more susceptible to eccentric contraction-induced muscle damage. The interesting clinical question is whether a muscle length-dependent shift in contractile mechanics in previously injured hamstrings also explains the high re-injury rate (approximately 33%) (Seward et al., 1993). If so, stretching would be a plausible acute intervention while eccentric training would be an obvious chronic intervention.

Summary

With respect to the effect of pre-participation stretching on performance, it is clear that an acute bout of stretching will decrease the ability to generate a maximal force (Table 1). However, these effects are less apparent when tests of muscle power are studied and may not be apparent when the pre-participation stretching is combined with other pre-participation activities typically used in a warm-up, such as practice drills and low intensity movements. In activities requiring large range of motions in various joints, such as gymnastics and ballet dance, participants need to perform some form of pre-participation activity to achieve the required range of motion for their performances. Whether this can be achieved by stretching alone, warm-up alone or by a combination of warm-up and stretching has not been established in the literature.

With respect to the effect of pre-participation stretching on injury risk, the epidemiological studies show that pre-participation stretching in addition to warm-up will have no impact on injury risk during activities where there is a preponderance of overuse injuries (van Mechelen et al., 1993; Pope et al., 1998, 2000). However, it should be noted that the stretching interventions applied in these studies may have been insufficient to induce an acute change in the viscoelastic properties of the muscles being stretched. There is some evidence to indicate that pre-participation stretching does reduce the risk of muscle strains (Ekstrand et al., 1983; Bixler & Jones, 1992; Amako et al., 2003; Hadala & Barrios, 2009), however, further research is needed in this area. The first step in assessing any potential effect of pre-participation stretching on subsequent injury is to establish the optimal stretching prescription with respect to decreasing passive resistance to stretch. Ideally, such an intervention could then be applied to a group of athletes in a sport known to have a high prevalence of muscle strain injuries in a randomized controlled fashion including; stretch only groups, warm-up only groups, stretch and warm-up groups and control groups. Whether such a study is feasible or practical remains to be determined.

From the existing literature the following stretching recommendations for injury prevention seem reasonable: (1) target pre-participation stretching to muscle groups known to be at risk for a particular sport, e.g. adductor strains and hip flexor strains in ice-hockey, and hamstring strains in soccer, Australian rules football, etc.; (2) apply at least four to five 60-s stretches to pain tolerance to the target muscle groups and perform bilaterally, in order to be confident of decreasing passive resistance to stretch; (3) to avoid any lingering stretch-induced stretch loss, perform some dynamic pre-participation drills before actual performance, e.g. sub-maximal ball kicking and dribbling drills in soccer, skating drills in ice hockey, etc. Hopefully future experimental and epidemiological studies will provide more substantial data to guide such recommendations.

Perspectives

Considering the widespread practice of pre-participation stretching in sports there is limited research assessing the efficacy of such practices. An acute bout of stretching can impair muscle strength but effects on sports performance are less apparent, and effects of stretching combined with other warm-up drills warrants further study. An inherent limitation in the research on injury prevention is that there has been inadequate consideration of the optimal intensity, frequency and duration of the stretching protocols employed. Despite these and other limitations there is some evidence that stretching does not reduce the

risk of sustaining overuse injuries but does reduce the risk of sustaining muscle strain injuries. Clearly further research is needed in the area.

Key words: muscle strength, muscle strain, muscle stiffness, stretch-induced strength loss.

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