Eur J Appl Physiol (2011) 111:2633–2651
DOI 10.1007/s00421-011-1879-2

REVIEW ARTICLE

A review of the acute effects of static and dynamic stretching on performance

David G. Behm · Anis Chaouachi

Received: 12 July 2010 / Accepted: 16 February 2011 / Published online: 4 March 2011

Abstract An objective of a warm-up prior to an athletic event is to optimize performance. Warm-ups are typically composed of a submaximal aerobic activity, stretching and a sport-specific activity. The stretching portion traditionally incorporated static stretching. However, there are a myriad of studies demonstrating static stretch-induced performance impairments. More recently, there are a substantial number of articles with no detrimental effects associated with prior static stretching. The lack of impairment may be related to a number of factors. These include static stretching that is of short duration (<90 s total) with a stretch intensity less than the point of discomfort. Other factors include the type of performance test measured and implemented on an elite athletic or trained middle aged population. Static stretching may actually provide benefits in some cases such as slower velocity eccentric contractions, and contractions of a more prolonged duration or stretch-shortening cycle. Dynamic stretching has been shown to either have no effect or may augment subsequent performance, especially if the duration of the dynamic stretching is prolonged. Static stretching used in a separate training session can provide health related range of motion benefits. Generally, a warm-up to minimize impairments and enhance performance should be composed of a submaximal intensity aerobic activity followed by large amplitude dynamic stretching and then completed with sport-specific dynamic activities. Sports that necessitate a high degree of static flexibility should use short duration static stretches with lower intensity stretches in a trained population to minimize the possibilities of impairments.

Keywords Flexibility · Range of motion · Strength · Power · Sprint

Communicated by Nigel A.S. Taylor.

D. G. Behm (✉)
School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's, NF A1C 5S7, Canada
e-mail: dbehm@mun.ca

A. Chaouachi
Tunisian Research Laboratory "Sport Performance Optimisation", National Center of Medicine and Science in Sports, Tunis, Tunisia

Introduction

Static stretching was considered an essential component of a warm-up for decades (Young and Behm 2002). The traditional warm-up consisted of a submaximal aerobic component (i.e. running, cycling) whose goal was to raise the body temperature 1–2°C (Young and Behm 2002; Young 2007). The increase in body and muscle temperature has been found to increase nerve conduction velocity, enzymatic cycling and increase muscle compliance (Bishop 2003; Young and Behm 2002). Traditionally, the second component was a bout of static stretching (Young and Behm 2002; Young 2007). Static stretching usually involves moving a limb to the end of its range of motion (ROM) and holding the stretched position for 15–60 s (Norris 1999; Young and Behm 2002). Static stretching has been demonstrated as an effective means to increase ROM about the joint (Bandy et al. 1997; Power et al. 2004). This bout of stretching is commonly followed by a segment of skill rehearsal where the players would perform dynamic movements similar to the sport or event for which they were preparing (Young and Behm 2002).

The increased ROM achieved with an acute bout of stretching has been attributed to changes in the length and stiffness (compliance) of the affected limb musculotendinous unit (MTU) and have been classified as elastic changes (temporary) (Alter 1996). Although the exact mechanisms responsible for chronic or plastic increases in ROM (flexibility) are debatable, the increases have been primarily attributed to decreased MTU stiffness (Wilson et al. 1991, 1992) as well as increased tolerance to stretch (Magnusson et al. 1996c).

In addition to increasing ROM, the proposed benefits of static stretching were the reduction (Safran et al. 1989) or prevention (Smith 1994) of injury, a decrease in subsequent muscle soreness (High et al. 1989) and improved performance (Young and Behm 2002; Young 2007). The improvement in performance has been suggested to be due to the enhanced ability to stretch or reach during a sport as well as the decreased resistance of a more compliant or less stiff muscle to the intended movement (Young 2007). However, a number of researchers have concluded that stretching has no effect on injury prevention (Gleim and McHugh 1997; Herbert and Gabriel 2002; Small et al. 2008). Other studies have illustrated that the most flexible individuals were more likely to suffer injuries than moderately flexible individuals (Bauman et al. 1982; Cowan et al. 1988). Furthermore, a substantial body of research appeared early in this decade that showed that sustained static stretching could impair subsequent performance (Behm et al. 2001, 2004, 2006; Behm and Kibele 2007; Fowles et al. 2000; Kokkonen et al. 1998; Nelson et al. 2001a, b; Power et al. 2004). These performance measures include laboratory-based physiological strength measures, such as maximal voluntary contraction (MVC) isometric force and isokinetic torque, training-related strength measures such as one repetition maximum lifts, power-related performance measures such as vertical jump, sprint, running economy, agility as well as measures of balance, which are more functional measures of athletic performance. However, the stretch literature is not unanimous in reporting stretch-induced impairments.

One of the first published articles (114 citations, Google Scholar, October 2010) of the present era investigating static stretch-induced effects on performance was published by Worrell et al. (1994). In opposition to the majority of studies, Worrell's group reported an enhancement in hamstring concentric and eccentric torque following four hamstrings stretches of 15–20 s each. Another early and more widely cited article (228 citations, Google Scholar, October 2010) in this area was published by Kokkonen et al. (1998) in the late 1990s. They illustrated a 7–8% decrease in knee flexion and extension force following six repetitions of five different lower limb stretches of 15-s each. Kokkonen's article was followed by two other highly cited investigations by Fowles et al. (2000) (257 citations Google Scholar, October 2010) and Behm et al. (2001) (159 citations Google Scholar, October 2010) that continued to ferment the plethora of articles regarding the effects of static stretching on subsequent performance. The Fowles et al. (2000) study included 13 plantar flexors (PF) static stretches of 135 s resulting in approximately 30 min of PF stretching. The consequence of this prolonged duration of stretching was a 28% decrease in PF maximum voluntary contraction (MVC) force immediately post-stretch with a continued 9% impairment after 60 min. Muscle activation as measured by the interpolated twitch technique (ITT) and electromyography (EMG) remained impaired for 15 min. Recently, Costa et al. (2010) used a similar duration of stretching with nine repetitions of 135 s of PF passive static stretch with 5–10 s rest between stretches resulting in decreases in peak twitch force and rate of force development as well as an increase in the electromechanical delay. Soon following the Fowles et al. (2000) study, Behm et al. (2001) reduced the volume of static stretching to 20 min of stretching on the quadriceps and reported decrements of 12, 20 and 12% for MVC force, EMG activity and evoked twitch force respectively.

From Worrell's study of 15 years ago to the present day, the perception regarding the benefits of static stretching in a warm-up has changed dramatically. There are many studies showing that static stretching can lead to impairments in subsequent performance. Figures 1 and 2 illustrate the far greater preponderance of studies reporting significant impairments as compared to no significant change or facilitation of strength/force and isokinetic power (Fig. 1) and jump height (Fig. 2) performance. Therefore, while static stretching predominantly leads to performance deficits, there are a number of studies that suggest static stretching has no significant effect or can improve performance. For example, Fig. 3 illustrates that static stretching does not lead to such pervasive negative

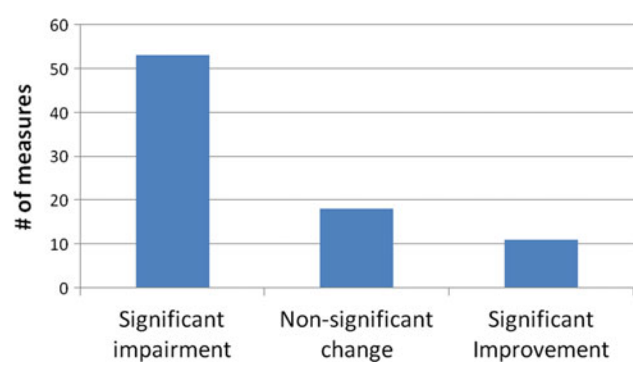

Fig. 1 The number of measures (tests) from 42 studies encompassing 1,606 participants that report static stretch-induced changes in force and power. Measures of force and power in these studies included isometric force and torque, isokinetic power, and one repetition maximum lifts, such as squats and bench press

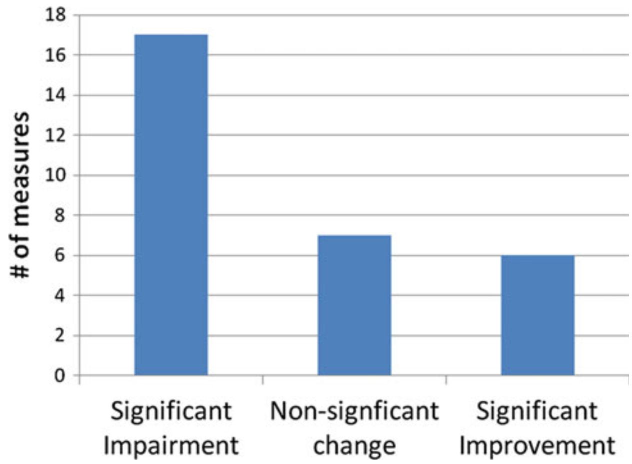

Fig. 2 The number of measures (tests) from 20 studies encompassing 484 participants that report the effect of static stretch on jump height performance. Changes in jump height in these studies included countermovement jumps (CMJ), squat jumps, and drop jumps

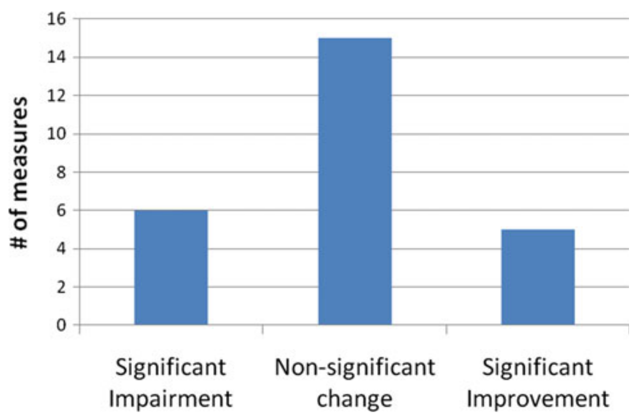

Fig. 3 The number of measures (tests) from 16 studies encompassing 415 participants that report the effect of static stretching on sprint and running performance

effects with sprinting and running activities. Presently, the overwhelming consensus is against static stretching prior to subsequent performance, especially involving higher velocities and power; however, there are populations and activities where static stretching may improve flexibility without impairing performance. Dynamic stretching which involves controlled movement through the active range of motion for each joint (Fletcher 2010) is currently replacing static stretching in the modern athletic warm-up. However, it is important not to ignore the studies that report no impairments as they may reveal stretch-related mechanisms and opportunities to employ static stretching prior to performance for various activities or populations. This review will attempt to investigate negative, null and positive responses to stretching and provide some clarity regarding the conflicting findings.

Search strategy

This review integrated studies that examined the acute effects of static and dynamic stretching on performance. A literature search was performed independently by the two authors using ASAP, ProQuest 5000, MEDLINE, SPORT Discus, AUSPORT, ScienceDirect, Web of Science and Google Scholar databases. The databases were selected as they contain extensive relevant literature in the areas of sports science. The search period ranged from 1989 to 2010. The electronic databases were searched using a number of key terms as selected by the authors: static stretching, dynamic stretching, ballistic stretching, flexibility, warm-up, prior exercise, performance, and acute effects. These keywords were used individually and/or combined. A search for relevant articles was also performed from the reference lists of the identified studies. Articles referenced by authors online or articles with restricted full text online were found in hardcopy form in library archives.

Inclusion criteria (or study selection)

The methodological design of the review included a set of criteria that had to be adhered to select only relevant studies. Studies were included in the review if they fulfilled the following selection criteria. (1) The study contained research questions regarding the effect of static and dynamic stretching as the experimental variables on performance and used (2) healthy and active human subjects. (3) The outcome was a physiological (e.g. MVC isometric force, isokinetic torque, one repetition maximum, balance and others) or performance (vertical jump, sprint, running economy, agility and others) measure. (4) Only studies from 1989 to June 2010 were reviewed; earlier studies, although considered, were excluded from assessment to review findings from more recently conducted studies reflecting recent static and dynamic stretching practices. (5) The study must have been written in the English language and published as an article in a peer-reviewed journal or conference proceeding; any abstracts or unpublished studies were excluded. Studies were further delineated with respect to their internal validity. Selection was based on the recommendations by Campbell and Stanley (1966) and included; (i) studies involving a control group, (ii) randomized control studies, (iii) studies using instruments with high reliability and validity.

Effect sizes (ES) which are a standardized value that permits the determination of the magnitude of the differences between the groups or experimental conditions (Cohen 1988) were calculated for each study that provided absolute mean data and standard deviations. Cohen assigned descriptors to the effect sizes such that effect sizes less than 0.4 represented a small magnitude of change while 0.41–0.7 and greater than 0.7 represented moderate and large magnitudes of change, respectively. Analysis of variance (ANOVA) measures and *t* tests (GBStat, Dynamic Microsystems Inc., Silver Springs Maryland) were performed using the percentage changes in measures from various studies when there were a sufficient number of studies to allow the analysis. Figure columns illustrate mean percentage changes with standard deviation bars.

Effect of stretching duration

The duration of the stretching protocols used in some studies do not always coincide with typical practice of athletes and fitness enthusiasts. A series of articles that surveyed North American strength and conditioning coaches from professional sports reported average stretch repetition durations of approximately 12 s (Ebben et al. 2005), 14.5 s (Simenz et al. 2005), 17 s (Ebben et al. 2004) and 18 s (Ebben and Blackard 2001) for baseball, basketball, hockey and football players respectively. A number of the aforementioned stretching studies have used extensive durations that involved 30–60 min (Avela et al. 2004; Fowles et al. 2000) or 15–20 min (Bacurau et al. 2009; Behm et al. 2001; Costa et al. 2010; Cramer et al. 2005) of static stretching. More moderate durations of static stretching of 90 s or less per muscle group (Brandenburg 2006; Kokkonen et al. 1998), 2 min (Cramer et al. 2004; Marek et al. 2005; Nelson et al. 2001a, b, 2005a; Yamaguchi et al. 2006), 3 min (Bacurau et al. 2009) and ≥5 min (Nelson et al. 2005b; Zakas et al. 2006) have also produced decrements. Tables 1, 2, 3 illustrate a sample of studies which documented strength or force (Table 1), jump height or power (Table 2) and sprint and agility (Table 3) impairments with static stretching durations of individual muscle groups from 30 s to 20 min. The majority of these studies employed relatively moderate durations of static stretching ranging from 90 s to over 2 min for each muscle group. Whereas the mean percentage strength and force impairments (Table 1: 6.9%) exceed the jump (Table 2: 2.7%) and sprint (Table 3: 2.4%) deficits, the magnitude of change calculated from effect sizes are all in the moderate range. Protocols implementing moderate durations of static stretching have also reported impairments in subsequent reaction and movement time (Behm et al. 2004) and balance (Behm et al. 2004; Nagano et al. 2006).

These static stretch-induced impairments can continue for 2 h. For example, Power et al. (2004) had subjects stretch the quadriceps, hamstrings and PF with two different stretches of three repetitions each for 45 s (270 s/muscle). They reported mean decreases in quadriceps MVC force (9.5%), muscle activation (5.4%) and increased ROM (7.4%) that endured for 2 h after stretching. Similarly Fowles et al. (2000) reported force deficits for 1 h following the stretch protocol. However, both protocols used stretching durations that exceeded normal athletic practice.

A factor mitigating the deleterious effects of static stretching may be the stretch duration. Young et al. (2006) and Knudson and Noffal (2005) were among the first to investigate volume and intensity effects with static stretching. Young et al. (2006) found that 1 min of stretching garnered significantly less jumping impairments than 2 or 4 min; hence a greater duration of stretching resulted in greater deficits. The literature tends to illustrate that when the total duration of static stretching of a single muscle group is more than 90 s (i.e. 3 stretches of 30 s each) there is strong evidence for performance impairments (Figs. 4, 5). However, if the total duration of static stretching is less than 90 s, there seems to be more variability in the evidence for impairments (Figs. 4, 5). Effect sizes calculated from studies testing force, torque and isokinetic power show trivial magnitudes of change with <30 s of static stretching as compared to moderate magnitudes with more than 90 s (Table 4). An ANOVA performed on the percentage changes in studies measuring force, torque and power pre- and post-static stretching shows a trend ($p = 0.09$) for a significantly greater impairment with studies employing over 90 s (−5.8% ± 6.4) versus <90 s (−3.3% ± 4.1) of static stretching. A less dramatic contrast is seen with jump height as the test variable, with trivial magnitudes for <30 s of static stretching as compared to small effect sizes for more than 90 s (Table 4). Significantly ($p = 0.05$) greater vertical jump height impairments were detected when comparing studies instituting more (−3.3% ± 3.4) versus less (−1.03% ± 2.5) than 90 s of static stretching. Percentage changes and effect sizes associated with sprint and run tests range from trivial to small. A review of the mean effect sizes in Table 4 also illustrates that the mean magnitude of change is significantly greater for strength measures than for jump and sprint measures. The role of the stretch shortening cycle and the length tension relationship as dependent factors with stretch-induced impairments is provided later in the review.

A number of studies have documented no significant change in force/torque (Beedle et al. 2008; Egan et al. 2006; Molacek et al. 2010; Torres et al. 2008; Winke et al. 2010) and throwing velocity (Haag et al. 2010; Torres et al. 2008) with stretching durations ranging from 30 to 120 s for individual muscle groups. Other studies using 45 s (Gonzalez-Rave et al. 2009; Knudson et al. 2001; Unick et al. 2005), ≤60 s (Robbins and Scheuermann 2008) and ≤90 s (Behm et al. 2006; Handrakis et al. 2010; Samuel et al. 2008) of static stretching have also reported no effects on jump heights. Nonetheless, there are

Table 1 Static-stretching induced force impairments

References	*n*	Stretch duration per muscle	Stretch intensity	Effect and percentage change	Effect size
Bacurau et al. (2009)	14	3 sets of 6 stretches × 30 s	NR	↓ 1 RM leg press 19.1%	1.93
Beedle et al. (2008)	19	3 reps × 15 s bench press-men	<POD	No sig effect on 1 RM bench or leg	0.01
		3 reps × 15 s leg press-men	<POD	Press 0.11% (bench) and 2.3% (leg)	0.09
Behm et al. (2004)	16	3 reps × 45 s	POD	No sig change in force 1.3%	0.08
Brandenburg (2006)	16	2 hamstrings stretches × 3 reps × 15 s	NR	↓ isometric torque 6.3%	0.29
		2 hamstrings stretches × 3 reps × 30 s		6.1%	0.24
Brandenburg (2006)	16	2 hamstrings stretches × 3 reps × 15 s	NR	↓ concentric torque 2.8%	0.12
		2 hamstrings stretches × 3 reps × 30 s		3.4%	0.13
Brandenburg (2006)	16	2 hamstrings stretches × 3 reps × 15 s	NR	↓ eccentric torque 5.3%	0.20
		2 hamstrings stretches × 3 reps × 30 s		5.8%	0.22
Cramer et al. (2004)	21	4 sets of 4 stretches × 30 s	<POD	↓ leg isokinetic peak torque 2.7%	0.51
Cramer et al. (2006)	13	4 sets of 4 stretches × 30 s at 60° s^{-1}	<POD	↓ leg isokinetic peak torque 1.1%	0.17
		4 sets of 4 stretches × 30 s at 180° s^{-1}	<POD	6.5%	0.86
Cramer et al. (2007a, b)	15	4 sets of 4 stretches × 30 s at 60° s^{-1}	<POD	↓ leg isokinetic peak torque 2.6%	0.14
		4 sets of 4 stretches × 30 s at 180° s^{-1}	<POD	1.8%	0.08
Franco et al. (2008)	19	1, 2 or 3 reps × 20 s	POD	↓ muscle endurance after 40 s 4.9%	0.21
Franco et al. (2008)	15	1 rep × 20 s	POD	↓ muscle endurance 7.8%	0.41
		1 rep × 40 s		19.2%	1.12
		1 PNF		24.5%	1.33
Garcia-Lopez et al. (2010)	25	2 reps × 25 s	<POD	↓ bench press lifting velocity	NA
Herda et al. (2008)	15	9 reps × 135 s	POD	↓ plantar flexor torque 10%	NA
Herda et al. (2010)	11	9 reps × 135 s	POD	↓ plantar flexor torque 11.5%	NA
Knudson and Noffal (2005)	57	10 reps of 10 s	<POD	↓ grip strength only after 40 s of stretch 4.9%	0.68
Kokkonen et al. (1998)	30	5 stretches × 3 reps × 15 s assisted	NR	↓ knee flexion/ext force 16%	NA
		5 stretches × 3 reps × 15 s unassisted	POD		
Marek et al. (2005)	19	4 repetitions × 30 s at 60° s^{-1}	POD	↓ isokinetic torque 0.4%	0.05
		4 repetitions × 30 s at 300° s^{-1}	POD	2.6%	0.26
Nelson et al. (2005a, b)	22	4 stretches × 4 reps of 30 s unassisted or assisted	<POD <POD	↓ muscle endurance 16.1%	0.95
Nelson et al. (2001a, b)	55	2 stretches × 4 reps of 30 s unassisted or assisted	Assisted-POD Unassisted-NR	↓ MVC at 162° but not shorter ROM	NA
Nelson et al. (2001a, b)	15	4 stretches × 4 reps × 30 s unassisted or assisted	Assisted-POD Unassisted-NR	↓ isokinetic torque at slower angular velocities, but not higher velocities 7.2%	NA
Nelson et al. (2005a, b)	31	5 quadriceps and hamstrings ballistic stretches × 6 reps × 15 s each (3 reps assisted and 3 reps unassisted)	Assisted-<POD Unassisted-POD	↓ knee flexion and extension 1 RM 3.2%	0.61
Ogura et al. (2007)	10	30 s vs. 60 s stretch	<POD	↓ MVC with 60 s stretch 8.7%	0.83

Table 1 continued

References	*n*	Stretch duration per muscle	Stretch intensity	Effect and percentage change	Effect size
Siatras et al. (2008)		1 rep of either 10, 20, 30 or 60 s		↓ isokinetic torque only after 30 and 60 s stretches	NA
Winchester et al. (2009)	18	1–6 reps × 30 s stretches	POD	↓ 1 RM knee flexion with all repetitions	NA
Yamaguchi et al. (2006)	12	6 stretches of 4 sets × 30 s at 5% MVC	POD	↓ leg extension power 10.8%	0.47
Yamaguchi et al. (2006)	12	6 stretches of 4 sets × 30 s at 30% MVC	POD	↓ leg extension power 3.7%	0.25
Yamaguchi et al. (2006)	12	6 stretches of 4 sets × 30 s at 60% MVC	POD	↓ leg extension power 10.6%	0.56
Zakas (2005)	14	1 × 30 s vs.	<POD	↓ isokinetic torque only	0.78
		10 × 30 s vs.	<POD	After multiple stretches	0.86
		16 reps × 30 s	<POD	2.8, 3.3, and 2.8%	0.79
Zakas et al. (2006)	16	3 reps × 15 s vs. 20 × 15 s-30° s^{-1}	<POD	↓ isokinetic torque 5.2%	0.32
		3 reps × 15 s vs. 20 × 15 s-60° s^{-1}	<POD	5.4%	0.36
		3 reps × 15 s vs. 20 × 15 s-120° s^{-1}	<POD	8.4%	0.60
		3 reps × 15 s vs. 20 × 15 s-180° s^{-1}	<POD	6.5%	0.47
		3 reps × 15 s vs. 20 × 15 s-300° s^{-1}	<POD	12.9%	0.89
		Means		6.9% ↓ ES = moderate magnitude	0.51

NR not reported, *NA* not available

more prolonged duration static stretching studies employing 2–8 min that also do not elicit isokinetic torque impairments (Cramer et al. 2007a, b; Ryan et al. 2008b).

To further obscure the clarity of the findings, other short duration static stretching protocols using only 30 s of stretching have recorded performance impairments (Winchester et al. 2009). In addition, Vetter (2007) used only 60 s of stretching for each muscle group resulting in decreased jump height, but no effect on sprint time. However, the extent of static-stretch-induced jump impairments in the Winchester study was only 0.6%, while Vetter reported 5.4% decrements. Deficits in concentric and eccentric leg extensor and flexor torque occurred following just two repetitions of 20 s static stretches (Sekir et al. 2009). Table 1 illustrates a number of studies where the longer durations of static stretching-induced greater impairments compared to shorter durations (Franco et al. 2008; Knudson and Noffal 2005; Ogura et al. 2007; Siatras et al. 2008; Zakas 2005). Thus, the message that shorter durations of static stretching do not negatively impact performance is not unanimous. Furthermore, for the recreational fitness enthusiasts, impairments of <5% may not be considered a significant consequence.

Based on the majority of the literature, it would seem logical to recommend that prolonged static stretching not be performed prior to a high level or competitive athletic or training performance. It would also seem prudent based on the conflicting literature that even shorter duration static stretching be minimized. Hence should static stretching ever be included in a warm up? There are many dynamic sports where enhanced static flexibility would be expected to affect performance. Some examples would include the ability of a goaltender in ice hockey to maximally abduct his/her legs when in a butterfly position, gymnasts performing and holding a split position, wrestling, martial arts, synchronized swimming, figure skating and others. Although some studies have indicated that dynamic stretching provides similar increases in static flexibility as static stretching (Beedle and Mann 2007), other studies have indicated that dynamic stretching is not as effective at increasing static flexibility as static stretching within a single warm-up session (Bandy et al. 1998; O'Sullivan et al. 2009) or with prolonged training (Covert et al. 2010). Hence, it could be important to include static stretching in the warm-up for specific sport flexibility applications. Based on the solid evidence showing impairments with more than 90 s of stretching and the mixed results when examining 30–90 s of stretching, as well as the trivial effect sizes for <30 s versus the small to moderate effect sizes for >30 s (Table 4), static stretching for each individual muscle should be <30 s in total duration. Recent research has demonstrated that just 36 s of static stretching (6 repetitions of 6 s each) can significantly improve ROM (Murphy et al. 2010). There may also be other factors contributing to the decision of whether to include short duration static stretching within the warm-up.

Table 2 Evidence of static-stretching induced jump impairments with relatively brief durations of stretching

References	*n*	Stretch duration per muscle	Stretch intensity	Effect and percentage change	Effect size
Behm et al. (2006)	18	3 reps × 30 s	POD	No effect on jump height but increased contact time by 5.4%	0.47
Bradley et al. (2007)	18	4 repetitions × 30 s	<POD	↓ VJ 4.0%	0.62
Cornwell et al. (2002)	16	1.5 min stretch of quadriceps and gluteals	NR	↓ concentric jump	NA
				↓ drop jump	
Fletcher and Monte-Colombo (2010)	21	2 reps × 15 s	<POD	↓ countermovement Jump 3.7%	0.37
				↓ drop jump 4.8%	0.49
Gonzalez-Rave et al. (2009)	24	3 stretches of 3 reps × 15 s CMJ	<POD	No effect on jump height 3.1% (CMJ) 11.11% (SJ)	0.25
		3 stretches of 3 reps × 15 s SJ			0.75
Holt and Lambourne (2008)	64	3 reps × 5 s	POD	↓ VJ	NA
Hough et al. (2009)	11	1 rep × 30 s	<POD	↓ VJ 1.7%	0.11
Knudson et al. (2001)	20	3 reps × 15 s	<POD	No sig effect on jump height 0.4%	0.02
Power et al. (2004)	12	3 reps × 45 s	POD	No effect on jump height 14.3%	1.00
Robbins and Scheuermann (2008)	20	2 reps of 15 s	POD	↓ VJ 0.8%	0.20
		4 reps of 15 s	POD	2.2%	0.58
		6 reps of 15 s	POD	3.2%	0.85
Samuel et al. (2008)	24	3 reps × 30 s	<POD	No sig effect on jump height	NA
Torres et al. (2008)	11	2 reps × 15 s—force	<POD	No change in throw performance 4.2% (force) and	0.29
		2 res × 15 s—power	<POD	2.2% (power)	0.15
Vetter (2007)	12	2 reps × 30 s (women)	NR	↓ VJ 0.35%	0.08
Vetter (2007)	14	2 reps × 30 s (men)	NR	↓ VJ 0.9%	0.25
Wallman et al. (2005)	14	3 reps × 30 s stretches	<POD	↓ VJ 5.6%	0.84
Young and Elliott (2001)	14	3 reps × 15 s	POD	↓ drop jump	NA
		Means		2.7% ↓ ES = moderate magnitude	0.43

NR not reported, *NA* not available

Contraction type responses to static stretching

The literature tends to indicate that different types of contractions are more or less susceptible to static stretch-induced deficits. For example, although a number of studies have shown that more flexible individuals (Gleim et al. 1990; Jones 2002; Trehearn and Buresh 2009) or those who have implemented static stretching immediately prior to the performance (Wilson et al. 2010) decreased running economy, others have shown no effect (Hayes and Walker 2007) or decreased (Godges et al. 1989) energy cost with running. An acute bout of stretching did not reduce the maximum duration of time that runners could continue at their VO_{2max} (Samogin Lopes et al. 2010). This discrepancy in running-related findings may be related to the type of contraction or action. Because static stretching can increase muscle compliance (Wilson et al. 1991, 1992), it can enhance the ability of the MTU to store elastic energy over a longer period (Bosco et al. 1982a, b; Cavagna et al. 1968; Edman et al. 1978). Some studies using longer duration contractions or slower stretch–shortening cycle (SSC) activities have shown either no effect or increased performance following stretching. Comparing both low (40 s) and high (150 s) volumes of static stretching, Molacek et al. (2010) did not find any significant change in 1 RM bench press. Similarly, Torres et al. (2008) reported no effect of static stretching on isometric bench press or bench press throws while Wilson et al. (1992) found a 5% increase in rebound bench press following 8 weeks of flexibility training. Furthermore, Cramer et al. (2006) reported no effect of static stretching on isokinetic eccentric contractions. When compared with sprinting-related contractions, the eccentric contractions were relatively slow being performed at 60° and 180° s^{-1}. These eccentric contractions and prolonged SSC of the bench press actions may have benefited from a more compliant muscle that possessed the ability to store elastic energy over a longer period. Some of the previously mentioned running studies that reported no or enhanced effects following stretching used either recreational runners (Godges et al. 1989) or had their subjects run at submaximal speeds (Hayes and Walker 2007). The prolonged SSC

Table 3 Evidence of static-stretching induced sprint and agility impairments with relatively brief durations of stretching

References	*n*	Stretch duration per muscle	Stretch intensity	Effect and percentage change	Effect size
Beckett et al. (2009)	12	6 reps × 20 s stretches	<POD	↓ repeated sprints 1.4%	0.87
Chaouachi et al. (2008)	48	2 reps × 20 s	<POD	↓ single 10 m sprint 0.4%	0.07
				↓ single 30 m sprint 1.2%	0.19
Fletcher and Anness (2007)	10	3 reps × 22 s—men	<POD	↓ 50 m sprint time compared with active dynamic stretch 2.5% (men) and 1.4% (women)	0.44
	8	3 reps × 22 s—women	<POD		0.87
Gelen (2010)	26	1 reps × 20 s of 5 stretches	<POD	↓ sprint and slalom dribbling of soccer ball 8.5%	1.56
		1 reps × 30 s of 5 stretches			
Mohammadtaghi et al. (2010)	19	1 rep × 30 s	<POD	↓ Illinois agility test time 5.1%	1.38
Nelson et al. (2005b)	16	4 reps × 30 s of 3 stretches	POD	↓ 20-m sprint time 1.2%	1.00
Sayers et al. (2008)	20	3 reps × 30 s of 3 stretches	2 stretches < POD	↓ sprint time 2.1%	0.36
			1 stretch POD		
Siatras et al. (2003)	11	2 reps × 30 s	<POD	↓ gymnast sprint speed 3.8%	0.09
Winchester et al. (2008)	22	3 reps × 30 s	POD	↓ sprint—1st 20 m run 1.2%	0.12
				2nd 20 m run 1.2%	0.11
				Combined 40 m run 1.7%	0.24
		Means		2.4% ↓ ES = moderate magnitude	0.56

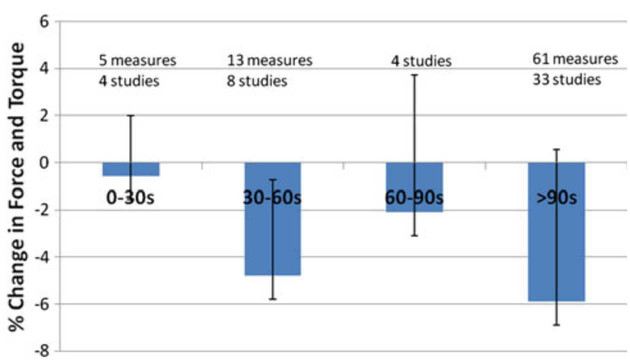

Fig. 4 The effect of static stretching duration on force/torque and power production. Measures of force and power in these studies included isometric force and torque, isokinetic power, and one repetition maximum lifts, such as squats and bench press. *Columns* represent mean percentage changes with standard deviation *bars*. Mean values may include multiple measures from a single study (e.g. 61 force or torque measures from 33 studies)

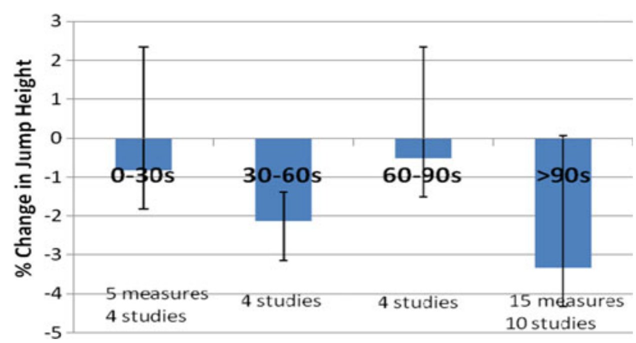

Fig. 5 The effect of static stretching duration on jump height performance. Changes in jump height in these studies included countermovement jumps (CMJ), squat jumps, and drop jumps. *Columns* represent mean percentage changes with standard deviation *bars*. Mean values may include multiple measures from a single study (e.g. 15 jump measures from 10 studies)

with eccentric contractions, bench press actions and longer distance running as well as longer ground contact or transition times, may be more advantageous with a more compliant and flexible MTU. This positive association between force output and muscle compliance is further supported by Walshe and Wilson (1997). They compared MTU stiffness and the ability to perform drop jumps from various heights. The results indicated that stiff participants were significantly disadvantaged at higher drop heights (80 and 100 cm) than their more compliant counterparts. They postulated that the stiffer MTU would have a decreased ability to mitigate the high loads, thus stimulating increased inhibition via the Golgi tendon organs. This inhibition would override the facilitation effect of the stretch reflex resulting from a bias towards a protective mechanism (Walshe and Wilson 1997) when high levels of force are placed on the muscle. Hence, while not all athletic actions benefit from a less complaint MTU, higher force output over relatively extended durations (prolonged SSC) may be advantaged by a more compliant MTU.

Conversely with more elite sprinters, static stretch-induced changes in the viscoelastic properties and stiffness of the MTU (Cornwell et al. 2002; Cramer et al. 2004, 2005; Fowles et al. 2000; Nelson et al. 2001a; Torres et al. 2007) might be expected to negatively impact the transmission of forces and the rate of force transmission, which

Table 4 Effect sizes and percentage changes associated with the effect of various durations of static stretching on force and isokinetic power, vertical jump height and sprint speed

Duration	Number of subjects	Effect size	Percentage change (%)
Force/power			
0–30 s	98	0.004	−0.5
30–90 s	329	0.62	−4.7
>90 s	1,203	0.61	−5.9
Mean	1,642 (sum)	0.55	−5.1
Jump height (s)			
0–30	94	0.08	−0.8
30–90	148	0.14	−1.2
>90	242	0.27	−3.3
Mean	554 (sum)	0.18	−2.4
Sprint speed (s)			
0–30	147	0.25	−1.3
30–90	186	0.29	−0.9
>90	36	0.08	−0.7
Mean	415 (sum)	0.28	−1.3

are essential variables in sprinting (Dintiman and Ward 2003) (Table 3). Wilson et al. (1994) reported that MTU stiffness was significantly related to isometric and concentric performance ($r = 0.57$ and 0.78, respectively). They suggested that a stiffer MTU augments force production via an improved force–velocity and length–tension relationship. A stiffer MTU would be more effective during the initial transmission of force, thus increasing rate of force development. A slacker parallel and series elastic component could increase the electromechanical delay (Costa et al. 2010) by slowing the period between myofilament crossbridge kinetics and the exertion of tension by the MTU on the skeletal system. A number of researchers have found that leg stiffness is either correlated with maximum sprint velocity (Chelly and Denis 2001) or joint stiffness increases with running speed (Farley and Morgenroth 1999; Kuitunen et al. 2002). Furthermore, a lengthened muscle due to an acute bout of static stretching could have a less than optimal crossbridge overlap which, according to the length–tension relationship (Rassier et al. 1999), could diminish muscle force output. Fowles et al. (2000) demonstrated an 8-mm increase in fascicle length of the soleus and lateral gastrocnemius with 30 min of stretching. The elongation of tendinous tissues can also have an effect on force output (Kawakami et al. 2002) through a reduction in either the passive or active stiffness of the MTU (Kokkonen et al. 1998). Static stretching may alter the length–tension relationship and/or the plastic deformation of connective tissues such that the maximal force-producing capabilities of the MTU could be limited (Fowles et al. 2000; Herda et al. 2008). Fowles et al. (2000) reported that after 15 min of recovery from intense stretching, most of the decreases in muscular force-generating capacity were attributable to intrinsic mechanical properties of the MTU rather than neural factors. Specifically, it was hypothesized that stretching may have altered the length–tension relationship and/or the plastic deformation of connective tissues such that the maximal force-producing capabilities of the MTU could be limited. It is possible, therefore, that stretching-induced alterations in the length–tension relationship may be manifested through changes in the angle–torque relationship, which in turn, may be evident by changes in the area under the angle–torque curve (Marek et al. 2005). Thus, dependent on the contraction velocity, SSC or contact time, a more compliant muscle due to stretching could impair performance in higher speed contractions or conversely enable the more efficient storage and transfer of energy with more prolonged actions. Changes in the length–tension relationship would have its greatest effect upon isometric contractions. The significantly greater effect sizes or magnitudes of change associated with static stretch-induced impairments in force/strength studies may be influenced by the many studies utilizing isometric contractions (see Tables 1, 2, 3, 4).

The literature seems to indicate that neural effects are more transient (shorter duration) (Guissard et al. 1988) or play a smaller (McHugh et al. 1992) or insignificant (Costa et al. 2010; Magnusson et al. 1996a, c; Weir et al. 2005) disruptive role than viscoelastic properties in static-stretch-induced impairments. The static stretching evidence indicates a greater contribution to impairments derives from viscoelastic or mechanical changes (Avela et al. 2004; Costa et al. 2010; Magnusson et al. 1995; McHugh et al. 1992, 1998; Weir et al. 2005). The impairments in these studies which utilized stretching durations of 90 s (Magnusson et al. 1995; McHugh et al. 1992), 2 min (Ryan et al. 2008a), 2.5 min (Magnusson et al. 1996b) to 20 min (Costa et al. 2010) persisted from 10 to 20 min (Ryan et al. 2008a) to 1 h (Magnusson et al. 1995, 1996b) post-stretching. Once again the evidence points to the employment of shorter duration of static stretching (<30 s) to minimize the more persistent and substantial changes to viscoelastic properties.

Effect of intensity of stretching

Based on personal experience and anecdotal evidence, a number of flexibility practitioners attempt to place the muscle under stress in the belief that stretching to the point of discomfort (POD) will bring about the greatest increases in ROM. Previous research involving prior static stretching to the POD have resulted in impairments of force (Behm et al. 2001, 2004, 2006; Fowles et al. 2000; Kokkonen et al. 1998; Nelson et al. 2001a; Power et al. 2004; Young and Behm 2003), jump height (Cornwell et al. 2002; Young and Elliott 2001; Young and Behm 2003), drop jump ground contact times (Behm et al. 2006), muscle activation (Behm et al. 2001; Power et al. 2004; Rosenbaum and Hennig 1995), reaction and movement time and balance (Behm et al. 2004). However, all these studies instituted stretching regimes that had the participants stretch to the POD. There has been some evidence in the literature to suggest that less than maximal intensity stretching might not produce these deficits (Knudson et al. 2001, 2004; Manoel et al. 2008; Young et al. 2006).

Young et al. (2006) manipulated the volume of stretching and in one condition had the participants stretch to 90% of POD. The submaximal intensity stretch of the plantar flexors was calculated by decreasing the range of motion by 10% from the ankle joint dorsiflexion angle achieved when the subjects were stretched at the POD. They found that 2 min of static stretching at 90% intensity had no effect on muscle performance (concentric calf raise and drop jump height). Knudson et al. (2001, 2004) published two studies where the subjects were stretched to a point "just before" discomfort. Neither study showed significant decreases in performance. In one study (Knudson et al. 2001), there was a trend towards impaired vertical jump height (3%), while the other study reported no change in tennis serve velocity (Knudson et al. 2004). Manoel et al. (2008) had subjects stretch to mild discomfort (3 repetitions of 30 s) and reported no effect on knee extension power at 60° and 180° s^{-1}. Beedle et al. (2008) employed three static stretches of 15 s each of moderate intensity stretching (stretch as far as possible without assistance) and reported no adverse effects upon bench press and leg press 1 RM. Other studies have also stretched to the point of mild discomfort and reported impairments in isokinetic peak torque (Cramer et al. 2004, 2005), vertical jump height (Bradley et al. 2007; Hough et al. 2009) and 30 m sprint time (Sayers et al. 2008). Other than the Young study (2006), the other studies used subjective intensities and did not accurately measure the degree of submaximal stretch intensity.

In contrast, Behm and Kibele (2007) did find stretch-induced impairments with university sport science students who were stretched four times for 30 s each for the quadriceps, hamstrings and PF at 100% (POD), 75% and 50% of POD or a control condition. The stretch intensities in this study were precisely monitored based on percentage changes in passive tension as measured with a strain gauge. All three stretching intensities adversely affected jump heights with significant decreases in drop, squat, and countermovement jump heights. The lower intensity stretching actually provided greater numerical increases in flexibility with 12.6–13.9% increases with less than POD versus 9.7% with POD stretching, although this difference was not statistically significant. Thus, while the literature that institutes stretching to the POD overwhelmingly is associated with stretch-induced impediments, studies using submaximal stretching intensities (<POD) do not provide clarity regarding static stretch-induced impairments. More studies are needed that accurately monitor the degree of stretch intensity and its subsequent effects on ROM and performance.

Static stretch intensity mechanisms

High intensity (POD) stretch-induced stress might have a detrimental effect on neuromuscular activation (Avela et al. 1999; Behm et al. 2001; Power et al. 2004). Avela et al. (1999) reported that following 1 h of passive stretching of the triceps surae there were significant decreases in MVC (23.2%), EMG (19.9%), and H-reflex (43.8%). Guissard et al. (2001) stretched the ankle joint to 10° and 20° of dorsiflexion and reported that the attenuation of reflex responses with small stretching amplitudes were mainly attributed to pre-motoneuronal or pre-synaptic mechanisms whereas large amplitude stretch-induced motoneuron excitation decreases were dominated by post-synaptic mechanisms. In an earlier article by the same laboratory (Guissard et al. 1988), the static stretch-induced decrease in H-reflex recovered quickly and was only limited to the duration of the stretch. It has been suggested that the decrease in the excitation of the motoneuron pool resulted from a reduction in excitatory drive from the Ia afferents onto the alpha motoneurons, possibly due to decreased resting discharge of the muscle spindles via increased compliance of the MTU (Avela et al. 1999). Less responsive muscle spindles could result in a reduction in the number of muscle fibers that are subsequently activated (Beedle et al. 2008; Cramer et al. 2004). Moreover, it is suggested that to compensate for the decrease in force production, a greater activation/stimulation rate was required, and this in turn resulted in a faster rate of neural fatigue. Further inhibitory influences on the motoneuron could arise from types III (mechanoreceptor) and IV (nociceptor) afferents (Fowles et al. 2000). However, this decreased excitation is more prevalent during the stretch and recovers immediately after the stretch (Fowles et al. 2000; Guissard et al. 2001). Beyond neuromuscular effects, higher intensity stretching has also been shown to impair blood flow through a muscle during the stretch (Nelson et al. 2005a). Hence, performance could also be affected by changes in blood circulation to the muscle."

Effect of study population

Previous studies cited in this review have demonstrated that greater durations and maximum intensity (POD) static stretching may contribute to stretch-induced impairments. Both factors suggest that the muscle has been placed under unaccustomed stress that may have led to deleterious changes in the muscle or neuromuscular system. It may be possible that the stretch-induced impairments reported in the literature are a training-specific phenomenon. Some authors have suggested that trained athletes might be less susceptible to the stretching-induced deficits than untrained (Egan et al. 2006; Unick et al. 2005). Would a greater ROM or training to increase ROM minimize stretch-induced deficits since the stress of stretching would not be as much of an unaccustomed stress? A more flexible (greater ROM) MTU or an MTU that is more tolerant of stretch tension might accommodate the stresses associated with an acute bout of stretching more successfully than a stiff MTU. A decrease in muscle stiffness has been reported following stretch training (Guissard and Duchateau 2004). In contrast, Magnusson et al. (1996c) reported no significant differences in stiffness, energy or peak torque around the knee joint after 3 weeks of stretch training. These authors suggested that the increased ROM achieved with training could be a consequence of an increased stretch tolerance. Regardless of the mechanisms, there have been conflicting studies using cross-sectional studies with elite athletes. Whereas studies using NCAA Division I female basketball players (Egan et al. 2006), and Division II female volleyball players (Dalrymple et al. 2010) reported no static-stretch-induced effect on subsequent peak torque or power and jumps respectively, another American study employing Louisiana University track and field athletes reported decreased sprint times following static stretching (Winchester et al. 2008). In addition, actively trained American college-aged women did not experience any significant impairment in vertical jump (Unick et al. 2005) following static or ballistic stretching. A group of elite Tunisian athletes demonstrated no deleterious effects from sequencing static, dynamic stretches and different intensities of stretch (eight combinations) on sprint, agility and jump performance (Chaouachi et al. 2010). Little and Williams (2006) reported no effect of static stretching on sprint times of highly trained male professional soccer players. It is difficult to compare these studies as a variety of stretch durations were utilized (45 s to >2 min per muscle group), as well there could be a gender effect affecting the variability in the results. Figure 6 illustrates the results from 99 studies that involved a static stretching intervention and measured either force or jump height. Statistical analysis conducted between the groups indicated the lack of significant difference between the groups of trained versus untrained studies.

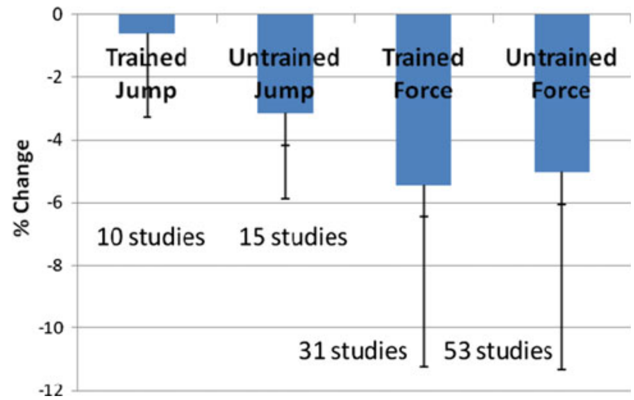

Fig. 6 Studies using trained and untrained subjects that report the effect of static stretching on force and jump performance

Fewer studies have examined subjects beyond the typical university age. A study examining trained and active middle aged adults reported no significant stretch-induced impairments in broad jump, single, triple, crossover and 6 m timed hop performances (Handrakis et al. 2010). Static stretching actually improved dynamic balance (Handrakis et al. 2010). The lack of impairments and balance enhancement occurred even though participants were subjected to four stretches with three repetitions of 30 s each (90 s total for each muscle) which in the majority of studies using younger populations results in deficits. It could be argued that since middle aged individuals tend to contract slower and have longer ground contact periods with SSC activities that a more compliant or flexible muscle would be advantageous, as it could store elastic energy for longer periods (Bosco et al. 1982b; Cavagna et al. 1968; Komi and Bosco 1978). Young elite athletes need nearly immediate transfer of elastic energy due to their shorter contact periods with SSC activities. In opposition to this age-related theory, older untrained women (mean 64.6 years ± 7.1) did experience MVC strength deficits following three repetitions of 30-s static stretches (Gurjao et al. 2009). Perhaps, the relatively trained or active middle aged martial artists in the Handrakis study (2010) had sufficient musculotendinous strength such that the stretching was not particularly stressful as compared to the older women (Gurjao et al. 2009) and with their relatively slower age-related movement times could capitalize on the longer storage and transfer time of a more compliant MTU. Because this review has illustrated more consistent stretch-induced deficits with force/strength and jump measures when compared with sprint or run measures (Figs. 1, 2, 3), the performance measures may have been a factor with the difference in the results.

Behm et al. (2006) compared individuals with a greater ROM to those with less flexibility hypothesizing that those with more flexibility would experience less strain from an acute bout of static stretching. However, in their cross-sectional correlation study, they showed that there was no relationship between ROM around hip and ankles with stretch-induced deficits (3 stretches with 3 repetitions of 30 s each at POD) in force and jump height. However, cross-sectional studies are fraught with variability difficulties, so training studies may give a clearer indication of the effects of flexibility training on static stretch-induced deficits.

In a 6-week longitudinal training study of 13–15-year-old youth, stretch and sprint-trained participants were more resistant to stretch-induced sprint deficits than the sprint only group. However, both groups still experienced acute static stretch-induced impairments with only two stretches of 20 s each for each lower body muscle group (Chaouachi et al. 2008). Another flexibility (static stretching) training study of 5 weeks duration utilizing recreationally active participants demonstrated post-training gains in sit and reach, hip flexion and extension ROM of 12–20%, but trained subjects still experienced deficits of 6–8% in knee extension and flexion MVC and 6% in countermovement jump following an acute session of static stretching using three stretches with three repetitions of 30 s each at POD (Behm et al. 2006). Hence, there is no consensus from the literature indicating an effect of training on the resistance to static stretch-induced deficits in performance.

Effect of the combination of static stretching with dynamic activities

As mentioned in the introduction, the traditional warm-up was a three-step process involving an aerobic warm-up, static stretching followed by dynamic skill rehearsal activities. Many of the static stretching studies although have studied static stretching in isolation. However, even when combined with a prior aerobic warm up (Behm et al. 2001; Behm and Kibele 2007; Ce et al. 2008; Fletcher and Anness 2007; Holt and Lambourne 2008; Power et al. 2004; Vetter 2007), dynamic warm up (Wallmann et al. 2008; Winchester et al. 2008) or post-stretch skill rehearsal (Young and Behm 2003), static stretching has still exerted negative influences upon subsequent performance. Chaouachi et al. (2008) concocted a sequencing study implementing eight stretch protocols that included (1) static stretch (SS) to point of discomfort (POD), (2) SS less than POD (SS < POD), (3) dynamic stretching (DS), (4) SS POD combined with DS, (5) SS < POD combined with DS, (6) DS combined with SS POD, (8) DS combined with SS < POD and (9) a control warm up condition. There were no significant effects on sprint, agility and jump performance. However, the subjects were elite or professional athletes which may have played a role in the non-significant outcomes. Similarly Gelen (2010) combined static and dynamic stretching with a prior aerobic warm-up and found no adverse effects upon sprint time, soccer dribbling ability or soccer penalty kick distance. The lack of impairments in these two studies may be related to the data from Fig. 3 which illustrated that sprint performance was not as strongly affected by prior static stretching. Young (2007) in a review paper suggests that if a moderate volume of static stretching is performed between the general and specific components of the warm-up, it has a limited impact on subsequent performance.

Hence, while there may be mitigating factors, such as types of contractions or actions, duration, intensity of stretching and population, static stretching should be used expeditiously during a warm-up to prevent the possibility of performance deficits. If the objective is to achieve chronic improvements in ROM, then static stretching should be instituted as a separate training program as its inclusion in the warm-up may be counterproductive to the ensuing performance. If the objective is acute improvements in ROM then dynamic stretching activities may provide a suitable alternative to static stretching within the warm-up. Research investigating dynamic stretching protocols may provide us with evidence for the appropriate warm-up stretching activity.

Dynamic stretching

Dynamic stretching that involves controlled movement through the active range of motion for a joint (Fletcher 2010) show either facilitation of power (Manoel et al. 2008; Yamaguchi et al. 2008) sprint (Fletcher and Anness 2007; Little and Williams 2006) and jump (Holt and Lambourne 2008; Hough et al. 2009; Jaggers et al. 2008; Pearce et al. 2009) performance or no adverse effect (Christensen and Nordstrom 2008; Samuel et al. 2008; Torres et al. 2008; Unick et al. 2005). In the context of dynamic stretching, the literature tends to indicate that shorter durations of dynamic stretching do not adversely affect performance (Table 5), and longer duration of dynamic stretches may facilitate performances (Fig. 7) (Hough et al. 2009; Pearce et al. 2009; Yamaguchi et al. 2008). An ANOVA comparing percentage changes in dynamic stretching studies (studies from Fig. 7) involving force and isokinetic power demonstrates significant ($p = 0.006$) performance enhancements with more (7.3% ± 5.3) compared with less (0.5% ± 2.3) than 90 s of dynamic stretching (Bacurau et al. 2009; Beedle et al. 2008; Bradley et al. 2007; Christensen and Nordstrom 2008; Gelen 2010; Jaggers et al. 2008; Papadopoulos et al.

Table 5 Effect of short term dynamic stretching on performance

References	*n*	Stretch duration per muscle	Stretch intensity	Effect and percentage change	Effect size
Bacurau et al. (2009)	14	20 min of ballistic stretching	NR	No effect on 1 RM leg press 11.7% ↑	0.74
Beedle et al. (2008)	19	3 reps of 15 s bench press-men	<POD	No effect on 1 RM 0.8% ↑	0.04
		3 reps of 15 s leg press-men	<POD	0.7% ↑	0.03
Beedle et al. (2008)	32	3 reps of 15 s bench press-women	<POD	No effect on 1 RM 0.4% ↑	0.03
		3 reps of 15 s leg press-women	<POD	0.9% ↑	0.05
Bradley et al. (2007)	18	4 reps of 5 stretches × 5 s hold × 25 s bob	NR	No effect of on VJ	NA
Christensen and Nordstrom (2008)	68	8 exercises × 5 reps	NR	No effect of on VJ 0.1% ↑	0.005
Gelen (2010)	26	12 exercises × 2 reps × 15 m-sprint Dribbling, penalty kick	NR	Sprint 4.1% ↑	0.95
				Slalom soccer dribbling 5.1% ↑	1.20
				Penalty kick 3.3%	1.25
Jaggers et al. (2008)	20	2 sets × 15 reps of 5 stretches	NR	No effect on jump height 4.4%	0.17
				Force 3.8% ↑	1.53
				Power 4.1% ↑	0.13
Papadopoulos et al. (2005)		6 repetitions of 30 s	NR	No effect on isokinetic torque	NA
Samuel et al. (2008)	24	2 repetitions × 30 s ballistic	<POD	No effect on VJ or torque	NA
Sekir et al. (2009)	10	6 min of dynamic stretching, ballistic	NR	↑ concentric torque output of quadriceps (8.4%) hamstrings (6.8%) and eccentric torque output of quadriceps (14.5%) and hamstrings (14.1%)	1.12 1.11 4.50 4.11
Torres et al. (2008)	11	7 exercises × 30 reps—force	NR	No effect on upper body strength 3.6% ↑ (force), 0.1% ↑ (power)	0.30
		7 exercises × 30 reps—power	NR		0.01
Unick et al. (2005)	16	4 exercises × 3 repetitions × 15 s × 24 s bob—ballistic	NR	No effect of on VJ—initial 0.9% ↑	0.06
				15 min 0.12% ↑	0.01
		Mean		4.1% ↑—ES = large magnitude	0.87

NR not reported, *NA* not available

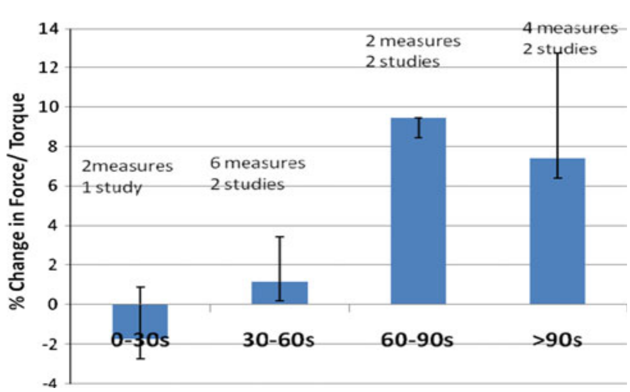

Fig. 7 The effect of dynamic stretching duration on force/torque and power production from 241 participants. Measures of force and power in these studies included isometric force and torque, isokinetic power, and one repetition maximum lifts such as squats and bench press. *Columns* represent mean percentage changes with standard deviation *bars*. Mean values may include multiple measures from a single study (e.g. 4 force or torque measures from two studies)

2005; Samuel et al. 2008; Sekir et al. 2009; Torres et al. 2008; Unick et al. 2005).

It appears that dynamic stretching is preferable to static stretching as part of a warm-up designed to prepare for physical activity due to the close similarity to movements that occur during subsequent exercises (Torres et al. 2008). 10 min of dynamic warm-up activities (stretching or aerobic activity) have been reported to result in improvements in shuttle run time, medicine ball throw distance and five step jump distance (McMillian et al. 2006), as well as a tendency ($p = 0.06$) for increased jump height (Curry et al. 2009). Hough et al. (2009) instituted 7 min of dynamic stretching resulting in increased vertical jump height and EMG activity. Furthermore, there have also been studies with shorter durations of dynamic stretching that demonstrated facilitation of performance. Herda et al. (2008) used four sets of three dynamic stretches of 30 s each and found increased EMG and mechanomyogram activity. Similarly, Manoel et al. (2008) reported improved knee extensor power at 60° and 180° s^{-1} with three repetitions of 30-s dynamic stretches. Another factor to consider is the intensity of the dynamic stretching. Dynamic stretch studies are inconsistent in their description of stretch intensity making it difficult to compare between studies. Although some studies do not report the intensity (e.g. frequency, range of motion) (Dalrymple et al. 2010; Manoel et al. 2008), others control the dynamic stretch intensity by reporting the frequency of movement (Bacurau et al. 2009; Fletcher 2010; Mohammadtaghi et al. 2010). Herman and Smith (2008) as another example used a combination of dynamic activities and stretches and indicated that they were performed at a slow to moderate cadence, but this was not precisely defined. A further complication is the definition or difference between dynamic activities and dynamic stretches. Further studies are needed to determine whether there is an advantage to perform warm-up activities that move the joint dynamically through a ROM or are dynamic activities through a partial ROM similarly effective?

Dynamic stretching activities at 100 beats/min resulted in significantly greater countermovement jump (CMJ) and drop jump heights than dynamic stretching activities using 50 beats/min (Fletcher 2010). Even the lower frequency dynamic stretching (50 beats/min) showed significantly greater performances in the jumps than the no stretch condition (Fletcher 2010). Although there is no clear distinction regarding the duration of dynamic stretching needed to enhance performance, there is clarity that dynamic stretching does not impair performance. As some studies have indicated that dynamic stretching provides similar acute increases in static flexibility as static stretching (Beedle and Mann 2007; Herman and Smith 2008) the use of dynamic rather than static stretching for the warm-up would tend to be a more judicious choice.

The mechanisms by which dynamic stretching improves muscular performance have been suggested to be elevated muscle and body temperature (Fletcher and Jones 2004), post-activation potentiation in the stretched muscle caused by voluntary contractions of the antagonist (Hough et al. 2009; Torres et al. 2008), stimulation of the nervous system, and/or decreased inhibition of antagonist muscles (Jaggers et al. 2008; Yamaguchi and Ishii 2005). As a result of these effects, dynamic stretching may enhance force and power development (Hough et al. 2009; Torres et al. 2008; Yamaguchi and Ishii 2005). Indeed, Faigenbaum et al. (2005) and Yamaguchi and Ishii (2005) hypothesized that the increases in force output after dynamic stretching are caused by an enhancement of neuromuscular function, and they implied that the dynamic stretching had a post-activation potentiation effect on performance via an increase the rate of cross-bridge attachments (Houston and Grange 1990). Consequently, it allows a greater number of cross-bridges to form, and resulting in an increase in force production (Behm 2004). However, Herda et al. (2008) reported that dynamic stretching did not improve muscular strength, although electromyographic amplitude increased, which may reflect a potentiating effect of the dynamic stretching on muscle activation. As the mechanisms of static and dynamic stretching are not the primary focus of this review, readers would be encouraged to read further material on this topic (Guissard and Duchateau 2006; Magnusson 1998).

Limitations

When assessing the literature, it is sometimes difficult to make comparisons between studies. In summary, some of the factors that may interfere with the interpretation of a body of literature may be related to gender issues (far fewer female subjects), the lack of randomization, and tester blinding, inter-tester reliability and hydration status of subjects. In addition, comparing uniarticular (i.e. dorsiflexion) tests of ROM to multiarticular (i.e. sit and reach) where various muscle groups can have differing levels of flexibility (i.e. lower back vs. hamstrings) can obscure comparisons. Furthermore, not all jumping activities involve similar range and speed of movement. Although squat jumps and drop jumps are both jumps, they differ dramatically in the SSC characteristics and may be affected differently by stretching. Testing immediately after a stretching routine or performing static stretching in isolation without aerobic-type exercise does not specifically mimic the typical warm-up routine of athletes. As mentioned previously, using subjective perceptions of stretch intensity leads to difficulty in ascertaining the effect of stretch intensity on performance. The difference between dynamic stretches and dynamic activities is not well defined in many studies and thus it is not known if it is necessary to move the joint through a full range of motion with dynamic activities to achieve significant increases in ROM. However, even with these limitations, the review of over 150 articles should still allow for some general interpretations and recommendations.

Conclusions and recommendations

Although there is strong evidence regarding the deleterious effects of static stretching prior to performance, the studies reporting no impairments or facilitation highlight possible mitigating factors. Static stretch-induced changes in muscle compliance which can affect the length–tension relationship of the muscle manifests its negative effects consistently and significantly with strength measures, especially when expressed with isometric contractions. Static stretching may not affect or possibly augment performance with dynamic SSC activities or contractions that involve a longer period for the storage of elastic energy. Submaximal speed running with longer SSC, relatively long contact times when jumping or hopping, application of forces over more prolonged periods as, for example, with a shot put or discus and eccentric contractions may not be adversely affected by prior static stretching. Furthermore, shorter durations of stretching within a warm-up, such as a total stretching duration per muscle of <30 s may not negatively impact subsequent performance especially if the population is more highly trained. However, it would be wise to be cautious when implementing static stretching of any duration or for any population when high-speed, rapid SSC, explosive or reactive forces are necessary, particularly if any decreases in performance, however small, would be important. For these types of movements, the neuromuscular system should be primed with activities that excite the system. According to the literature, dynamic stretches and activities will either have no detrimental effect or may augment performance. Longer durations of dynamic stretching and activity seem to provide a positive response to the neuromuscular system enhancing performance. The optimal warm-up should be composed of a submaximal intensity aerobic activity followed by large amplitude dynamic stretching and then completed with sport specific dynamic activities. As static stretching can still increase ROM, it still plays an important role for health-related benefits associated with flexibility and particular sports or activities that necessitate a great increase in static ROM relative to the flexibility of the athlete or patient. However, static stretching should normally not be pursued prior to strength, high speed, explosive or reactive activities. All individuals should include static stretching in their overall fitness and wellness activities for the health and functional benefits associated with increased ROM and musculotendinous compliance. However, a separate static stretch training workout time or during post-exercise cool-down should be planned independent of other training workouts or competitions to achieve a more permanent change in flexibility for health or performance.

Acknowledgments This research was partially funded by the Natural Science and Engineering Research Council (NSERC) of Canada.

References

Alter MJ (1996) Science of flexibility. Human Kinetics Publishers, Champaign

Avela J, Kyröläinen H, Komi PV (1999) Altered reflex sensitivity after repeated and prolonged passive muscle stretching. J Appl Physiol 86:1283–1291

Avela J, Finni T, Liikavainio T, Niemela E, Komi PV (2004) Neural and mechanical responses of the triceps surae muscle group after 1 h of repeated fast passive stretches. J Appl Physiol 96:2325–2332

Bacurau RF, Monteiro GA, Ugrinowitsch C, Tricoli V, Cabral LF, Aoki MS (2009) Acute effect of a ballistic and a static stretching exercise bout on flexibility and maximal strength. J Strength Cond Res 23:304–308

Bandy WD, Irion JM, Briggler M (1997) The effect of time and frequency of static stretching on flexibility of the hamstring muscles. Phys Ther 77:1090–1096

Bandy WD, Irion JM, Briggler M (1998) The effect of static stretch and dynamic range of motion training on the flexibility of the hamstring muscles. J Orthop Sports Phys Ther 27:295–300

Bauman CL, Knapik JJ, Jones BH, Harris JM, Vaughan (1982) An approach to musculoskeletal profiling of women in sports. In: Cantu IR, Gillesoie W (eds) Sports medicine, sports science: bridging the gap. Health Publications, Lexington, MA, pp 61–72

Beckett JR, Schneiker KT, Wallman KE, Dawson BT, Guelfi KJ (2009) Effects of static stretching on repeated sprint and change of direction performance. Med Sci Sports Exerc 41:444–450

Beedle BB, Mann CL (2007) A comparison of two warm-ups on joint range of motion. J Strength Cond Res 21:776–779

Beedle B, Rytter SJ, Healy RC, Ward TR (2008) Pretesting static and dynamic stretching does not affect maximal strength. J Strength Cond Res 22:1838–1843

Behm DG (2004) Force maintenance with submaximal fatiguing contractions. Can J Appl Physiol 29:274–290

Behm DG, Kibele A (2007) Effects of differing intensities of static stretching on jump performance. Eur J Appl Physiol 101:587–594

Behm DG, Button DC, Butt JC (2001) Factors affecting force loss with prolonged stretching. Can J Appl Physiol 26:261–272

Behm DG, Bambury A, Cahill F, Power K (2004) Effect of acute static stretching on force, balance, reaction time, and movement time. Med Sci Sports Exerc 36:1397–1402

Behm DG, Bradbury EE, Haynes AT, Hodder JN, Leonard AM, Paddock NR (2006) Flexibility is not related to stretch-induced deficits in force or power. J Sports Sci Med 5:33–42

Bishop D (2003) Warm up I: potential mechanisms and the effects of passive warm up on exercise performance. Sports Med 33:439–454

Bosco C, Tarkka I, Komi PV (1982a) Effect of elastic energy and myoelectrical potentiation of triceps surae during stretch-shortening cycle exercise. Int J Sports Med 3:137–140

Bosco C, Tihanyi J, Komi PV, Fekete G, Apor P (1982b) Store and recoil of elastic energy in slow and fast types of human skeletal muscles. Acta Physiol Scand 116:343–349

Bradley PS, Olsen PD, Portas MD (2007) The effect of static, ballistic, and proprioceptive neuromuscular facilitation stretching on vertical jump performance. J Strength Cond Res 21:223–226

Brandenburg JP (2006) Duration of stretch does not influence the degree of force loss following static stretching. J Sports Med Phys Fitness 46:526–534

Campbell DT, Stanley JC (1966) Experimental and quasi-experimental designs for research, 2nd edn. Oxford Press, London, pp 46–112

Cavagna GA, Dusman B, Margaria R (1968) Positive work done by a previously stretched muscle. J Appl Physiol 24:21–32

Ce E, Margonato V, Casasco M, Veicsteinas A (2008) Effects of stretching on maximal anaerobic power: the roles of active and passive warm-ups. J Strength Cond Res 22:794–800

Chaouachi A, Chamari K, Wong P, Castagna C, Chaouachi M, Moussa-Chamari I, Behm DG (2008) Stretch and sprint training reduces stretch-induced sprint performance deficits in 13- to 15-year-old youth. Eur J Appl Physiol 104:513–523

Chaouachi A, Castagna C, Chtara M, Brughelli M, Turki O, Galy O, Chamari K, Behm DG (2010) Effect of warm-ups involving static or dynamic stretching on agility, sprinting, and jumping performance in trained individuals. J Strength Cond Res 24:2001–2011

Chelly SM, Denis C (2001) Leg power and hopping stiffness: relationship with sprint running performance. Med Sci Sports Exerc 33:326–333

Christensen BK, Nordstrom BJ (2008) The effects of proprioceptive neuromuscular facilitation and dynamic stretching techniques on vertical jump performance. J Strength Cond Res 22:1826–1831

Cohen J (1988) Statistical power analysis for the behavioural sciences. L. Erbaum Associates, Hillside, pp 14–68

Cornwell A, Nelson A, Sidaway B (2002) Acute effects of stretching on the neuromechanical properties of the triceps surae muscle complex. Eur J Appl Physiol 86:428–434

Costa PB, Ryan ED, Herda TJ, Walter AA, Hoge KM, Cramer JT (2010) Acute effects of passive stretching on the electromechanical delay and evoked twitch properties. Eur J Appl Physiol 108:301–310

Covert CA, Alexander MP, Petronis JJ, Davis DS (2010) Comparison of ballistic and static stretching on hamstring muscle length using an equal stretching dose. J Strength Cond Res 24(11): 3008–3014. doi:10.1519/JSC.0b013e3181bf3bb0

Cowan D, Jones B, Tomlinson P, Robinson J, Polly D (1988) The epidemiology of physical training injuries in US infantry trainees: methodology, population, and risk factors. US Army Research Institute of Environmental Medicine Technology NO:T4-89

Cramer JT, Housh TJ, Johnson GO, Miller JM, Coburn JW, Beck TW (2004) Acute effects of static stretching on peak torque in women. J Strength Cond Res 18:236–241

Cramer JT, Housh TJ, Weir JP, Johnson GO, Coburn JW, Beck TW (2005) The acute effects of static stretching on peak torque, mean power output, electromyography, and mechanomyography. Eur J Appl Physiol 93:530–539

Cramer JT, Housh TJ, Coburn JW, Beck TW, Johnson GO (2006) Acute effects of static stretching on maximal eccentric torque production in women. J Strength Cond Res 20:354–358

Cramer JT, Beck TW, Housh TJ, Massey LL, Marek SM, Danglemeier S, Purkayastha S, Culbertson JY, Fitz KA, Egan AD (2007a) Acute effects of static stretching on characteristics of the isokinetic angle–torque relationship, surface electromyography, and mechanomyography. J Sports Sci 25:687–698

Cramer JT, Housh TJ, Johnson GO, Weir JP, Beck TW, Coburn JW (2007b) An acute bout of static stretching does not affect maximal eccentric isokinetic peak torque, the joint angle at peak torque, mean power, electromyography, or mechanomyography. J Orthop Sports Phys Ther 37:130–139

Curry BS, Chengkalath D, Crouch GJ, Romance M, Manns PJ (2009) Acute effects of dynamic stretching, static stretching, and light aerobic activity on muscular performance in women. J Strength Cond Res 23:1811–1819

Dalrymple KJ, Davis SE, Dwyer GB, Moir GL (2010) Effect of static and dynamic stretching on vertical jump performance in collegiate women volleyball players. J Strength Cond Res 24:149–155

Dintiman G, Ward B (2003) Sport speed, 3rd edn. Human Kinetics, Windsor, pp 34–108

Ebben WP, Blackard DO (2001) Strength and conditioning practices of National Football League strength and conditioning coaches. J Strength Cond Res 15:48–58

Ebben WP, Carroll RM, Simenz CJ (2004) Strength and conditioning practices of National Hockey League strength and conditioning coaches. J Strength Cond Res 18:889–897

Ebben WP, Hintz MJ, Simenz CJ (2005) Strength and conditioning practices of Major League Baseball strength and conditioning coaches. J Strength Cond Res 19:538–546

Edman KAP, Elzinga G, Noble MIM (1978) Enhancement of mechanical performance by stretch during tetanic contractions of vertebrate skeletal muscle fibres. J Physiol 281:139–155

Egan AD, Cramer JT, Massey LL, Marek SM (2006) Acute effects of static stretching on peak torque and mean power output in National Collegiate Athletic Association Division I women's basketball players. J Strength Cond Res 20:778–782

Faigenbaum AD, Bellucci M, Bernieri A, Bakker B, Hoorens K (2005) Acute effects of different warm-up protocols on fitness performance in children. J Strength Cond Res 19:376–381

Farley CT, Morgenroth DC (1999) Leg stiffness primarily depends on ankle stiffness during human hopping. J Biomech 32:267–273

Fletcher IM (2010) The effect of different dynamic stretch velocities on jump performance. Eur J Appl Physiol 109:491–498

Fletcher IM, Anness R (2007) The acute effects of combined static and dynamic stretch protocols on fifty-meter sprint performance in track-and-field athletes. J Strength Cond Res 21:784–787

Fletcher IM, Jones B (2004) The effect of different warm-up stretch protocols on 20 meter sprint performance in trained rugby union players. J Strength Cond Res 18:885–888

Fletcher IM, Monte-Colombo MM (2010) An investigation into the possible physiological mechanisms associated with changes in performance related to acute responses to different preactivity stretch modalities. Appl Physiol Nutr Metab 35:27–34

Fowles JR, Sale DG, MacDougall JD (2000) Reduced strength after passive stretch of the human plantar flexors. J Appl Physiol 89:1179–1188

Franco BL, Signorelli GR, Trajano GS, de Oliveira CG (2008) Acute effects of different stretching exercises on muscular endurance. J Strength Cond Res 22:1832–1837

Garcia-Lopez D, Izquierdo M, Rodriguez S, Gonzalez-Calvo G, Sainz N, Abadia O, Herrero AJ (2010) Interest stretching does not influence the kinematic profile of consecutive bench-press sets. J Strength Cond Res 24:1361–1368

Gelen E (2010) Acute effects of different warm-up methods on sprint, slalom dribbling, and penalty kick performance in soccer players. J Strength Cond Res 24:950–956

Gleim G, McHugh MP (1997) Flexibility and its effects on sports injury and performance. Sports Med 24:289–297

Gleim GW, Stachenfeld NS, Nicholas JA (1990) The influence of flexibility on the economy of walking and jogging. J Orthop Res 8:814–823

Godges JJ, MacRae H, Longdon C, Tinberg C (1989) The effects of two stretching procedures on the economy of walking and jogging. J Orthop Sport Phys Ther 7:350–357

Gonzalez-Rave JM, Machado L, Navarro-Valdivielso F, Vilas-Boas JP (2009) Acute effects of heavy-load exercises, stretching exercises, and heavy-load plus stretching exercises on squat jump and countermovement jump performance. J Strength Cond Res 23:472–479

Guissard N, Duchateau J (2004) Effect of static stretch training on neural and mechanical properties of the human plantar-flexor muscles. Muscle Nerve 29:248–255

Guissard N, Duchateau J (2006) Neural aspects of muscle stretching. Exerc Sport Sci Rev 34:154–158

Guissard N, Duchateau J, Hainaut K (1988) Muscle stretching and motoneuron excitability. Eur J Appl Physiol 58:47–52

Guissard N, Duchateau J, Hainaut K (2001) Mechanisms of decreased motoneurone excitation during passive muscle stretching. Exp Brain Res 137:163–169

Gurjao AL, Goncalves R, de Moura RF, Gobbi S (2009) Acute effect of static stretching on rate of force development and maximal

voluntary contraction in older women. J Strength Cond Res 23:2149–2154
Haag SJ, Wright GA, Gillette CM, Greany JF (2010) Effects of acute static stretching of the throwing shoulder on pitching performance of national collegiate athletic association division III baseball players. J Strength Cond Res 24:452–457
Handrakis JP, Southard VN, Abreu JM, Aloisa M, Doyen MR, Echevarria LM, Hwang H, Samuels C, Venegas SA, Douris PC (2010) Static stretching does not impair performance in active middle-aged adults. J Strength Cond Res 24:825–830
Hayes PR, Walker A (2007) Pre-exercise stretching does not impact upon running economy. J Strength Cond Res 21:1227–1232
Herbert RD, Gabriel M (2002) Effects of stretching before and after exercising on muscle soreness and risk of injury: systematic review. BMJ 325:468–472
Herda TJ, Cramer JT, Ryan ED, McHugh MP, Stout JR (2008) Acute effects of static versus dynamic stretching on isometric peak torque, electromyography, and mechanomyography of the biceps femoris muscle. J Strength Cond Res 22:809–817
Herda TJ, Ryan ED, Costa PB, Walter AA, Hoge KM, Uribe BP, Mclagan JR, Stout JR, Cramer JT (2010) Acute effects of passive stretching and vibration on the elctromechanical delay and musculotendinous stiffness of the plantar flexors. Electromyogr Clin Neurophysiol 50:137–148
Herman SL, Smith DT (2008) Four-week dynamic stretching warm-up intervention elicits longer-term performance benefits. J Strength Cond Res 22:1286–1297
High DM, Howley ET, Franks BD (1989) The effects of static stretching and warm-up on prevention of delayed-onset muscle soreness. Res Quart Exerc Sport 60:357–361
Holt BW, Lambourne K (2008) The impact of different warm-up protocols on vertical jump performance in male collegiate athletes. J Strength Cond Res 22:226–229
Hough PA, Ross EZ, Howatson G (2009) Effects of dynamic and static stretching on vertical jump performance and electromyographic activity. J Strength Cond Res 23:507–512
Houston ME, Grange RW (1990) Myosin phosphorylation, twitch potentiation, and fatigue in human skeletal muscle. Can J Physiol Pharm 68:908–913
Jaggers JR, Swank AM, Frost KL, Lee CD (2008) The acute effects of dynamic and ballistic stretching on vertical jump height, force, and power. J Strength Cond Res 22:1844–1849
Jones AM (2002) Running economy is negatively related to sit-and-reach test performance in international-standard distance runners. Int J Sport Med 23:40–43
Kawakami Y, Kubo K, Kanehisa H, Fukunaga T (2002) Effect of series elasticity on isokinetic torque-angle relationship in humans. Eur J Appl Physiol 87:381–387
Knudson D, Noffal G (2005) Time course of stretch-induced isometric strength deficits. Eur J Appl Physiol 94:348–351
Knudson D, Bennett K, Corn R, Leick D, Smith C (2001) Acute effects of stretching are not evident in the kinematics of the vertical jump. J Strength Cond Res 15:98–101
Knudson DV, Noffal GJ, Bahamonde RE, Bauer JA, Blackwell JR (2004) Stretching has no effect on tennis serve performance. J Strength Cond Res 18:654–656
Kokkonen J, Nelson AG, Cornwell A (1998) Acute muscle stretching inhibits maximal strength performance. Res Quart Exerc Sport 69:411–415
Komi PV, Bosco C (1978) Utilization of stored elastic energy in leg extensor muscles by men and women. Med Sci Sports Exerc 10:261–265
Kuitunen S, Komi PV, Kyrolainen H (2002) Knee and ankle joint stiffness in sprint running. Med Sci Sports Exerc 34:166–173
Little T, Williams AG (2006) Effects of differential stretching protocols during warm-ups on high-speed motor capacities in professional soccer players. J Strength Cond Res 20:203–207
Magnusson SP (1998) Passive properties of human skeletal muscle during stretch maneuvers. A review. Scand J Med Sci Sports 8:65–77
Magnusson SP, Simonsen EB, Aagaard P, Gleim GW, McHugh MP, Kjaer M (1995) Viscoelastic response to repeated static stretching in the human hamstring muscle. Scand J Med Sci Sports 5:342–347
Magnusson SP, Simonsen EB, Aagaard P, Dyhre-Poulsen P, McHugh MP, Kjaer M (1996a) Mechanical and physical responses to stretching with and without preisometric contraction in human skeletal muscle. Arch Phys Med Rehabil 77:373–378
Magnusson SP, Simonsen EB, Aagaard P, Kjaer M (1996b) Biomechanical responses to repeated stretches in human hamstring muscle in vivo. Am J Sports Med 24:622–627
Magnusson SP, Simonsen EB, Aagaard P, Sorensen H, Kjaer M (1996c) A mechanism for altered flexibility in human skeletal muscle. J Physiol 497(Pt 1):291–298
Manoel ME, Harris-Love MO, Danoff JV, Miller TA (2008) Acute effects of static, dynamic, and proprioceptive neuromuscular facilitation stretching on muscle power in women. J Strength Cond Res 22:1528–1534
Marek SM, Cramer JT, Fincher AL, Massey LL, Dangelmaier SM, Purkayastha S, Fitz KA, Culbertson JY (2005) Acute effects of static and proprioceptive neuromuscular facilitation stretching on muscle strength and power output. J Athl Train 40:94–103
McHugh M, Magnusson S, Gleim G, Nicholas J (1992) Viscoelastic stress relaxation in human skeletal muscle. Med Sci Sport Exerc 24:1375–1382
McHugh MP, Kremenic IJ, Fox MB, Gleim GW (1998) The role of mechanical and neural restraints to joint range of motion during passive stretch. Med Sci Sports Exerc 30:928–932
McMillian DJ, Moore JH, Hatler BS, Taylor DC (2006) Dynamic vs. static-stretching warm up: the effect on power and agility performance. J Strength Cond Res 20:492–499
Mohammadtaghi AK, Sahebozamani M, Tabrizi KG, Yusof AB (2010) Acute effects of different stretching methods on Illinois agility test in soccer players. J Strength Cond Res 24:148–156
Molacek ZD, Conley DS, Evetovich TK, Hinnerichs KR (2010) Effects of low- and high-volume stretching on bench press performance in collegiate football players. J Strength Cond Res 24:711–716
Murphy JR, Di Santo MC, Alkanani T, Behm DG (2010) Activity before and following short duration static stretching improves range of motion vs. a traditional warm-up. Appl Physiol Nutr Metab 35:1–12
Nagano A, Yoshioka S, Hay DC, Himeno R, Fukashiro S (2006) Influence of vision and static stretch of the calf muscles on postural sway during quiet standing. Hum Mov Sci 25:422–434
Nelson A, Allen J, Cornwell A, Kokkonen J (2001a) Inhibition of maximal voluntary isometric torque production by acute stretching is joint-angle specific. Res Q Exerc Sport 72:68–70
Nelson AG, Guillory IK, Cornewell A, Kokkonen J (2001b) Inhibition of maximal voluntary isokinetic torque production following stretching is velocity-specific. J Strength Cond Res 15:241–246
Nelson AG, Kokkonen J, Arnall DA (2005a) Acute muscle stretching inhibits muscle strength endurance performance. J Strength Cond Res 19:338–343
Nelson AG, Kokkonen J, Eldredge C (2005b) Strength inhibition following an acute stretch is not limited to novice stretchers. Res Q Exerc Sport 76:500–506
Norris CM (1999) The complete guide to stretching, 1st edn. Human Kinetics Publishing, Windsor, pp 23–76

O'Sullivan K, Murray E, Sainsbury D (2009) The effect of warm-up, static stretching and dynamic stretching on hamstring flexibility in previously injured subjects. BMC Musculoskelet Disord 10:37–42

Ogura Y, Miyahara Y, Naito H, Katamoto S, Aoki J (2007) Duration of static stretching influences muscle force production in hamstring muscles. J Strength Cond Res 21:788–792

Papadopoulos G, Siatras T, Kellis S (2005) The effect of static and dynamic stretching exercises on the maximal isokinetic strength of the knee extensors and flexors. Isokinetics Exerc Sci 13:285–291

Pearce AJ, Kidgell DJ, Zois J, Carlson JS (2009) Effects of secondary warm up following stretching. Eur J Appl Physiol 105:175–183

Power K, Behm D, Cahill F, Carroll M, Young W (2004) An acute bout of static stretching: effects on force and jumping performance. Med Sci Sports Exerc 36:1389–1396

Rassier DE, MacIntosh BR, Herzog W (1999) Length dependence of active force production in skeletal muscle. J Appl Physiol 86:1445–1457

Robbins JW, Scheuermann BW (2008) Varying amounts of acute static stretching and its effect on vertical jump performance. J Strength Cond Res 22:781–786

Rosenbaum D, Hennig E (1995) The influence of stretching and warm-up exercises on achilles tendon reflex activity. J Sport Sci 13:481–490

Ryan ED, Beck TW, Herda TJ, Hull HR, Hartman MJ, Costa PB, Defreitas JM, Stout JR, Cramer JT (2008a) The time course of musculotendinous stiffness responses following different durations of passive stretching. J Orthop Sports Phys Ther 38:632–639

Ryan ED, Beck TW, Herda TJ, Hull HR, Hartman MJ, Stout JR, Cramer JT (2008b) Do practical durations of stretching alter muscle strength? A dose–response study. Med Sci Sports Exerc 40:1529–1537

Safran M, Seaber A, Garrett W (1989) Warm-up and muscular injury prevention: an update. Sports Med 8:239–249

Samogin Lopes FA, Menegon EM, Franchini E, Tricoli V, de MBR (2010) Is acute static stretching able to reduce the time to exhaustion at power output corresponding to maximal oxygen uptake? J Strength Cond Res 24:1650–1656

Samuel MN, Holcomb WR, Guadagnoli MA, Rubley MD, Wallmann H (2008) Acute effects of static and ballistic stretching on measures of strength and power. J Strength Cond Res 22:1422–1428

Sayers AL, Farley RS, Fuller DK, Jubenville CB, Caputo JL (2008) The effect of static stretching on phases of sprint performance in elite soccer players. J Strength Cond Res 22:1416–1421

Sekir U, Arabaci R, Akova B, Kadagan SM (2009) Acute effects of static and dynamic stretching on leg flexor and extensor isokinetic strength in elite women athletes. Scand J Med Sci Sports

Siatras T, Papadopoulos G, Mameletzi DN, Vasilios G, Kellis S (2003) Static and dynamic acute stretching effect on gymnasts' speed in vaulting. Ped Exerc Sci 15:383–391

Siatras TA, Mittas VP, Mameletzi DN, Vamvakoudis EA (2008) The duration of the inhibitory effects with static stretching on quadriceps peak torque production. J Strength Cond Res 22:40–46

Simenz CJ, Dugan CA, Ebben WP (2005) Strength and conditioning practices of National Basketball Association strength and conditioning coaches. J Strength Cond Res 19:495–504

Small K, Mc NL, Matthews M (2008) A systematic review into the efficacy of static stretching as part of a warm-up for the prevention of exercise-related injury. Res Sports Med 16:213–231

Smith C (1994) The warm-up procedure: to stretch or not to stretch: a brief review. J Orthop Sports Phys Ther 19:12–17

Torres R, Appell HJ, Duarte JA (2007) Acute effects of stretching on muscle stiffness after a bout of exhaustive eccentric exercise. Int J Sports Med 28:590–594

Torres EM, Kraemer WJ, Vingren JL, Volek JS, Hatfield DL, Spiering BA, Ho JY, Fragala MS, Thomas GA, Anderson JM, Hakkinen K, Maresh CM (2008) Effects of stretching on upper body muscular performance. J Strength Cond Res 22:1279–1285

Trehearn TL, Buresh RJ (2009) Sit-and-reach flexibility and running economy of men and women collegiate distance runners. J Strength Cond Res 23:158–162

Unick J, Kieffer HS, Cheesman W, Feeney A (2005) The acute effects of static and ballistic stretching on vertical jump performance in trained women. J Strength Cond Res 19:206–212

Vetter RE (2007) Effects of six warm-up protocols on sprint and jump performance. J Strength Cond Res 21:819–823

Wallman HW, Mercer JA, McWhorter JW (2005) Surface electromyographic assessment of the effect of static stretching of the gastrocnemius on vertical jump performance. J Strength Cond Res 19:684–688

Wallmann HW, Mercer JA, Landers MR (2008) Surface electromyographic assessment of the effect of dynamic activity and dynamic activity with static stretching of the gastrocnemius on vertical jump performance. J Strength Cond Res 22:787–793

Walshe AD, Wilson GJ (1997) The influence of musculotendinous stiffness on drop jump performance. Can J Appl Physiol 22:117–132

Weir DE, Tingley J, Elder GCB (2005) Acute passive stretching alters the mechanical properties of human plantar flexors and the optimal angle for maximal voluntary contraction. Eur J Appl Physiol 93:614–623

Wilson G, Wood G, Elliott B (1991) The relationship between stiffness of the musculature and static flexibility: an alternative explanation for the occurrence of muscular injury. Int J Sport Med 12:403–407

Wilson G, Elliot B, Wood G (1992) Stretching shorten cycle performance enhancement through flexibility training. Med Sci Sport Exerc 24:116–123

Wilson GJ, Murphy A, Pryor JF (1994) Musculotendinous stiffness: its relationship to eccentric, isometric and concentric performance. J Appl Physiol 76:2714–2719

Wilson JM, Hornbuckle LM, Kim JS, Ugrinowitsch C, Lee SR, Zourdos MC, Sommer B, Panton LB (2010) Effects of static stretching on energy cost and running endurance performance. J Strength Cond Res 24:2274–2279

Winchester JB, Nelson AG, Landin D, Young MA, Schexnayder IC (2008) Static stretching impairs sprint performance in collegiate track and field athletes. J Strength Cond Res 22:13–19

Winchester JB, Nelson AG, Kokkonen J (2009) A single 30-s stretch is sufficient to inhibit maximal voluntary strength. Res Q Exerc Sport 80:257–261

Winke MR, Jones NB, Berger CG, Yates JW (2010) Moderate static stretching and torque production of the knee flexors. J Strength Cond Res 24:706–710

Worrell T, Smith T, Winegardner J (1994) Effect of hamstring stretching on hamstring muscle performance. J Orthop Sports Physical Ther 20:154–159

Yamaguchi T, Ishii K (2005) Effects of static stretching for 30 seconds and dynamic stretching on leg extension power. J Strength Condit Res 19:677–683

Yamaguchi T, Ishii K, Yamanaka M, Yasuda K (2006) Acute effect of static stretching on power output during concentric dynamic constant external resistance leg extension. J Strength Cond Res 20:804–810

Yamaguchi T, Ishii K, Yamanaka M, Yasuda K (2008) Acute effects of dynamic stretching exercise on power output during concentric dynamic constant external resistance leg extension. J Strength Cond Res 21:1238–1244
Young WB (2007) The use of static stretching in warm-up for training and competition. Int J Sports Physiol Perform 2:212–216
Young W, Behm D (2002) Should static stretching be used during a warm-up for strength and power activities? Strength Cond J 24:33–37
Young WB, Behm DG (2003) Effects of running, static stretching and practice jumps on explosive force production and jumping performance. J Sports Med Phys Fitness 43:21–27
Young W, Elliott S (2001) Acute effects on static stretching, proprioceptive neuromuscular facilitation stretching, and maximum voluntary contractions on explosive force production and jumping performance. Res Q Exerc Sport 72:273–279
Young W, Elias G, Power J (2006) Effects of static stretching volume and intensity on plantar flexor explosive force production and range of motion. J Sport Med Phys Fitness 46:403–411
Zakas A (2005) The effect of stretching duration on the lower extremity flexibility of adolescent soccer players. J Bodywork Mov Ther 9:220–225
Zakas A, Doganis G, Papakonstandinou V, Sentelidis T, Vamvakoudis E (2006) Acute effects of static stretching duration on isokinetic peak torque production of soccer players. J Bodywork Mov Ther 10:89–95