Acute Effects of Practical Hamstring Stretching: Implications for Clinical Practice in the Sports Medicine Setting

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ABSTRACT

Single bouts of stretching can elicit acute transient decreases in strength known as the stretching-induced force deficit. This study examined the acute effects of practical stretching durations on hamstrings strength, work, and power. Forty men and women performed isokinetic leg flexion at 60° s^{-1} and 180° s^{-1} before and after 2 minutes of stretching. Four experimental groups included static, ballistic, and proprioceptive neuromuscular facilitation (PNF) stretching, and no stretching. Peak torque, peak torque-to-body weight ratio (PTBW), total work, and average power did not change after static or PNF for the men or women. Peak torque, PTBW, and total work decreased after ballistic stretching at 180° s^{-1} for the men, and average power increased after ballistic stretching at 180° s^{-1} for the women. Despite mixed results regarding ballistic stretching, practical durations (approximately 2 minutes) of static or PNF stretching for the hamstrings may be incorporated prior to performance events to prevent stretching-induced force deficit. [*Athletic Training & Sports Health Care.* 2014;6(2):59-66.]

For most physically active individuals, stretching has long been a standard part of warming up prior to athletic events or exercise.[1] Stretching has been recommended because it was thought that stretching increases joint range of motion[2] and decreases the risk of injury,[3] although the latter has been debated.[4] Muscle stretching before training and competition has been advocated as an effective injury-prevention strategy.[5-7] Poor flexibility has been highlighted as a risk factor for muscle strains[8] and, more specifically, has been suggested as a modifiable risk factor in the prevention of hamstring muscle injury.[9] Researchers believe that stretching can play a role in hamstring muscle strain prevention by improving force absorption for a given length of muscle, thereby making it more resistant to stretch injury.[10] Greater flexibility may reduce the risk of strain injury due to better compliance and ability of the passive components of the muscle–tendon unit to absorb energy.[11] This improved flexibility and compliance may reduce the incidence of hamstring muscle injuries.[8,11-15]

Over the past 15 years, many studies have examined the acute effects of stretching on performance,[16-34] and the general outcome of these studies was that a single bout of stretching elicits acute transient decreases in strength and power.[35] This observation has been termed the stretching-induced force deficit,[33] or, more broadly stated, the stretching-induced performance deficit. Subsequently, the perception and attitude toward stretching prior to performance-based activities has shifted. Preactivity stretching has been questioned and perhaps avoided due to stretching-induced performance deficits reported in high-quality, high-impact

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journal articles.[16,24,26,33] However, the clinical relevance and value of stretching cannot be discounted based solely on performance outcomes.

Because hamstring strains have been documented as the most common injury in the Australian Football League[36] (16.5% over the past 10 seasons) and the second most frequent injury in the National Football League preseason camps,[37] and because they account for 6% of injuries in intercollegiate basketball,[38] there is a need to identify best practices in the prevention of injury to this muscle group. Furthermore, when closely examining the stretching durations and "time-under-stretch" (ie, actual length of time a particular muscle is placed under a stretch condition) for the muscles being studied, the experimental stretching was so extensive that the results may not be practically or clinically significant. An early study by Fowles et al[26] is perhaps the most commonly cited study regarding the stretching-induced force deficit.[33] The authors applied 30 minutes of passive stretching for the plantar flexors and reported a 25% decrease in strength immediately after the stretching and that strength remained diminished by 8% to 12% at 60 minutes after stretching. The authors stated that this experiment simulated an intense maximal stretch far beyond what an athlete may attempt before activity or as part of a flexibility training program.[26]

More recent studies have reported a 10% decrease in strength after 20 minutes of stretching,[28] 7% decrease after 10 minutes of stretching,[39] and <4% nonsignificant decrease in strength after a warm-up and <4 minutes of stretching.[40,41] Ryan et al[33] recently addressed the question of dose-dependent decrements in strength after stretching. The authors concluded that practical durations of stretching of ≤8 minutes do not negatively impact plantar flexor strength, whereas 10 minutes of stretching may elicit strength deficits. However, Ryan et al[33] suggested that the dose-dependent effects of stretching may also be influenced by the muscle being stretched. It was hypothesized that larger proximal muscles (such as the leg flexors) may experience stretching-induced decreases in muscle activation more than smaller distal muscles (plantar flexors). Consequently, the leg flexors tested in the current study may be susceptible to stretching-induced force deficit, even after practical durations of stretching; however, this hypothesis has not been tested.

The mode of stretching, including static, proprioceptive neuromuscular facilitation (PNF), and ballistic stretching, may also be a factor in how a muscle group responds. Nelson and Kokkonen[31] showed that following a ballistic stretching session, the 1-repetition maximum for both leg flexion and leg extension was significantly less than that observed in the nonstretching control group. Marek et al[30] compared 8 minutes of static versus PNF stretching of the leg extensors and reported that both modes of stretching reduced quadriceps strength at slow ($60°·s^{-1}$) and fast ($300°·s^{-1}$) isokinetic velocities. The authors emphasized that the 3% reduction in strength observed after stretching was small and that rehabilitation professionals and clinicians should weigh the benefit of maintaining a functional range of motion to the potential risk of small transient decreases in strength. However, no previous studies have tested these hypotheses for potential reductions in leg flexor (hamstring) strength at slow and fast isokinetic velocities after practical durations of static, PNF, and ballistic stretching.

A combination of abnormalities in strength and flexibility has been reported as increasing the risk of hamstring strain.[42] The principle of hamstring injury prevention needs to address and integrate the evidence-based factors, including appropriate duration of stretching. The identification of appropriate and clinically practical stretching durations of the hamstrings represents one of the tenets for developing appropriate preventative measures. The outcomes of this study will allow clinicians to select appropriate stretches and durations of stretch to lessen the impact of force reduction after acute stretching programs. Therefore, this study was designed to examine the acute effects of practical durations (2 minutes) of static, PNF, or ballistic stretching on leg flexor (hamstrings) strength, work, and power output during slow ($60°·s^{-1}$) and fast ($180°·s^{-1}$) isokinetic velocities in men and women.

METHOD

Participants

Twenty healthy men (mean age = 22 ± 3 years, mean height = 177 ± 7 cm, mean weight = 85 ± 15 kg) and 20 healthy women (mean age = 24 ± 11 years, mean height = 165 ± 8 cm, mean weight = 67 ± 12 kg) volunteered for participation in this study. Participants with a recent injury of the right leg were excluded from the study. The study was approved by the university's institutional review board. All participants completed a health history questionnaire and signed a written informed consent form prior to participation in this study.

Research Design

This study incorporated a randomized, counterbalanced, repeated measures and parallel experimental design to compare the effects of static, PNF, and ballistic stretching to a no-stretching condition on leg flexor muscle strength, work, and power output. All measurements and stretching procedures were conducted on the right leg and hamstrings muscle group. Independent variables included time (prestretch versus poststretch repeated measures), stretch (static versus ballistic versus PNF versus no stretch [factorial groups]), and velocity (60° s^{-1} versus 180° s^{-1} repeated measures). The dependent variables were peak torque, total work, peak torque to body weight ratio (PTBW), and average power. Participants were randomly assigned to 1 of 4 stretching groups so that 10 participants were assigned to each group (5 men, 5 women): static stretching, PNF stretching, ballistic stretching, and a no stretching control group. The isokinetic speeds were counterbalanced during data collection, which helped to reduce any potential order effects of the velocities.

The following order of procedures occurred during each participant's visit: 1) a 5-minute warm-up on a stationary bicycle ergometer at 50 W, 2) prestretching isokinetic tests, 3) stretching intervention, and 4) poststretching isokinetic tests. The poststretching isokinetic tests were performed immediately (within approximately 2 minutes) after the stretching protocol.

Procedures

A calibrated Biodex System II isokinetic dynamometer (Biodex Medical Systems Inc, Shirley, New York) was used to measure peak torque, PTBW, total work, and average power. The participants were placed in a prone position with a restraining strap over the hips. During the isokinetic tests, participants were allowed 5 submaximal practice warm-up repetitions at each testing velocity, followed by a 90-second rest. Three maximal voluntary concentric isokinetic leg flexion muscle actions were performed at 60° s^{-1} and 180° s-1 with a 2-minute rest period between angular velocities. Poststretching isokinetic tests were completed using the same procedures as the prestretching tests.

Stretching Interventions

Participants assigned to the static stretching group underwent passive hamstrings stretching by a trained athletic health care specialist (M.S.O.). The static stretching consisted of the participant lying supine on the treatment table. The leg was manually held in full extension by the investigator (M.S.O.) while the thigh was flexed until firm-pressure resistance was felt by the investigator or until the participant verbally acknowledged pain. This passive stretch was held for 30 seconds and was repeated 4 times with a 20-second rest between stretches.

Participants in the ballistic stretching group actively stretched their own hamstrings with quick, ballistic movements. The participant was instructed to lie supine on the treatment table with his or her thigh flexed to 90°. The participant was then instructed to slowly extend his or her right leg until resistance or a stretch was felt in the hamstrings. This same movement was repeated 5 times slowly, followed by 10 quick leg extension movements. The participant was instructed to perform each quick movement until a mild-to-moderate stretch was felt. Twenty seconds was allowed between each ballistic stretching set, and each set was repeated 4 times.

The PNF group participated in the hold–relax PNF stretching technique. This type of stretch is commonly used by practitioners as a technique for improving flexibility.[43] The hold–relax stretching technique involves a passive stretch of the target muscle group that is immediately followed by an isometric contraction of the stretched muscles, which is immediately followed by a second passive stretch of the target muscle group. In the current study, the hold–relax PNF stretching began with the participant lying supine. An investigator trained in PNF techniques (M.S.O.) passively flexed the participant's right thigh with the leg held in a fully extended position. This passive stretch was held for 10 seconds. The participant was then instructed to isometrically extend his or her thigh against the investigator's hand with as much force as possible for 10 seconds. Immediately after the 10-second contraction, the investigator applied another passive stretch

TABLE 1

Female Study Participants' Mean ± Standard Deviation Values for Peak Torque, Peak Torque-to-Body Weight Ratio, Total Work, and Average Power Before and After Static, Proprioceptive Neuromuscular Facilitation, and Ballistic Stretching

CONDITION	PEAK TORQUE (Nm)	PTBW (%)	TOTAL WORK (Nm)	AVERAGE POWER (W)
Static stretching, 60° s^{-1}				
Prestretching	48.19 ± 9.53	25.76 ± 7.92	70.51 ± 75.79	27.56 ± 5.70
Poststretching	50.49 ± 6.94	26.72 ± 6.34	157.44 ± 67.57	61.44 ± 77.32
Static stretching, 180° s^{-1}				
Prestretching	35.36 ± 9.18	18.66 ± 6.09	123.87 ± 63.99	36.72 ± 22.72
Poststretching	33.35 ± 8.19	17.50 ± 5.12	119.23 ± 37.61	59.54 ± 53.56
Ballistic stretching, 60° s^{-1}				
Prestretching	61.36 ± 13.75	27.32 ± 6.85	225.36 ± 36.96	31.96 ± 11.32
Poststretching	59.33 ± 16.58	26.36 ± 6.67	248.58 ± 92.86	37.34 ± 11.93
Ballistic stretching, 180° s^{-1}				
Prestretching	34.68 ± 10.98	15.52 ± 5.58	129.78 ± 88.25	31.48 ± 12.29
Poststretching	38.86 ± 9.54	18.58 ± 5.98	155.27 ± 59.94	42.64 ± 14.57[a]
PNF stretching, 60° s^{-1}				
Prestretching	64.08 ± 13.75	33.48 ± 4.78	216.20 ± 40.00	34.32 ± 13.52
Poststretching	62.86 ± 11.67	32.94 ± 4.50	205.76 ± 52.16	32.16 ± 5.85
PNF stretching, 180° s^{-1}				
Prestretching	45.80 ± 7.90	23.96 ± 2.14	180.89 ± 35.47	45.36 ± 22.82
Poststretching	45.91 ± 9.15	23.98 ± 2.90	210.37 ± 40.50	45.36 ± 18.80
No stretching (control), 60° s^{-1}				
Prestretching	50.60 ± 27.05	33.20 ± 4.45	211.34 ± 104.52	29.30 ± 15.83
Poststretching	52.42 ± 24.12	32.54 ± 2.38	193.56 ± 122.39	31.28 ± 18.03
No stretching (control), 180° s^{-1}				
Prestretching	43.41 ± 3.71	22.04 ± 3.55	137.67 ± 69.88	37.70 ± 24.97
Poststretching	44.80 ± 4.18	23.40 ± 2.32	152.31 ± 73.24	39.50 ± 22.34

Abbreviations: PTBW, peak torque-to-body weight ratio; PNF, proprioceptive neuromuscular facilitation.

[a] Significant at $P \leqslant .05$.

by flexing the right thigh with the leg held in a fully extended position. This sequence was repeated 4 times with a 20-second rest between repetitions.

Statistical Analyses

Eight separate 3-way mixed factorial analysis of variance (stretch [static stretching versus ballistic stretching versus PNF versus no stretching] × time [prestretching versus poststretching] × velocity [60° s^{-1} versus 180° s^{-1}]) were conducted on peak torque, PTBW, total work, and average power for both the men and women. Follow-up analyses included 1-way factorial analysis of variance, independent samples *t* tests, and paired samples *t* tests. An alpha level of $P \leqslant .05$ was considered statistically significant for all analyses. Computer software was used to calculate all analysis of variance and *t* test models (PASW version 18.0; IBM Inc, Seattle, Washington).

RESULTS

Tables 1-2 show the means and standard deviations for all prestretch and poststretch experimental conditions in the women and men, respectively. For the women, at both 60° s^{-1} and 180° s^{-1}, there were no changes ($P >$ .05) in peak torque, PTBW, or total work from pre- to poststretching for any group (static, PNF, and ballis-

TABLE 2

Male Study Participants' Mean ± Standard Deviation Values for Peak Torque, Peak Torque-to-Body Weight Ratio, Total Work, and Average Power Before and After Static, Proprioceptive Neuromuscular Facilitation, and Ballistic Stretching

CONDITION	PEAK TORQUE (Nm)	PTBW (%)	TOTAL WORK (Nm)	AVERAGE POWER (W)
Static stretching, 60° s^{-1}				
Prestretching	120.18 ± 21.04	48.48 ± 7.51	445.42 ± 87.37	69.02 ± 15.46
Poststretching	120.15 ± 26.22	48.24 ± 8.22	412.14 ± 138.89	71.88 ± 15.13
Static stretching, 180° s^{-1}				
Prestretching	91.30 ± 21.77	36.62 ± 7.13	364.09 ± 75.88	111.16 ± 36.39
Poststretching	93.36 ± 28.47	37.22 ± 9.00	366.94 ± 62.91	122.12 ± 34.82
Ballistic stretching, 60° s^{-1}				
Prestretching	101.44 ± 19.63	45.24 ± 7.28	407.40 ± 123.61	60.24 ± 23.15
Poststretching	104.94 ± 30.21	46.48 ± 11.30	418.49 ± 149.48	67.62 ± 23.76
Ballistic stretching, 180° s^{-1}				
Prestretching	86.61 ± 18.97	38.46 ± 6.40	375.15 ± 91.63	115.04 ± 51.11
Poststretching	78.26 ± 22.84[a]	34.60 ± 8.27[a]	99.88 ± 102.37[a]	100. 42 ± 50.08
PNF stretching, 60° s^{-1}				
Prestretching	131.57 ± 21.72	48.36 ± 4.30	528.74 ± 57.33	73.80 ± 8.79
Poststretching	118.55 ± 28.02	43.56 ± 6.73	428.79 ± 73.93	67.52 ± 9.23
PNF stretching, 180° s^{-1}				
Prestretching	95.34 ± 21.38	35.14 ± 5.76	380.77 ± 70.05	117.88 ± 34.24
Poststretching	95.75 ± 18.68	35.30 ± 4.93	385.22 ± 89.50	118.48 ± 23.40
No stretching (control), 60° s^{-1}				
Prestretching	107.00 ± 16.88	40.14 ± 4.37	362.55 ± 138.72	55.86 ± 18.24
Poststretching	105.97 ± 16.09	39.92 ± 5.43	441.40 ± 44.34	62.66 ± 11.34
No stretching (control), 180° s^{-1}				
Prestretching	88.62 ± 18.89	32.90 ± 2.91	314.80 ± 51.89	98.02 ± 12.57
Poststretching	90.22 ± 18.62	33.52 ± 2.76	346.52 ± 44.03	102.00 ± 29.07

Abbreviations: PTBW, peak torque-to-body weight ratio; PNF, proprioceptive neuromuscular facilitation.

[a] Significant at $P \leq .05$.

tic stretching or no stretching). A 35% increase ($P = .048$) in average power from pre- to poststretching in the women's ballistic stretching group at 180° s^{-1} was noted (**Figure**), but there were no differences ($P > .05$) in average power among the groups at poststretching. For the men, there were no changes ($P > .05$) in average power from pre- to poststretching for any group (static stretching, PNF, and ballistic stretching or no stretching). However, there was a 10% reduction in peak torque and PTBW ($P = .017$ and .022, respectively), as well as a 20% decrease ($P = .019$) in total work at 180° s^{-1} in the ballistic stretching group (**Figure**). No other stretching-related changes were observed in peak torque, PTBW, or total work at 60° s^{-1} among the groups ($P > .05$).

DISCUSSION

To our knowledge, this was the first study to show that a practical duration (2 minutes) of either static or PNF stretching was not sufficient to elicit any reductions in hamstrings muscle strength (peak torque and PTBW), work (total work), or power output (average power) in men or women. These findings are somewhat consistent with those of Costa et al,[18] who reported no changes in peak torque of the leg flexors in men at 60° s^{-1}, 180° s^{-1}, and 300° s^{-1} following 8 minutes of static stretch-

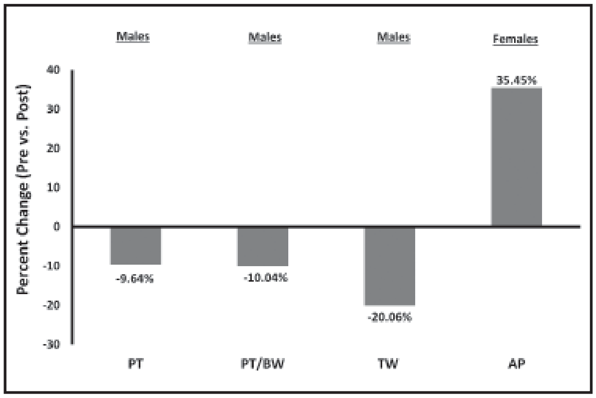

Figure. Significant percentage changes in pre- and poststretching peak torque (PT), peak torque-to-body weight ratio (PT/BW) and total work (TW) in males and average power (AP) in females in response to ballistic stretching.

ing; however, they observed 2% to 9% decreases in hamstrings-to-quadriceps ratios. Acute bouts of static stretching have been shown to decrease hamstrings performance. For example, Herda et al[27] found decreases in isometric hamstrings strength at the 2 shortest muscle lengths after 9 minutes of static stretching. Costa et al[19] reported 3% to 9% reductions in hamstrings peak torque at 60° s^{-1}, 180° s^{-1}, and 300° s^{-1} after 8 minutes of time-under-stretch but no changes in the hamstrings-to-quadriceps ratios in women. Recently, Costa et al[20] reported 9% to 11% decreases in concentric hamstrings peak torque and 16% to 18% decreases in eccentric hamstrings peak torque (as well as 7% to 12% reductions in the functional and conventional hamstrings-to-quadriceps ratios) after a similar 8-minute static stretching protocol for the hamstrings in women. Collectively, the results of the current study, together with those of previous studies, have suggested that shorter durations of stretching (approximately 2 minutes) may not affect hamstrings performance, whereas longer durations (approximately 8 to 9 minutes) of stretching may be slightly detrimental (3% to 19% reductions) to hamstrings strength and power output—particularly when stretching and testing the isolated hamstrings.

The current study has not been the first to suggest a dose–response relationship between the duration of stretching and the subsequent magnitude of performance decrements. Ryan et al[33] reported no stretching-induced changes in plantar flexor strength after 2, 4, or 8 minutes of passive stretching. However, they graphed the percentage of changes in plantar flexor strength observed in previous studies after 10, 20, and 30 minutes of stretching and, in conjunction with results from previous investigations, found that there may be a threshold-stretching duration between 8 and 10 minutes that may distinguish between significant and nonsignificant decreases in plantar flexor strength in untrained individuals.[33] Therefore, it is possible that the hamstrings muscles may exhibit a similar dose–response relationship between the duration of stretching and acute force deficit.

Not all studies have been consistent with the proposed dose–response relationship hypothesized by the researchers of the current study. For example, Robbins and Scheuermann[44] stretched the quadriceps, hamstrings, and plantar flexors for durations of 30, 60, and 90 seconds each and reported that only the 90-second stretching condition was sufficient to reduce vertical jump height. In addition, Sekir et al[45] applied 80 seconds of unassisted static stretching for the hamstrings and quadriceps (160 seconds of total time-under-stretch) and reported 8% decreases in hamstrings peak torque at 60° s^{-1} and 180° s^{-1}. However, it may be difficult to test the dose–response hypothesis for the hamstrings specifically by comparing studies that stretched multiple muscles[44,45] and tested multiple joint strength and power parameters.[44] Therefore, future studies need to clarify the dose–response relationship between the duration of targeted hamstrings stretching and isolated hamstrings strength to compare the dose–response curves of other muscle groups, such as the plantar flexors.[33]

The current study did show increases in average power for the women and decreases in peak torque, PTBW, and total work for the men after 2 minutes of ballistic stretching at 180° s^{-1}. These findings indicate that the acute responses to ballistic stretching may differ from responses to static and PNF stretching. Bradley et al[46] reported decreases in vertical jump height after 10 minutes of static stretching and PNF but no significant changes after ballistic stretching. Jaggers et al[47] showed that 8 minutes of ballistic stretching exercises did not alter jump height, force, or power, whereas a similar duration of dynamic stretching increased power. However, based on the consensus of the literature comparing modes of stretching prior to performance-related activities, dynamic stretching has consistently demonstrated increases or no changes in performance,[27,48] which may be useful information for practitioners looking to incorporate stretching before athletic performance.

The increase in average power for the women and the decreases in torque and work for the men after ballistic stretching in the current study was consistent with previously reported gender differences in response to stretching. For example, Hoge et al[49] suggested that 20 minutes of time-under-stretch for the hamstrings elicited increases in stretch tolerance for women but not for men. These authors reported stretching-induced increases in range of motion for the women, with no concomitant change for the men. Furthermore, musculotendinous stiffness did not change after this stretching protocol in either women or men, which was somewhat unusual given the duration and intensity of the stretching. However, not all studies have reported gender differences in acute response to a single session of stretching. For example, Samuel et al[48] compared the acute effects of static and ballistic stretching on vertical jump, strength, and power output and found no gender differences. Knudson et al[50] also reported no gender-specific differences in tennis serve speed or accuracy after a bout of stretching. Therefore, the results of the current study underscore the debate surrounding gender differences in response to an acute bout of stretching. Future research should focus on gender-specific adaptations in musculotendinous stiffness in response to stretching programs. In addition, future studies should also investigate practical stretching durations to identify the appropriate stretch stimulus to elicit reduction in stiffness in patients of differing ages across the lifespan.

IMPLICATIONS FOR CLINICAL PRACTICE

The results of this study indicate that 2 minutes of static or PNF stretching of the hamstrings does not reduce strength, work, or power output of the hamstrings in either men or women. However, 2 minutes of ballistic stretching had mixed effects by decreasing strength and work in men at 180° s^{-1} and increasing power in women at 180° s^{-1}. The general conclusions of the combined results of the current study and previous studies[19,20,27] may be that shorter practical durations of static or PNF stretching (approximately 2 minutes) can be incorporated prior to performance events, whereas longer stretching durations (8 to 9 minutes) may elicit acute force deficits. Allied health professionals who routinely use static stretching in athletic performance situations or prior to strength assessments to measure rehabilitation progress may consider relatively short durations (approximately 2 minutes) of static or PNF stretching of the hamstrings to maintain a functional range of motion while also limiting the acute deficits in strength observed after longer durations of stretching. ■

REFERENCES

1. Shellock FG, Prentice WE. Warming-up and stretching for improved physical performance and prevention of sports-related injuries. *Sports Med.* 1985;2(4):267-278.
2. Bandy WD, Irion JM, Briggler M. The effect of time and frequency of static stretching on flexibility of the hamstring muscles. *Phys Ther.* 1997;77(10):1090-1096.
3. Ekstrand J, Gillquist J, Moller M, Oberg B, Liljedahl SO. Incidence of soccer injuries and their relation to training and team success. *Am J Sports Med.* 1983;11(2):63-67.
4. Shrier I. Stretching before exercise does not reduce the risk of local muscle injury: a critical review of the clinical and basic science literature. *Clin J Sport Med.* 1999;9(4):221-227.
5. Kajala UM, Orava S, Jarvinen M. Hamstring injuries: current trends in treatment and prevention. *Sports Med.* 1997;23(6):397-404.
6. Petersen J, Holmich P. Evidence based prevention of hamstring injuries in sport. *Br J Sports Med.* 2005;39(6):319-323.
7. Safran MR, Seaber AV, Garrett WE Jr. Warm-up and muscular injury prevention. An update. *Sports Med.* 1989;8(4):239-249.
8. Witvrouw E, Danneels L, Asselman P, D'Have T, Cambier D. Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. A prospective study. *Am J Sports Med.* 2003;31(1):41-46.
9. Brooks JH, Fuller CW, Kemp SP, Reddin DB. Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *Am J Sports Med.* 2006;34(8):1297-1306.
10. Verrall GM, Slavotinek JP, Barnes PG. The effect of sports specific training on reducing the incidence of hamstring injuries in professional Australian Rules football players. *Br J Sports Med.* 2005;39(6):363-368.
11. Witvrouw E, Mahieu N, Danneels L, McNair P. Stretching and injury prevention: an obscure relationship. *Sports Med.* 2004;34(7):443-449.
12. Cross KM, Worrell TW. Effects of a static stretching program on the incidence of lower extremity musculotendinous strains. *J Athl Train.* 1999;34(1):11-14.
13. Dadebo B, White J, George KP. A survey of flexibility training protocols and hamstring strains in professional football clubs in England. *Br J Sports Med.* 2004;38(4):388-394.
14. Gabbe BJ, Finch CF, Bennell KL, Wajswelner H. Risk factors for hamstring injuries in community level Australian football. *Br J Sports Med.* 2005;39(2):106-110.
15. Worrell TW, Perrin DH, Gansneder BM, Gieck JH. Comparison of isokinetic strength and flexibility measures between hamstring injured and noninjured athletes. *J Orthop Sports Phys Ther.* 1991;13(3):118-125.
16. Behm DG, Button DC, Butt JC. Factors affecting force loss with prolonged stretching. *Can J Appl Physiol.* 2001;26(3):261-272.
17. Church JB, Wiggins MS, Moode FM, Crist R. Effect of warm-up and flexibility treatments on vertical jump performance. *J Strength Cond Res.* 2001;15(3):332-336.

18. Costa PB, Ryan ED, Herda TJ, Defreitas JM, Beck TW, Cramer JT. Effects of static stretching on the hamstrings-to-quadriceps ratio and electromyographic amplitude in men. *J Sports Med Phys Fitness*. 2009;49(4):401-409.
19. Costa PB, Ryan ED, Herda TJ, DeFreitas JM, Beck TW, Cramer JT. Effects of stretching on peak torque and the H:Q ratio. *Int J Sports Med*. 2009;30(1):60-65.
20. Costa PB, Ryan ED, Herda TJ, et al. Acute effects of static stretching on peak torque and the hamstrings-to-quadriceps conventional and functional ratios. *Scand J Med Sci Sports*. 2013;23(1):38-45.
21. Costa PB, Ryan ED, Herda TJ, Walter AA, Hoge KM, Cramer JT. Acute effects of passive stretching on the electromechanical delay and evoked twitch properties. *Eur J Appl Physiol*. 2010;108(2):301-310.
22. Cramer JT, Beck TW, Housh TJ, et al. Acute effects of static stretching on characteristics of the isokinetic angle-torque relationship, surface electromyography, and mechanomyography. *J Sports Sci*. 2007;25(6):687-698.
23. Cramer JT, Housh TJ, Johnson GO, Miller JM, Coburn JW, Beck TW. Acute effects of static stretching on peak torque in women. *J Strength Cond Res*. 2004;18(2):236-241.
24. Cramer JT, Housh TJ, Weir JP, Johnson GO, Coburn JW, Beck TW. The acute effects of static stretching on peak torque, mean power output, electromyography, and mechanomyography. *Eur J Appl Physiol*. 2005;93(5-6):530-539.
25. Evetovich TK, Nauman NJ, Conley DS, Todd JB. Effect of static stretching of the biceps brachii on torque, electromyography, and mechanomyography during concentric isokinetic muscle actions. *J Strength Cond Res*. 2003;17(3):484-488.
26. Fowles JR, Sale DG, MacDougall JD. Reduced strength after passive stretch of the human plantar flexors. *J Appl Physiol*. 2000;89(3):1179-1188.
27. Herda TJ, Cramer JT, Ryan ED, McHugh MP, Stout JR. Acute effects of static versus dynamic stretching on isometric peak torque, electromyography, and mechanomyography of the biceps femoris muscle. *J Strength Cond Res*. 2008;22(3):809-817.
28. Herda TJ, Ryan ED, Smith AE, et al. Acute effects of passive stretching vs vibration on the neuromuscular function of the plantar flexors. *Scand J Med Sci Sports*. 2009;19(5):703-713.
29. Kokkonen J, Nelson AG, Cornwell A. Acute muscle stretching inhibits maximal strength performance. *Res Q Exerc Sport*. 1998;69(4):411-415.
30. Marek SM, Cramer JT, Fincher AL, et al. Acute effects of static and proprioceptive neuromuscular facilitation stretching on muscle strength and power output. *J Athl Train*. 2005;40(2):94-103.
31. Nelson AG, Kokkonen J. Acute ballistic muscle stretching inhibits maximal strength performance. *Res Q Exerc Sport*. 2001;72(4):415-419.
32. Power K, Behm D, Cahill F, Carroll M, Young W. An acute bout of static stretching: effects on force and jumping performance. *Med Sci Sports Exerc*. 2004;36(8):1389-1396.
33. Ryan ED, Beck TW, Herda TJ, et al. Do practical durations of stretching alter muscle strength? A dose-response study. *Med Sci Sports Exerc*. 2008;40(8):1529-1537.
34. Young W, Elliott S. Acute effects of static stretching, proprioceptive neuromuscular facilitation stretching, and maximum voluntary contractions on explosive force production and jumping performance. *Res Q Exerc Sport*. 2001;72(3):273-279.
35. Shrier I. Does stretching improve performance? A systematic and critical review of the literature. *Clin J Sport Med*. 2004;14(5):267-273.
36. Orchard JW, Seward H, Orchard JJ. Results of 2 decades of injury surveillance and public release of data in the Australian Football League. *Am J Sports Med*. 2013;41:734-741.
37. Feeley BT, Kennelly S, Barnes RP et al. Epidemiology of National Football League training camp injuries from 1998 to 2007. *Am J Sports Med*. 2008;36(8):1597-1603.
38. Meeuwisse WH, Sellmer R, Hagel BE. Rates and risks of injury during intercollegiate basketball. *Am J Sports Med*. 2003;31(3):379-385.
39. Weir DE, Tingley J, Elder GC. Acute passive stretching alters the mechanical properties of human plantar flexors and the optimal angle for maximal voluntary contraction. *Eur J Appl Physiol*. 2005;93(5-6):614-623.
40. Alpkaya U, Koceja D. The effects of acute static stretching on reaction time and force. *J Sports Med Phys Fitness*. 2007;47(2):147-150.
41. Young W, Elias G, Power J. Effects of static stretching volume and intensity on plantar flexor explosive force production and range of motion. *J Sports Med Phys Fitness*. 2006;46(3):403-411.
42. Worrell TW. Factors associated with hamstring injuries. An approach to treatment and preventative measures. *Sports Med*. 1994;17(5):338-345.
43. Puentedura EJ, Huijbregts PA, Celeste S, et al. Immediate effects of quantified hamstring stretching: hold-relax proprioceptive neuromuscular facilitation versus static stretching. *Phys Ther Sport*. 2011;12(3):122-126..
44. Robbins JW, Scheuermann BW. Varying amounts of acute static stretching and its effect on vertical jump performance. *J Strength Cond Res*. 2008;22(3):781-786.
45. Sekir U, Arabaci R, Akova B, Kadagan SM. Acute effects of static and dynamic stretching on leg flexor and extensor isokinetic strength in elite women athletes. *Scand J Med Sci Sports*. 2010;20(2):268-281.
46. Bradley PS, Olsen PD, Portas MD. The effect of static, ballistic, and proprioceptive neuromuscular facilitation stretching on vertical jump performance. *J Strength Cond Res*. 2007;21(1):223-226.
47. Jaggers JR, Swank AM, Frost KL, Lee CD. The acute effects of dynamic and ballistic stretching on vertical jump height, force, and power. *J Strength Cond Res*. 2008;22(6):1844-1849.
48. Samuel MN, Holcomb WR, Guadagnoli MA, Rubley MD, Wallmann H. Acute effects of static and ballistic stretching on measures of strength and power. *J Strength Cond Res*. 2008;22(5):1422-1428.
49. Hoge KM, Ryan ED, Costa PB, et al. Gender differences in musculotendinous stiffness and range of motion after an acute bout of stretching. *J Strength Cond Res*. 2010;24(10):2618-2626.
50. Knudson DV, Noffal GJ, Bahamonde RE, Bauer JA, Blackwell JR. Stretching has no effect on tennis serve performance. *J Strength Cond Res*. 2004;18(3):654-656.