Comparison of Ballistic and Static Stretching on Hamstring Muscle Length Using an Equal Stretching Dose

Christopher A. Covert,[1] Melanie P. Alexander,[2] John J. Petronis,[3] and D. Scott Davis[3]

[1]*Mountain River Physical Therapy, Parkersburg, West Virginia;* [2]*The PT Group, Jeannette, Pennsylvania; and* [3]*Department of Human Performance and Exercise Science, Division of Physical Therapy, West Virginia University, Morgantown, West Virginia*

Abstract

Covert, CA, Alexander, MP, Petronis, JJ, and Davis, DS. Comparison of ballistic and static stretching on hamstring muscle length using an equal stretching dose. *J Strength Cond Res* 24(11): 3008–3014, 2010—The purpose of this investigation was to determine which stretching technique, static or ballistic, is most effective for increasing hamstring muscle length when delivered at the same stretching dose over a 4-week training program. A single-blind, randomized controlled trial design was used in this investigation. Thirty-two participants (16 women and 16 men) between the ages of 18 and 27 years participated in the study. All participants who had a pre-training knee extension angle of less than 20° were excluded from the study. Subjects were randomly assigned to one of 3 groups: ballistic stretching, static stretching, or control group. Participants in the experimental stretching groups (ballistic and static stretching) performed one 30-second stretch 3 times per week for a period of 4 weeks. Statistical analysis consisted of a 2-way analysis of variance (group × sex) with an a priori alpha level of 0.05. No interaction between group and sex was identified ($p = 0.4217$). The main effect of sex was not statistically significant ($p = 0.2099$). The main effect for group was statistically significant at $p < 0.0001$. Post hoc analysis revealed that both static and ballistic stretching group produced greater increases in hamstring length than the control group. The static stretching group demonstrated a statistically greater increase in hamstring muscle length than the ballistic stretching group. No injuries or complications were attributed to either stretching program.

Key Words flexibility, knee extension angle, exercise

Address correspondence to Dr. Duane S. Davis, dsdavis@hsc.wvu.edu.

24(11)/3008–3014

Journal of Strength and Conditioning Research

Introduction

Stretching is a routine part of many rehabilitation programs and a component of many training regimens for athletes and recreational fitness enthusiasts. Stretching programs are designed to increase muscle length to allow for increased joint range of motion (14,26). Some benefits of stretching include restoration of normal joint range of motion (14), injury prevention (7,8,14,15), and improved physical performance (26,32). However, some authors have questioned the role of stretching for decreasing injury risk and improving physical performance (1,14,16,17,21,23,27,31). Despite this controversy, stretching has a long tradition and will likely continue to be a component of many training and rehabilitation programs (15,20,28,33). Therefore, coaches, personal trainers, and athletes need to be aware of the most effective and efficient ways to achieve optimal increases in muscle length.

Static stretching is a frequently used and efficacious method of increasing muscle length when properly applied using the necessary stretching parameters (2–4,9,11,31). Researchers have examined a variety of static stretching parameters. For example, Sady et al. (22) used 3 repetitions of 6 seconds, completed 3 days per week for 6 weeks. They reported no significant change in hamstring muscle length using these parameters. In contrast, Bandy and Irion (2) found that both 30- and 60-second static stretches of the hamstring muscles were more effective than a 15-second stretch performed 5 days per week for 6 weeks. However, a 60-second static stretch was not found to be more effective than a 30-second static stretch (2). In a different study, Bandy et al. (3) reported that performing static stretching 3 times a day was not significantly different from that performed 1 time per day. Davis et al. (9) using a consistent stretching dose among experimental groups found significant gains in hamstring muscle length after one 30-second static stretch 3 days per week for a 4-week period. Based on the current literature, it appears that the parameters of the stretch are just as important as the type of stretching performed (2–4,9,22).

In comparison with static stretching, much less is known about ballistic stretching. Some authors advocate that ballistic stretching is more functional than other stretching techniques for individuals who participate in activities that require high-velocity movements (17,19,33). However, there are differing opinions about the safety of ballistic stretching with some authors expressing concern over the risk of musculoskeletal injury, particularly as it relates to muscle strain (3,19,29). The most frequently cited reason for this belief is that ballistic stretching involves repeated rapid stretching of the muscle (19,26,31). This rapid stretch may activate the muscle spindle, thus preventing adequate muscle relaxation before the subsequent stretch. Some have hypothesized that this may cause microtrauma to the muscle (26,31). In a recent literature review, Weerapong et al. (31) reported that there was no scientific evidence to substantiate the claim that ballistic stretching poses a higher risk for adverse effects on the muscle than other stretching techniques.

In addition to the general dearth of evidence associated with ballistic stretching, a literature review was only able to identify 2 published investigations, which compared ballistic stretching with other stretching techniques in a blinded, randomized controlled investigation using a consistent stretching dose (17). An early investigation on ballistic stretching was conducted by Sady et al. (22), which compared ballistic stretching with a control group. Subjects in the ballistic stretching group performed 20 rapid repetitions of ballistic stretching throughout the full range of motion. There was no information provided relative to the rate of ballistic stretching. Sady et al. (22) reported that the ballistic stretching group did not experience a statistically significant difference in hamstring muscle length compared with the control group (22).

Bannerman et al. (5) investigated the impact of ballistic and static stretching on the length of the soleus muscle in male rugby players. Subjects were randomly assigned to receive either static or ballistic stretching for 15 seconds. The protocol required stretching 2 times per week over a 5-week period. The participants completed a 90-minute general training program before the 15-second ballistic or static stretch. They reported no difference in muscle length between the static and ballistic stretching groups. Although Bannerman et al. (5) used a consistent stretching dose between groups, they did not include a control group, and there was no discussion whether the tester was blinded to group assignment.

Woolstenhulme et al. (33) examined the effects of 20 minutes of basketball warm-up activity, including static stretching, ballistic stretching, sprinting, or basketball shooting (control) on hamstring muscle length and vertical jump height. The stretching protocol was performed 2 times per week for 6 weeks and included consistent parameters of 2 repetitions of 4 stretches that were performed for 30 seconds each. Woolstenhulme et al. (33) reported that there was no significant difference in hamstring muscle length between the static and ballistic stretching groups as measured by the sit-and-reach test.

LaRoche and Connolly (17) compared ballistic and static stretching groups with a control group over a 4-week stretching program. The subjects in ballistic and static stretching groups received stretching 3 days per week. The subjects in both groups received 10 sets of 30-second stretching for a total stretching dose of 3,600 seconds over the course of the 4-week program. Both groups showed an increase in hamstring muscle length compared with the control group, but there was no statistical difference between the static and ballistic stretching groups.

There is a current dearth of randomized controlled trials that examine the efficacy of ballistic stretching compared with other types of stretching, especially when the stretching parameters are consistent among the stretching groups and the tester is blind to group assignment. Therefore, the aim of this study was to determine which stretching technique, static or ballistic stretching, is most effective in increasing hamstring muscle length when performed using a consistent stretching dose in a single-blind, randomized controlled trial. The null hypothesis was that there would be no significant difference in muscle length change between static and ballistic stretching groups.

Methods

Experimental Approach to the Problem

A single-blind, randomized controlled trial was used for this investigation. Consistent stretching parameters were used for both experimental groups to allow for a comparison based on stretching technique. The independent variable in this investigation was the stretching technique (static, ballistic, or control). The dependent variable was change in hamstring muscle length over a 4-week stretching program as measured by knee extension angle. Ballistic and static stretching techniques were chosen due to the paucity of research comparing these 2 methods of stretching on muscle length. Furthermore, the design enabled the researchers to establish if one 30-second ballistic stretch applied at a rate of 1 cycle per second is efficacious compared with a control.

Subjects

Before data collection, written consent was obtained from all subjects, and the investigation was approved by the university's Institutional Review Board for the Protection of Human Subjects. All subjects were 18 years of age or older. Participants were recruited through electronic advertisement in the university community and by word-of-mouth. The target population for this investigation included men and women between the ages of 18 and 40 years. Hamstring tightness was defined as a knee extension angle of greater than or equal to 20° (20). Individuals were excluded from the investigation if they reported previous trauma to the lower extremities that may affect the length of the hamstring muscles. This included femur, pelvis, or tibia fracture, any injury or surgery involving the hamstring muscles, joint replacement of the knee or hip, or a strain of the hamstring muscles. Additionally, individuals with previous pathology of the knee that may prevent full range of motion were excluded from the investigation. These included ligament injury, osteoarthritis, rheumatoid arthritis, or meniscal pathology.

Table 1. Means and *SD* for age (years) among groups for women and men.

	Overall	Control	Ballistic	Static
Men + women	21.97 ± 2.61	21.45 ± 3.06	22.7 ± 2.67	21.82 ± 2.14
Women	22.7 ± 1.8	22.2 ± 1.1	24.5 ± 2.4	22 ± 1.2
Men	21.2 ± 3.2	20.8 ± 4.1	21.3 ± 2.5	21.5 ± 3.5

Participants were also excluded if they had a diagnosis of lumbar intervertebral disc pathology, trauma to the lumbar spine, or previous spinal surgery. Individuals who were participating in a stretching program or who had participated in a stretching program in the past 6 months were excluded from the study. Additionally, participants were informed that they would be excluded from the study if they began a new stretching program during the study period. Participants were also asked to maintain their usual level of physical activity throughout the duration of the study.

Sixty-two individuals initially consented to participate in the study; however, 3 were excluded from the study based on previous medical history per the exclusion criteria. Thus, 59 individuals were screened for hamstring length. Thirty-two (16 women and 16 men) of the eligible 59 participants met the inclusion criteria for hamstring length and were included in the randomization. Participants were randomly assigned using a random number table to one of 3 groups, ballistic stretching (6 men and 4 women), static stretching (4 men and 7 women), or the control (6 men and 5 women) group. Means and *SD*s of the participants are reported in Table 1.

Procedures

This investigation was conducted in a university's health sciences center laboratory. After randomizing participants to one of the 3 treatment groups, baseline hamstring length measurements using the knee extension angle technique were obtained. Inter-tester reliability for knee extension angle measurements has been previously reported by multiple authors and range from 0.93 to 0.98 (12,25,30), whereas intra-tester reliability has been reported to be 0.86–0.99 (12,13,25,30).

Baseline knee extension angle measurements were performed with the participant lying supine on a plinth. A Saunders Digital Inclinometer (Saunders Group, Inc., Chaska, MN, USA) was placed 4 in. below the tibial crest on the most anterior portion of the tibial shaft to assess the knee extension angle. A second gravity inclinometer (Macklanburg-Duncan, Oklahoma City, OK, USA) was strapped 4 in. above the superior pole of the patella on the anterior thigh to assist in maintaining 90° of hip flexion (Figure 1). All measurements were performed on the participant's dominant lower extremity. The dominant leg was determined by self-report.

Figure 1. Knee extension angle test: inclinometer placement.

The participant's dominant hip was positioned in 90° of hip flexion by investigator A and maintained in this position throughout the measurement procedure. The contralateral lower extremity was strapped to the treatment plinth to control pelvic motion. The stabilization strap was placed along the midshaft of the contralateral femur. Pelvic motion

Figure 2. Ballistic stretching technique.

was carefully monitored through visual assessment during the testing procedure. Investigator A passively extended the knee to the point where the participant reported experiencing a strong but tolerable stretch in the posterior thigh. At that point, investigator B recorded the knee extension angle reported by investigator A. Investigator A was not involved in the stretching protocol and therefore was blind to group assignment throughout the investigation. The same testing procedure was conducted at the end of the 4-week study period to evaluate change in hamstring muscle length. Investigator A is a licensed physical therapist with more than 40 years of clinical experience.

Warm-up Protocol. Each participant performed a 2-minute warm-up on a stationary bicycle before their respective stretching protocol. The control group also performed a 2-minute warm-up but received no stretching intervention. The Borg Rating of Perceived Exertion scale (RPE) was used to maintain consistency in the intensity of the warm-up among participants. After explaining the scale to the participants, each subject was instructed to maintain a pace that was equivalent to an RPE of 12.

Static Stretching Protocol. The static stretching procedure was performed while each participant was lying supine on a plinth. The investigator passively flexed the subject's dominant hip to 90° of flexion; the investigator then slowly extended the knee with the ankle in a relaxed plantarflexed position until the participant reported a strong but tolerable stretch in the posterior thigh. At that point, a 30-second static stretch was applied maintaining a strong but tolerable stretching force. The investigator observed the contralateral lower extremity throughout the stretch to ensure that the hip and knee remained extended and flat on the plinth. Each participant received one 30-second stretch 3 days per week for 4 weeks for a total stretching dose of 360 seconds.

Table 2. Means and *SD* for knee extension angle (°) at pre- and post-test and change.

	Control	Ballistic	Static
Pretest	27.6 ± 4.72	28.8 ± 4.73	31.2 ± 5.41
Post-test	31.3 ± 6.68	25 ± 8.84	19.3 ± 8.65
Change (pre − post)	−3.3 ± 4.67	3.8 ± 8.34	11.9 ± 5.97

Ballistic Stretching Protocol. The subjects in the ballistic stretching group were seated on the edge of a plinth with the dominant knee fully extended (Figure 2). The nondominant lower extremity was positioned off the edge of the plinth with the foot resting flat on the floor. The height of the plinth was then adjusted, so the tibia was

Table 3. Two-way analysis of variance ($n = 32$).

Source	Degrees of freedom	Sum of squares	F ratio	Probability > F
Group	2	1,195.3178	14.5829	<0.0001*
Sex	1	67.7415	1.6529	0.2099
Group × sex	2	73.1782	0.8928	0.4217

*Significant at $p < 0.05$.

approximately perpendicular to the floor. The dominant lower extremity remained on the plinth in full knee extension with the ankle in a relaxed plantarflexion position to avoid neural tension. The participant was then instructed to flex the trunk forward at the hips until they felt a strong but tolerable stretch. The subjects then actively performed a small (3–5°) bouncing motion at end range at a rate of 1 cycle per second for 30 seconds. A metronome (Qwik Time QT-3 digital, Evets Corp., San Clemente, CA, USA) set at 1 $b \cdot s^{-1}$ was used to give the participant feedback regarding the rate at which the ballistic stretching should be performed. This was completed 3 days per week for 4 weeks for a total stretching dose of 360 seconds. At the initial training session, the investigator demonstrated the stretching procedure for the participant while providing verbal instructions regarding proper posture, stretching intensity, and rate. At subsequent training sessions, the participant was given verbal reminders regarding his or her posture, stretching intensity, and rate as needed.

Statistical Analyses

Descriptive statistics were performed to examine the mean and *SD*s for each group both before and after the training program. To determine if there was a difference in age, sex, or hamstring length among groups at baseline, a 1-way analysis of variance (ANOVA) was used. To answer the primary hypothesis, a 2-way ANOVA was used to examine the interaction and main effects of group and sex. The alpha level to reject the null hypothesis was set a priori at $p \leq 0.05$ for all analyses. The assumptions of normality and homogenous variance were met using Shapiro-Wilk's test ($p = 0.9229$) and O'Brien's test ($p = 0.2851$). A post hoc analysis was performed using Tukey-Kramer's honestly significant difference test to determine where significant differences existed among groups. Statistical analysis was performed using JMP 5.0 (SAS Institute Inc., Cary, NC, USA).

Results

There was no significant difference in hamstring muscle length among groups at baseline. Furthermore, there was no significant difference among groups for sex or age at baseline. For each group, the mean and *SD* for knee extension angle at pre- and post-test are reported in Table 2. The 2-way ANOVA revealed no interaction ($p = 0.4217$) among group and sex (Table 3). Analysis of the main effects revealed no difference based on sex ($p = 0.2099$). The main effect for group was found to be statistically significant ($p < 0.0001$). Post hoc testing revealed a statistically significant increase in hamstring muscle length for both the static and ballistic stretching groups compared with the control group. There was also a statistically significant difference between ballistic and static stretching groups with the static stretching group demonstrating a greater increase in hamstring muscle length. The Cohen's d effect size indices were large (static vs. control = 2.35; ballistic vs. control = 1.21, and static vs. ballistic = 1.14). Thus, power analysis revealed a power of 0.99.

Discussion

The primary purpose of this investigation was to determine if ballistic or static stretching is more effective at increasing hamstring muscle length when using an equal stretching dose. A secondary purpose was to determine if ballistic stretching using the prescribed stretching parameters produces an increase in hamstring muscle length compared with a control. The investigators believe that using an equal stretching dose is the most valid method to compare stretching techniques (9). Based on previous literature examining static stretching, a single 30-second stretch was chosen as the stretching dose in this investigation (2,3,9). Furthermore, using a single 30-second stretch is more time efficient and is more likely to increase compliance when used in a rehabilitation or training program.

Based on the results of this investigation, it appears that ballistic stretching is not as effective at increasing hamstring muscle length as static stretching when using a single 30-second stretching dose 3 days per week for a 4-week training program. Currently, there is no evidence in the literature indicating the best parameters for ballistic stretching. Although the ballistic stretching group demonstrated statistically significant improvements in hamstring length compared with the control, the mean improvement of 3.8° is not likely to be functionally or clinically significant. Conversely, the mean improvement in the static stretching group of 11.9° does appear to be functionally and clinically significant.

It is well established that static stretching is an effective and safe method to increase hamstring muscle length. This study confirms the results of previous studies indicating that static stretching is an effective and efficient method of increasing hamstring muscle length (2–4,9). In contrast, ballistic stretching has not been adequately studied (2,5,17,33). This may be due to the commonly held belief that ballistic stretching may cause muscle injury (6,24).

Despite this commonly held belief, there is limited evidence to support this contention. Smith et al. (24) found that both the static and ballistic stretching groups reported delayed-onset muscle soreness (DOMS), but none of the participants in their investigation had any significant injuries from either stretching technique. Additionally, Smith et al. (24) reported that the static stretching group had significantly more DOMS than did the ballistic stretching group. Beedle and Mann (6) in their comparison of static and ballistic stretching reported that most of the participants in the ballistic stretching group reported no muscle soreness.

In this investigation, a total of 6 participants reported hamstring muscle soreness, 2 participants in the static stretching group, 3 in the ballistic stretching group, and 1 in the control group. However, none of the participants reported hamstring muscle soreness greater than a 3/10 on the numeric pain rating scale. Additionally, none of the participants in this study reported significant injury to the hamstring muscles throughout the duration of the study. One participant in the ballistic stretching group reported pain in the region of the anterior superior iliac spine on the contralateral side. Based on a history and physical examination by an investigator, it was determined that the subject's pain was not related to their participation in this investigation.

Previous investigators (5,17,18,22,33) who compared static and ballistic stretching have reported no significant differences among stretching groups. However, these investigations did not report if the participants were limited in hamstring muscle length at baseline. Thus, these investigations may have included individuals who had excessive hamstring muscle length. The difference among groups found in this study may be related to the fact that all participants in this investigation had less than ideal hamstring muscle length at baseline. Additionally, in some of the previous investigations, the stretching dose was not consistent among stretching groups or the tester was not blind to the group assignment. Differences in outcome measures may have also played a role (10). Bannerman et al. (5) measured changes in soleus muscle length while in a weight-bearing position, LaRoche and Connolly (17) used a custom-built isokinetic dynamometer to measure hamstring length, and Woolstenhulme et al. (33) used the sit-and-reach test as an outcome measure for hamstring muscle length.

Due to the limitation of age range (18–27 years) of the participants in this investigation, generalizability of the results is limited. Additionally, no attempt was made to recruit subjects based on activity level or body composition. Future investigations may consider controlling for these variables. Another limitation of this investigation is that only muscle length of the hamstrings was tested; therefore, it is unknown if other muscles will respond similarly. This investigation did not examine all possible stretching doses; therefore, it is unknown how variations in duration of stretch, rate of stretch, and length of the training program may affect the results of ballistic stretching.

The operational definition of "tight hamstrings" in this investigation resulted in the exclusion of 27 potential subjects who were not found to have tight hamstrings. Most of the excluded subjects were women. Thus, the exclusion criteria based on baseline muscle length resulted in a homogenous sample based on sex (16 women and 16 men).

The effects of stretching on muscle force, risk of injury, and athletic performance are complex and remain controversial (1,14,15,16,21,23,27,28,31). Despite this ongoing controversy, it appears that muscle stretching will remain an integral part of rehabilitation and training programs when inadequate muscle length is negatively affecting joint range of motion and athletic performance. The results of this investigation support the use of static stretching using a 30-second stretching dose 3 days per week for a 4-week training program.

Practical Applications

The development and maintenance of adequate muscle length is a vital requisite for many athletes and recreational enthusiasts. Coaches, personal trainers, and athletes need to be aware of the most efficacious stretching techniques and parameters. The results of this investigation reveal that static stretching is superior to ballistic stretching when using a 30-second stretching dose 3 days per week for a 4-week stretching program in young adult women and men. Based on the results of this investigation, strength and conditioning professionals who seek to use effective and efficient stretching programs should choose static stretching rather than ballistic stretching in the young adult population. Although this study supports static stretching compared with ballistic stretching, the commonly held belief that ballistic stretching increases the incidence of muscular injury beyond minor DOMS should be questioned based on the response of subjects in this investigation.

Acknowledgments

The authors thank the following individuals for their assistance with the investigation: Anne Swisher, PT, PhD, CCS; Jody Bowser, DPT; Derek Clark, DPT; Miranda Ellis, DPT; Whitney Whittaker, DPT; Brittany Volker, DPT; and Shawn Bosley, DPT.

References

1. Bacurau, RF, Monteiro, GD, Ugrinowitsch, C, Tricoli, V, Cabral, LF, and Aoki, MS. Acute effect of a ballistic and a static stretching exercise bout on flexibility and maximal strength. *J Strength Cond Res* 23: 304–308, 2009.
2. Bandy, WD and Irion, JM. The effect of time on static stretch on the flexibility of the hamstring muscles. *Phys Ther* 74: 845–850, 1994.
3. Bandy, WD, Irion, JM, and Briggler, M. The effect of time and frequency of static stretching on flexibility of the hamstring muscles. *Phys Ther* 77: 1090–1096, 1997.
4. Bandy, WD, Irion, JM, and Briggler, M. 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, 1998.

5. Bannerman, N, Pentecost, E, Rutter, S, Willoughby, S, and Vujnovich, A. Increase in soleus muscle length: A comparison between two stretching techniques. *N Z J Physiother* 24: 15–18, 1996.

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

7. Bixler, B and Jones, RL. High school football injuries: Effects of a post-halftime warm-up and stretching routine. *Fam Prac Res J* 12: 131–139, 1992.

8 Cross, KM and Worrell, TW. Effects of a static stretching program on the incidence of lower extremity musculotendinous strains. *J Athl Train* 34: 11–14, 1999.

9. Davis, DS, Ashby, PE, McCale, KL, McQuain, JA, and Wine, JM. The effectiveness of 3 stretching techniques on hamstring flexibility using consistent stretching parameters. *J Strength Cond Res* 19: 27–32, 2005.

10. Davis, DS, Quinn, RO, Whiteman, CT, Williams, JD, and Young, CR. Concurrent validity of four clinical tests used to measure hamstring flexibility. *J Strength Cond Res* 22: 583–588, 2008.

11. De Vries, HA. Evaluation of static stretching procedures for improvements of flexibility. *Res Q* 33: 222–229, 1962.

12. Gabbe, BJ, Bennell, KL, Wajswelner, H, and Finch, CF. Reliability of common lower extremity musculoskeletal screening tests. *Phys Ther Sports* 5: 90–97, 2004.

13. Gajdosik, RL, Rieck, MA, Sullivan, DK, and Wightman, SE. Comparison of four clinical tests for assessing hamstring muscle length. *J Orthop Sports Phys Ther* 18: 614–618, 1993.

14. Haff, GG, Cramer, JT, Beck, TW, Egan, AD, Davis, DS, McBride, J, and Wathen, D. Round table discussion: Flexibility training. *Strength Cond J* 28: 64–85, 2006.

15. Hartig, D, and Henderson, JM. Increasing hamstring flexibility decreases lower extremity overuse injuries in military basic trainees. *Am J Sports Med* 27: 173–176, 1999.

16. Jaggers, JR, Swank, AM, Frost, KL, and Lee, CD. The acute effects of dynamic and ballistic stretching on vertical jump height, force, and power. *J Strength Cond Res* 22: 1844–1849, 2008.

17. LaRoche, DP and Connolly, DA. Effects of stretching on passive muscle tension and response to eccentric exercise. *Am J Sports Med* 34: 1000–1007, 2006.

18. Mahieu, NN, McNair, P, De Muynck, M, Stevens, V, Blanckaert, I, Smites, N, and Witvrouw, E. Effect of static and ballistic stretching on the muscle-tendon tissue properties. *Med Sci Sports Exerc* 39: 494–501, 2007.

19. Malone, TR, Garrett, WE, and Zachazewski, JE. Muscle: Deformation, injury, repair. In: *Athletic Injuries and Rehabilitation.* Zachazewski, JE, Magee, DJ, and Quillen, WS, eds. Philadelphia: WB Saunders Company, 1996. pp. 86–88.

20. Nelson, RT and Bandy, WD. Eccentric training and static stretching improve hamstring flexibility of high school males. *J Athl Train* 39: 254–258, 2004.

21. Pope, RP, Herbert, RD, Kirwan, JD, and Graham, BJ. A randomized trial of preexercise stretching for prevention of lower extremity injury. *Med Sci Sports Exerc* 32: 271–277, 2000.

22. Sady, SP, Wortman, M, and Blanke, D. Flexibility training: Ballistic, static or proprioceptive neuromuscular facilitation? *Arch Phys Med Rehabil* 63: 261–263, 1982.

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

24. Smith, LL, Brunetz, MH, Chenier, TC, McCammon, MR, Houmard, JA, Franklin, ME, and Israel RG. The effects of static and ballistic stretching on delayed onset muscle soreness and creatine kinase. *Res Q Exerc Sport* 64: 103–107, 1993.

25. Sullivan, MK, DeJulia, JJ, and Worrell, TW. Effect of pelvic position and stretching method on hamstring muscle flexibility. *Med Sci Sports Exerc* 24: 1383–1389, 1992.

26. Taylor, DC, Dalton, JD, Seaber, AV, and Garret, WE. Viscoelastic properties of muscle-tendon units: The biomechanical effects of stretching. *Am J Sports Med* 18: 300–309, 1990.

27. Thacker, SB, Gilchrist, J, Stroup, DF, and Kimsey, CD. The impact of stretching on sports injury risk: A systematic review of the literature. *Med Sci Sports Exerc* 36: 371–378, 2004.

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

29. Vujnovich, AL and Dawson, NJ. The effect of therapeutic muscle stretch on neural processing. *J Orthop Sports Phys Ther* 20: 145–153, 2004.

30. Webright, WG, Randolph, BJ, and Perrin, DH. Comparison of nonballistic active knee extension in neural slump position and static stretch techniques on hamstring flexibility. *J Orthop Sports Phys Ther* 26: 7–13, 1997.

31. Weerapong, P, Hume, PA, and Kolt, GS. Stretching: Mechanisms and benefits for sport performance and injury prevention. *Phys Ther Rev* 9: 189–206, 2004.

32 Wiemann, K and Hahn, K. Influences of strength, stretching and circulatory exercises on flexibility parameters of the human hamstrings. *Int J Sports Med* 18: 340–346, 1997.

33. Woolstenhulme, MT, Griffiths, CM, Woolstenhulme, EM, and Parcell, AC. Ballistic stretching increases flexibility and acute vertical jump height when combined with basketball activity. *J Strength Cond Res* 20: 799–803, 2006.