IJSPT

CLINICAL COMMENTARY

CURRENT CONCEPTS IN MUSCLE STRETCHING FOR EXERCISE AND REHABILITATION

Phil Page, PT, PhD, ATC, CSCS, FACSM

ABSTRACT

Stretching is a common activity used by athletes, older adults, rehabilitation patients, and anyone participating in a fitness program. While the benefits of stretching are known, controversy remains about the best type of stretching for a particular goal or outcome. The purpose of this clinical commentary is to discuss the current concepts of muscle stretching interventions and summarize the evidence related to stretching as used in both exercise and rehabilitation.

Key words: Exercise, fitness, rehabilitation, stretching

CORRESPONDING AUTHOR

Phil Page, PT, PhD, ATC, CSCS, FACSM
Baton Rouge, Louisiana USA
Email: drphilpage@gmail.com

INTRODUCTION

Human movement is dependent on the amount of range of motion (ROM) available in synovial joints. In general, ROM may be limited by 2 anatomical entities: joints and muscles. Joint restraints include joint geometry and congruency as well as the capsuloligamentous structures that surround the joint. Muscle provides both passive and active tension: passive muscle tension is dependent on structural properties of the muscle and surrounding fascia, while dynamic muscle contraction provides active tension (Figure 1). Structurally, muscle has viscoelastic properties that provide passive tension. Active tension results from the neuro-reflexive properties of muscle, specifically peripheral motor neuron innervation (alpha motor neuron) and reflexive activation (gamma motor neuron).

Obviously, there are many factors and reasons for reduced joint ROM only one of which is muscular tightness. Muscle "tightness" results from an increase in tension from active or passive mechanisms. Passively, muscles can become shortened through postural adaptation or scarring; actively, muscles can become shorter due to spasm or contraction. Regardless of the cause, tightness limits range of motion and may create a muscle imbalance.

Clinicians must choose the appropriate intervention or technique to improve muscle tension based on the cause of the tightness. Stretching generally focuses on increasing the length of a musculotendinous unit, in essence increasing the distance between a muscle's origin and insertion. In terms of stretching, muscle tension is usually inversely related to length: decreased muscular tension is related to increased muscle length, while increased muscular tension is related to decreased muscle length. Inevitably, stretching of muscle applies tension to other structures such as the joint capsule and fascia, which are made up of different tissue than muscle with different biomechanical properties.

Three muscle stretching techniques are frequently described in the literature: Static, Dynamic, and Pre-Contraction stretches (Figure 2). The traditional and most common type is static stretching, where a specific position is held with the muscle on tension to a point of a stretching sensation and repeated. This can be performed passively by a partner, or actively by the subject (Figure 3).

There are 2 types of dynamic stretching: active and ballistic stretching. Active stretching generally involves moving a limb through its full range of motion to the end ranges and repeating several times. Ballistic stretching includes rapid, alternating movements or 'bouncing' at end-range of motion; however, because of increased risk for injury, ballistic stretching is no longer recommended.[1]

Pre-contraction stretching involves a contraction of the muscle being stretched or its antagonist before

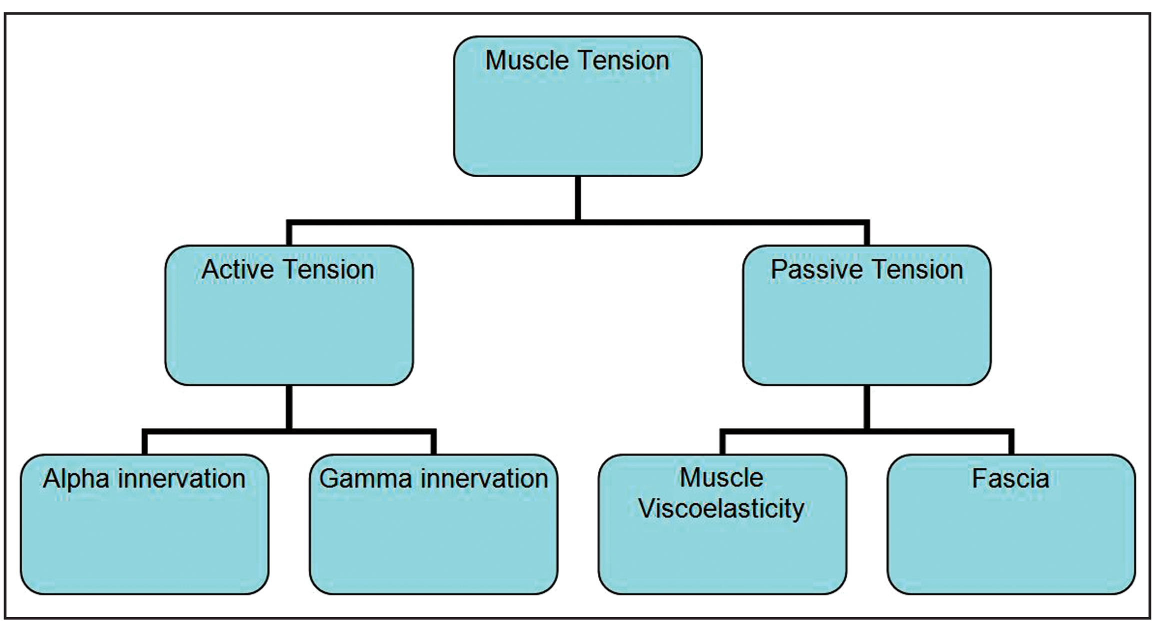

Figure 1. *Factors contributing to muscle tension.*

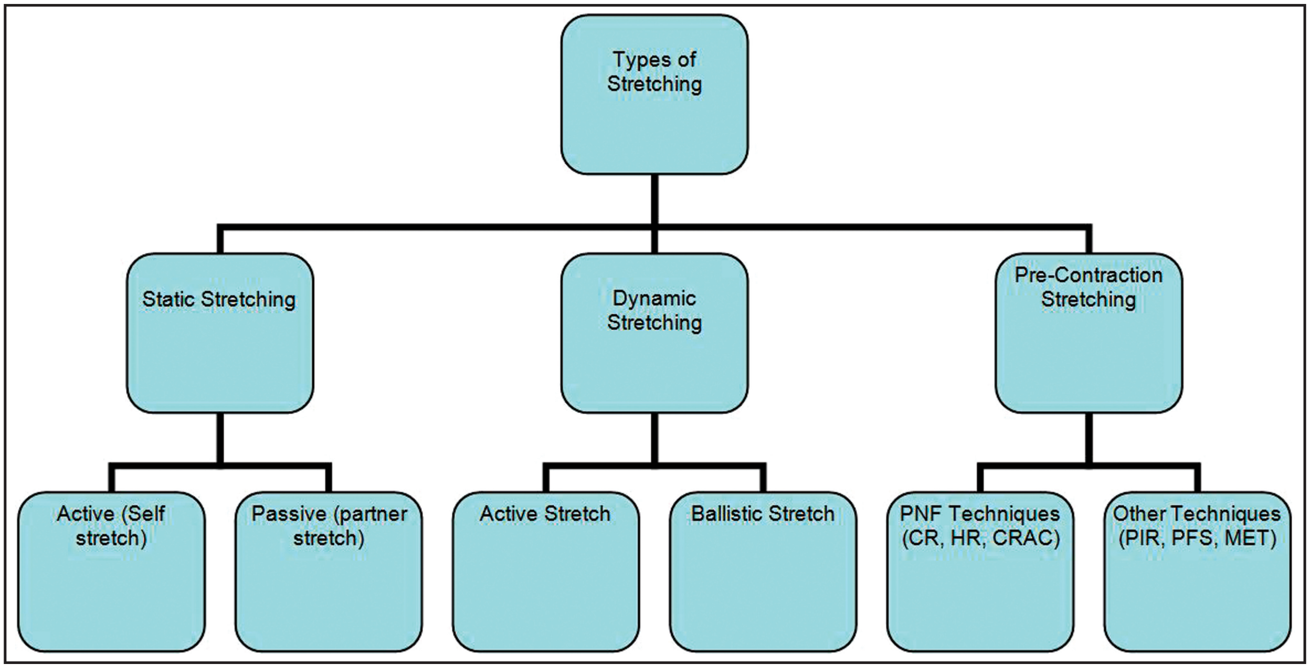

Figure 2. *Techniques of Muscle Stretching. HR = Hold relax; CR = Contract relax; CRAC = Contract relax, agonist contract; PIR = Post-isometric relaxation; PFS = Post-facilitation stretching, MET = Medical exercise therapy.*

Figure 3. *Static stretching of the posterior shoulder (Used with permission of the Hygenic Corporation).*

stretching. The most common type of pre-contraction stretching is proprioceptive neuromuscular facilitation (PNF) stretching. There are several different types of PNF stretching (Table 1) including "contract relax" (C-R), "hold relax" (H-R), and "contract-relax agonist contract" (CRAC); these are generally performed by having the patient or client contract the muscle being used during the technique at 75 to 100% of maximal contraction, holding for 10 seconds, and then relaxing. Resistance can be provided by a partner or with an elastic band or strap (Figure 4).

Other types of pre-contraction stretching include "post-isometric relaxation" (PIR). This type of technique uses a much smaller amount of muscle contraction (25%) followed by a stretch. Post-facilitation stretch (PFS) is a technique developed by Dr. Vladimir Janda that involves a maximal contraction of the

Table 1. *Types of PNF stretching.*

Contract Relax (CR)	Contraction of the muscle through its spiral-diagonal PNF pattern, followed by stretch
Hold Relax (HR)	Contraction of the muscle through the rotational component of the PNF pattern, followed by stretch
Contract-Relax Agonist Contract (CRAC)	Contraction of the muscle through its spiral-diagonal PNF pattern, followed by contraction of opposite muscle to stretch target muscle

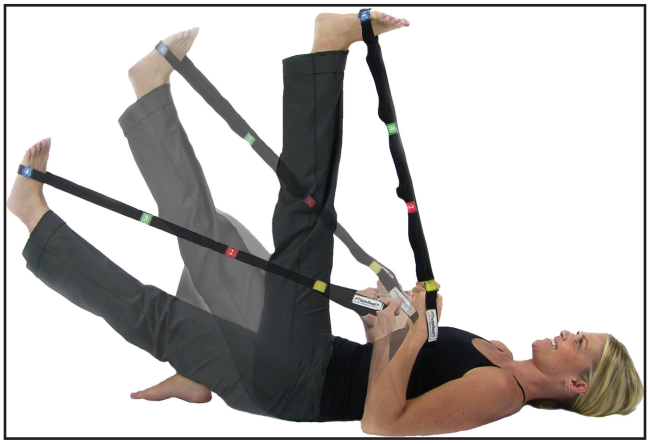

Figure 4. *Contract-Relax stretching with stretching strap (Used with permission of the Hygenic Corporation).*

Figure 5. *Post-Facilitation Stretching of hamstrings (Used with permission of the Hygenic Corporation).*

muscle at mid-range (Figure 5) with a rapid movement to maximal length followed by a 15-second static stretch.[2]

STRETCHING RESEARCH

Many studies have evaluated various effects of different types and durations of stretching. Outcomes of these studies can be categorized as either acute or training effects. Acute effects measure the immediate results of stretching, while training effects are the results of stretching over a period of time. Stretching studies also vary by the different muscles or muscle groups that are being examined and the variety of populations studied, thereby making interpretation and recommendations somewhat difficult and relative. Each of these factors must therefore be considered when making conclusions based on research studies. Several systematic reviews of stretching are available to provide general recommendations.[3-6]

The effectiveness of stretching is usually reported as an increase in joint ROM (usually passive ROM); for example, knee or hip ROM is used to determine changes in hamstring length. Static stretching often results in increases in joint ROM. Interestingly, the increase in ROM may not be caused by increased length (decreased tension) of the muscle; rather, the subject may simply have an increased tolerance to stretching. Increases in muscle length are measured by "extensibility", usually where a standardized load is placed on the limb and joint motion is measured. Increased tolerance to stretch is quantified by measuring the joint range of motion with a non-standardized load. This is an important question to consider when interpreting the results of studies: was the improvement based on actual muscle lengthening (ie, increased extensibility) or just an increase in tolerance to stretch?[7] Chan and colleagues[8] showed that 8 weeks of static stretching increased muscle extensibility; however, most static stretching training studies show an increase in ROM due to an increase in stretch tolerance (ability to withstand more stretching force), not extensibility (increased muscle length).[9-12]

Static stretching is effective at increasing ROM. The greatest change in ROM with a static stretch occurs between 15 and 30 seconds;[13,14] most authors suggest that 10 to 30 seconds is sufficient for increasing flexibility.[14-17] In addition, no increase in muscle elongation occurs after 2 to 4 repetitions.[18]

Unfortunately, however, static stretching as part of a warm-up immediately prior to exercise has been shown detrimental to dynamometer-measured muscle strength[19-29] and performance in running and jumping.[30-39] The loss of strength resulting from acute static stretching has been termed, "stretch-induced strength loss."[3] The specific causes for this type of stretch induced loss in strength is not clear; some suggest neural factors,[31,40] while others suggest mechanical factors.[19,23] Furthermore, the strength loss may be related to the length of the muscle at the time of testing[23] or the duration of the stretch.[25] Interestingly, a maximal contraction of the muscle being stretched before static stretching may decrease stretch-induced strength loss.[41]

Table 2. *Stretching Techniques Comparative Matrix, based on studies comparing at least 2 techniques.*

Technique		Static			Dynamic			Pre-Contraction	
Outcome		↑	↓	NSD*	↑	↓	NSD**	↑	↓
ROM	Acute	O'Sullivan [85]		de Weijer [54] (↑) young [55] (nc) Curry [56] (↑) Beedle [57] (↑)	Nelson [86]		Chow [76] (↑) Sullivan [78](↑) Condon [45] (↑) Feland [42] (↑) Ford [80] (↑) Godges [81] (↑) Marek [83] (↑) Caplan [82] (↑)	Ferber [67] Weng [68] Worrell [69] Wallin [70] Tanigawa [71] Sady [72] Cornelius [73] Funk [74] Moore [48] Osternig [50] Fasen [75]	
	Training	Davis [87]		Webright [88] (↑) Sainz [89] (↑) Winters [90] (↑) Chow [76] (↑) Nelson [86] (↑)	Meroni [91]		Shadmehr [84] (↑) Yukatsir [77] (↑)		
Strength	Acute		Herda [19]		Yamaguchi [62] Manoel [27]		Babult [26] (↓) Marek [83] (↓)	Worrell [69]	
	Training		Sekir [29]						
Performance	Acute	OConnor [92]	Young [33] Taylor [38] Fletcher [34]	Young [55] (nc) Wallmann [58] (nc) McMillian [59] (nc) Dalrymple [60] (nc) Torres [61] (nc)	Fletcher [65] Hough [31] Ce [32] Pearce [63] Fletcher [34]		Caplan [82] (↑) Godges [81] (↑)		
	Training	Bandy [93]			Herman [64]		Yuktasir [77] (nc)		

*No significant difference between static and dynamic stretching (nc = no change; ↑ = improved; ↓ = diminished)
**No significant difference between pre-contraction stretch and static stretching

Contraction of a muscle performed immediately before it is stretched is effective at increasing ROM. While most pre-contraction stretching is associated with PNF-type contract-relax or hold-relax techniques using 75 to 100% of a maximal contraction, Feland et al[42] showed that submaximal contractions of 20 or 60% are just as effective, thus supporting the effectiveness of post-isometric relaxation stretching. Interestingly, ROM increases are seen bilaterally with pre-contraction stretching,[43] supporting a possible neurologic phenomenon.

The specific phenomenon associated with an increase in flexibility following a pre-stretch contraction remains unclear. Many have assumed that muscle experiences a refractory period after contraction known as 'autogenic inhibition', where muscle relaxes due to neuro-reflexive mechanisms, thus increasing muscle length. Interestingly, electromyographic (EMG) studies have shown that muscle activation remains the same[7,44] or increases after contraction.[45-50] Some researchers have speculated that the associated increases in ROM are related to increased stretch tolerance[51,52] rather than a neurological phenomenon. Some researchers suggest that Hoffman reflexes (H-reflexes) are depressed with a pre-contraction stretch.[45,53] The H-reflex is an EMG measurement of the level of excitability of a muscle: lower H-reflexes are associated with lower excitability. It is possible that the lowered excitability levels may allow muscle to relax through the gamma motor neuron system despite an increased activation through the alpha system. Obviously, more research is needed to investigate these neurological effects of pre-contraction stretching.

COMPARING STRETCHING MODES

Several authors have compared static and dynamic stretching on ROM, strength, and performance (See Table 2). Both static and dynamic stretching appear equally effective at improving ROM acutely or over time with training.[54-57] Several authors have found no improvement in performance when comparing static and dynamic stretching.[55,58-61] In contrast to static stretching, dynamic stretching is not associated with strength or performance deficits, and actually has been shown to improve dynamometer-measured power[27,62] as well as jumping and running performance.[31,32,34,56,59,63,64]

The literature is conflicting regarding the effects of warm-up stretching prior to exercise. Static and dynamic warm-ups are equally effective at increasing ROM prior to exercise.[56,57] Some researchers report static stretching after warm-up decreases performance,[32,33,35] while others report no change or an increase in performance.[32,38,64,65] While static stretching is generally followed by an immediate decrease in strength, static stretching performed before[66] or after warm-up[57] does not decrease strength. The volume of static stretching may also affect performance: Robbins et al[37] reported that 4 repetitions of 15-second holds of static stretching did not affect vertical jump, while 6 repetitions reduced performance.

A pre-stretch contraction has been associated with greater acute gains in ROM compared to static stretching in many studies;[48,50,67-75] however, several studies show similar increases in ROM[45,76-84] and performance[77,81,82,84] when comparing pre-contraction stretching and static stretching. Both acute static stretching and pre-contraction stretching have been shown to decrease strength.[26,83]

RECOMMENDATIONS

Static, dynamic, and pre-contraction stretching are all effective methods of increasing flexibility and muscle extensibility; however, these modes may be more effective in specific populations. Several authors have noted an individualized response to stretching;[48,56,60] therefore, stretching programs may need to be individualized.

Well-rounded Exercise Programs

For a general fitness program, the American College of Sports Medicine[1] recommends static stretching for most individuals that is preceded by an active warm-up, at least 2 to 3 days per week. Each stretch should be held 15-30 seconds and repeated 2 to 4 times.

Many exercise studies on older adults include stretching exercises as part of a well-rounded exercise program. Unfortunately, there is no clear dose-response for flexibility training in older adults because stretching interventions are often combined with strengthening, balance, and cardiovascular activities, making it difficult to isolate stretching's effectiveness. Older adults may need longer stretch times than the recommended 15 to 30 seconds; Feland et al[85] found that 60-second holds of static stretches were associated with greater improvements in hamstring flexibility in older adults compared to shorter duration holds. Ten weeks of static stretching of the trunk muscles was able to increase spinal mobility (combined flexion and extension ROM) in older adults.[86] Static stretching of the hip flexors and extensors may also improve gait in older adults.[87] Furthermore, the effectiveness of type of stretching seems to be related to age and sex: men and older adults under 65 years respond better to contract-relax stretching, while women and older adults over 65 benefit more from static stretching.

Warm-up for Sports and Exercise

Stretching performed as part of a warm-up prior to exercise is thought to reduce passive stiffness and increase range of movement during exercise. In general, it appears that static stretching is most beneficial for athletes requiring flexibility for their sports (e.g. gymnastics, dance, etc.). Dynamic stretching may be better suited for athletes requiring running or jumping performance[30] during their sport such as basketball players or sprinters.

Stretching has not been shown to be effective at reducing the incidence of overall injuries.[88] While there is some evidence of stretching reducing musculotendinous injuries,[88] more evidence is needed to determine if stretching programs alone can reduce muscular injuries.[3]

Rehabilitation

Stretching is a common intervention performed during rehabilitation. Stretching is prescribed to increase muscle length and ROM, or to align collagen fibers during healing muscle.

Several researchers have investigated different muscle stretching techniques on subjects with tight hamstrings. Some authors report that both static and pre-contraction stretching are able increase acute hamstring flexibility,[47,54,89] while others suggest static stretching[90-92] or PNF stretching[10,71] are more effective. It appears that 6 to 8 weeks of static stretching is sufficient to increase hamstring length.[14,93,94]

Stretching is effective for the treatment of orthopedic conditions or injury; however, as with other populations, outcomes may be based on the individual patient. Static stretching has been shown to be more effective than dynamic stretching for those recovering from hamstring strains.[95] In addition, it has been reported that athletes with hamstring strains recover faster by performing more intensive stretching than by performing less intensive stretching.[96] Patients with knee osteoarthritis can benefit from static stretching to increase knee ROM;[97] however, PNF stretching may be more effective.[68] Chow et al reported that total knee replacement patients benefited from 2 weeks of either static, dynamic or PNF stretching to increase ROM.[76]

Stretching is often included in physical therapy interventions for management of shoulder, back and knee pain. Despite positive outcomes of these types of studies and improvements in flexibility, it is difficult to isolate the effectiveness of the stretching component of the total treatment plan because the protocols usually include strengthening and other interventions in addition to stretching.

A recent review[98] of stretching for contractures found no improvement in joint mobility orthopedic-related contractures. Orthopedic contractures often result from shortness in non-contractile tissues such as capsuloligamentous structures rather than muscle tightness.

Researchers have shown that 12 months of stretching is as effective as strengthening exercises or manual therapy in patients with chronic neck pain.[99,100] In addition, patients with chronic musculoskeletal pain demonstrate an increased tolerance to stretch after 3 weeks of static stretching.[12] Lewit and Simons[101] reported an immediate 94% reduction in pain associated with trigger points after applying a PIR technique. These studies support stretching in pain management programs.

Stretching appears to have no benefit for neurological patients who have had a stroke or spinal cord injury.[98] Because of a strong neurological component and long-standing muscle shortening associated with these conditions, it's no surprise that simple muscle stretching techniques are not effective.

SUMMARY

The benefits of stretching seem to be individual to the population studied. Several factors must be considered when making clinical recommendations from the literature. To increase ROM, all types of stretching are effective, although PNF-type stretching may be more effective for immediate gains. To avoid decrease in strength and performance that may occur in athletes due to static stretching before competition or activity, dynamic stretching is recommended for warm-up. Older adults over 65 years old should incorporate static stretching into an exercise regimen. A variety of orthopedic patients can benefit from both static and pre-contraction stretching, although patients with joint contractures do not appear to benefit from stretching.

REFERENCES

1. Medicine ACoS. *ACSM's guidelines for exercise testing and prescription*. 7th ed. Baltimore: Lippincot Williams Wilkins; 2006.
2. Page P, Frank CC, Lardner R. *Assessment and treatment of muscle imbalance: The Janda Approach*. Champaign, IL: Human Kinetics; 2010.
3. McHugh MP, Cosgrave CH. To stretch or not to stretch: the role of stretching in injury prevention and performance. *Scandinavian journal of medicine & science in sports.* Apr 2010;20(2):169-181.
4. Small K, Mc NL, Matthews M. 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.* Jul 2008;16(3):213-231.
5. Thacker SB, Gilchrist J, Stroup DF, Kimsey CD, Jr. The impact of stretching on sports injury risk: a systematic review of the literature. *Med Sci Sports Exerc.* Mar 2004;36(3):371-378.
6. Katalinic OM, Harvey LA, Herbert RD, Moseley AM, Lannin NA, Schurr K. Stretch for the treatment and prevention of contractures. *Cochrane Database Syst Rev.* 2010(9):CD007455.
7. Magnusson SP, Simonsen EB, Aagaard P, Sorensen H, Kjaer M. A mechanism for altered flexibility in human skeletal muscle. *J Physiol.* Nov 15 1996;497 (Pt 1):291-298.
8. Chan SP, Hong Y, Robinson PD. Flexibility and passive resistance of the hamstrings of young adults using two different static stretching protocols. *Scandinavian journal of medicine & science in sports.* Apr 2001;11(2):81-86.
9. Ylinen J, Kankainen T, Kautiainen H, Rezasoltani A, Kuukkanen T, Hakkinen A. Effect of stretching on hamstring muscle compliance. *J Rehabil Med.* Jan 2009;41(1):80-84.
10. Halbertsma JP, Goeken LN. Stretching exercises: effect on passive extensibility and stiffness in short hamstrings of healthy subjects. *Arch Phys Med Rehabil.* Sep 1994;75(9):976-981.

11. Ben M, Harvey LA. Regular stretch does not increase muscle extensibility: a randomized controlled trial. *Scandinavian journal of medicine & science in sports.* Feb 2010;20(1):136-144.
12. Law RY, Harvey LA, Nicholas MK, Tonkin L, De Sousa M, Finniss DG. Stretch exercises increase tolerance to stretch in patients with chronic musculoskeletal pain: a randomized controlled trial. *Phys Ther.* Oct 2009;89(10):1016-1026.
13. McHugh MP, Magnusson SP, Gleim GW, Nicholas JA. Viscoelastic stress relaxation in human skeletal muscle. *Med Sci Sports Exerc.* Dec 1992;24(12):1375-1382.
14. Bandy WD, Irion JM. The effect of time on static stretch on the flexibility of the hamstring muscles. *Phys Ther.* Sep 1994;74(9):845-850; discussion 850-842.
15. Bandy WD, Irion JM, Briggler M. The effect of time and frequency of static stretching on flexibility of the hamstring muscles. *Phys Ther.* Oct 1997;77(10):1090-1096.
16. Ayala F, de Baranda Andujar PS. Effect of 3 different active stretch durations on hip flexion range of motion. *J Strength Cond Res.* Feb 2010;24(2):430-436.
17. Cipriani D, Abel B, Pirrwitz D. A comparison of two stretching protocols on hip range of motion: implications for total daily stretch duration. *J Strength Cond Res.* May 2003;17(2):274-278.
18. Taylor DC, Dalton JD, Jr., Seaber AV, Garrett WE, Jr. Viscoelastic properties of muscle-tendon units. The biomechanical effects of stretching. *Am J Sports Med.* May-Jun 1990;18(3):300-309.
19. 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.* May 2008;22(3):809-817.
20. Nelson AG, Guillory IK, Cornwell C, Kokkonen J. Inhibition of maximal voluntary isokinetic torque production following stretching is velocity-specific. *J Strength Cond Res.* May 2001;15(2):241-246.
21. Nelson AG, Kokkonen J, Arnall DA. Acute muscle stretching inhibits muscle strength endurance performance. *J Strength Cond Res.* May 2005;19(2):338-343.
22. 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.* Aug 2004;36(8):1389-1396.
23. McHugh MP, Nesse M. Effect of stretching on strength loss and pain after eccentric exercise. *Med Sci Sports Exerc.* Mar 2008;40(3):566-573.
24. Brandenburg JP. Duration of stretch does not influence the degree of force loss following static stretching. *J Sports Med Phys Fitness.* Dec 2006;46(4):526-534.
25. Siatras TA, Mittas VP, Mameletzi DN, Vamvakoudis EA. The duration of the inhibitory effects with static stretching on quadriceps peak torque production. *J Strength Cond Res.* Jan 2008;22(1):40-46.
26. Babault N, Kouassi BY, Desbrosses K. Acute effects of 15 min static or contract-relax stretching modalities on plantar flexors neuromuscular properties. *J Sci Med Sport.* Mar 2010;13(2):247-252.
27. Manoel ME, Harris-Love MO, Danoff JV, Miller TA. Acute effects of static, dynamic, and proprioceptive neuromuscular facilitation stretching on muscle power in women. *J Strength Cond Res.* Sep 2008;22(5):1528-1534.
28. Fowles JR, Sale DG, MacDougall JD. Reduced strength after passive stretch of the human plantarflexors. *J Appl Physiol.* Sep 2000;89(3):1179-1188.
29. 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. *Scandinavian journal of medicine & science in sports.* Apr 2010;20(2):268-281.
30. Behm DG, Kibele A. Effects of differing intensities of static stretching on jump performance. *Eur J Appl Physiol.* Nov 2007;101(5):587-594.
31. Hough PA, Ross EZ, Howatson G. Effects of dynamic and static stretching on vertical jump performance and electromyographic activity. *J Strength Cond Res.* Mar 2009;23(2):507-512.
32. Ce E, Margonato V, Casasco M, Veicsteinas A. Effects of stretching on maximal anaerobic power: the roles of active and passive warm-ups. *J Strength Cond Res.* May 2008;22(3):794-800.
33. 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.* Sep 2006;46(3):403-411.
34. Fletcher IM, Anness R. The acute effects of combined static and dynamic stretch protocols on fifty-meter sprint performance in track-and-field athletes. *J Strength Cond Res.* Aug 2007;21(3):784-787.
35. Kistler BM, Walsh MS, Horn TS, Cox RH. The acute effects of static stretching on the sprint performance of collegiate men in the 60- and 100-m dash after a dynamic warm-up. *J Strength Cond Res.* Sep 2010;24(9):2280-2284.
36. Wilson JM, Hornbuckle LM, Kim JS, et al. Effects of static stretching on energy cost and running endurance performance. *J Strength Cond Res.* Sep 2010;24(9):2274-2279.

37. Robbins JW, Scheuermann BW. Varying amounts of acute static stretching and its effect on vertical jump performance. *J Strength Cond Res.* May 2008;22(3):781-786.

38. Taylor KL, Sheppard JM, Lee H, Plummer N. Negative effect of static stretching restored when combined with a sport specific warm-up component. *J Sci Med Sport.* Nov 2009;12(6):657-661.

39. Sayers AL, Farley RS, Fuller DK, Jubenville CB, Caputo JL. The effect of static stretching on phases of sprint performance in elite soccer players. *J Strength Cond Res.* Sep 2008;22(5):1416-1421.

40. Behm D, Button DC, Butt JC. Factors affecting force loss with prolonged stretching. *Can J Appl Physiol.* 2001;26(3):262-272.

41. Kay AD, Blazevich AJ. Concentric muscle contractions before static stretching minimize, but do not remove, stretch-induced force deficits. *J Appl Physiol.* Mar 2010;108(3):637-645.

42. Feland JB, Marin HN. Effect of submaximal contraction intensity in contract-relax proprioceptive neuromuscular facilitation stretching. *Br J Sports Med.* Aug 2004;38(4):E18.

43. Markos PD. Ipsilateral and contralateral effects of proprioceptive neuromuscular facilitation techniques on hip motion and electromyographic activity. *Phys Ther.* Nov 1979;59(11):1366-1373.

44. Cornelius WL. Stretch evoked EMG activity by isometric coontraction and submaximal concentric contraction. *Athletic Training.* 1983;18:106-109.

45. Condon SM, Hutton RS. Soleus muscle electromyographic activity and ankle dorsiflexion range of motion during four stretching procedures. *Phys Ther.* Jan 1987;67(1):24-30.

46. Mitchell UH, Myrer JW, Hopkins JT, Hunter I, Feland JB, Hilton SC. Neurophysiological reflex mechanisms' lack of contribution to the success of PNF stretches. *J Sport Rehabil.* 2009;18:343-357.

47. Youdas JW, Haeflinger KM, Kreun MK, Holloway AM, Kramer CM, Hollman JH. The efficacy of two modified proprioceptive neuromuscular facilitation stretching techniques in subjects with reduced hamstring muscle length. *Physiother Theory Pract.* May 2010;26(4):240-250.

48. Moore MA, Hutton RS. Electromyographic investigation of muscle stretching techniques. *Med Sci Sports Exerc.* 1980;12(5):322-329.

49. Osternig LR, Robertson R, Troxel R, Hansen P. Muscle activation during proprioceptive neuromuscular facilitation (PNF) stretching techniques. *American journal of physical medicine.* Oct 1987;66(5):298-307.

50. Osternig LR, Robertson RN, Troxel RK, Hansen P. Differential responses to proprioceptive neuromuscular facilitation (PNF) stretch techniques. *Med Sci Sports Exerc.* Feb 1990;22(1):106-111.

51. Mahieu NN, Cools A, De Wilde B, Boon M, Witvrouw E. Effect of proprioceptive neuromuscular facilitation stretching on the plantar flexor muscle-tendon tissue properties. *Scandinavian journal of medicine & science in sports.* Aug 2009;19(4):553-560.

52. Mitchell UH, Myrer JW, Hopkins JT, Hunter I, Feland JB, Hilton SC. Acute stretch perception alteration contributes to the success of the PNF "contract-relax" stretch. *J Sport Rehabil.* May 2007;16(2):85-92.

53. Moore MA, Kukulka CG. Depression of Hoffmann reflexes following voluntary contraction and implications for proprioceptive neuromuscular facilitation therapy. *Phys Ther.* Apr 1991;71(4):321-329; discussion 329-333.

54. de Weijer VC, Gorniak GC, Shamus E. The effect of static stretch and warm-up exercise on hamstring length over the course of 24 hours. *J Orthop Sports Phys Ther.* Dec 2003;33(12):727-733.

55. Young W, Clothier P, Otago L, Bruce L, Liddell D. Acute effects of static stretching on hip flexor and quadriceps flexibility, range of motion and foot speed in kicking a football. *J Sci Med Sport.* Mar 2004;7(1):23-31.

56. Curry BS, Chengkalath D, Crouch GJ, Romance M, Manns PJ. Acute effects of dynamic stretching, static stretching, and light aerobic activity on muscular performance in women. *J Strength Cond Res.* Sep 2009;23(6):1811-1819.

57. Beedle BB, Mann CL. A comparison of two warm-ups on joint range of motion. *J Strength Cond Res.* Aug 2007;21(3):776-779.

58. Wallmann HW, Mercer JA, Landers MR. 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.* May 2008;22(3):787-793.

59. McMillian DJ, Moore JH, Hatler BS, Taylor DC. Dynamic vs. static-stretching warm up: the effect on power and agility performance. *J Strength Cond Res.* Aug 2006;20(3):492-499.

60. Dalrymple KJ, Davis SE, Dwyer GB, Moir GL. Effect of static and dynamic stretching on vertical jump performance in collegiate women volleyball players. *J Strength Cond Res.* Jan 2010;24(1):149-155.

61. Torres EM, Kraemer WJ, Vingren JL, et al. Effects of stretching on upper-body muscular performance. *J Strength Cond Res.* Jul 2008;22(4):1279-1285.

62. Yamaguchi T, Ishii K. Effects of static stretching for 30 seconds and dynamic stretching on leg extension power. *J Strength Cond Res.* Aug 2005;19(3):677-683.

63. Pearce AJ, Kidgell DJ, Zois J, Carlson JS. Effects of secondary warm up following stretching. *Eur J Appl Physiol.* Jan 2009;105(2):175-183.

64. Herman SL, Smith DT. Four-week dynamic stretching warm-up intervention elicits longer-term performance benefits. *J Strength Cond Res.* Jul 2008;22(4):1286-1297.

65. Fletcher IM, Jones B. The effect of different warm-up stretch protocols on 20 meter sprint performance in trained rugby union players. *J Strength Cond Res.* Nov 2004;18(4):885-888.

66. Behm DG, Bambury A, Cahill F, Power K. Effect of acute static stretching on force, balance, reaction time, and movement time. *Med Sci Sports Exerc.* Aug 2004;36(8):1397-1402.

67. Ferber R, Gravelle DC, Osternig LR. Effect of proprioceptive neuromuscular facilitation stretch techniques on trained and untrained older adults. *Journal of aging and physical activity.* 2002;10:132-142.

68. Weng MC, Lee CL, Chen CH, et al. Effects of different stretching techniques on the outcomes of isokinetic exercise in patients with knee osteoarthritis. *Kaohsiung J Med Sci.* Jun 2009;25(6):306-315.

69. Worrell TW, Smith TL, Winegardner J. Effect of hamstring stretching on hamstring muscle performance. *J Orthop Sports Phys Ther.* Sep 1994;20(3):154-159.

70. Wallin D, Ekblom B, Grahn R, Nordenborg T. Improvement of muscle flexibility. A comparison between two techniques. *Am J Sports Med.* Jul-Aug 1985;13(4):263-268.

71. Tanigawa MC. Comparison of the hold-relax procedure and passive mobilization on increasing muscle length. *Phys Ther.* Jul 1972;52(7):725-735.

72. Sady SP, Wortman M, Blanke D. Flexibility training: ballistic, static or proprioceptive neuromuscular facilitation? *Arch Phys Med Rehabil.* Jun 1982;63(6):261-263.

73. Cornelius WL, Ebrahim K, Watson J, Hill DW. The effects of cold application and modified PNF stretching techniques on hip joint flexibility in college males. *Res Q Exerc Sport.* Sep 1992;63(3):311-314.

74. Funk DC, Swank AM, Mikla BM, Fagan TA, Farr BK. Impact of prior exercise on hamstring flexibility: a comparison of proprioceptive neuromuscular facilitation and static stretching. *J Strength Cond Res.* Aug 2003;17(3):489-492.

75. Fasen JM, O'Connor AM, Schwartz SL, et al. A randomized controlled trial of hamstring stretching: comparison of four techniques. *J Strength Cond Res.* Mar 2009;23(2):660-667.

76. Chow TP, Ng GY. Active, passive and proprioceptive neuromuscular facilitation stretching are comparable in improving the knee flexion range in people with total knee replacement: a randomized controlled trial. *Clin Rehabil.* Oct 2010;24(10):911-918.

77. Yuktasir B, Kaya F. Investigation into the long-term effects of static and PNF stretching exercises on range of motion and jump performance. *J Bodyw Mov Ther.* Jan 2009;13(1):11-21.

78. Sullivan MK, Dejulia JJ, Worrell TW. Effect of pelvic position and stretching method on hamstring muscle flexibility. *Med Sci Sports Exerc.* Dec 1992;24(12):1383-1389.

79. Feland JB, Myrer JW, Merrill RM. Acute changes in hamstring flexibility: PNF versus static stretch in senior athletes. *Physical Therapy in Sport.* 2001;2(4):186-193.

80. Ford P, McChesney J. Duration of maintained hamstring ROM following termination of three stretching protocols. *J Sport Rehabil.* Feb 2007;16(1):18-27.

81. Godges JJ, Macrae H, Longdon C, Tinberg C, Macrae PG. The effects of two stretching procedures on hip range of motion and gait economy. *J Orthop Sports Phys Ther.* 1989;10(9):350-357.

82. Caplan N, Rogers R, Parr MK, Hayes PR. The effect of proprioceptive neuromuscular facilitation and static stretch training on running mechanics. *J Strength Cond Res.* Jul 2009;23(4):1175-1180.

83. 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.* Jun 2005;40(2):94-103.

84. Shadmehr A, Hadian MR, Naiemi SS, Jalaie S. Hamstring flexibility in young women following passive stretch and muscle energy technique. *J Back Musculoskelet Rehabil.* 2009;22(3):143-148.

85. Feland JB, Myrer JW, Schulthies SS, Fellingham GW, Measom GW. The effect of duration of stretching of the hamstring muscle group for increasing range of motion in people aged 65 years or older. *Phys Ther.* May 2001;81(5):1110-1117.

86. Rider RA, Daly J. Effects of flexibility training on enhancing spinal mobility in older women. *J Sports Med Phys Fitness.* Jun 1991;31(2):213-217.

87. Rodacki AL, Souza RM, Ugrinowitsch C, Cristopoliski F, Fowler NE. Transient effects of stretching

exercises on gait parameters of elderly women. *Man Ther.* Apr 2009;14(2):167-172.

88. Small K, Mc Naughton L, Matthews M. 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.* 2008;16(3):213-231.

89. Webright WG, Randolph BJ, Perrin DH. Comparison of nonballistic active knee extension in neural slump position and static stretch techniques on hamstring flexibility. *J Orthop Sports Phys Ther.* Jul 1997;26(1): 7-13.

90. Davis DS, Ashby PE, McCale KL, McQuain JA, Wine JM. The effectiveness of 3 stretching techniques on hamstring flexibility using consistent stretching parameters. *J Strength Cond Res.* Feb 2005;19(1): 27-32.

91. Depino GM, Webright WG, Arnold BL. Duration of maintained hamstring flexibility after cessation of an acute static stretching protocol. *J Athl Train.* Jan 2000;35(1):56-59.

92. Bandy WD, Irion JM, 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.* Apr 1998;27(4):295-300.

93. Ferreira GN, Teixeira-Salmela LF, Guimaraes CQ. Gains in flexibility related to measures of muscular performance: impact of flexibility on muscular performance. *Clin J Sport Med.* Jul 2007;17(4): 276-281.

94. Aquino CF, Fonseca ST, Goncalves GG, Silva PL, Ocarino JM, Mancini MC. Stretching versus strength training in lengthened position in subjects with tight hamstring muscles: a randomized controlled trial. *Man Ther.* Feb 2010;15(1):26-31.

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

96. Malliaropoulos N, Papalexandris S, Papalada A, Papacostas E. The role of stretching in rehabilitation of hamstring injuries: 80 athletes follow-up. *Med Sci Sports Exerc.* May 2004;36(5):756-759.

97. Reid DA, McNair PJ. Passive force, angle, and stiffness changes after stretching of hamstring muscles. *Med Sci Sports Exerc.* Nov 2004;36(11):1944-1948.

98. Katalinic OM, Harvey LA, Herbert RD, Moseley AM, Lannin NA, Schurr K. Stretch for the treatment and prevention of contractures. *Cochrane Database Syst Rev.* 2010;9:CD007455.

99. Hakkinen A, Kautiainen H, Hannonen P, Ylinen J. Strength training and stretching versus stretching only in the treatment of patients with chronic neck pain: a randomized one-year follow-up study. *Clin Rehabil.* Jul 2008;22(7):592-600.

100. Ylinen J, Kautiainen H, Wiren K, Hakkinen A. Stretching exercises vs manual therapy in treatment of chronic neck pain: a randomized, controlled cross-over trial. *J Rehabil Med.* Mar 2007;39(2):126-132.

101. Lewit K, Simons DG. Myofascial pain: relief by post-isometric relaxation. *Arch Phys Med Rehabil.* Aug 1984;65(8):452-456.