Peristaltic Pulse Dynamic Compression of the Lower Extremity Enhances Flexibility

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Abstract

Sands, WA, Murray, MB, Murray, SR, McNeal, JR, Mizuguchi, S, Sato, K, and Stone, MH. Peristaltic pulse dynamic compression of the lower extremity enhances flexibility. *J Strength Cond Res* 28(4): 1058–1064, 2014–This study investigated the effects of peristaltic pulse dynamic compression (PPDC) on range-of-motion (ROM) changes in forward splits. Serious stretching usually involves discomfort and large time investments. Tissue structural changes and stretch tolerance have heretofore been considered the primary mechanisms of enhanced ROM. The PPDC treatment was computer controlled. Circumferential and segmented inflation pressures were induced by feet to hip leggings. Nine subjects, experienced in stretching and a forward split position, volunteered. The subjects were familiarized with the protocol and randomly assigned to an initial condition: experimental (PPDC), or control (CONT). The study involved a crossover design. Second conditions were tested within 1–5 days. All tests were 2 trials of right and left forward splits. Split flexibility was assessed by measuring the height of the anterior superior iliac spine of the rear leg from the floor. Pelvic posture was controlled by rear leg position. The PPDC treatment was 15 minutes of seated PPDC. The control condition was the same except that leggings were not inflated. Pressures of 5 cells in the leggings were set at factory defaults, 70 mm Hg sequentially. Difference score results indicated statistically significant ($p \leq 0.05$) differences by condition and the condition by leg interaction. The rapid acute changes in ROM (PPDC: right 25.3%, left 33.3%; CONT: right 12.2%, left 1.0%) support the premise that changes in ROM were dependent on mechanisms other than tissue structural changes and/or stretch tolerance. PPDC provides a means of rapidly enhancing acute ROM requiring less discomfort and time.

Key Words stretch tolerance, thixotropy, acute effects

Introduction

Flexibility is one of the pillars of physical fitness and is a dominant characteristic in gymnasts, divers, martial artists, figure skaters, and others (31). "Flexibility has been defined as the range-of-motion at a single joint or a series of joints and reflects the ability of the muscle-tendon units to elongate within the physical restrictions of the joint" (13). Flexibility is the outcome, which is obtained via the mechanism of stretching. "Slow stretching," more commonly called "static stretching," is the most common modality for improving range of motion (ROM) in a joint (31). Static stretch positions are also the means by which flexibility is most commonly measured (10). Most measurements of flexibility changes are angular positions of adjoining limbs or distances of anatomical landmarks to specific points (10).

Several new methods that augment stretching have been introduced in recent years. These new methods call into question the widely accepted idea that flexibility is merely a matter of stretching biomaterials, such as muscle, ligament, and tendon. For example, long- and short-term changes in ROM have been demonstrated, with some conflicting results, using vibration (17,18,37,41,42), learning (19,21–23,25–27,43), general anesthesia (21), and heat or cold (3,6,7,9,32).

Athletes have relied on focused stretching, gradual development of stretch tolerance (22,25,27), and sport- and exercise-specific extreme ROM positions to improve flexibility. Stretching can be uncomfortable, even painful. Sports that place a high premium on extreme ROM positions often encourage athletes to assume painful positions as a part of stretching. Injuries caused by stretching are rare but do occur (31). New methods of enhancing stretching may reduce discomfort while enhancing time efficiency and thereby serve as an asset to those athletes who need to develop flexibility through stretching (16,17,31,38).

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Peristaltic pulse dynamic compression (PPDC) is an artificial process of rhythmic applications of circumferential pressures to a limb in a peristaltic (i.e., sequential compression) manner in a distal to proximal direction. The technology is normally used to promote blood flow and remove waste products from patients suffering from lymphedema and for athlete recovery. Athletes at the U.S. Olympic Training Center, Recovery Center used the donated devices primarily for recovery purposes. In the midst of studying these devices, it became apparent that the athletes were experiencing an unusual and unexpected rapid and acute increase in flexibility following use. The athletes repeatedly and enthusiastically reported and demonstrated to one of the authors that they could suddenly achieve lower extremity positions that they had never achieved in the past. The following study is a response to the serendipitous observation of Olympic-level athletes and their experiences with PPDC. The purpose of this study was to investigate the effects of PPDC on subsequent ROM changes in left and right forward splits in trained subjects. We hypothesized that the PPDC would increase ROM over the control condition.

Methods

Experimental Approach to the Problem

Can PPDC of the lower extremities improve the acute forward splits flexibility among athletes highly experienced in stretching? This study involved a simple comparison of forward split ROM in the same female athletes on different days who were either treated or not treated with a PPDC device before flexibility testing. A pain rating was used to assess the athlete's motivation by her willingness to tolerate more pain as she more aggressively pursued a lower split position. Increased ROM would be confirmed by showing a forward split position that was lower following PPDC treatment than the CONT treatment.

Subjects

Nine female subjects (mean ± *SD*: age 19.11 ± 1.1 years; height 168.9 ± 8.0 cm; mass 59.9 ± 9.1 kg; years dancing 12.3 ± 5.0 years) from the Colorado Mesa University's Department of Theatre Arts, experienced in both stretching and the forward split position, volunteered to participate in this study. The study was approved by the Colorado Mesa University and the East Tennessee State University Institutional Review Boards for the Study of Human Subjects. The subjects were informed verbally and in writing regarding the study requirements. None of the participants were under 18 years of age. All signed an IRB approved consent form prior to participation. The athletes were familiarized with the laboratory testing protocol and rehearsed the testing protocol before the start of data collection. These athletes were already familiar with stretching, specifically the forward split, as a part of their training and performance.

Procedures

PPDC was provided by a device consisting of 2 inflatable leggings connected to a computer-controlled air pump via plastic tubing (NormaTec, Newton, MA, USA) (Figure 1). Each legging consisted of 5 inflatable PPDC cells or chambers that were connected to hoses near the waist. The subjects put the leggings on like a typical pair of pants. The computerized air pump was able to inflate each cell with a different pressure, cyclically inflating and partially deflating. The pump was set to factory defaults of 70 mm Hg peak pressure per cell, 30-second rest, and inflations sequencing from distal to proximal. The pump includes a computerized timer and a repeatable PPDC pressure sequence.

Flexibility measurement involved placing the subject in her lowest forward split position and measuring the height of the anterior superior iliac spine (ASIS) of the pelvis of the rear leg from the floor (Figure 2). This position and approach were chosen based on previous experience (18,29,39,41) and ecological relevance of this position to athlete performance. The shank of the flexed rear leg was placed vertically against the side of a matted block to control for pelvic alignment. A 5-minute warm-up (0.5 kp) was conducted on a laboratory standard Monark (Chicago, IL, USA) stationary cycle ergometer. The ergometer seat was adjusted to fit the subject, and the seat height was recorded and repeated during the second test session. The second test session occurred within 1 to 5 days of the first at the same time of day, plus-or-minus 2 hours.

The subjects were familiarized with the laboratory, instrumentation and equipment, and study procedures before data collection. The subjects reported to the laboratory by appointment 2 additional times. The PPDC-first or CONT-first conditioning and the order of the forward split test sides (right or left) were randomly assigned. Subjects were barefoot and wore a leotard or shorts and t-shirt. The test protocol, following familiarization, included the measurement of height and mass and querying information regarding age and years of stretching experience. The subject then performed a 5-minute warm-up on the Monark ergometer, and 3 minutes of self-selected warm-up activities before the pretest of forward split ROM. Following the pretest split measurements, the subject underwent either a PPDC treatment or a CONT treatment, both involving the PPDC device. In the PPDC condition, the device was turned on, and the PPDC treatment proceeded under computer control for 15 minutes. In the CONT condition, the subject wore the PPDC leggings and sat for 15 minutes in the same position as the PPDC condition (seated with feet elevated on a facing chair; Figure 1) but with the device turned off. The time between treatment and testing in individual test sessions was less than 30 seconds. Following the PPDC or CONT conditions, the subject made a subsequent appointment and repeated the procedures above and the remaining PPDC or CONT condition. The second test of the remaining condition took place from 1 to 5 days after the pretest and plus or minus 2 hours.

The split test consisted of 2 trials of lowering to a forward split with the rear leg flexed 90° at the knee and the rear

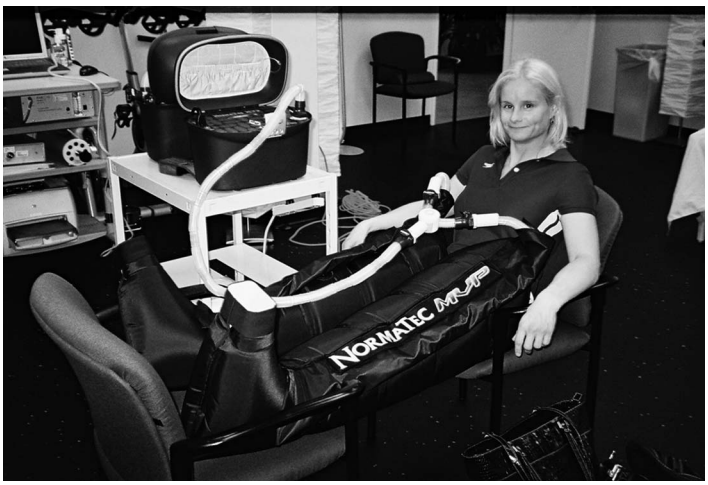

Figure 1. Experimental condition using the peristaltic pulse dynamic compression leggings. Note that the leggings are inflated and applying circumferential pressure to 5 cells along the lengths of the legs.

shank placed vertically against a matted gymnastics block. The rear leg position helped prevent the turning of the pelvis in the direction of the rear leg via passive insufficiency of the rear leg hip flexors (30,40–42). In addition, the subjects were coached to achieve a pelvic position that was as "square" as possible. The "square" position refers to the idea that the frontal plane of the pelvis is perpendicular to the sagittal plane positions of the forward and rearward legs. Once the subject was as low as she could go (ischial tuberosity closest to the floor), then the height of the ASIS was measured vertically from the floor using a meter stick to the nearest half centimeter. The measurement took place on the side of the rear leg. The principal investigator first located the ASIS via palpation, then without moving the hand, the meter stick was placed and a measurement taken. Following each maximum split trial, the subject rose to a comfortable position while still maintaining the forward and rearward legs in a stride position above a position of discomfort. Comfortable and slow lowering to the split position was facilitated by placing 2 support aids, one on each side of the subject. The supports assisted upright balance by allowing the subject to use her arms to support her weight while raising and lowering to and from the lowest split position. The rest between trials was approximately 30 seconds. After the rest period, the subject descended again to her lowest point, and after the leg and pelvic alignment were checked, the measurement of the ASIS height was repeated. This procedure was repeated for 2 trials and then the subject switched to the other the side split and underwent the same procedures. If the subject was able to place her ischial tuberosity on the floor, the trial was repeated with a measured block under the heel of the forward leg. The block prevented the subject from reaching a lower limit position with the ischial tuberosity touching the floor. The measured block was then used on all subsequent trials of the specific leg and split height was calculated with the block height included (Figure 2).

Figure 2. Staged test protocol position. Note the flexed rear leg holding the shank vertical to control pelvic alignment. A ruler is shown near the anterior superior iliac spine, which is identified by a white piece of tape.

Following each trial, the subject was asked to rate the pain she felt while in the lowest split position from 0 to 10. The pain scale was described as 0 indicating no pain and 10 as the worst pain she had ever felt. Both trial pain scores were recorded to obtain evidence regarding whether the subject varied her motivation across

trials (i.e., tried harder by enduring more discomfort in the split position(s)).

Analysis

The research design was a pretest, posttest, crossover control with repeated measures. The analyses consisted of descriptive statistics, confidence intervals, effect size estimates, reliability analysis, and a 2 × 2 treatment (experimental vs. control) by split side (right vs. left) factorial analysis of variance (ANOVA) with repeated measures on all dimensions of the calculated difference scores of the means of the 2 split position trials. Pain ratings were analyzed by 2 Wilcoxon signed rank tests (pretests vs. posttests for each split side) following reliability analyses (Chronbach's α). All main and interaction effects were assessed at the $p \leq 0.05$ level of statistical significance because of the exploratory nature of this study (12). Data analyses were conducted using the Statistical Package for the Social Sciences, SPSS (version 11.5, Chicago, IL, USA) and a modification of a statistical spreadsheet as provided by Hopkins (11) for split measurements trials reliability.

Results

Reliability

Forward split measurements were obtained from 2 trials, 2 splits sides (right and left), and 2 conditions. Trials reliability analyses indicated that the absolute errors ranged from 0.9 to 1.6 cm and relative error ranged from 3% to 8%. Intraclass correlations were all ≥0.99.Pain ratings internal consistency calculations resulted in large intraclass correlations (standardized item α, from α = 0.95–0.99). No statistically significant differences were found between pain ratings for the 2 trials of each split position ($p > 0.05$).

Primary Analysis

Table 1 presents the results of a 2 × 2 factorial ANOVA with repeated measures on both dimensions of the pretest and posttest split-height difference scores. A statistically

Table 1. Repeated-measures factorial ANOVA–difference scores.*

Variable	$F_{(df)}$	p	Partial η^2	Power	95% Confidence intervals	
					PPDC Exp (cm)	CONT Con (cm)
PPDC vs. CONT	$10.4_{(1,8)}$	0.01	0.57	0.81	12.17–2.98	2.67–0.44
Right leg split vs. left leg split	$0.009_{(1,8)}$	0.94	0.001	0.05	Right leg 7.02–2.01	Left leg 7.7–1.52
Interaction (condition × split side)	$5.8_{(1,8)}$	0.043	0.42	0.56		
Leg (R/L) compared with PPDC/CONT (95% confidence intervals)						
R leg × PPDC (cm)		9.96 to 2.38				
R leg × CONT (cm)		4.79 to 0.93				
L leg × PPDC (cm)		15.00 to −2.95				
L leg × CONT (cm)		1.84 to −1.34				

*ANOVA = analysis of variance; PPDC = peristaltic pulse dynamic compression; CONT = control; Exp = experimental; Con = control; R = right forward leg of the split position; L = left forward leg of the split position.

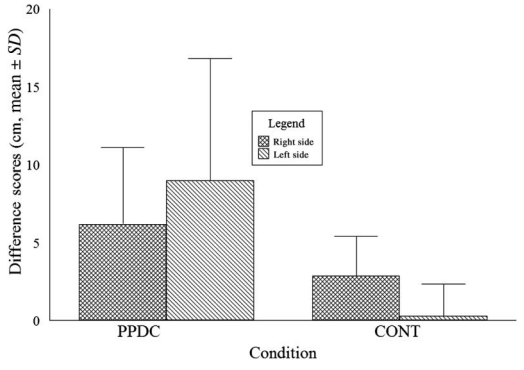

Figure 3. Primary analysis. Experimental vs. control conditions by split side.

significant effect was observed for condition; and for the condition by left and right split interaction ($p \leq 0.05$). The investigators had little interest in the interaction that may simply reflect that all the subjects had a right-side-dominant forward split. Percentage and absolute changes (mean ± *SD*) from pretest to posttest for each condition and leg were as follows: experimental right leg 25.3%, 6.2 ± 4.9 cm; experimental left leg 33.3%, 9 ± 7.8 cm; control right leg 12.2%, 2.8 ± 2.5 cm; control left leg 1.0%, 0.25 ± 2.1 cm. Effect size estimates (partial η^2) indicated a large effect size for both the condition and the interaction effects. Figure 3 shows the difference scores as a condition by forward leg of the split with greater potential for change on their non-dominant or left side.

Pain Ratings Analysis

Wilcoxon signed rank tests of pain ratings of the 2 sides of the splits (right versus left) and pretest versus posttests did not reach statistical significance (right split, prepost: $Z = -1.13$, $p = 0.26$; left split, pre–post: $Z = -1.02$, $p = 0.31$).

Discussion

The primary purpose of this study was to determine the efficacy of PPDC on the acute flexibility of subjects, specifically in a forward split. This study showed that PPDC was effective in enhancing acute ROM when compared with a control condition (Table 1, Figure 3). The factorial ANOVA results and the effect size estimates indicate that the results were strongly indicative of the effectiveness of PPDC treatment before flexibility testing. The results of PPDC treatment mirrored recent results from the use of vibration to enhance ROM (18,29,31,39–41). Previous literature has shown that ROM improvements from static stretching decay following treatment and stretching in a matter of minutes, rapidly at first and then slowly (4,5,35). Long-term studies of PPDC are not available. Tangentially, at least 1 study of vibration for flexibility showed approximately 100% improvement after 4 weeks of continued use in male child gymnasts (41). Future studies are needed to ascertain if PPDC produces vibration-like results.

Magnusson et al have been clear proponents of the idea of "stretch tolerance" as the key to increased ROM (19,23–25,27,28,43). Stretch tolerance refers to the idea that flexibility is a learned skill and that tolerance for pain and learning new extreme positions over long-term training periods are the dominant underlying mechanisms to enhance ROM. Stretch tolerance, as a neural rather than biomaterial factor in enhanced ROM, is at least partially supported by the effectiveness of PPDC (this study), vibration, thermal, and anesthetic treatments. Reliability analyses of pain ratings data were stable and reliable across trials (8,34). The pain ratings analyses also indicated that the subjects did not seem to change their motivation in a statistically significant way, which would lead to the judgment that they did not seem to try harder on one test or trial than another. Interestingly, patients undergoing surgery or spinal manipulation have achieved increases in ROM while anesthetized that they could not achieve while conscious (20,21). The role of anesthesia in stretching and flexibility is important because the information adds support to the idea that changes in ROM can be achieved, in the short term, by a change in central nervous system activity to the musculotendinous area being stretched and that a length change in biomaterials may not be the dominant, or only, mechanism leading to increased ROM. Moreover, the findings that ROM can be changed rapidly and acutely indicates that while stretch tolerance may be an important factor, the time required to develop stretch tolerance is lacking in this and other acute ROM studies.

If effective stretching appears to be largely a learned skill, a product of central and spinal nervous control, then it is unlikely the magnitude of changes seen in the present study using PPDC and previous studies using vibration, heat, and anesthesia could be the result of mechanically lengthening biomaterials. The influence of muscle sensory receptors and associated reflexes (i.e., muscle spindles and Golgi tendon organs) are unknown in this study. Moreover, if the use of artificial means to enhance ROM changes can achieve greater ROM with the same or less discomfort, the athlete may be able to exploit these approaches to enhance his or her flexibility more rapidly and comfortably (31). This study showed an increased change in ROM involving the non-dominant side that may be because of an increased potential for ROM change on that side (29).

The rapid and relatively large changes in ROM observed in this study using PPDC supports the premise that stretching behavior is unlikely to be determined only by the relatively slow processes of tissue lengthening and/or the long-term learning of stretch tolerance. Rapid changes in muscle length and flexibility have also been demonstrated using vibration (18,39–41), anesthesia (20,21), and temperature (3,6,9). The PPDC and vibration are unlikely to enhance tissue length or stretch tolerance because of the short-term nature of the treatment application. However, vibration, compression, and temperature may contribute to the perturbation or shaking of the myoplasm of muscle cells.

Explaining these short-term rapid changes in ROM may fall to the thixotropic properties of muscle for a mechanistic answer. Thixotropy refers to the property of muscle that allows the sarcoplasm to shift from a "gel-like" state (more resistant to lengthening) to a "liquid-like" state (less resistant to lengthening) and back depending on the local milieu of the cell (1,2,15,33,36,44). Residual cross-bridge attachment has been postulated as a mechanism for resistance to stretch observed in resting, and particularly sore muscles (14,36). Future research should investigate the long-term use of PPDC and explore the potential for increasing the duration of PPDC-induced changes in ROM extending its effectiveness beyond acute changes. Future research should extend this study by using this treatment method repeatedly over

longer training periods and involve PPDC with other known adjuncts to stretching.

Practical Applications

PPDC was shown here to enhance acute improvements in forward split ROM. The PPDC fits within the group of new methods and technologies for stretching that seem to result in acute rapid changes in ROM. Continued use of PPDC may result in training effects beyond the acute effects and thereby continue to enhance ROM with continued training. The device used for this study is currently in use by dozens of athletes and collegiate and professional teams, along with the athletes at the U.S. Olympic Training Center who use the Recovery Center. The treatment time for this modality is relatively short, and the resulting changes in acute ROM may be attractive to those coaches and athletes who need to demonstrate large ROMs in training and competition.

References

1. Axelson, HW. Human motor compensations for thixotropy-dependent changes in muscular resting tension after moderate joint movements. *Acta Physiol Scand* 182: 295–304, 2004.
2. Axelson, HW and Hagbarth, KE. Human motor control consequences of thixotropic changes in muscular short range stiffness. *J Physiol* 15: 279–288, 2001.
3. Burke, DG, Holt, LE, Rasmussen, R, MacKinnon, NC, Vossen, JF, and Pelham, TW. Effects of hot or cold water immersion and modified proprioceptive neuromuscular facilitation flexibility exercise on hamstring length. *J Athl Train* 36: 16–19, 2001.
4. de Weijer, VC, Gorniak, GC, and 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* 33: 727–733, 2003.
5. Depino, GM, Webright, WG, and Arnold, BL. Duration of maintained hamstring flexibility after cessation of an acute static stretching protocol. *J Athl Train* 35: 56–59, 2000.
6. Draper, DO, Castro, JL, Feland, B, Schulthies, S, and Eggett, D. Shortwave diathermy and prolonged stretching increase hamstring flexibility. *J Orthop Sports Phys Ther* 34: 13–20, 2004.
7. Draper, DO, Miner, L, Knight, KL, and Ricard, MD. The carry-over effects of diathermy and stretching in developing hamstring flexibility. *J Athl Train* 37: 37–42, 2002.
8. Field, A. *Discovering Statistics Using SPSS for Windows.* Thousand Oaks, CA: Sage, 2000.
9. Funk, D, Swank, AM, Adams, KJ, and Treolo, D. Efficacy of moist heat pack application over static stretching on hamstring flexibility. *J Strength Cond Res* 15: 123–126, 2001.
10. Harvey, D and Mansfield, C. Measuring flexibility for performance and injury prevention. In: *Physiological Tests for Elite Athletes.* C.J. Gore, ed. Champaign, IL: Human Kinetics, 2000, pp. 98–113.
11. Hopkins, W. G. A Spreadsheet for Analysis of Straightforward Controlled Trials. *Sportscience* 7. Available at: http://www.sportsci.org/jour/03/wghtrials.htm. Accessed 2013.
12. Huberty, CJ and Morris, JD. Multivariate analysis versus multiple univariate analyses. *Psychol Bull* 105: 302–308, 1989.
13. Hubley-Kozey, CL. Testing flexibility. In: *Physiological Testing of the High-Performance Athlete.* J. Duncan MacDougall, H.A. Wenger, and HJ Green, eds. Champaign, IL: Human Kinetics, 1991. pp. 309–359.
14. Hutton, RS. Neuromuscular basis of stretching exercises. In: *Strength and Power in Sport.* P.V. Komi, ed. Oxford, England: Blackwell Scientific Publications, 1992. pp. 29–38.
15. Ishihara, Y, Izumizaki, M, Atsumi, T, and Homma, I. After effects of mechanical vibration and muscle contraction on limb position-sense. *Muscle Nerve* 30: 486–492, 2004.
16. Issurin, VB. Vibrations and their applications in sport a review. *J Sports Med Phys Fitness* 45: 324–336, 2005.
17. Issurin, VB, Liebermann, DG, and Tenenbaum, G. Effect of vibratory stimulation on maximal force and flexibility. *J Sports Sci* 12: 561–566, 1994.
18. Kinser, AM, Ramsey, MW, O'Bryant, HS, Ayres, CA, Sands, WA, and Stone, MH. Vibration and stretching effects on flexibility and explosive strength in young gymnasts. *Med Sci Sports Exerc* 40: 133–140, 2008.
19. Klinge, K, Magnusson, SP, Simonsen, EB, Aagaard, P, Klausen, K, and Kjaer, M. The effect of strength and flexibility training on skeletal muscle electromyographic activity, stiffness, and viscoelastic stress relaxation response. *Am J Sports Med* 25: 710–716, 1997.
20. Kohlbeck, FJ and Haldeman, S. Medication-assisted spinal manipulation. *Spine J* 2: 288–302, 2002.
21. Krabak, BJ, Laskowski, ER, Smith, J, Stuart, MJ, and Wong, GY. Neurophysiologic influences on hamstring flexibility: A pilot study. *Clin J Sports Med* 11: 241–246, 2001.
22. Magnusson, SP. Passive properties of human skeletal muscle during stretch maneuvers. A review. *Scand J Med Sci Sports* 8: 65–77, 1998.
23. Magnusson, SP, Aagard, P, Simonsen, E, and Bojsen-Møller, F. A biomechanical evaluation of cyclic and static stretch in human skeletal muscle. *Int J Sports Med* 19: 310–316, 1998.
24. Magnusson, SP, Aaagaard, P, and Nielson, JJ. Passive energy return after repeated stretches of the hamstring muscle-tendon unit. *Med Sci Sports Exerc* 32: 1160–1164, 2000.
25. Magnusson, SP, Simonsen, EB, Aagaard, P, Boesen, J, Johannsen, F, and Kjaer, M. Determinants of musculoskeletal flexibility: Viscoelastic properties, cross-sectional area, EMG and stretch tolerance. *Scand J Med Sci Sports* 7: 195–202, 1997.
26. Magnusson, SP, Simonsen, EB, Aagaard, P, Dyhre-Poulsen, P, McHugh, MP, and Kjaer, M. Mechanical and physical responses to stretching with and without preisometric contraction in human skeletal muscle. *Arch Phys Med Rehabil* 77: 373–378, 1996.
27. Magnusson, SP, Simonsen, EB, Aagaard, P, and Kjaer, M. Biomechanical responses to repeated stretches in human hamstring muscle in vivo. *Am J Sports Med* 24: 622–628, 1996.
28. Magnusson, SP, Simonsen, EB, Aagaard, P, Sørensen, H, and Kjaer, M. A mechanism for altered flexibility in human skeletal muscle. *J Physiol* 497: 291–298, 1996.
29. McNeal, JR, Edgerly, S, Sands, WA, and Kawaguchi, J. Acute effects of vibration-assisted stretching are more evident in the non-dominant limb. *Eur J Sport Sci* 11: 45–50, 2011.
30. McNeal, JR and Sands, WA. Acute static stretching reduces lower extremity power in trained children. *Pediatr Exerc Sci* 15: 139–145, 2003.
31. McNeal, JR and Sands, WA. Stretching for performance enhancement. *Current Sports Med Rep* 5: 141–146, 2006.
32. Nelson, RT and Bandy, WD. An update on flexibility. *Strength Cond J* 27: 10–16, 2005.
33. Nordez, A, McNair, PJ, Casari, P, and Cornu, C. Static and cyclic stretching: Their different effects on the passive torque-angle curve. *J Sci Med Sport* 13: 156–160, 2010.
34. O'Donoghue, P. *Statistics.* New York, NY: Routledge, 2012.
35. O'Sullivan, K, Murray, E, and Sainsbury, D. The effect of warm-up, static stretching and dynamic stretching on hamstring flexibility in previously injured subjects. *BMC Musculoskel Dis* 10: 37, 2009.
36. Proske, U and Morgan, DL. Do cross-bridges contribute to the tension during stretch of passive muscle? *J Muscle Res Cell Motil* 20: 433–442, 1999.

37. Sands, WA. Flexibility. In: *Strength and Conditioning Biological Principles and Practical Applications*. M. Cardinale, R. Newton, and K. Nosaka, eds. Hoboken, NJ: John Wiley& Sons, Ltd, 2010. pp. 391–400.

38. Sands, WA, McNeal, JR, and Stone, MH. Vibration, split stretching, and static vertical jump performance in young male gymnasts. *Med Sci Sports Exerc* 41: S255, 2009.

39. Sands, WA, McNeal, JR, Stone, MH, Haff, GG, and Kinser, AM. Effect of vibration on forward split flexibility and pain perception in young male gymnasts. *Int J Sports Physiol Perform* 3: 469–481, 2008.

40. Sands, WA, McNeal, JR, Stone, MH, Kimmel, WL, Haff, GG, and Jemni, M. The effect of vibration on active and passive range of motion in elite female synchronized swimmers. *Eur J Sport Sci* 8: 217–233, 2008.

41. Sands, WA, McNeal, JR, Stone, MH, Russell, EM, and Jemni, M. Flexibility enhancement with vibration: Acute and long-term. *Med Sci Sports Exerc* 38: 720–725, 2006.

42. Sands, WA, Stone, MH, Smith, SL, and McNeal, JR. Enhancing forward split flexibility: USA synchronized Swimming. *Synchro Swimming USA* 13: 15–16, 2005.

43. Weppler, CH and Magnusson, SP. Increasing muscle extensibility: A matter of increasing length or modifying sensation? *Phys Ther* 90: 438–439, 2010.

44. Wiktorsson-Moller, M, Oberg, B, Ekstrand, J, and Gillquist, J. Effects of warming up, massage, and stretching on range of motion and muscle strength in the lower extremity. *Am J Sports Med* 11: 249–252, 1983.