Physical Therapy in Sport 13 (2012) 180–188

Contents lists available at SciVerse ScienceDirect

Physical Therapy in Sport

journal homepage: www.elsevier.com/ptsp

The effect of heat applied with stretch to increase range of motion: A systematic review

Jiro Nakano[a,*], Cristiane Yamabayashi[b,1], Alex Scott[c,2], W. Darlene Reid[c,3]

[a] Unit of Physical Therapy and Occupational Therapy Sciences, Graduate School of Health Sciences, Nagasaki University, 1-7-1 Sakamoto, Nagasaki-city, Nagasaki 852-8520, Japan
[b] Muscle Biophysics Laboratory, Vancouver Coastal Health Research Institute, Room 617-828 West 10th Avenue, Vancouver, BC, V5Z 1M9, Canada
[c] Department of Physical Therapy, University of British Columbia 212-2177 Wesbrook Mall, Vancouver, BC, V6T1Z3, Canada

ARTICLE INFO

Article history:
Received 18 May 2011
Received in revised form
20 September 2011
Accepted 28 November 2011

Keywords:
Heat
Stretch
Range of motion
Therapeutic ultrasound
Shortwave diathermy
Hot pack

ABSTRACT

Application of heat to muscle is commonly advocated to enhance the efficacy of stretching. However, the effect of this combined therapy using different methods of heating, applied to different muscles, and after one or multiple treatments, is not known.

To perform a systematic review to address the question: Does stretching augmented by heat application result in greater gains in range of motion (ROM) compared to stretch alone?

The following databases were searched for original articles that evaluated our question: MEDLINE, EMBASE, CINAHL, the Cochrane Central Register of Controlled Trials, SPORTDiscus and PEDro databases. After title and abstract screening followed by full-text screening, the quality of included articles was assessed and their data was abstracted. Screening, data abstraction and quality assessment was performed and consensus was achieved by two reviewers. Range of motion (ROM) data were synthesized by meta-analyses for overall effect and subgroup analysis according to muscle group, method of heat application, single or multiple treatments, and reported tightness of muscle. Twelve studies were included and reported the effects of stretch with or without heat on ROM of 352 participants. Heat applications included ultrasound, shortwave diathermy and hot packs. Meta-analyses and subgroup analyses demonstrated greater increases in ROM after heat and stretch (H + S) than heat alone. Subgroup analysis of muscle groups and the method of heat application showed some trends, but no significant differences. Multiple treatments (more so than single treatments) showed consistent treatment effects of H + S versus stretch alone amongst subgroups. Muscles described as tight did not show a greater treatment effect in response to H + S compared to muscles not reported as tight.

Heating provides an added benefit on stretch related gains of ROM in healthy people.

1. Introduction

Stretching is widely used by athletes, trainers, coaches, and therapists as a means to gain, maintain, or restore muscle flexibility in symptomatic or asymptomatic populations (Brukner & Khan, 2002). The goal of stretching can vary widely, including such diverse aims as maximizing sports performance, preventing injury, minimizing age-related loss of flexibility, recovering range of motion following injury or immobilization, and alleviating muscle soreness (Halbertsma & Goeken, 1994; Hartig & Henderson, 1999; Herbert & Gabriel, 2002). Despite the enthusiasm for stretching in the sports medicine community and the general population, there is still substantial controversy regarding its ability to achieve these varied goals (Taylor, Dalton, Seaber, & Garrett, 1990; Witvrouw, Mahieu, Danneels, & McNair, 2004). Although stretching has been used for many years, opinions vary widely as to the best manner of its application (Taylor et al., 1990). Variables to be considered include the magnitude, duration and timing of stretching (Draper, Miner, Knight, & Ricard, 2002); the use of static or active techniques such as proprioneuroceptive feedback (PNF) or muscle energy technique (Ryan, Rossi, & Lopez, 2010; Shadmehr, Hadian, Naiemi, & Jalaie, 2009); the use of positioning and

* Corresponding author. Tel.: +81 095 819 7919.
E-mail addresses: nakano-j@nagasaki-u.ac.jp (J. Nakano), cristiane.yamabayashi@ubc.ca (C. Yamabayashi), alex.scott@ubc.ca (A. Scott), darlene.reid@ubc.ca (W.D. Reid).
[1] Tel.: +1 604 875 4111x62574.
[2] Tel.: +1 604 827 4959.
[3] Tel.: +1 604 875 4111x66056.

1466-853X/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ptsp.2011.11.003

assistive devices such as belts or traction devices (Hertling & Kessler, 1996); and self-stretch versus therapist-applied stretch (Sainz de Baranda & Ayala, 2010). To further complicate the interpretation of clinical trials, stretching is often combined with other modalities, such as dynamic warm-up, massage, vibration (Feland, Hawks, Hopkins, Hunter, Johnson, & Eggett, 2010), or heat. A recent systematic review concluded that hamstring stretching can achieve meaningful gains in range of motion, but the authors did not make any conclusion or recommendations regarding the best treatment parameters (Decoster, Cleland, Altieri, & Russell, 2005).

The application of heat to muscle is commonly advocated as a means to enhance the efficacy of stretching. Potential mechanisms by which heat could enhance the results of stretching relate either to increased tissue temperature, increased blood flow, or reduced muscle activity (i.e. relaxation). With respect to temperature, heating could directly influence the intramuscular collagen given that Type I collagen, which provides the main passive resistive component in muscle tissue (Taylor et al., 1990), becomes more extensible with increasing temperature (Warren, Lehmann, & Koblanski, 1976). Additionally, increased temperature could reduce the viscosity of muscle, resulting in greater length changes at lower loads (Low & Reed, 1994; Taylor et al., 1990). Increased muscle blood flow in response to heating has been postulated to reduce muscle spasm by improving local circulation and clearance of waste products (Low & Reed, 1994). One study, however, demonstrated that heat stress applied via a water perfused suit resulted in increased blood flow through superficial, but not deep veins of the lower limb (Abraham, Leftheriotis, Desvaux, Saumet, & Saumet, 1994).

Heat can be delivered by a variety of means including continuous therapeutic ultrasound (US) (Chan, Myrer, Measom, & Draper, 1998), shortwave diathermy (Garrett, Draper, & Knight, 2000), microwave (Giombini, Di Cesare, Casciello, Sorrenti, Dragoni, & Gabriele, 2002), hot packs (Draper & Hopkins, 2008), or hydrotherapy (Viitasalo et al., 1995), which may vary in their physiological and clinical effects. Despite widespread use, we were not able to identify a conclusive review of the effectiveness of heat applied before or during a stretch. Therefore, we performed a systematic review to address the following question: Does stretching augmented by heat application result in greater gains in range of motion (ROM) compared to stretch alone? Using a systematic review methodology, we retrieved and reviewed all relevant randomized controlled trials that examined the application of heat and stretch (H + S) versus stretch alone, and conducted meta-analyses of the available evidence.

2. Methods

2.1. Search strategy

Electronic searches were performed on the databases – MEDLINE, EMBASE, CINAHL, the Cochrane Central Register of Controlled Trials, SPORTDiscus and PEDro – up to September 2, 2010. A primary search with the term "stretch" was combined with the terms: "stiffness", "range of motion", "flexibility", "extensibility", or "muscle length", and secondly, with "heat", "thermal therapy", "microwave", "diathermy", "phototherapy", "ultrasound", "infrared radiation", "ultraviolet radiation." Reference lists of included articles were scanned for additional citations. The full search strategy is available upon request.

2.2. Study criteria and selection

Studies were included if : 1) participants were healthy subjects (healthy was defined as able bodied with no chronic disease); 2) the design was a randomized controlled trial (RCT) including cross-over designs, published in peer reviewed journals; 3) stretch plus a heating stimulus was compared to stretch only; 4) outcomes of ROM were reported; 5) full-text was available. Studies were excluded if the study participants had previous musculoskeletal injury, neurological or muscle disease, or were post-surgery. Two independent reviewers screened titles and abstracts of all retrieved citations for eligibility. Full text articles were retrieved for review if articles showed potential for inclusion criteria or if there was insufficient information in the abstract and title to make a decision. Disagreements regarding selected articles were discussed between reviewers until consensus was achieved or a third reviewer was included to reach a majority decision.

2.3. Evaluation of methodological quality

Two independent reviewers performed quality assessments using the PEDro scale (Physiotherapy Evidence Database, 1999). This scale has shown good reliability for scoring RCTs (Maher, Sherrington, Herbert, Moseley, & Elkins, 2003). The PEDro consists of 11 items related to scientific rigor. Items 2 to 11 contributes to internal validity, and if met, are given 1 point. The first item relates to external validity and is not included in the final score (Table 1). Quality assessment was performed independently by two reviewers and any disagreement was discussed until consensus was reached.

2.4. Data analyses

Meta-analyses were performed using Review Manager Version 5.0. (Copenhagen, The Nordic Cochrane Centre, The Cochrane Collaboration, 2008) to determine if the H + S treatment increased

Table 1
Detailed description of PEDro Scores.

Study (year published)	PEDro scores[a]										
	1	2	3	4	5	6	7	8	9	10	11	Total of 2–11
Aijaz et al. (2007)	Yes	1	0	1	1	0	0	1	1	1	1	7
Akbari et al. (2006)	Yes	1	0	1	0	0	0	1	1	1	1	6
Brodowicz et al. (1996)	Yes	1	0	0	0	0	0	1	0	1	1	4
Brucker et al. (2005)	Yes	1	0	1	0	0	0	1	0	1	1	5
Draper, Anderson et al. (1998)	Yes	1	0	1	0	0	0	1	0	1	1	5
Draper et al. (2004)	Yes	1	0	1	1	0	0	1	1	1	1	7
Henricson et al. (1984)	Yes	1	0	1	0	0	0	1	1	1	1	6
Knight et al. (2001)	Yes	1	0	1	0	0	1	1	1	1	1	7
Lentell et al. (1992)	Yes	1	0	1	0	0	0	1	0	1	1	5
Peres et al. (2002)	No	1	0	1	0	0	0	0	0	1	1	4
Taylor et al. (1995)	Yes	1	1	0	0	0	0	0	0	1	1	4
Wessling et al. (1987)	Yes	1	0	1	0	0	0	1	1	1	1	6
Total for each item		12	1	10	2	0	1	10	6	12	12	66

1: eligibility criteria were specified.
2: subjects were randomly allocated to groups (in a crossover study, subjects were randomly allocated an order in which treatments were received).
3: allocation was concealed.
4: the groups were similar at baseline regarding the most important prognostic indicators.
5: there was blinding of all subjects.
6: there was blinding of all therapists who administered the therapy.
7: there was blinding of all assessors who measured at least one key outcome.
8: measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups.
9: all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analyzed by "intention to treat".
10: the results of between-group statistical comparisons are reported for at least one key outcome.
11: the study provides both point measures and measures of variability for at least one key outcome.
[a] PEDro score.

ROM more than stretch alone. Outcomes were analyzed as continuous outcomes using a fixed-effect model to calculate a weighted mean difference and 95% confidence interval (CI). A *P* value equal or less than 0.05 indicated statistical significance for an overall effect. Heterogeneity was investigated using the chi-square test, and a *P* value equal or less than 0.10 indicated statistical significance. Subgroup analyses were also performed according to the method of heat application (US, shortwave diathermy or hot pack); after one treatment session or multiple treatments defined as five or more days of treatment); muscle group (hamstrings, triceps surae or shoulder external rotator muscles); whether the study specifically stated that "tight muscle" was an inclusion criteria; and whether there was a sustained effect after application of stretch and heat were discontinued. In studies that reported ROM bilaterally, the data from the right side was analyzed. In studies where ROM was measured in multiple directions, the data for flexion or extension was analyzed.

3. Results

3.1. Search and selection

Fig. 1 is a flow chart that illustrates the different stages of the search and selection of studies included in the review. The initial search of the electronic database identified 718 titles and abstracts, of which 22 were retrieved for full-text review. When the exclusion criteria were applied, twelve studies satisfied the criteria to be included in this review (Aijaz, Chaudhary, & Quddus, 2007; Akbari, Moodi, Moein, & Nazok, 2006; Brodowicz, Welsh, & Wallis, 1996; Brucker, Knight, Rubley, & Draper, 2005; Draper, Anderson, Schulthies, & Ricard, 1998; Draper, Castro, Feland, Schulthies, & Eggett, 2004; Henricson, Fredriksson, Persson, Pereira, Rostedt, & Westlin, 1984; Knight, Rutledge, Cox, Acosta, & Hall, 2001; Lentell, Hetherington, Eagan, & Morgan et al., 1992; Peres, Draper, Knight, & Ricard, 2002; Taylor, Waring, & Brashear, 1995; Wessling, DeVane, & Hylton, 1987). The main reasons for exclusion were: 1) outcomes of ROM were not reported, or 2) the interventions and the comparison groups did not include a stretch alone group, or a H + S group.

3.2. Quality assessment

A detailed description of PEDro scores obtained is shown in Table 1. Six studies (Aijaz et al., 2007; Akbari et al., 2006; Draper et al., 2004; Henricson et al., 1984; Knight et al., 2001; Wessling et al., 1987) showed a PEDro score of more than five, three studies (Brucker et al., 2005; Draper, Anderson et al., 1998; Lentell et al., 1992) scored five and three studies (Brodowicz et al., 1996; Brucker et al., 2005; Draper, Anderson et al., 1998; Peres et al., 2002; Taylor et al., 1995) showed a score of four. The most frequent omissions in the studies were: the lack of blinding of participants (10 studies), therapists (12 studies) or assessors (11 studies); and the randomization method was not described in sufficient detail to ascertain that allocation was concealed (11 studies). Due to the relatively small number of studies, all were included in the systematic review. Meta-analysis demonstrated that lower ranked studies resulted in a similar magnitude of outcome as the higher ranked studies. Additionally, the average scores of the included studies were not lower than the average ranking in the literature (Sherrington, Moseley, Herbert, Elkins, & Maher, 2010).

3.3. Characteristics of participants

The characteristics of the participants are illustrated in Table 2. The total number of participants was 352. Because two cross-over design studies (Taylor et al., 1995; Wessling et al., 1987) were included, 54 subjects performed both interventions and were counted twice, bringing the total number of participants included in the meta-analyses to 406. The H + S group included 222 and the stretch alone group included 184 participants. Detailed demographic data was not reported in all studies, but the majority of the participants were adults and adolescent in their twenties, while one study (Akbari et al., 2006) included 40 participants between twelve and fourteen years old. The male: female ratio varied among four studies (Brucker et al., 2005; Draper, Anderson et al., 1998; Knight et al., 2001; Taylor et al., 1995), four studies included only male participants (Aijaz et al., 2007; Akbari et al., 2006; Brodowicz et al., 1996; Lentell et al., 1992), one study only females (Wessling et al., 1987) and two studies (Draper et al., 2004; Peres et al., 2002) did not report the gender breakdown of each group. Participants were limited to persons having tight muscles in four studies (Aijaz et al., 2007; Akbari et al., 2006; Draper et al., 2004; Knight et al., 2001), and the remaining studies did not use muscle tightness as inclusion criteria.

3.4. Characteristics of interventions

The interventions applied in the studies are illustrated in Table 2. Stretch was performed in the hamstring muscles in six

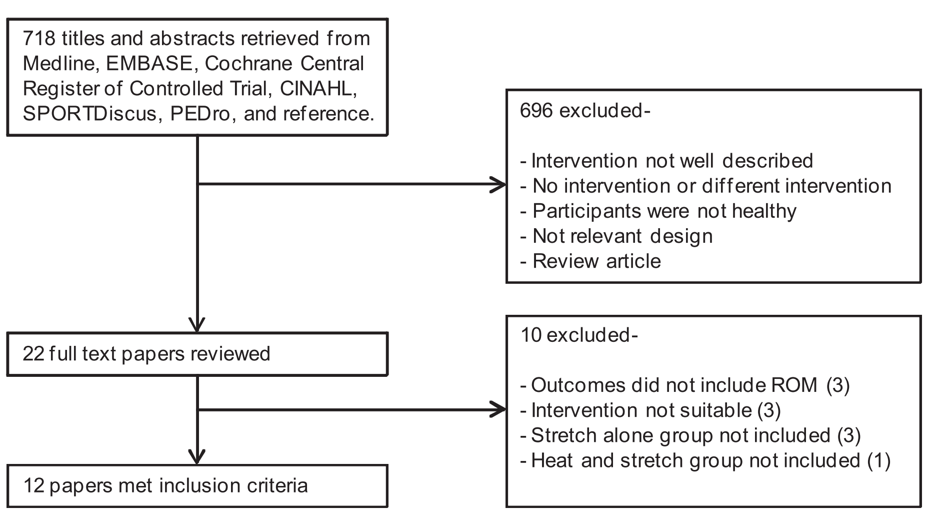

Fig. 1. Flow chart with different phases of the search and selection of the studies included.

Table 2
Characteristics of participants and interventions.

Study (year published)	Participants	Age[a] (range of age)	Muscles[b] (muscle state)	Heating device and conditions	Number of treatments
Aijaz et al. (2007)	30 M healthy students	24.1 ± 2.5	Triceps surae (Tight muscle)	Ultrasound 1-MHz, 7 min (during stretch)	Once daily for 5 days
Akbari et al. (2006)	40 M healthy people	(12–14)	Hamstrings (Tight muscle)	Ultrasound 1-MHz, 2 W/cm^2, 5 min (before stretch)	Once daily, 3 days/wk for 3 wks
Brodowicz, et al. (1996)	16 M healthy baseball players	20.7 ± 1.2	Hamstrings (No mention)	Hot pack 43–46 °C, 20 min (before stretch)	One time only
Brucker et al. (2005)	8 M/15 F healthy people	22.7 ± 2.1	Triceps surae (No mention)	Diathermy (shortwave) 150 W, 800 bursts/s, 400 μs burst duration, 800 μs interburst, 20 min (15 min before and 5 min during stretch)	Once daily, 5 days/wk for 3 wks
Draper, Anderson et al. (1998)	18 M/22 F healthy students	20.4 ± 2.5	Triceps surae (No mention)	Ultrasound 3-MHz, 1.5 W/cm^2, 7 min (before stretch)	Twice daily for 5 days
Draper et al. (2004)	20 healthy college students	21.5	Hamstrings (Tight muscle)	Diathermy (shortwave) 150 W/burst, 800 bursts/s, 400 μs burst duration, 800 μs interburst, 15 min (10 min before and 5 min during stretch)	Once daily for 5 days
Henricson et al. (1984)	10 M/10 F healthy hospital personnel, students, and athletes	30.0 ± 2.7 (25–39)	Hamstrings (No mention)	Hot pack 43 °C, 20 min (before stretch)	One time only
Knight et al. (2001)	33 M/27 F healthy volunteers	27.0 (17–50)	Triceps surae (Tight muscle)	Hot pack 73.9 °C, 15 min (before stretch) Ultrasound 1-MHz, 1.5 W/cm^2, 7 min (before stretch)	Once daily, 3 days/wk for 6 wks
Lentell et al. (1992)	40 M recreational athletes	25.0 ± 4.5 (19–36)	Shoulder external rotators (No mention)	Hot pack 66 °C, 20 min (during stretch)	3 times within 5 days
Peres et al. (2002)	19 healthy college students	22.5 ± 2.0	Hamstrings (No mention)	Diathermy (shortwave) 150 W/burst, 800 bursts/s, 400 μs burst duration, 800 μs interburst, 20 min (15 min before and 5 min during stretch)	Once daily, 5 days/wk for 3 wks
Taylor et al. (1995)	12 M /12 F Army population	25.5 (18–39)	Hamstrings (No mention)	Hot pack 77 °C , 20 min (before stretch)	One time only
Wessling et al. (1987)	30 F healthy college students	(20–30)	Triceps surae (No mention)	Ultrasound 1.5 W/cm^2, 7 min (during stretch)	One time only

F: female; M: male.
[a] Mean age (±SD) are stated for age. When the SD and mean were missing, the age range is stated.
[b] Tight muscle: Participants were limited to persons having tight muscles; No mention: Muscle tightness was not mentioned as inclusion criteria.

studies (Akbari et al., 2006; Brodowicz et al., 1996; Draper et al., 2004; Henricson et al., 1984; Peres et al., 2002; Taylor et al., 1995) triceps surae muscles in five studies (Aijaz et al., 2007; Brucker et al., 2005; Draper, Anderson et al., 1998; Knight et al., 2001; Wessling et al., 1987) and shoulder external rotator muscles in one study (Lentell et al., 1992). The static stretching method was used as the intervention in all studies, and a hold-relax protocol was used in one study (Henricson et al., 1984). Stretch and heating protocols varied between studies. In brief, the number of sessions varied from one session given on a single day to 18 sessions over a period of six weeks. When multiple treatment sessions were performed, usually the protocol called for one treatment per day, but Draper, Anderson et al. (1998) had a twice daily protocol. The stretch duration varied from 15 s to 35 min. The intensity of stretch was not reported in six studies (Akbari et al., 2006; Brodowicz et al., 1996; Draper, Anderson et al., 1998; Henricson et al., 1984; Knight et al., 2001; Taylor et al., 1995). Some studies adjusted the intensity of stretch according to the individual's body weight (Aijaz et al., 2007; Brucker et al., 2005; Lentell et al., 1992; Peres et al., 2002), and some used the same stretch intensity (i.e. load) for all individuals (Akbari et al., 2006; Draper et al., 2004; Wessling et al., 1987) included two different stretching protocols (four sets of 15 s stretch or two sets of 30 s stretch).

Heat was delivered by therapeutic US in five studies (Aijaz et al., 2007; Akbari et al., 2006; Draper, Anderson et al., 1998; Knight et al., 2001; Wessling et al., 1987), shortwave diathermy in three (Brucker et al., 2005; Draper et al., 2004; Peres et al., 2002), and hot packs in five (Brodowicz et al., 1996; Henricson et al., 1984; Knight et al., 2001; Lentell et al., 1992; Taylor et al., 1995). Knight et al. (2001) study included two different heating interventions performed in two different groups (US and hot pack). The US frequency differed between studies; some performed it with a frequency of 1 and others 3 MHz, while it was not reported in one study (Wessling et al., 1987). The US was applied for 5 to 7 min. In the three studies using shortwave diathermy (Brucker et al., 2005; Draper et al., 2004; Peres et al., 2002), the parameters used were: 150 W/burst, 800 bursts/s, 400 μs burst duration, 800 μs interburst interval, with different durations of 5 to 20 min. Hot packs were applied for 15 to 20 min with temperatures ranging from 43 to 77 °C. US, shortwave diathermy and hot packs were applied before and/or during stretch interventions in the H + S group.

3.5. Meta-analyses

3.5.1. Single treatment

Meta-analyses of nine studies (Brodowicz et al., 1996; Brucker et al., 2005; Draper, Anderson et al., 1998; Draper et al., 2004; Henricson et al., 1984; Lentell et al., 1992; Peres et al., 2002; Taylor et al., 1995; Wessling et al., 1987) that evaluated ROM after one treatment session showed an overall effect in favor of H + S group ($P = 0.005$; n = 286; 95%CI: 0.51, 2.82) (Fig. 2). The test for subgroup difference demonstrated no significant difference among

Study or Subgroup	Heat and stretch Mean	SD	Total	Stretch alone Mean	SD	Total	Weight	Mean Difference IV, Fixed, 95% CI
1. Ultrasound								
Draper DO 1998	4	4	20	2	6	20	14.6%	2.00 [-1.16, 5.16]
Wessling KC 1987	2.6	3.6	30	1.5	3.2	30	49.2%	1.10 [-0.62, 2.82]
Subtotal (95% CI)			**50**			**50**	**63.8%**	**1.31 [-0.21, 2.82]**
Heterogeneity: Chi² = 0.24, df = 1 (P = 0.62); I² = 0%								
Test for overall effect: Z = 1.69 (P = 0.09)								
2. Diathermy								
Brucker JB 2005	2.9	4.4	14	1.7	3.5	9	13.9%	1.20 [-2.05, 4.45]
Draper DO 2004	8.1	7.6	10	5.5	7.7	10	3.3%	2.60 [-4.11, 9.31]
Peres SE 2002	2.5	4.2	8	1.8	3.2	11	12.1%	0.70 [-2.77, 4.17]
Subtotal (95% CI)			**32**			**30**	**29.3%**	**1.15 [-1.09, 3.38]**
Heterogeneity: Chi² = 0.25, df = 2 (P = 0.88); I² = 0%								
Test for overall effect: Z = 1.01 (P = 0.31)								
3. Hot pack								
Brodowicz GR 1996	4.2	21.8	8	2	22.6	8	0.3%	2.20 [-19.56, 23.96]
Henricson AS 1984	11	12	10	5	12	10	1.3%	6.00 [-4.52, 16.52]
Lentell G 1992	11	7.1	22	6	5.4	18	0.0%	5.00 [1.12, 8.88]
Taylor BF 1995	5.7	10.6	24	4.1	7.8	24	5.3%	1.60 [-3.67, 6.87]
Subtotal (95% CI)			**42**			**42**	**6.9%**	**2.47 [-2.13, 7.07]**
Heterogeneity: Chi² = 0.54, df = 2 (P = 0.76); I² = 0%								
Test for overall effect: Z = 1.05 (P = 0.29)								
Total (95% CI)			**124**			**122**	**100.0%**	**1.34 [0.13, 2.55]**
Heterogeneity: Chi² = 1.28, df = 7 (P = 0.99); I² = 0%								
Test for overall effect: Z = 2.17 (P = 0.03)								
Test for subgroup differences: Chi² = 0.26, df = 2 (P = 0.88), I² = 0%								

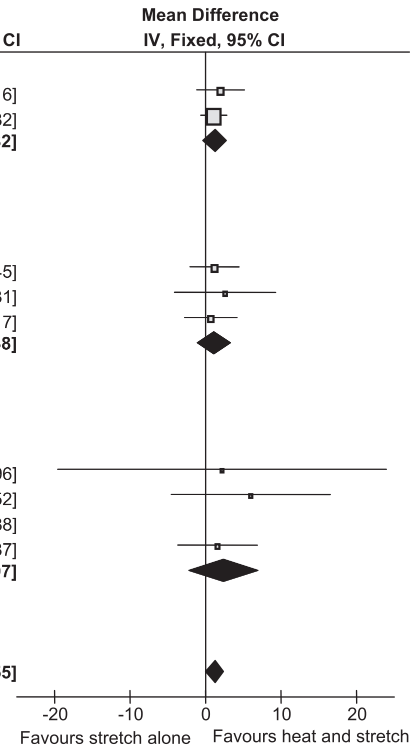

Fig. 2. Forest plot of meta-analyses showing comparison of heat and stretch versus stretch alone measured after a single treatment according to method of heat application.

subgroups according to method of heat application ($P = 0.26$, I2 = 26%). Within subgroups, hot packs demonstrated a significantly greater effect size after H + S compared to stretch alone ($P = 0.009$; n = 124; 95%CI: 0.98, 6.91), but a similar within subgroup pattern was not shown for H + S applied with US or diathermy ($P = 0.09$; n = 100; 95%CI:-0.21, 2.82, $P = 0.31$; n = 62; 95%CI:-1.09, 3.38, respectively).The test for subgroup differences according to muscle group demonstrated no significant differences ($P = 0.17$, I2 = 43.3%).

3.5.2. Multiple treatments

Eight studies performed stretch protocol for three days or more (Aijaz et al., 2007; Akbari et al., 2006; Brucker et al., 2005; Draper, Anderson et al., 1998; Draper et al., 2004; Knight et al., 2001; Lentell et al., 1992; Peres et al., 2002), For the analysis, the increased ROM was calculated from the baseline data minus the post- stretch value on the final day (Fig. 3). The studies of Akbari et al. (2006) and Knight et al. (2001) appeared twice in the meta-analyses because they included two different treatment groups. The meta-analysis of multiple treatments showed greater gains of ROM in H + S group compared to stretch alone group ($P < 0.00001$; n = 291; 95%CI: 1.12, 2.37). The test for subgroup difference demonstrated no significant difference among subgroups according to the method of heat application ($P = 0.13$, I2 = 51.1%). Within methods of heat application, significant improvements in ROM were shown when either US or diathermy was performed with stretch compared to stretch alone ($P < 0.00001$; n = 149; 95%CI: 0.94, 2.28; $P = 0.0007$; n = 62; 95%CI: 1.64, 6.12, respectively) (Knight et al., 2001; Lentell et al., 1992). The test for subgroup difference according to muscle group demonstrated no significant differences ($P = 0.30$, I2 = 16.9%). Within muscle groups, significant improvements in ROM for hamstrings ($P = 0.001$; n = 60; 95%CI: 1.10, 4.59) and triceps surae muscles ($P < 0.00001$; n = 191; 95%CI: 0.85, 2.21) were shown with H + S over multiple treatments compared to stretch alone over multiple treatments.

3.5.3. Sustained effect

To examine the prolonged effect of H + S, ROM was measured days later after the last day of stretch in four studies. Draper et al. (2004) and Lentell et al. (1992) measured ROM three days after the last treatment day, Peres et al. (2002) after six days and Brucker et al. (2005) after 21 days. The first day pre-stretch was used as the baseline ROM. The overall effect showed a greater retention of ROM in the H + S group than stretch alone group ($P < 0.0001$; n = 102; 95% CI: 2.11, 6.37). Although analysis did not show a different effect size between subgroups according to method of heat application, within subgroup analysis demonstrated significant differences favoring the H + S group for diathermy ($P = 0.0006$; n = 62; 95%CI: 1.68, 6.18); and hot pack applications ($P = 0.04$, n = 40, 95%CI: 0.30, 13.70).

3.5.4. Tightness of muscle

Of the same eight studies (Aijaz et al., 2007; Akbari et al., 2006; Brucker et al., 2005; Draper, Anderson et al., 1998; Draper et al., 2004; Knight et al., 2001; Lentell et al., 1992; Peres et al., 2002) that analyzed multiple treatments, four studies (Aijaz et al., 2007; Akbari et al., 2006; Draper et al., 2004; Knight et al., 2001) limited the participants to persons with tight muscles, and the remaining four studies did not mention tightness as an inclusion criteria (Brucker et al., 2005; Draper, Anderson et al., 1998; Lentell et al., 1992; Peres et al., 2002). There was no significant difference between subgroups according to tightness of muscle ("tight muscle" group and "no mention of tight muscle" group) ($P = 0.57$, I2 = 0%). Within subgroup analyses, however, showed that both groups gained ROM after multiple treatments of H + S versus stretch alone ($P < 0.00001$; n = 169; 95%CI: 1.00, 2.34; $P = 0.01$; n = 122; 95%CI: 0.52, 3.85, respectively).

Study or Subgroup	Heat and stretch Mean	SD	Total	Stretch alone Mean	SD	Total	Weight	Mean Difference IV, Fixed, 95% CI
1. Ultrasound								
Aijaz YR 2007	9.1	1	15	7.5	1.1	15	68.1%	1.60 [0.85, 2.35]
Akbari A 2006	5.4	2.4	10	3.4	2.9	10	7.1%	2.00 [-0.33, 4.33]
Akbari A 2006	7.7	3.2	10	5	3.3	10	4.7%	2.70 [-0.15, 5.55]
Draper DO 1998	5	4	20	5	6	20	3.9%	0.00 [-3.16, 3.16]
Knight CA 2001	7.4	6.8	20	6.1	6.2	19	2.3%	1.30 [-2.78, 5.38]
Subtotal (95% CI)			**75**			**74**	**86.1%**	**1.61 [0.94, 2.28]**
Heterogeneity: Chi² = 1.69, df = 4 (P = 0.79); I² = 0%								
Test for overall effect: Z = 4.73 (P < 0.00001)								
2. Diathermy								
Brucker JB 2005	7.6	4.4	14	4.7	3.5	9	3.7%	2.90 [-0.35, 6.15]
Draper DO 2004	15.8	7.6	10	5.2	7.7	10	0.9%	10.60 [3.89, 17.31]
Peres SE 2002	8.1	4.2	8	4.9	3.2	11	3.2%	3.20 [-0.27, 6.67]
Subtotal (95% CI)			**32**			**30**	**7.7%**	**3.88 [1.64, 6.12]**
Heterogeneity: Chi² = 4.36, df = 2 (P = 0.11); I² = 54%								
Test for overall effect: Z = 3.40 (P = 0.0007)								
3. Hot pack								
Knight CA 2001	4.9	5.7	21	6.2	5.8	19	3.0%	-1.30 [-4.87, 2.27]
Lentell G 1992	11	5.7	22	8	5.5	18	3.2%	3.00 [-0.48, 6.48]
Subtotal (95% CI)			**43**			**37**	**6.2%**	**0.90 [-1.59, 3.40]**
Heterogeneity: Chi² = 2.86, df = 1 (P = 0.09); I² = 65%								
Test for overall effect: Z = 0.71 (P = 0.48)								
Total (95% CI)			**150**			**141**	**100.0%**	**1.74 [1.12, 2.37]**
Heterogeneity: Chi² = 12.99, df = 9 (P = 0.16); I² = 31%								
Test for overall effect: Z = 5.51 (P < 0.00001)								
Test for subgroup differences: Chi² = 4.09, df = 2 (P = 0.13), I² = 51.1%								

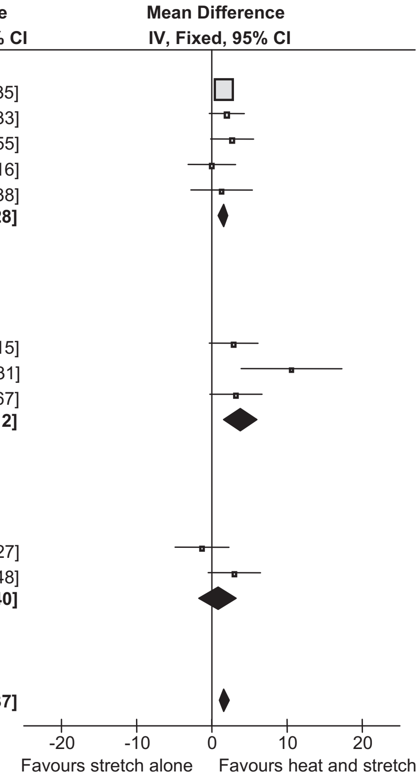

Fig. 3. Forest plot of meta-analysis showing comparison of heat and stretch versus stretch alone measured after multiple treatments according to method of heat application.

4. Discussion

Using a meta-analysis, our review of 12 RCTs involving 352 healthy participants (Aijaz et al., 2007; Akbari et al., 2006; Brodowicz et al., 1996; Brucker et al., 2005; Draper, Anderson et al., 1998; Draper et al., 2004; Henricson et al., 1984; Knight et al., 2001; Lentell et al., 1992; Peres et al., 2002; Taylor et al., 1995; Wessling et al., 1987) demonstrated that both single and multiple treatments of H + S improved ROM compared to stretch alone. Furthermore, increased ROM was sustained longer after treatment cessation of H + S compared to stretch alone. The greater effect of H + S was relatively robust among different muscles groups. Investigation to determine if any application method of H + S was better than another did not reveal significant differences. Included RCTs had low to moderate PEDro scores, however, deficiencies of design and quality scores were similar or higher than median scores of RCTs in sports physiotherapy (Roig et al., 2009; Sherrington et al., 2010). The consistent superior effect size of H + S, regardless of the muscle group, type of heat application, number of treatment (single, multiple, sustained) lends credence to the finding that H + S is more effective than stretch alone.

4.1. Methodological quality

The threshold score in methodological quality that can be classified as acceptable is equivocal (Decoster et al., 2005; Labelle, Guibert, Joncas, Newman, Fallaha, & Rivard, 1992; Roig et al., 2009; Sherrington et al., 2010). The RCTs in this systematic review had an average of PEDro score of 5.5 out of a possible 10 points, and three studies achieved 7 points (70%); this average is higher than the median of 4.0 and 5.0 PEDro scores recently reported for 615 sports physiotherapy trials and 11,503 other RCTs (Sherrington et al., 2010). The most common deficiencies in research design were that lack of blinding of therapist, assessors, and/or subjects, similar to Sherrington et al. (2010) findings when reviewing PEDro scores of 12,408 RCTs. The blinding of subjects and clinicians when applying heat may not be feasible and it is difficult to ascertain if this would provide a strong bias toward H + S compared to stretch alone. However, blinding of assessors would be optimal, especially given the subjective nature of ROM, which has previously been acknowledged (Decoster et al., 2005; French, Cameron, Walker, Reggars, & Esterman, 2006; Harvey, Herbert, & Crosbie, 2002). We strongly recommend that future studies investigating stretching or heating modalities include blinding of assessors in the research methodology.

4.2. Single and multiple treatment effects

The results of this review suggest that gains in ROM can occur even after a single exposure to stretch and heat, although these initial gains may be of small magnitude. A significant effect favoring heat and stretch after a single treatment was observed in the subgroup of the shoulder external rotator muscles. Although this subgroup comprised only a single study of Lentell et al. (1992), one could speculate that the shoulder muscles may be more responsible to acute changes in muscle length than the other larger muscle groups studied. Previous systematic reviews have concluded that multiple treatments involving static stretch alone can improve ROM, and this systematic review supports this finding (Decoster et al., 2005; Harvey et al., 2002; Radford, Burns, Buchbinder, Landorf, & Cook, 2006). In addition, the meta-analyses revealed that multiple treatments of heat combined with stretch can potentiate the effects of stretch.

Within the hot packs subgroup analysis of single treatment effects, subjects who received hot packs to the shoulder did show a clinically significant effect; this may reflect the fact that shoulder external rotator muscles and joint structures are more easily influenced than the triceps surae by superficial heating. In contrast, the subgroup of subjects who received multiple treatment by US (4/8 studies) and diathermy (3/8 studies), showed a clear difference in effect size ($P = 0.00001$, $P = 0.0007$, respectively) which was not seen with hot packs. It is difficult to make firm conclusions on the basis of this analysis, as the different outcomes among studies may have resulted from a variety of factors, such as different magnitudes of stretch force and different ROM assessment methods.

4.3. Sustained effect

Previous study has shown that improvements in ROM of knee extension following stretching could last as little as three minutes after a single stretching treatment (Depino, Webright, & Arnold, 2000). Thus, we considered it important to examine the potential for a sustained effect of stretching. In four studies (Brucker et al., 2005; Draper et al., 2004; Lentell et al., 1992; Peres et al., 2002) included in the meta-analysis for sustained effect, multiple treatments of heating and stretching were performed (except Lentell et al.), which is in line with current clinical practice (i.e. multiple treatments are presumed to be required to achieve sustained gains in ROM). The results suggest that heat applied with stretch provide sustained gains in ROM compared to stretch alone. Three of these four studies (Brucker et al., 2005; Draper et al., 2004; Peres et al., 2002) employed diathermy and one study used hot packs (Taylor et al., 1995). Of these studies, the one that achieved the highest PEDro score (7) also demonstrated the largest effect in favor of H + S (diathermy) (Draper et al., 2004). Thus, the analysis was not able to provide definitive conclusions regarding which heating device leads to the largest sustained effects.

4.4. Difference of method of heat application

In the studies included in this systematic review, three kinds of heat application were used as interventions: therapeutic US, shortwave diathermy and hot packs. Therapeutic US and diathermy are more effective than hot packs at heating deep soft tissues. In previous studies, US with 1 MHz, 1.5 W/cm^2 and diathermy with 150 W per burst could heat underlying tissues at 3 cm depth (Garrett et al., 2000). At this depth, the heating effect would reach muscle fibers, intramuscular connective tissue (endomysium and perimysium), the muscle sheath (perimysium), overlying adipose, and skin. US delivered at 3 MHz was not as effective at heating deep tissue as ultrasound delivered at 1 MHz; significant tissue heating occurred at 1.2∼2.5 cm depth tissue (Draper & Ricard, 1995; Herbert & Gabriel, 2002). Hot packs are reportedly effective only to a 1 cm depth, affecting mainly skin and adipose tissue (Draper, Harris, Schulthies, Durrant, Knight, & Ricard, 1998). In the five studies (Aijaz et al., 2007; Akbari et al., 2006; Draper, Anderson et al., 1998; Knight et al., 2001; Wessling et al., 1987) which used therapeutic US, three studies (Aijaz et al., 2007; Akbari et al., 2006; Knight et al., 2001) used 1 MHz US, one study (Draper, Anderson et al., 1998) used 3 MHz and the remaining study did not report the wavelength (Wessling et al., 1987). This systematic review did not detect significant differences among subgroups according to method of heat application. This may be explained by differences in experimental protocols (heating application differences, muscle groups, gender, age, number of subjects). However, multiple hot pack treatments appeared to result in effects of a smaller magnitude than the effects achieved with US or diathermy for the larger muscle groups (hamstrings, triceps surae). This trend was not statistically significant. Hot packs showed a clear benefit in improving shoulder ROM (Fig. 3), suggesting that reduced depth of penetration may not be as crucial as previously assumed.

4.5. Mechanisms of heat in potentiating effects of stretch

This systematic review demonstrates that heat is able to potentiate the ability of stretching to increase flexibility, with both acute and sustained effects. The mechanism by which stretching results in increased flexibility is controversial; thus, it is not clear how heat may be influencing the effects of stretching. Increased ROM could result from one or a combination of the following: 1) improved flexibility of connective tissue, 2) altered viscoelastic properties, 3) addition of sarcomeres or 4) altered sensation of stretch.

In vitro studies have demonstrated that muscle heated to 40 °C undergoes greater elongation at a given load compared with unheated muscle (Noonan, Best, Seaber, & Garrett, 1993). This effect is due to increased collagen extensibility, reduced connective tissue viscosity and viscoelasticity of muscle fiber at higher temperatures, and may be one way that heating improves ROM, even after a single exposure (Lehmann et al., 1970; Mutungi & Ranatunga, 1998; Warren et al., 1976), although this postulate has not been confirmed in vivo in humans, to our knowledge. With regard to sustained effects of stretching on flexibility, some authors have suggested that structural changes may take place over time in response to stretching (Reid & McNair, 2004). Prolonged immobilization of muscle in a lengthened position resulted in an addition of number of sarcomeres and permanent lengthening of the contractile tissues (Williams & Goldspink, 1978). This change is considered as the structural adjustment of muscle to maintain the greatest functional length (Tabary, Tabary, Tardieu, Tardieu, & Goldspink, 1972; Williams & Goldspink, 1978). However, there is no evidence that heat stimulation could potentiate the effects of stretch on the addition of sarcomeres. Current evidence suggests that the long lasting effects of stretching is a consequence of altered stretch perception, with no evidence of altered muscle length or viscoelastic properties (Ylinen, Kankainen, Kautiainen, Rezasoltani, Kuukkanen, & Hakkinen, 2009). How heat may influence the altered perception of stretch is not currently known. In the case of US therapy, energy is delivered in the form of mechanical (acoustic) energy which stimulates mechanotransduction pathways and may mimic some of the effects of mechanical loading including enhanced calcium signaling (Zhou, Schmelz, Seufferlein, Li, Zhao, & Bachem, 2004). In rat calf muscle immobilized for 4 weeks, US treatment (frequency, 1 MHz; intensity, 1.0 W/cm^2) resulted in better maintenance of longitudinally oriented collagen fibrils in the endomysium (Okita, Nakano, Kataoka, Sakamoto, Origuchi, & Yoshimura, 2009), suggesting the existence of effects other than those due purely to tissue heating.

4.6. Tightness of muscle

In this systematic review, interestingly, the beneficial effect of heating was demonstrated for subjects with and without reported muscle tightness. However, the limitation of this comparison is that some of the studies may have included subjects with limited ROM in spite of not reporting this criteria as an inclusion criterium. Thus, although the finding that heat can positively influence both normal and tight muscles should be interpreted with caution.

Limitations of the review

This review is limited by only including English language publications and the possibility of missing key studies that were not retrieved by our search terms. Studies may have been missed if they were from journals not included in the databases searched. In this systematic review, there were too few studies to definitively compare heating methods or muscle-specific effects in the subgroup analyses. Nonetheless, this was not the primary goal of the review.

A major limitation in comparison of the studies was the method of ROM measurement. Measurement of the ROM included use of a standard goniometer (Aijaz et al., 2007; Akbari et al., 2006; Draper et al., 2004; Henricson et al., 1984; Knight et al., 2001; Lentell et al., 1992; Wessling et al., 1987), manual (Draper, Anderson et al., 1998) or digital inclinometer (Brucker et al., 2005; Peres et al., 2002; Taylor et al., 1995), or flexometer (Brodowicz et al., 1996). The passive force to limbs when measuring ROM was properly controlled by dynamometer (Henricson et al., 1984), weights (Peres et al., 2002) and gravity-assistance (Lentell et al., 1992) in three papers. In other reports, however, the passive force applied to limbs to achieve end ROM was dependent on subjective determinants of participants and examiners although it has been shown to be reliable when repeated measures are taken by the same examiner (Clapis, Davis, & Davis, 2008; Holm, Bolstad, Lütken, Ervik, Røkkum, & Steen, 2000; Maher et al., 2003).

5. Conclusion

The current review demonstrates that the application of heat potentiates the effect of stretching on improving ROM of a variety of muscle groups. Heating provided a beneficial influence both on the acute gain of ROM, and on sustained gain of ROM evident after multiple treatments in healthy people. Future studies should focus on determining the most efficient method of heat application in healthy and symptomatic populations in a variety of muscle groups, as there may be anatomic variations that would influence the ideal heating modality for a given muscle.

Conflict of interest statement

There is no potential conflict of interest existing with respect to the authors of this paper.

Funding

This study was not supported by any sources of funding.

Acknowledgment

This work supported by the Michael Smith Foundation for Health Research and the British Columbia Lung Association.

References

Abraham, P., Leftheriotis, G., Desvaux, B., Saumet, M., & Saumet, J. L. (1994). Venous return in lower limb during heat stress. *American Journal of Physiology, 267*(4 Pt 2), H1337–1340.

Aijaz, Y. R., Chaudhary, P., & Quddus, N. (2007). Ultrasound and prolonged long duration stretching increase triceps surae muscle extensibility more than identical stretching alone. *Indian Journal of Physiotherapy and Occupational Therapy, 1*(3), 11–18.

Akbari, A., Moodi, H., Moein, A. A., & Nazok, R. (2006). The effect of therapeutic ultrasound and duration of stretching of the hamstring muscle group on the passive knee extension. *Journal of Medical Sciences, 6*(6), 968–973.

Brodowicz, G. R., Welsh, R., & Wallis, J. (1996). Comparison of stretching with ice, stretching with heat, or stretching alone on hamstring flexibility. *Journal of Athletic Training, 31*(4), 324–327.

Brucker, J. B., Knight, K. L., Rubley, M. D., & Draper, D. O. (2005). An 18-day stretching regimen, with or without pulsed, shortwave diathermy, and ankle dorsiflexion after 3 weeks. *Journal of Athletic Training, 40*(4), 276–280.

Brukner, P., & Khan, K. M. (2002). *Clinical sports medicine*. Sydney: McGraw-Hill.

Chan, A. K., Myrer, J. W., Measom, G. J., & Draper, D. O. (1998). Temperature changes in human patellar tendon in response to therapeutic ultrasound. *Journal of Athletic Training, 33*(2), 130–135.

Clapis, P. A., Davis, S. M., & Davis, R. O. (2008). Reliability of inclinometer and goniometric measurements of hip extension flexibility using the modified Thomas test. *Physiotherapy Theory and Practice, 24*(2), 135–141.

Decoster, L. C., Cleland, J., Altieri, C., & Russell, P. (2005). The effects of hamstring stretching on range of motion: a systematic literature review. *Journal of Orthopaedic & Sports Physical Therapy, 35*(6), 377–387.

Depino, G. M., Webright, W. G., & Arnold, B. L. (2000). Duration of maintained hamstring flexibility after cessation of an acute static stretching protocol. *Journal of Athletic Training, 35*(1), 56–59.

Draper, D. O., Anderson, C., Schulthies, S. S., & Ricard, M. D. (1998). Immediate and residual changes in dorsiflexion range of motion using an ultrasound heat and stretch routine. *Journal of Athletic Training, 33*(2), 141–144.

Draper, D. O., Castro, J. L., Feland, B., Schulthies, S., & Eggett, D. (2004). Shortwave diathermy and prolonged stretching increase hamstring flexibility more than prolonged stretching alone. *Journal of Orthopaedic & Sports Physical Therapy, 34*(1), 13–20.

Draper, D. O., Harris, S. T., Schulthies, S., Durrant, E., Knight, K. L., & Ricard, M. (1998). Hot-pack and 1-MHz ultrasound treatments have an additive effect on muscle temperature increase. *Journal of Athletic Training, 33*(1), 21–24.

Draper, D. O., & Hopkins, T. J. (2008). Increased intramuscular and intracapsular temperature via ThermaCare Knee Wrap application. *Medicine Science Monitor, 14*(6), PI7–11.

Draper, D. O., Miner, L., Knight, K. L., & Ricard, M. D. (2002). The carry-over effects of diathermy and stretching in developing hamstring flexibility. *Journal of Athletic Training, 37*(1), 37–42.

Draper, D. O., & Ricard, M. D. (1995). Rate of temperature decay in human muscle following 3 MHz ultrasound: the stretching window revealed. *Journal of Athletic Training, 30*(4), 304–307.

Feland, J. B., Hawks, M., Hopkins, J. T., Hunter, I., Johnson, A. W., & Eggett, D. L. (2010). Whole body vibration as an adjunct to static stretching. *International Journal of Sports Medicine, 31*(8), 584–589.

French, S. D., Cameron, M., Walker, B. F., Reggars, J. W., & Esterman, A. J. (2006). Superficial heat or cold for low back pain. *Cochrane Database of Systematic Reviews, 25*(1), CD004750.

Garrett, C. L., Draper, D. O., & Knight, K. L. (2000). Heat distribution in the lower leg from pulsed short-wave diathermy and ultrasound treatments. *Journal of Athletic Training, 35*(1), 50–55.

Giombini, A., Di Cesare, A., Casciello, G., Sorrenti, D., Dragoni, S., & Gabriele, P. (2002). Hyperthermia at 434 MHz in the treatment of overuse sport tendinopathies: a randomised controlled clinical trial. *International Journal of Sports Medicine, 23*(3), 207–211.

Halbertsma, J. P. K., & Goeken, L. N. H. (1994). Stretching exercises – effect on passive extensibility and stiffness in short hamstrings of healthy-subjects. *Archives of Physical Medicine and Rehabilitation, 75*(9), 976–981.

Hartig, D. E., & Henderson, J. M. (1999). Increasing hamstring flexibility decreases lower extremity overuse injuries in military basic trainees. *American Journal of Sports Medicine, 27*(2), 173–176.

Harvey, L., Herbert, R., & Crosbie, J. (2002). Does stretching induce lasting increases in joint ROM? A systematic review. *Physiotherapy Research International, 7*(1), 1–13.

Henricson, A. S., Fredriksson, K., Persson, I., Pereira, R., Rostedt, Y., & Westlin, N. E. (1984). The effect of heat and stretching on the range of hip motion. *Journal of Orthopaedic & Sports Physical Therapy, 6*(2), 110–115.

Herbert, R. D., & Gabriel, M. (2002). Effects of stretching before and after exercising on muscle soreness and risk of injury: systematic review. *British Medical Journal, 325*(7362), 468–470.

Hertling, D., & Kessler, R. M. (1996). *Management of common musculoskeletal disorders*. New York: Lipincott.

Holm, I., Bolstad, B., Lütken, T., Ervik, A., Røkkum, M., & Steen, H. (2000). Reliability of goniometric measurements and visual estimates of hip ROM in patients with osteoarthrosis. *Physiotherapy Research International, 5*(4), 241–248.

Knight, C. A., Rutledge, C. R., Cox, M. E., Acosta, M., & Hall, S. J. (2001). Effect of superficial heat, deep heat, and active exercise warm-up on the extensibility of the plantar flexors. *Physical Therapy, 81*(6), 1206–1214.

Labelle, H., Guibert, R., Joncas, J., Newman, N., Fallaha, M., & Rivard, C. H. (1992). Lack of scientific evidence for the treatment of lateral epicondylitis of the elbow. An attempted meta-analysis. *Journal of Bone and Joint Surgery, 74*(5), 646–651.

Lehmann, J. F., Masock, A. J., Warren, C. G., & Koblanski, J. N. (1970). Effect of therapeutic temperatures on tendon extensibility. *Archives of Physical Medicine and Rehabilitation, 51*(8), 481–487.

Lentell, G., Hetherington, T., Eagan, J., & Morgan, M. (1992). The use of thermal agents to influence the effectiveness of a low-load prolonged stretch. *Journal of Orthopaedic & Sports Physical Therapy, 16*(5), 200–207.

Low, J., & Reed, A. (1994). *Electrotherapy explained*. Oxford: Butterworth Heinemann Ltd.

Maher, C. G., Sherrington, C., Herbert, R. D., Moseley, A. M., & Elkins, M. (2003). Reliability of the PEDro scale for rating quality of randomized controlled trials. *Physical Therapy, 83*(8), 713–721.

Mutungi, G., & Ranatunga, K. W. (1998). Temperature-dependent changes in the viscoelasticity of intact resting mammalian (rat) fast- and slow-twitch muscle fibres. *Journal of Physiology, 508*(Pt 1), 253–265.

Noonan, T. J., Best, T. M., Seaber, A. V., & Garrett, W. E. (1993). Thermal effects on skeletal muscle tensile behavior. *American Journal of Sports Medicine, 21*(4), 517–522.

Okita, M., Nakano, J., Kataoka, H., Sakamoto, J., Origuchi, T., & Yoshimura, T. (2009). Effects of therapeutic ultrasound on joint mobility and collagen fibril arrangement in the endomysium of immobilized rat soleus muscle. *Ultrasound in Medicine & Biology, 35*(2), 237–244.

Peres, S. E., Draper, D. O., Knight, K. L., & Ricard, M. D. (2002). Pulsed shortwave diathermy and prolonged long-duration stretching increase dorsiflexion range of motion more than identical stretching without diathermy. *Journal of Athletic Training, 37*(1), 43–50.

Physiotherapy Evidence Database.PEDro scale. (1999). Retrieved accessed October 1, 2010, from. http://www.pedro.org.au/english/downloads/pedro-scale/.

Radford, J. A., Burns, J., Buchbinder, R., Landorf, K. B., & Cook, C. (2006). Does stretching increase ankle dorsiflexion range of motion? A systematic review. *British Journal of Sports Medicine, 40*(10), 870–875.

Reid, D. A., & McNair, P. J. (2004). Passive force, angle, and stiffness changes after stretching of hamstring muscles. *Medicine & Science in Sports & Exercise, 36*(11), 1944–1948.

Roig, M., O'Brien, K., Kirk, G., Murray, R., McKinnon, P., Shadgan, B., et al. (2009). The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *British Journal of Sports Medicine, 43*(8), 556–568.

Ryan, E. E., Rossi, M. D., & Lopez, R. (2010). The effects of the contract-relax-antagonist-contract form of proprioceptive neuromuscular facilitation stretching on postural stability. *Journal of Strength and Conditioning Research, 24*(7), 1888–1894.

Sainz de Baranda, P., & Ayala, F. (2010). Chronic flexibility improvement after 12 week of stretching program utilizing the ACSM recommendations: hamstring flexibility. *International Journal of Sports Medicine, 31*(6), 389–396.

Shadmehr, A., Hadian, M. R., Naiemi, S. S., & Jalaie, S. (2009). Hamstring flexibility in young women following passive stretch and muscle energy technique. *Journal of Back and Musculoskeletal Rehabilitation, 22*(3), 143–148.

Sherrington, C., Moseley, A. M., Herbert, R. D., Elkins, M. R., & Maher, C. G. (2010). Ten years of evidence to guide physiotherapy interventions: Physiotherapy Evidence Database (PEDro). *British Journal of Sports Medicine, 44*(12), 836–837.

Tabary, J. C., Tabary, C., Tardieu, C., Tardieu, G., & Goldspink, G. (1972). Physiological and structural changes in the cat's soleus muscle due to immobilization at different lengths by plaster casts. *Journal of Physiology, 224*(1), 231–244.

Taylor, D. C., Dalton, J. D., Jr., Seaber, A. V., & Garrett, W. E., Jr. (1990). Viscoelastic properties of muscle-tendon units. The biomechanical effects of stretching. *American Journal of Sports Medicine, 18*(3), 300–309.

Taylor, B. F., Waring, C. A., & Brashear, T. A. (1995). The effects of therapeutic application of heat or cold followed by static stretch on hamstring muscle length. *Journal of Orthopaedic & Sports Physical Therapy, 21*(5), 283–286.

Viitasalo, J. T., Niemela, K., Kaappola, R., Korjus, T., Levola, M., Mononen, H. V., et al. (1995). Warm underwater water-jet massage improves recovery from intense physical exercise. *European Journal of Applied Physiology and Occupational Physiology, 71*(5), 431–438.

Warren, C. G., Lehmann, J. F., & Koblanski, J. N. (1976). Heat and stretch procedures: an evaluation using rat tail tendon. *Archives of Physical Medicine and Rehabilitation, 57*(3), 122–126.

Wessling, K. C., DeVane, D. A., & Hylton, C. R. (1987). Effects of static stretch versus static stretch and ultrasound combined on triceps surae muscle extensibility in healthy women. *Physical Therapy, 67*(5), 674–679.

Williams, P. E., & Goldspink, G. (1978). Changes in sarcomere length and physiological properties in immobilized muscle. *Journal of Anatomy, 127*(Pt 3), 459–468.

Witvrouw, E., Mahieu, N., Danneels, L., & McNair, P. (2004). Stretching and injury prevention: an obscure relationship. *Sports Medicine, 34*(7), 443–449.

Ylinen, J., Kankainen, T., Kautiainen, H., Rezasoltani, A., Kuukkanen, T., & Hakkinen, A. (2009). Effect of stretching on hamstring muscle compliance. *Journal of Rehabilitation Medicine, 41*(1), 80–84.

Zhou, S., Schmelz, A., Seufferlein, T., Li, Y., Zhao, J., & Bachem, M. G. (2004). Molecular mechanisms of low intensity pulsed ultrasound in human skin fibroblasts. *Journal of Biological Chemistry, 279*(52), 54463–54469.