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Title: Can chronic stretching change the muscle-tendon mechanical properties? A review.

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Abstract

Purpose. It is recognized that stretching is an effective method to chronically increase the joint range of motion. However, the effects of stretching training on the muscle-tendon structural properties remain unclear. This systematic review with meta-analysis aimed to determine whether chronic stretching alter the muscle-tendon structural properties.

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Methods. Published papers regarding longitudinal stretching (static, dynamic and/or PNF) intervention (either randomized or not) in humans of any age and health status, with more than 2 weeks in duration and at least 2 sessions per week, were searched in PubMed, PEDro, ScienceDirect and ResearchGate databases. Structural or mechanical variables from joint (maximal tolerated passive torque or resistance to stretch) or muscle-tendon unit (muscle architecture, stiffness, extensibility, shear modulus, volume, thickness, cross sectional area, and slack length) were extracted from those papers.

Results. A total of 26 studies were selected, with a duration ranging from 3 to 8 weeks, and an average total time under stretching of 1165s per week. Small effects were seen for maximal tolerated passive torque, but trivial effects were seen for joint resistance to stretch, muscle architecture, muscle stiffness, and tendon stiffness. A large heterogeneity was seen for most of the variables.

Conclusion. Stretching interventions with 3-8 weeks duration do not seem to change either the muscle or the tendon properties, although it increases the extensibility and tolerance to a greater tensile force. Adaptations to chronic stretching protocols shorter than 8 weeks seem to mostly occur at a sensory level.

Key-words: Dynamic Stretching, Flexibility Training, Mechanical Properties, Muscle Architecture, Static stretching, Stiffness, Proprioceptive Neuromuscular Facilitation

Introduction

Various types of physical training, such as resistance training, induce structural and mechanical changes in the muscle-tendon unit (MTU), by altering muscle volume, cross sectional area, thickness, fascicle length, pennation angle, and tendon stiffness.[1,2] These changes have been related to alterations of muscular functional properties (e.g. force-length-velocity relationship),[3] and injury occurrence.[4] Although several studies focused on strength training,[2] few have examined the effects of stretching interventions.[5]

It is agreed that chronic stretching interventions induce an increase in the joint maximal range of motion (ROM).[6,7] Two main mechanisms have been proposed to explain the joint ROM increase.[8] Firstly, through an increase of tolerance to stretch (i.e. *sensory theory*), indicating that MTU can tolerate more passive tension after the intervention but without a change of tension for a given length. And secondly, through a decrease of joint resistance to stretch (e.g. joint passive torque at a given angle), that could be due to both a change in MTU mechanical properties (e.g., decrease in the stiffness of tissues) or geometry (e.g., increase in fascicle length). Such changes can be considered as chronic structural adaptations, i.e. *mechanical theory*.[8]

Previous studies showed an increase in joint ROM without changes in joint resistance to the stretch after short-term (i.e., 2-8 weeks) stretching protocols,[9,10] and consequently supporting that the chronic increase of the joint ROM is mainly due to a higher stretch tolerance. On the other hand, other studies have showed a resistance to stretch decrease after a stretching intervention.[11,12] A possible reason for such different results may be related to the different stretching types, duration of intervention, and doses (i.e. volume and intensity) used among the studies. Therefore, while the main aim of stretching interventions in both sport and clinical practice is to affect the MTU structure and mechanical properties,[2,13] the actual efficiency of these interventions remains unclear.

This study aimed to systematically review the literature regarding the chronic effects of stretching interventions (> 2-weeks of training) on the MTU structure, including geometry (e.g., fascicle length and angle, muscle and tendon cross sectional area or volume), and mechanical properties (e.g. joint passive torque, passive muscle stiffness, and tendon stiffness). We included in this analysis different stretching types due to the low number of studies on this topic. Based on extracted data, a meta-analysis was performed on each variable, and results were discussed for the stretching type (i.e. static, dynamic, and PNF), intervention duration, volume (i.e., time under stretch), and intensity (i.e., degree of muscle extensibility or degree of joint range of motion).

Methods

This systematic review and meta-analysis was prepared according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement.[14] Details of study selection, data collection, and statistical methods have all been described previously.[15,16]

Search strategies

Detailed electronic searches were performed in the following databases: PubMed, PEDro and ScienceDirect. In additional ResearchGate, a social networking site for scientists and researchers, was also examined for any other potentially eligible papers or full text. Finally, personal libraries of all coauthors were reviewed for eligible papers. A structured search included papers published prior to 01 August 2016. Manual search was performed covering the areas of chronic stretching and MTU, using the following key terms and strings, either singly or in combination: stretching, flexibility, training, fascicle angle, fascicle length, muscle stiffness, tendon stiffness, joint, passive torque, stiffness, muscle volume, elastography, ultrasound, MRI, shear modulus. Detailed search strategy for each database is presented in the appendix.

Study selection

All procedures for study selection such as literature search, identification, screening, quality assessment, and data extraction have been performed by two independent reviewers (RA and GLS). The process of the study selection is shown in Figure 1. First, the titles were initially reviewed during the electronic searches to assess papers' suitability, whereas all papers beyond the scope of this systematic review and meta-analysis were excluded. Second, abstracts were screened using predefined inclusion and exclusion criteria. Third, full texts of the remaining papers that met the inclusion criteria were retrieved and included in the ongoing procedure, and reviewed by the two reviewers to reach a final decision on inclusion in the meta-analysis. Finally, reference lists from retrieved manuscripts were also examined for any other potentially eligible papers. All disagreements between the reviewers for any step were resolved by consensus or arbitration through a third reviewer (SF). If full text of any paper was not available, the corresponding author was contacted by mail or Researchgate.

Study selection criteria

Studies were considered eligible if they: (1) were randomized and non-randomized longitudinal intervention including human participants regardless of age and health status; (2) included static, dynamic (ballistic), and/or PNF stretching; (3) involved an interventions of ≥2 weeks in durations; (4) consisted of at least 2 sessions/week; and (5) included at least one joint mechanical variable [maximal tolerated passive torque or resistance to stretch (passive torque at a given angle, angle at a given passive torque, or slope from the passive torque-angle relationship; i.e. passive joint stiffness)], or one muscle-tendon structural/mechanical variable (fascicle length or angle, muscle or tendon stiffness, muscle or tendon extensibility, muscle or tendon shear modulus, muscle or tendon thickness, muscle or tendon cross sectional area, muscle or tendon slack length).

Data extraction

Cochrane Consumers and Communication Review Group's data extraction standardized protocol was used to extract: (1) study characteristics including author(s) and year of publication; (2) participant information such as sample size, age, health status and sex; (3) description of the intervention, including types of stretching, intensity, duration and frequency; and (iv) study outcomes (according to the variables described above, plus the maximal range of motion). When a variable was assessed by more than one criterion (e.g. passive torque assessed at neutral position vs. a fixed joint angle), the criteria most suitable and who had more tests across studies was chosen. Also, when data were not fully detailed in the study manuscript, the authors were contacted via email to provide that information.

The stiffness outcome was considered when a force parameter change was divided by a displacement parameter change. Extensibility was considered as the maximal change in tissue length. The total time under stretching (TTUS) per week was quantified when the study stretch duration and frequency (i.e. repetitions per session, and number of sessions) were reported.

Statistical analysis

Analysis was performed in the Comprehensive Meta-analysis software, version 2 (Biostat Inc, Englewood, NJ). The standardized mean differences (i.e. an effect size parameter) and 95% confidence intervals (CIs) were calculated for the included studies. A random effects meta-analysis was conducted to determine the pooled effect of chronic stretching on muscle-tendon mechanical properties.

Effect Size (ES) was determined by calculating the standardized mean difference, when raw values, standard deviations (SD), and sample sizes (n) were available, using the follow formula: ES = (raw mean change$_1$ – raw mean change$_2$) / $SD_{Post\text{-}Pooled}$. The following formula was used to calculate $SD_{Post\text{-}Pooled}$:

$$SD_{Post\text{-}Pooled} = \sqrt{\frac{(n_1-1)\,SD_1^2+(n_2-1)SD_2^2}{n_1+n_2-2}}$$

The magnitude of the ES was interpreted using the following criteria: trivial (<0.20), small (0.21–0.60), moderate (0.61–1.20), large (1.21–2.00), very large (2.01–4.00) and extremely large (>4.00) changes.[15,16] The I^2 (i.e. measure of inconsistency) was used to examine between-study variability; values of 25, 50 and 75% represent low, moderate and high statistical heterogeneity, respectively.[17]

Results

Studies selection

A total of 9500 articles were identified from the database search with an additional 14 articles identified through personal libraries. Following the removal of duplicates and selection according to the inclusion criteria, a total of 26 studies were selected to be included in this systematic review (i.e. 23 studies examined static stretching, 3 studies examined dynamic stretching, and 3 studies examined the PNF stretching); whereas 2 of these were exclusively used for qualitative analysis (Fig. 1). The results from these studies are showed in Table 1. None of the studies covered all the variables. Thus, depending on the variable, data from 24 studies were used for meta-analysis. No studies were found for the variables muscle or tendon cross sectional area, volume, slack length, and thickness. On average, the selected studies had a intervention duration of 5.1 weeks (range: 3-8 weeks), and a TTUS per week of 1165s (range: 270-3150s).

Effects on Joint Mechanical Properties

Chronic stretching had a small effect for increasing the maximal joint passive torque (ES=0.54; 95%CI=0.15-1.92) (Fig. 2); however, a high study heterogeneity was observed (I^2=74.1%). Trivial effects were seen for joint torque at a given angle (ES=0.01; 95%CI= -0.56-0.58; I^2=81.5%), and angle at a given torque (ES=-0.01; 95%CI= -0.27-0.26; I^2=0%); but a small effect was observed for the slope of the torque-angle relationship (ES=-0.30; 95%CI=-0.92-0.32; I^2=83.5%) (Fig. 3).

Effects on Muscle and Tendon Properties

Trivial effects were found for muscle stiffness (ES=-0.19; 95%CI=-0.77-0.39; I^2=69.6%), fascicle length (ES=-0.09; 95%CI=-0.37-0.20; I^2=0%), and fascicle angle (ES=0.02; 95%CI=-031-0.34; I^2=0%) (Fig. 4). For the studies not included in meta-analysis (because raw data was not reported): Blazevich et al.[24] and Nakamura et al.[12] reported an increased maximal muscle extensibility after a static stretching intervention of 3-weeks (120s performed twice daily) and 4-weeks (120s performed daily), respectively; and, Ichihashi et al.[39] reported a decreased hamstring shear modulus after a 4-week static stretching (300s for 3 times a week).

Regarding the effects on tendon properties, the chronic stretching was seen to have trivial effects on the tendon stiffness (ES=-0.06; 95%CI=-0.32-0.20; I^2=27.8%) (Fig. 4); whereas one study reported a lower tendon extensibility at the end of 3-week stretching.[24]

Discussion

In the present study, we systematically reviewed the studies that aimed to examine the effects of chronic stretching on the muscle-tendon structure and mechanical properties. The main findings were: i) chronic stretching (3-8 weeks) has small effect on the maximal tolerated passive torque; ii) no statistical changes were observed for the muscle-tendon mechanical properties after a chronic stretching intervention; and iii) a moderate to high heterogeneity was found for most of the variables.

Effects on Joint, Muscle, and Tendon Properties

Previous studies have proposed the use of chronic stretching to alter the muscle-tendon mechanical properties,[2,13] and thus supporting the *mechanical theory* to explain the increase in the joint maximal ROM increase. However, the *sensory theory* has been raised from studies that have observed an increased maximal joint ROM and tolerated passive torque, in the absence of changes in the joint/muscle-tendon mechanical properties.[9,38] The results of the present meta-analysis support the *sensory theory*. However, we are unaware if the loading applied to the MTU might not be sufficient to trigger structural or mechanical adaptations. Three reasons support this possibility.

First, the stretching protocols of the selected studies lasted in average of 5.1 weeks (range: 3-8 weeks). This might not be sufficient to induce changes in the muscle-tendon structure *in* *vivo*. For example, most of strength training studies showed that neural adaptations occurs in the first weeks of training while structural changes requires longer interventions,[2] and that a minimal duration is required to trigger changes in muscle volume or architecture. Thus, the earlier changes in strength are mainly explained by neural adaptations.[41] It is also possible that a minimal duration of the stretching protocol, that remains to be determined, is required to induce adaptations in muscle-tendon structure. It is important to note that we found only 3 studies with at least 8 weeks that analysed the effects of stretching interventions on fascicle length. Interestingly, 2 studies reported an increase of fascicle length in both healthy [5] (i.e. 8-week intervention) and pathologic [42] (i.e. 1-year intervention) populations, while another did not.[22]

Second, little attention has been given to the stretch intensity variable,[43] while the stretching intensity can determine, for instance, the increase in fascicle length during the stretching procedures. Classical animal studies have shown an increase of serial sarcomere number (i.e. which influences the fascicle length) due to passive stretching,[44,45] and this adaptation seems to be dependent upon the muscle lengthening degree.[46] This might explain why a 8-week stretching intervention resulted in a biceps femoris long head fascicle length increase in Freitas et al. study,[5] but not in Lima et al. study,[22] since a high intense non-rest interval protocol (i.e. 450s stretching per session) *versus* a classical (i.e. rest interval) static stretching protocol (3×30s per session) was performed. It should be noted that the absence of rest between stretching repetitions favours the achievement of a higher stretch intensity.[47]

Third, we contend that the mechanical effects might have occurred in non-muscular and structures that poorly influence the joint torque.[48] Indeed, two recent studies suggest that the peripheral nerves and the fascia can limit the joint ROM. First, Andrade et al.[49] have shown recently that ankle maximal dorsiflexion ROM is strongly influenced by the hip flexion in the absence of changes in ankle passive torque and medial gastrocnemius passive tension. Considering that ankle, knee and hip joints influence the sciatic nerve stiffness,[50] the peripheral nerve can be involved in ankle ROM limitation. Second Cruz-Montecinos et al. have reported that pelvis motion causes the displacement of deep fascia under medial gastrocnemius, and this displacement was related to the maximal score of a sit and reach test.[51] Together, these results suggest that the sciatic nerve tract and the lower limb deep fascia (i.e. both tissues that crosses both the ankle and hip joints) might restrict the joint ROM by moving the hip/pelvis. In that case, some mechanical adaptations after chronic stretching interventions might occur at a nerve and fascia level. Such adaptations have been unable to be detected in previous studies due to the lack of appropriate measurements. Note that the new possibility to perform localized measurements of stiffness using shear wave elastography would enable to test this hypothesis in the future.[55]

Methodological considerations

In the present study we observed a high heterogeneity for most of the variables. Such variability may be due to the different protocols used (i.e. time under stretch per week, stretch intensity, and stretching type). We have noted that the studies reported different stretching intensity criteria based on the participant's perception; for instance, "the point before discomfort" *vs.* "point of mild discomfort" *vs.* "point of discomfort" *vs.* "onset of pain". The variability of stretching intensity criteria may evoke different MTU lengthening between studies, and considering that the acute mechanical effects varies depending on the stretching intensity,[47,52] this might explain the heterogeneity. Also, the time under stretch might determine whether the mechanical adaptations occur or not. For example, in respect to the effect on the joint passive stiffness, the average total time under stretch per week was clearly higher in those studies reporting a stiffness decrease after the stretching intervention (i.e. 1880s per week)[11-12, 27] compared to those reporting a stiffness increase (i.e. 700s per week)[19,32,37]. The chronic stretching effects might also depend on the stretching type used. For instance, the PNF (contract-relax) may target the tendon stiffness to a greater extent than other methods,[53] since the the contraction during the passive stretch overstretches the tendon. In the two PNF studies that we found,[20,29] both reported a decrease of tendon stiffness (although only one study reported to be statistically significant). Also, in respect to muscle stiffness, two out of three static studies reported a stiffness decrease,[24,34] but in only one the effect was statistically significant.[34] In addition, we also commend that other factors such as age or health status could also explain the results heterogeneity, due to their relation to the sensory system properties. However, due to the low number of studies it was not possible to perform meta-regression for each variable, in order to determine whether the variables heterogeneity is related to the stretching type of participant's characteristics. Thus, this remains to be examined in the future.

Moreover, many of previous studies have used the joint stiffness outcome (i.e. by means of passive torque at a given angle, angle at a given torque, or based on the slope of the torque-angle relationship) to infer MTU stiffness. Although, such inference contemplates bias because many MTU´s cross a single joint and adaptations may vary between muscles.[54] Therefore, it is not possible to infer about a single MTU based on torque measurement. Some studies have used ultrasonography in B-mode to assess muscle-tendon junction displacement of a specific muscle during the joint passive motion.[18,24] From here, they have estimated the muscle stiffness by dividing the muscle force (i.e. joint torque normalized to moment arm and estimated percentage of contribution to total active joint torque within synergistic muscles based on cross section area) to the muscle-tendon junction displacement. However, this technique remains limited by the global torque measurement which is due to several structures and is not limited to one MTU. Also, the estimated muscle force is based on muscle size and do not account for specific tissue tension; and the proximal muscle-tendon junction is not controlled, which can affect the muscle lengthening measurement. To overcome these limitations, the shear wave elastography technique has been proposed to examine localized muscle stiffness during passive conditions.[55] Two studies have used this technique to examine the effects of chronic stretching on muscle shear modulus.[35,39] Akagi et al. (2014) measured the shear modulus along the transverse direction of the muscle, and this measurement is less appropriate and sensible to changes in muscle stiffness.[56] Interestingly, Ichihashi et al. (2016) reported that a 4-week static stretching (900s of static stretching per week) decreased the biceps femoris, semitendinosus, and semimembranosus shear modulus measured along the main direction of the muscle fascicles.[39] This opens a new way to quantify the effects of chronic stretching on the mechanical properties of a given muscle. Another methodological limitation noted is that the previous studies has been limited to examine only the plantar flexors (i.e. mainly medial gastrocnemius) and knee flexors (i.e. hamstrings). As in strength training, the hypertrophic response differ between muscles,[57] we are unaware if other tissues (e.g. from upper limbs) adapt differently to chronic stretching. However, due to the limit number of studies, this issue remains to be examined in the future.

Perspective

The present systematic review results, suggest that the early (i.e. until 6-8 weeks) chronic adaptations to stretching evoke mainly alterations in the sensory system in the absence of (or with marginal) structural changes of the MTU. We found that chronic stretching has trivial effects on the muscle-tendon mechanical properties, although with small effect on the tolerated maximal tolerated passive torque. In addition, we found a moderate to high heterogeneity for most of the variables. For the selecting studies, the maximum stretching intervention duration was 8 weeks, and the average total time under stretch per week was 1165s. Due to the insufficient number of studies it is not possible to determine whether the results heterogeneity are explained by the stretching dose. The mechanisms involved in such sensory adaptation remains to be determined.[8] It may involve changes in peripheral or/and central nervous components. Structural MTU adaptations in consequence of stretching may need greater intervention duration (e.g. > 8-12 weeks), or greater stretching stimulus per period of time (i.e. greater stretching intensity per session, or greater time under stretching per week). However, the effects of longer interventions, with higher stretching doses, remains to be analyzed. In addition, non-muscular factors as connective tissues crossing the joints (i.e. fascia) and peripheral nerves may be more sensible to mechanical changes than skeletal muscle itself, that is surrounded and composed by connective tissue.

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Figures Caption

Figure 1. Flow chart diagram of the study selection.

Figure 2. Forest plot of the effect sizes and 95% CI of the maximal tolerated passive torque.
Legend: CI, confidence interval; Std diff, standardised difference
No details regarding the stretch duration, number of repetitions, and number of exercises. Only for the total session time.

Figure 3. Forest plot of the effect sizes and 95% CI of the changes in joint stiffness parameters: passive torque at a given angle, angle at a given passive torque, and slope of the torque-angle curve.
Legend: CI, confidence interval; Std diff, standardised difference
No details regarding the stretch duration, number of repetitions, and number of exercises. Only for the total session time.

Figure 4. Forest plot of the effect sizes and 95% CI of the changes in muscle stiffness, fascicle length, fascicle angle, and tendon stiffness.
CI, confidence interval; Std diff, standardised difference.

Table Caption

Table 1. Summary of characteristics of all studies meeting the inclusion criteria.

Legend: C, control group; d, days; E, experimental group; FA, fascicle angle; FL, fascicle length; Hyst, hysteresis; Stiff-APT, joint stiffness by angle at a given torque; Stiff-PTGA, joint stiffness by passive torque at a given angle; Stiff-Slope, joint stiffness by the slope of the torque-angle relationship; mTPT, maximal tolerated passive torque; n, sample size; PExt, passive extensibility; PNF, proprioceptive neuromuscular facilitation; SM, shear modulus; Stiff, stiffness; TERT, total end-range (stretching) time; wks, weeks; ↑, increase; ↓, decrease.
* Statistical significant ($p<0.05$).
# No details regarding the stretch duration, number of repetitions, and number of exercises. Only for the total session time.
#1 No information regarding p-value.

Appendix 1 – MEDLINE search strategy

1. Flexib*
2. Stiff*
3. Extensib*
4. Joint Range of Motion
5. Stretch*
6. or/1-5
7. muscle
8. tendon
9. or/7-8
10. Pennation Angle
11. Fascicle angle
12. Passive Torque
13. Passive tension
14. Muscle volume
15. Cross sectional area
16. Elastography
17. Shear modulus
18. Elastic modulus
19. Ultrasound
20. Magnetic resonance imaging
21. or/10-20
22. Chronic effects
23. training effects
24. long term effects effects
25. or/22-24
26. 6 and 9 and 21 and 25

((Flexib*) OR (Stiff*) OR (Extensib*) OR (Joint Range of Motion) OR (Stretch*)) AND ((Muscle) OR (Tendon)) AND ((Pennation Angle) OR (Fascicle angle) OR (Passive Torque) OR (Passive tension) OR (Muscle volume) OR (Cross sectional area) OR (Elastography) OR (Shear modulus) OR (Elastic modulus) OR (Ultrasound) OR (Magnetic resonance imaging)) AND ((Chronic effects) OR (training effects) OR (long term effects) OR (effects))

Appendix 2 – ScienceDirect search strategy

((Flexib*) OR (Stiff*) OR (Extensib*) OR ("Joint Range of Motion") OR (Stretch*)) AND ((Muscle) OR (Tendon)) AND (("Pennation Angle") OR ("Fascicle angle") OR ("Passive Torque") OR ("Passive tension") OR ("Muscle volume") OR ("Cross sectional area") OR (Elastography) OR ("Shear modulus") OR ("Elastic modulus") OR (Ultrasound) OR ("Magnetic resonance imaging")) AND (("Chronic effects") OR ("training effects") OR ("long term effects") OR (effects)) AND NOT (animal) AND LIMIT-TO(topics, "**patient**,muscle,mri,child,knee,image,joint,**back pain**,treatment,shoulder,tendon,**acl,spinal cord**") AND LIMIT-TO(contenttype, "JL,BS","Journal")

Appendix 3 – Google Scholar search strategy

1. ontitle: stretching flexibility OR stiffness OR extensibility OR "range of motion" "effects" -animal

Appendix 4 – PEDro search strategy

1. Stretch* chronic effects.ti/ab. and clinical trial.method

Search date : 05/02/16 (RA + GLS) = 53 references found

2. Stretch* long-term effects.ti/ab. and clinical trial.method

Search date : 05/02/16 (RA + GLS) = 34 references found

3. Stretch* training effects.ti/ab. and clinical trial.method

Search date : 05/02/16 (RA + GLS) = 135 references found

Table 1. Summary of characteristics of all studies meeting the inclusion criteria.

Study	Population: Type	n	Age	Stretching intervention: Tissues	Duration	Training method	TERT / Week	Outcomes (% of change): Joint	Muscle	Tendon
Konrad & Tilp, 2014a	Police cadets, male and female	E=19	22.8	Plantar flexors	6 wks	Static, self-stretching	600s (5d/wk, 4x30s)	mROM: 17.5% ↑*; Stiff-PTGA: 3.69%↓; Stiff-Slope: 5%↑	Stiff: 8.86%↑; FL: 1.37%↑; FA: 0-4.5%↑	Stiff: 0.76%↑
		C=15		-		-	-			
Gajdosik et al. 2007	Unconditioned, female	E=6	22	Plantar flexors	6 wks	Static, self-stretching	750s (5d/wk, 10x15s)	mROM: 34.7% ↑*; mTPT: 76.7%↑*; Stiff-PTGA: 73.9%↑*; Stiff-Slope: 33.8%↑	-	-
		C=4		-		-	-			
Mahieu et al. 2006	Recreational athletes, male and female	E=31	22	Plantar flexors	6 wks	Static, self-stretching	700s (7d/wk, 5x20s)	mROM: 9.19%↑*; Stiff-PTGA: 7.67%↓*	-	Stiff: 37.57%↓
		E=21				Ballistic, self-stretching	700s (7d/wk, 5x20s)	mROM: 11.27%↑*; Stiff-PTGA: 0.73%↓	-	Stiff: 37.72%↓*
		C=29		-		-	-	-	-	-
Mahieu et al. 2009	Recreational athletes, male and female	E=21	22.4	Plantar flexors	6 wks	PNF, self-stretching	1260s (7d/wk, 5x36s)	mROM: 21.12%↑*; Stiff-PTGA: 7.11%↓	-	Stiff: 0.63%↓
		C=29		-		-	-	-	-	-
Nakamura et al. 2012	Male	E=9	21.4	Plantar flexors	4 wks	Static, self-stretching	840s (7d/wk, 5x60s)	mROM: 20.3%↑*; Stiff-PTGA: 13.42%↓*	Pext: 43.1%↑*; FL: 1.48%↓	-
		C=9		-		-	-			
Lima et al. 2014	Physically active, male	E=12	19.1	Knee flexors	8 wks	Static, assisted-stretching	270s (3d/wk, 3x30s)	mROM: 5.97%↑*	FL: 3.83% ↓; FA: 0.72%↑	-
		C=12		-		-	-			
Kubo et al. 2002	Recreational athletes, male	E=8	24.6	Plantar flexors	2.86 wks	Static, self-stretching	3150s (7d/wk, 5x45sx2)	Stiff-Slope: 13.28↓	-	Stiff: 2.49%↓; Hyst: 37.19%↓*
		C=8		-		-	-			
Blazevich et al. 2014	Male	E=15	18.6	Plantar flexors	3 wks	Static, self-stretching	1680s (7d/wk, 4x30sx2)	mROM: 19.9%↑*; mTPT: 28%↑*; Stiff-PTGA: 9.93%↓	Pext: 12.24%↑*; Stiff: 18%↓*; FL: 1.5%↑	Stiff: 7.9%↑
		C=9		-		-	-			
Freitas & Mil-Homens 2015	Recreational athletes, male	E=5	21.2	Knee flexors	8 wks	Static, assisted-stretching	1575s (3.5d/wk, 1x450s)	mROM: 11.2%↑*	FL: 13.6%↑*; FA: 10.8%↓	-
		C=5		-		-	-			

Guissard et al. 2004	Male and female	E=12	21-35	Plantar flexors	6 wks	Static, self-stretching	3000s (5d/wk, 5x30sx4)	mROM: 30.8%↑*; mTPT: 2.59↓; Stiff-Slope: 48.68%↓ *	-	-
		C=12		-		-	-			
Chan et al. 2001	Male and female	E=10	21.2	Knee flexors	8 wks	Static, self-stretching	450s (3d/wk, 5x30s)	mROM: 7.05%↑*; mTPT: 4.29%↓	-	-
		C=10		-		-	-			
		E=10	19.7	Knee flexors	4 wks	Static, self-stretching	450s (3d/wk, 5x30s)	mROM: 5.33%↑; mTPT: 20.63%↑	-	-
		C=10		-		-	-			
Folpp et al. 2006	University population, Male and female	E=20	24	Knee flexors	4 wks	Static, self-stretching	6000s# (5d/wk, 1200s)	mROM: 13.04%↑#1; mTPT: 21.81%↑#1; Stiff-APT:1.5%↑	-	-
		C=20		-		-	-			
Marshal et al. 2011	University population, Male and female	E=11	22.7	Knee flexors	4 wks	Static, self-stretching	1800s (5d/wk, 3x30sx4)	mROM: 20.9%↑*; mTPT: 43.52%↑; Stiff-Slope:31%↓*	-	-
		C=11		-		-	-			
Konrad & Tilp, 2014b	Police cadets, male and female	E=16	22.8	Plantar flexors	6 wks	Dynamic, self-stretching	600s (5d/wk, 4x30s)	mROM: 11.83% ↑*; Stiff-PTGA: 3.97%↓; Stiff-Slope: 4.82%↑	Stiff: 7.61%↑; FL: 0%; FA: 0%	Stiff: 6.45%↑
		C=15		-		-	-			
Konrad & Tilp, 2014c	Police cadets, male and female	E=20	23.5	Plantar flexors	6 wks	PNF, self-stretching	720s (5d/wk, 4x36s)	mROM: 6.43% ↑*; Stiff-PTGA: 5.66%↓; Stiff-Slope: 5.06%↓	Stiff: 1.42%↑; FL: 1.41%↑; FA: 0.6%↓	Stiff: 14.22%↓*
		C=15		-		-	-			
LaRoche et al. 2006	Recreational athletes, male	E=10	28,11	Knee flexors	6 wks	Dynamic, self-stretching	900s (3d/wk, 10x30s)	mROM: 9.3% ↑*; mTPT: 25.4% ↑*; Stiff-Slope: 10%↓	-	-
		E=9	31			Static, self-stretching	900s (3d/wk, 10x30s)	mROM: 9.5% ↑*; mTPT: 30.1% ↑*; Stiff-Slope: 10.3%↓	-	-
		C=10	34	-		-	-	-	-	-
Ylinen et al (2009	Recreational athletes, male	E=12	34	Plantar flexors	4 wks	Static, self-stretching	1260s (7d/wk, 6x30s)	mROM:24.6% ↑*; mTPT: 22.1% ↑*	-	-
		C=12		-		-	-			
Reid et al. 2011	Secondary schools students	E=21	69.3	Knee flexors	6 wks	Static, self-stretching	900s (5d/wk, 3x60s)	mROM: 11.1%↑*; mTPT: 49.5%↑*; Stiff-APT: 8.4%↓*; Stiff-Slope: 35.5%↑*	-	-
		C=18		-		-	-			
Law et al. 2009	Musculoskeletal pain	E=30	43	Knee flexors	2.6 wks	Static, self-stretching	420s (6d/wk, 1x60s)	mROM: 14.5%↑*; mTPT:	-	-

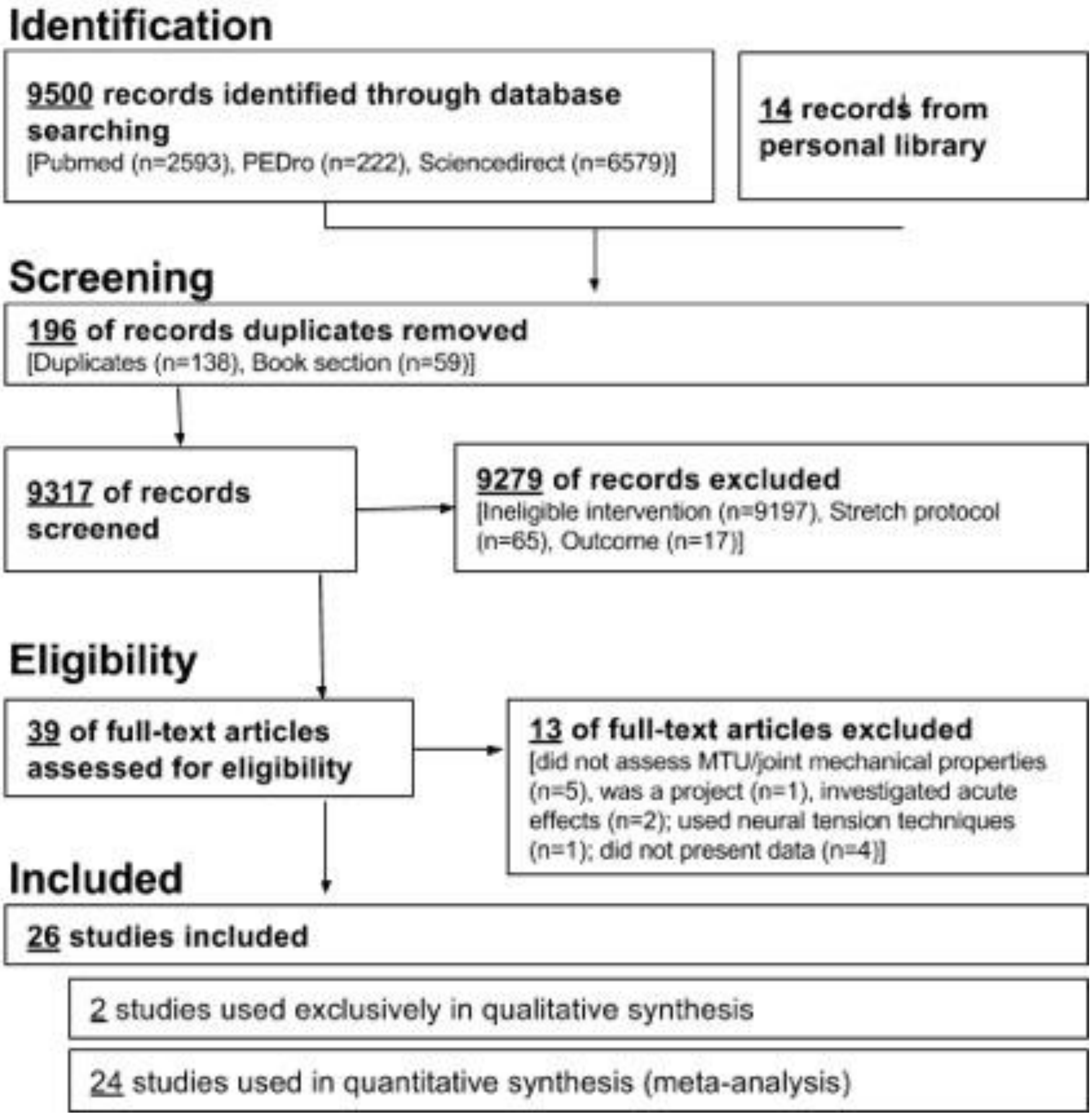
	patients, male and female	C=30		-		-	-	22.2%↑*; Stiff-APT: 5.2%↑		
Nakamura et al. 2016	Recreational athletes, male	E=12	24.6	Plantar flexors	4 wks	Static, assisted-stretching	360s (3d/wk, 4x30s)	mROM: 26.2%↑*; mTPT: 48.3%↑*	Stiff: 23.5%↓*	-
		C=12		-		-	-			
Akagi et al. 2014	Recreational athletes and sedentary, male	E=19	23.7	Plantar flexors	5 wks	Static, self-stretching	2160s (6d/wk, 3x120s)	mROM: 17.1%↑*; Stiff-Slope: 6.7%↓*	-	-
		C=19		-		-	-			
Reid et al. 2004	Secondary schools students, male	E=23	15.8	Knee flexors	6 wks	Static, self-stretching	450s (5d/wk, 3x30s)	mROM: 11.1%↑*; mTPT: 57.4%↑*; Stiff-Slope: 26.3%↑*	-	-
		C=20		-		-	-			
Gajdosik et al. 2005	Community dwelling, female	E=10	74.2	Plantar flexors	8 wks	Static, self-stretching	450s (3d/wk, 10x15s)	mROM: 45.9%↑*; mTPT: 60.8%↑*; Stiff-PTGA: 43.5%↑; Stiff-Slope: 5.4%↑*	-	-
		C=9		-		-	-			
Halbertsma et al. 1994	University population, Male and female	E=7	31.3	Knee flexors	4 wks	PNF, self-stretching	4200s (7d/wk, 300sx2)	mROM: 7.2%↑*; mTPT: 32.3%↑*	-	-
		C=7		-		-				
Ichihashi et al. 2016	Military conscripts, male	E=15	22.7	Knee flexors	4 wks	Static, assisted-stretching	900s (3d/wk, 300s)	-	SM: 12.8-21.5%↓*	-
		C=15		-		-	-			
Ben & Harvey	Hospital staff, male and female	E=15	37	Knee flexors	6 wks	Static, self-stretching	9000s# (5d/wk, 1800s)	mROM: 0%; mTPT: 1.9%↑; Stiff-APT:7.3%↑	-	-
		E=15				Static, self-stretching	9000s# (5d/wk, 1800s)	mROM: 12.6%↑*; mTPT: 20.4%↑*; Stiff-APT:7.5%↑		
		C=30		-		-	-	-		

Legend: C, control group; d, days; E, experimental group; FA, fascicle angle; FL, fascicle length; Hyst, hysteresis; Stiff-APT, joint stiffness by angle at a given torque; Stiff-PTGA, joint stiffness by passive torque at a given angle; Stiff-Slope, joint stiffness by the slope of the torque-angle relationship; mTPT, maximal tolerated passive torque; n, sample size; PExt, passive extensibility; PNF, proprioceptive neuromuscular facilitation; SM, shear modulus; Stiff, stiffness; TERT, total end-range (stretching) time; wks, weeks; ↑, increase; ↓, decrease.

* Statistical significant ($p<0.05$).

No details regarding the stretch duration, number of repetitions, and number of exercises. Only for the total session time.

#1 No information regarding p-value.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Screening
196 of records duplicates removed
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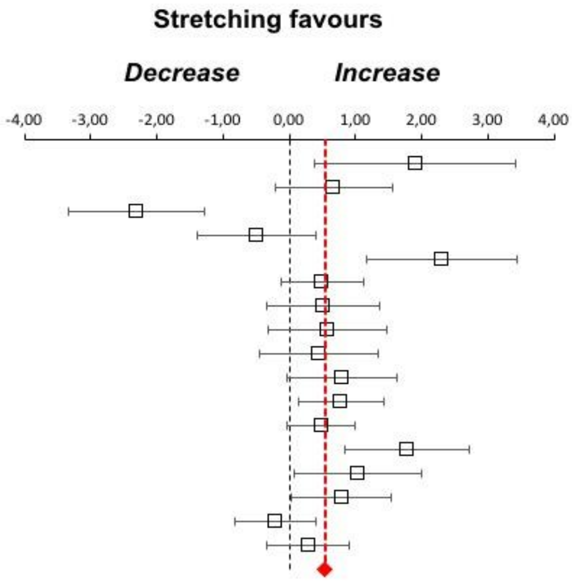
9317 of records screened
9279 of records excluded
[Ineligible intervention (n=9197), Stretch protocol (n=65), Outcome (n=17)]
Eligibility
39 of full-text articles assessed for eligibility
13 of full-text articles excluded
[did not assess MTU/joint mechanical properties (n=5), was a project (n=1), investigated acute effects (n=2); used neural tension techniques (n=1); did not present data (n=4)]
Included
26 studies included
2 studies used exclusively in qualitative synthesis
24 studies used in quantitative synthesis (meta-analysis)

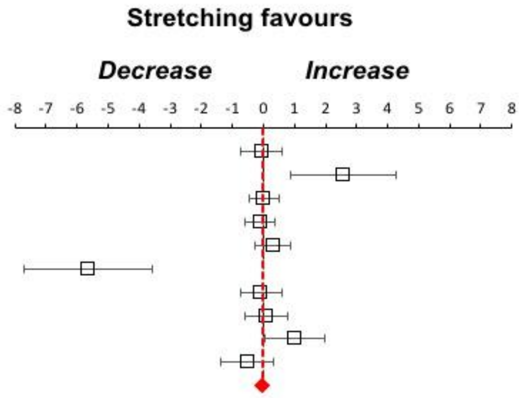
Maximal tolerated passive torque

Study name	Intervention	Std diff in means	Lower limit	Upper limit	p-value
Gajdosik et al. (2007)	6wks, static 750s/wk	1.90	0.39	3.41	0.01
Blazevich et al. (2014)	3 wks, static 1680/wk	0.67	-0.22	1.56	0.14
Guissard et al. (2004)	6 wks, static 3000s/wk	-2.30	-3.33	-1.27	0.00
Chan et al. (2000)	8 wks, static 450s/wk	-0.50	-1.39	0.39	0.28
Chan et al. (2000)	4 wks, static 450s/wk	2.30	1.17	3.43	0.00
Folpp et al. (2006)	4 wks, static 6000s/wk #	0.50	-0.13	1.13	0.12
Marshall et al. (2011)	4 wks, static 1800s/wk	0.52	-0.33	1.37	0.23
Laroche et al (2006)	6 wks, dynamic 900s/wk	0.57	-0.33	1.46	0.21
Laroche et al (2006)	6 wks, static 900s/wk	0.45	-0.44	1.33	0.32
Ylinen et al (2009)	4 wks, static 1260s/wk	0.79	-0.04	1.63	0.06
Reid et al (2011)	6 wks, static 900s/wk	0.78	0.13	1.44	0.02
Law et al (2009)	2.6 wks, static 420s/wk	0.48	-0.03	0.99	0.07
Nakamura et al. (2016)	4 wks, static 360s/wk	1.77	0.83	2.72	0.00
Gajdosik (2005)	6 wks, static 450s/wk	1.03	0.07	1.99	0.03
Halbersta et al	4 wks, PNF 4200s/wk	0.79	0.03	1.54	0.04
Ben & Harvey (2010)	6 wks, static 9000s/wk #	-0.21	-0.83	0.41	0.51
Ben & Harvey (2010)	6 wks, static 9000s/wk #	0.28	-0.34	0.91	0.37
	Overall (I^2=74.1%)	0.54	0.15	0.92	0.01



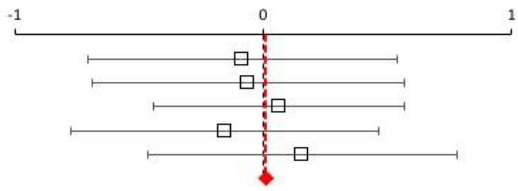
Passive torque at a given angle

Study name	Intervention	Std diff in means	Lower limit	Upper limit	p-value
Konrad & Tilp (2014a)	6 wks, static 600s/wk	-0.06	-0.74	0.61	0.85
Gajdosik (2007)	6wks, static 750s/wk	2.58	0.89	4.28	0.00
Mahieu et al. (2009)	6wks, PNF 1260s/wk	0.02	-0.48	0.52	0.93
Mahieu et al. (2006)	6wks, static 700s/wk	-0.11	-0.61	0.39	0.67
Mahieu et al. (2006)	6wks, dynamic 700s/wk	0.31	-0.25	0.87	0.28
Nakamura et al (2012)	4 wks, static 840s/wk	-5.63	-7.69	-3.57	0.00
Konrad & Tilp (2014b)	6 wks, dynamic 600s/wk	-0.07	-0.74	0.60	0.83
Konrad et al (2014)	6 wks, PNF 720s/wk	0.09	-0.61	0.80	0.80
Gajdosik (2005)	6 wks, static 450s/wk	1.03	0.07	1.98	0.04
Blazevich et al. (2014)	3 wks, static 1680/wk	-0.51	-1.37	0.34	0.24
	Overall (I^2=80%)	-0.04	-0.57	0.49	0.89



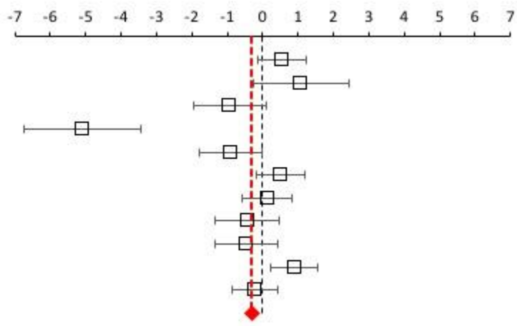
Angle at a given passive torque

Study name	Intervention	Std diff in means	Lower limit	Upper limit	p-value
Folpp et al. (2006)	4 wks, static 6000s/wk #	-0.08	-0.70	0.54	0.79
Reid et al (2011)	6 wks, static 900s/wk	-0.06	-0.69	0.57	0.85
Law et al (2009)	2.6 wks, static 420s/wk	0.06	-0.44	0.57	0.81
Ben & Harvey (2010)	6 wks, static 9000s/wk #	-0.15	-0.77	0.47	0.63
Ben & Harvey (2010)	6 wks, static 9000s/wk #	0.16	-0.46	0.78	0.62
	Overall (I^2=0%)	-0.01	-0.27	0.26	0.95



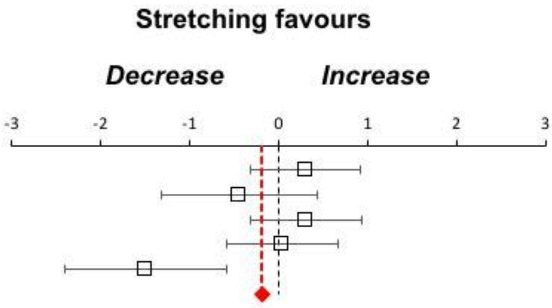
Slope of torque-angle curve

Study name	Intervention	Std diff in means	Lower limit	Upper limit	p-value
Konrad & Tilp (2014a)	6 wks, static 600s/wk	0.55	-0.14	1.24	0.12
Gajdosik et al. (2007)	5 wks, static 750s/wk	1.08	-0.27	2.43	0.12
Kubo et al. (2002)	2.86 wks, static 3150s/wk	-0.92	-1.95	0.11	0.08
Guissard et al. (2004)	6 wks, static 3000s/wk	-5.09	-6.74	-3.44	0.00
Marshall et al. (2011)	4 wks, static 1800s/wk	-0.91	-1.79	-0.03	0.04
Konrad & Tilp (2014b)	6 wks, dynamic 600s/wk	0.51	-0.17	1.19	0.14
Konrad et al (2014)	6 wks, PNF 720s/wk	0.14	-0.57	0.84	0.71
Laroche (2006)	6 wks, dynamic 900s/wk	-0.43	-1.34	0.48	0.36
Laroche (2006)	6 wks, static 900s/wk	-0.47	-1.36	0.42	0.30
Reid et al (2011)	6 wks, static 900s/wk	0.90	0.24	1.56	0.01
Akagi et al (2014)	5 wks, static 2160s/wk	-0.21	-0.85	0.43	0.52
	Overall (I^2=83.5%)	-0.30	-0.92	0.32	0.345



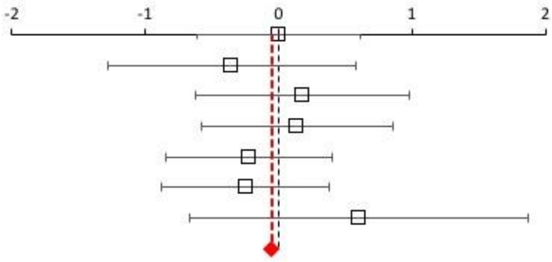
Muscle stiffness

Study name	*Intervention*	Std diff in means	Lower limit	Upper limit	p-value
Konrad and Tilp (2014)	6 wks, static 600s/wk	0.31	-0.31	0.92	0.33
Blazevich et al. (2014)	3 wks, static 1680s/wk	-0.44	-1.32	0.43	0.32
Konrad et Tilp (2014)	6 wks, dynamic 600s/wk	0.31	-0.32	0.93	0.34
Konrad et al. (2014)	6 wks, PNF 720s/wk	0.04	-0.59	0.67	0.91
Nakamura et al (2016)	4 wks, static 360s/wk	-1.49	-2.40	-0.59	0.00
	Overall (I^2=69.6%)	-0.19	-077	0.39	0.52



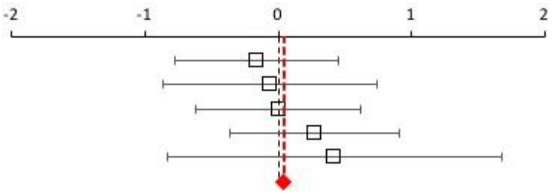
Fascicle length

Study name	*Intervention*	Std diff in means	Lower limit	Upper limit	p-value
Konrad and Tilp (2014a)	6 wks, static 600s/wk	0.00	-0.61	0.61	1.00
Nakamura et al. (2012)	4 wks, static 840s/wk	-0.35	-1.28	0.58	0.46
Lima et al. (2014)	8 wks, static 270s/wk	0.17	-0.63	0.98	0.67
Blazevich et al. (2014)	3 wks, static 1680s/wk	0.14	-0.58	0.85	0.71
Konrad et Tilp (2014b)	6 wks, dynamic 600s/wk	-0.22	-0.84	0.40	0.48
Konrad et al. (2014)	6 wks, PNF 720s/wk	-0.25	-0.88	0.38	0.44
Freitas et al. (2015)	8 wks, static 1575s/wk	0.60	-0.67	1.86	0.36
	Overall (I^2=0%)	-0.05	-0.33	0.22	0.71



Fascicle angle

Study name	*Intervention*	Std diff in means	Lower limit	Upper limit	p-value
Konrad and Tilp (2014a)	6 wks, static 600s/wk	-0.16	-0.78	0.45	0.60
Lima et al. (2014)	8 wks, static 270s/wk	-0.06	-0.86	0.74	0.88
Konrad et Tilp (2014b)	6 wks, dynamic 600s/wk	0.00	-0.62	0.62	1.00
Konrad et al. (2014)	6 wks, PNF 720s/wk	0.27	-0.36	0.90	0.40
Freitas et al. (2015)	8 wks, static 1575s/wk	-0.16	-0.78	0.45	0.60
	Overall (I^2=0%)	0.04	-0.27	0.36	0.79



Tendon stiffness

Study name	*Intervention*	Std diff in means	Lower limit	Upper limit	p-value
Konrad & Tilp (2014a)	6 wks, static 600s/wk	-0.14	-0.75	0.48	0.66
Mathieu et al. (2009)	6wks, PNF 1260s/wk	0.14	-0.36	0.64	0.59
Mathieu et al. (2006)	6wks, static 700s/wk	0.09	-0.41	0.59	0.73
Mathieu et al. (2006)	6wks, dynamic 700s/wk	-0.67	-1.24	-0.10	0.02
Kubo et al. (2002)	2.86 wks, static 3150s/wk	-0.25	-1.23	0.73	0.62
Blazevich et al. (2014)	3 wks, static 1680s/wk	0.39	-0.48	1.27	0.38
Konrad & Tilp (2014b)	6 wks, dynamic 600s/wk	0.40	-0.22	1.03	0.21
Konrad et al. (2014)	6 wks, PNF 720s/wk	-0.40	-1.03	0.24	0.22
	Overall (I^2=27.8%)	-0.06	-0.32	0.20	0.66