Immediate Effect of Exercise on Achilles Tendon Properties: Systematic Review

STEVEN J. OBST, ROD S. BARRETT, and RICHARD NEWSHAM-WEST

School of Rehabilitation Sciences and Center for Musculoskeletal Research, Griffith Health Institute, Griffith University, AUSTRALIA

ABSTRACT

OBST, S. J., R. S. BARRETT, and R. NEWSHAM-WEST. Immediate Effect of Exercise on Achilles Tendon Properties: Systematic Review. *Med. Sci. Sports Exerc.*, Vol. 45, No. 8, pp. 1534–1544, 2013. **Introduction**: Understanding the mechanical and morphological adaptation of the Achilles tendon (AT) in response to acute exercise could have important implications for athletic performance, injury prevention, and rehabilitation. The purpose of this study was to conduct a systematic review and critical evaluation of the literature to determine the immediate effect of a single bout of exercise on the mechanical and morphological properties of the AT *in vivo*. **Methods**: Five electronic research databases were systematically searched for intervention-based studies reporting mechanical and morphological properties of the AT after a single bout of exercise. **Results**: Searches revealed 3292 possible articles; 21 met the inclusion criteria. There is evidence that maximal isometric contractions and prolonged static stretching (>5 min) of the triceps surae complex cause an immediate decrease in AT stiffness, whereas prolonged running and hopping have minimal effect. Limited but consistent evidence exists, indicating that AT hysteresis is reduced after prolonged static stretching. Consistent evidence supports a reduction in free AT diameter (anterior–posterior) after dynamic ankle exercise, and this change appears most pronounced in the healthy tendon and after eccentric exercise. **Conclusions**: The mechanical and morphological properties of the AT *in vivo* are affected by acute exercise in a mode- and dose-dependent manner. Transient changes in AT stiffness, hysteresis, and diameter after unaccustomed exercise modes and doses may expose the tendon to increased risk of strain injury and impact on the mechanical function of the triceps surae muscle–tendon unit. **Key Words:** PHYSICAL ACTIVITY, STRETCH SHORTEN CYCLE, STRETCHING, STIFFNESS, CROSS-SECTIONAL AREA, DIAMETER

The Achilles tendon (AT) forms a dynamic link between the triceps surae and calcaneus and is the largest and strongest tendon in the body (49). Despite this, the AT is also one of the most commonly injured tendons, prevalent in both athletic and sedentary populations (50,76). As well as experiencing large forces (up to 11 kN stretch during running [33]), the AT is described as being a compliant tendon, because it undergoes relatively large length changes during functional activities, with peak strains of 4.8% and 5.6% being reported for walking and running (43) and up to 8.2% for single-leg hopping (42). During stretch–shorten cycle (SSC) movements, strain energy is stored in the AT during lengthening, most of which is rapidly recovered during shortening, thereby contributing to work generation by the muscle–tendon unit (MTU) (25,53). A further consequence of AT compliance is that the calf muscle fibers located in series with the AT are able to operate at lengths and velocities that are favorable for force production, and hence, the compliance of the healthy human AT is optimized for locomotion (44,45,70).

It has been well documented that the mechanical and/or morphological properties of the AT are altered in aging, in disease, and in response to changes in mechanical loading. AT stiffness is reduced in individuals with chronic tendinopathy (6), in older adults (62,63), and after prolonged immobilization (54,69). In contrast, trained endurance and jumping athletes have a larger AT cross-sectional area (CSA) (34,55,71), and sprinters have higher AT stiffness (4), compared with untrained controls. Similarly, long-term isometric (3,9), eccentric (59), and ballistic stretching (56) interventions result in increased AT stiffness and Young modulus, whereas other types of exercise training including plyometric (17,18), concentric, and static stretching (35) have been reported to have little or no effect on tendon properties. Inherent differences in the tendon stress–strain characteristics (i.e., magnitude, rate, duration and frequency) between exercise modes and doses coupled with the suggestion that tendons exhibit stress–strain-dependent limits or

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Address for correspondence: Steven J. Obst, B.Phty., B.Ex.Sc., B.H.M.S., School of Rehabilitation Sciences and Center for Musculoskeletal Research, Griffith Health Institute, Griffith University, Gold Coast Campus, Queensland 4222, Australia; E-mail: s.obst@griffith.edu.au.

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thresholds for adaptation may, in part, provide a rationale for the differential changes in AT mechanical and morphological properties with long-term training (3,5,41).

In addition to understanding the effect of long-term training on AT mechanical and/or morphological properties, it is also necessary to examine the immediate effects of specific exercise modes and doses on these properties. This is important for several reasons. First, cycle and/or time-dependent fatigue of a tendon in response to loading during exercise may expose the tendon to increased risk of injury, as has been previously demonstrated by studies of human (76) and animal tendons *in vitro* (74). Having the same material properties, a more compliant and thin tendon after exercise would be expected to experience higher stress and strain for a given force and thus be more likely to be injured during subsequent exercise. It might also be reasonable to expect that compared with a healthy tendon, this "weakening" effect would be more pronounced in injured or diseased tendon. For this reason, it is important to identify what exercise modes and doses the human AT *in vivo* is able to tolerate without a change in baseline mechanical and/or morphological properties, which would be suggestive of tendon fatigue and thus reduced tensile strength. Furthermore, exercise modes recommended for the management of Achilles tendinopathy, such as eccentric training, may elicit unique changes in tendon properties that provide an insight into the mechanisms underlying their effectiveness. Finally, a transient increase in tendon compliance after an exercise bout may compromise the mechanical function of the MTU during subsequent exercise with possible implications for SSC performance and economy of human locomotion (2,44,45,73).

In view of the recent growth of literature investigating the immediate effects of exercise on tendon properties, and the potential implications of these changes for tendon function and performance, as well as in injury prevention and rehabilitation, a systematic review and critical evaluation of the literature is warranted. The purpose of this review was therefore to determine the immediate effect of a single exercise bout on the mechanical and morphological properties of the human AT *in vivo*.

METHODS

Search strategy. The review was conducted according to the PRISMA guidelines (58) for conducting and reporting systematic reviews. Initial electronic database searches were performed by one reviewer (SJO) during April to July (last search, 30/07/12) for articles examining the immediate effect of exercise on the *in vivo* mechanical and/or morphological properties of the human AT. Searches were performed using the MEDLINE via Ovid (1950–2012), SPORTDiscus via EBSCO (1985–2012), CINAHL via EBSCO (1981 to present), Web of Science (1950 to present), and Scopus (1960–2012) electronic databases. Key terms were grouped and searched within the article title, abstract, and keywords using the conjunction "or." A typical search string was as follows: [(achilles OR gastroc* OR "triceps surae") AND (tendon* OR tendin*) AND (morpholog* OR length OR diameter OR area OR mechanic* OR stiffness OR elasticity OR modulus OR strain) AND (exercis* OR loading OR contraction OR training OR stretch*) Limit to Humans], where * denotes a truncation to ensure all variants of the term were included. Key journals identified after the title and abstract screen were also searched using the string "Achilles tendon" AND exercise. Furthermore, reference lists of all eligible articles were hand searched to retrieve any additional articles.

Articles retrieved in the original search were exported into a single Endnote file (version X4; Thomson Reuters, Carlsbad, CA) and duplicate records removed. The title and abstract of each article were screened by one reviewer (SJO) and irrelevant articles excluded. Where insufficient information was available from the abstract, the full text version was inspected. The remaining full text articles were assessed for inclusion by one investigator (SJO). Full journal articles reporting *in vivo* mechanical (i.e., stiffness, Young modulus, and hysteresis) and/or morphological (i.e., CSA, diameter, slack length, and volume) properties of the AT (i.e., distal to gastrocnemius muscle–tendon junction) and free AT (i.e., distal to soleus muscle–tendon junction) obtained immediately before and within 30 min of a single exercise bout were included. Articles were excluded if they 1) used a single subject or case study design, 2) failed to report both pre- and postexercise data, 3) included participants with neurological conditions (e.g., cerebral palsy), or 4) used an involuntary muscle stimulation exercise intervention. Where articles reported data at multiple time points postexercise, only the first (i.e., most immediate) data set was used. Articles selected for exclusion were verified by a second examiner (RNW), and any discrepancies were resolved through discussion.

Methodological quality assessment. The methodological quality of included articles was evaluated using a modified version of the assessment tool developed by Galna et al. (20). The tool consisted of 14 criteria that evaluate the internal and external validity and repeatability of the study (see Table, SDC 1, Methodological quality assessment of included articles). Each item was scored out of 1 (i.e., 1 = yes, 0.5 yes, but lacks detail, and 0 = no) with a total possible score of 14. Included articles were independently evaluated by two reviewers with any disagreement resolved via consensus meeting. The level of agreement between the two reviewers was measured using Cohen unweighted kappa (κ) statistic (SPSS statistics, version 20.0.0; SPSS Inc., Chicago, IL) (12).

Data extraction and analysis. Mechanical and morphological data from the included studies were extracted from the included articles by one reviewer (SJO) and checked by a second reviewer (RNW). Study characteristics including sample size, participant characteristics, exercise intervention, and testing methodology were also extracted. To facilitate comparison of results across studies, pre- and postintervention means and SD for each outcome measure were used to calculate standardized effect sizes (Cohen *d*) and corresponding 95% confidence intervals (CI) (13). For the study by Mademli et al. (47) that reported tendon lengths at multiple force increments (i.e., 0–900 N), length measurements taken at 300, 600, and 900 N of force were extracted to represent the overall study findings. Furthermore, for the study by Shalabi et al. (72), only data for participant groups that received identical exercise interventions were included. In cases where the numerical data needed to calculate effect size (ES) were not available from the original article, data were digitized from figures in the original article (29,31) or the respective author(s) were contacted and requested to provide the necessary information.

Effect size data were reported separately for mechanical and morphological properties. Because of the heterogeneity of the interventions and measurement methods, pooling of the data across studies was not possible, and hence, a meta-analysis was not performed. All effect size data (mean and 95% CI) were presented as forest plots to allow visual comparison between grouped studies, with bolded error bars indicating statistical significance as reported in the original article. Data were further grouped according to the type of exercise intervention used.

RESULTS

Search results. Electronic database searches yielded a total of 3292 potentially eligible articles. Searches of key journals and reference lists of eligible articles failed to reveal additional articles of interest. After removal of duplicates (*n* = 1485) and irrelevant articles based on title and abstract screening, 41 articles remained, of which further 20 articles were removed on the basis of inclusion and exclusion criteria, leaving a final yield of 21 articles (Fig. 1).

Participant characteristics. The sample size of included studies ranged from 7 (26,35) to 35 (10) participants, with a mean and SD of 14.5 ± 7.9 participants. Fourteen articles included only male participants (7,15,16,21,22,26,36,39,46,47,57,60,61,75), one included only female participants (19), and the remaining included a mix of both sexes (10,28,29,65,66,72). With the exception of Mademli et al. (46,47), all articles assessed young to middle-age participants ranging from 20 to 49 yr old. Of the 21 included articles, two examined the effects of exercise on tendinopathic tendons (22,72), whereas the remaining articles included only healthy asymptomatic tendons. Mademli and Arampatzis (46), Burgess et al. (10), and Shalabi et al. (72) were the only studies reporting group comparisons, comparing the effects of exercise on tendon properties in young versus elderly, male versus female, and symptomatic versus asymptomatic participants, respectively.

Study characteristics. Twelve studies reported only tendon mechanical properties, seven reported only morphological properties, and the remaining two reported both (Fig. 1). Of the 14 studies measuring tendon mechanical properties,

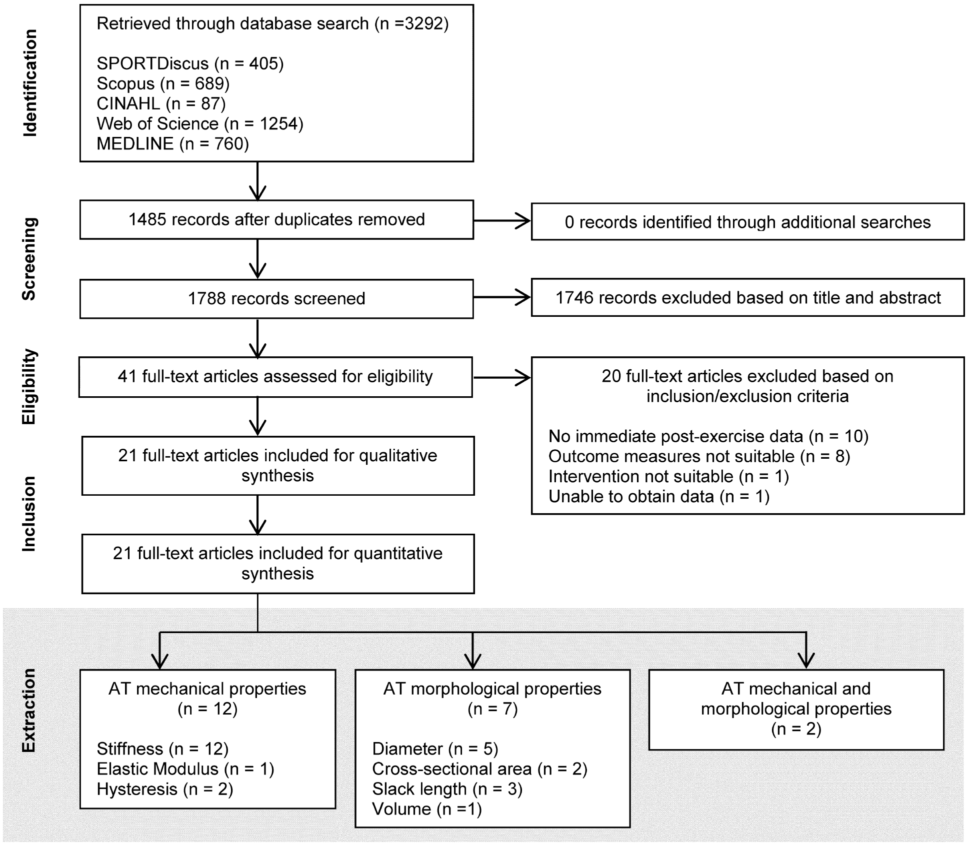

FIGURE 1— Flow chart outlining the article selection process in accordance with PRISMA guidelines (58).

TABLE 1. Characteristics of included studies.

Reference	Sample	Age (yr), Mean (SD) and/or Range	Population	Exercise Intervention	Tendon Outcome Measure	Methodologies
Avela et al. (7)	*n* = 8, male only	25, 20–39	Healthy active	1-h cyclic stretch (10° DF at 200°·s^{-1})	Slack length	US over MG belly
Burgess et al. (10)	*n* = 35 (17 female, 18 male)	F: 20 (4.5)	Healthy active	5-min passive DF stretch at 35–40 N·m	Stiffness	US over MG MTJ
		M: 22 (4.7)			Young modulus	Stiffness defined as slope of LD curve at 100% MVC during MVIC
					Hysteresis	
					CSA	
					Slack length	
Fahlstrom and Alfredson (15)	*n* = 21, male only	39 (8), 27–52	Floor ball players	1-h floor ball match	Diameter	US at thickest point, 3 cm and 4 cm proximal to insertion
Farris et al. (16)	*n* = 12, male only	27 (5)	Recreational runners	30-min run at 12 km·h^{-1}	Stiffness	US over MG MTJ
					CSA	Stiffness defined as slope of LD curve between 50% and 100% MVC during hopping
					Slack length	
Fredberg et al. (19)	*n* = 10, female only	26	Elite handball players	150 heel raises in 1.5 min	Diameter	US 2 cm proximal to insertion
Grigg et al. (21)	*n* = 11, male only	25.9 (4.9)	Healthy active	1) 3 × 15 eccentric heel raises (120% BW) 2) 3 × 15 concentric heel raises (120% BW)	Diameter	US 2 cm proximal to insertion
Grigg et al. (22)	*n* = 20, male only	49 (4.5) 48.2 (3.8)	Tendinopathy and healthy active	3 × 15 eccentric heel raises (BW only)	Diameter	US 4 cm proximal to insertion
Kato et al. (26)	*n* = 7, male only	22.9 (1.1)	Healthy active	20-min static DF stretch at approximately 30 N·m	Stiffness	US over MG MTJ
						Stiffness defined as slope of LD curve between 0 and 15 and 16–30 N·m during passive testing
Kay and Blazevich (28)	*n* = 16 (8 female, 8 male)	20.2 (2.6)	Healthy active	1) 6 × 8 s MVIC PF in 0° DF 2) 3 × 60 s static DF stretch at point of discomfort	Stiffness	US over MG MTJ Stiffness defined as slope of LD curve at 90% ROM during MVCC
Kay and Blazevich (29)	*n* = 18 (9 female, 9 male)	21.3 (3.3)	Healthy active	1) 6 × 8 s MVCC PF in 0° DF 2) 3 × 60 s static DF stretch at point of discomfort	Stiffness	US over MG MTJ Stiffness defined as slope of LD curve at 90% ROM during MVCC
Kubo et al. (36)	*n* = 8, male only	24.1 (1.6)	Healthy active	1) 50 × 3 s MVIC PF 2) 5-min static stretch at 35° DF (initial torque = 36.8 N·m)	Stiffness Hysteresis	US over MG belly Stiffness defined as slope of LD curve above 50% MVC during MVIC
Kubo et al. (39)	*n* = 7, male only	25.3 (1.4)	Healthy active	10-min static stretch at 35° DF (initial torque = 36.1 N·m)	Stiffness	US over MG belly
				Hysteresis		Stiffness defined as slope of LD curve above 50% MVC during MVIC
Mademli and Arampatzis (46)	*n* = 26, male only	Elderly: 65 (3)	Healthy active	Sustained 40% MVIC PF to exhaustion (mean duration: elderly = 407 s; young = 249 s; mean strain: elderly = 1.97%; young = 1.94%)	Stiffness	US over MG belly
		Young: 30 (7)				Stiffness defined slope of LD between 50% and 100% MVC during MVIC

(continued on next page)

TABLE 1. *(Continued)*

Reference	Sample	Age (yr), Mean (SD) and/or Range	Population	Exercise Intervention	Tendon Outcome Measure	Methodologies
Mademli et al. (47)	*n* = 14, male only	65.2 (3.6)	Healthy active	1) Repeated 70% MVCC PF to exhaustion (mean duration = 1,178 s; mean strain = 2.4%) 2) Sustained 40% MVIC PF to exhaustion (mean duration = 407 s; mean strain = 1.9%)	Stiffness	US over MG belly Stiffness defined as tendon elongation between 0 and 900 N in 100-N increments during MVIC
Mizuno et al. (57)	*n* = 11, male only	23.2 (2.6)	Healthy active	5 × 1 min static DF stretch at end ROM	Stiffness	US over MG MTJ Stiffness defined as the slope of the LD at 5°, 10°, and 15° DF during passive testing
Morse et al. (60)	*n* = 8, male only	20.5 (0.9)	Healthy active	5 × 1 min static DF stretch at end ROM	Stiffness	US over MG MTJ Stiffness defined as the slope of the LD curve between 0° and 25° DF during passive testing
Nakamura et al. (61)	*n* = 15 Male only	21.5 (1.2)	Healthy active	5 × 1 min static DF stretch at end ROM	Stiffness	US over MG MTJ Stiffness defined as slope of the LD curve between 15° and 25° DF during passive testing
Park et al. (65)	*n* = 10 (5 female; 5 male)	22.9 (3.4)	Healthy active	1) 6-min run at 3 $m \cdot s^{-1}$ 2) 5 × 30 s static stretch at 30° DF	Stiffness	US over MG MTJ Stiffness defined as peak force over peak displacement during MVIC
Peltonen et al. (66)	*n* = 10 (4 female, 6 male)	26 (3)	Healthy active	Two-legged hopping to fatigue, mean number of hops = 1,885	Stiffness	US over MG MTJ Stiffness defined as slope of LD >10 MPa stress (i.e., approximately 10%–20% MVC) during MVIC
Shalabi et al. (72)	*n* = 22 (7 female, 15 male)	28–57	Tendinopathy	6 × 15 eccentric heel raises (100% BW) 6 × 15 concentric heel raises (10% BW)	Volume	MRI
Wearing et al. (75)	*n* = 30, male only	37 (13)	Healthy active	90–100 heel raises (100%–150% BW)	Diameter	US 2 cm proximal to insertion

MVIC, maximum voluntary isometric contraction; MVCC, maximal voluntary concentric contraction; DF, dorsiflexion; PF, plantarflexion; BW, body weight; ROM, range of motion; LD, load-displacement; US, ultrasound; MRI, magnetic resonance imaging; MG, medial gastrocnemius.

four used a passive stretching protocol (26,57,60,61), whereas the remaining 10 studies used isometric (10,36,39,46,47,65,66), concentric (28,30), or dynamic hopping protocols (66). Fourteen articles investigated the effect of active exercise interventions ranging from running (16,65) and hopping (66) to isolated contractions using a dynamometer (28,30,36,46,47). Eleven articles investigated the effect of sustained or repeated passive stretching with total durations ranging from 150 s (65) to 20 min (26) (mean duration ± SD = 441 ± 494 s, median = 300 s). All measurements of tendon mechanical properties and slack length were made with respect to the displacement of the medial gastrocnemius musculotendinous junction (MTJ). Likewise, all measurements of tendon morphological properties, with the exception of slack length, were limited to the portion of the AT distal to the soleus MTJ. All included articles reported initial postexercise measurements collected immediately or within 5 min after the completion of the exercise intervention, with the exception of Fredberg et al. (19) who reported free AT diameter data collected 20 min postexercise. A more detailed description of the included studies is provided in Table 1 (Supplemental Digital Content 1, http://links.lww.com/MSS/A225).

Methodological quality of included studies. The mean ± SD total score for methodological quality assessment was 10.9 ± 2.0 out of a possible score of 14, with a range of 5.02 (19) to 13.5 (29) (see Table, SDC 1, Methodological quality assessment of included articles). Mean scores greater than 0.75 out of 1 were recorded for 12 out of the 14 criteria used. Descriptions of the recruitment and sampling procedures (0.36), inclusion and exclusion criteria (0.55), reliability of methods (0.48), and clinical implications of the findings (0.43) were the most poorly scored criteria, whereas only 4 out of 12 of studies reporting AT mechanical properties explicitly described the inclusion of AT preconditioning protocols (10,46,47,66). Despite some methodological limitations, no studies were excluded from the review on the basis of the quality assessment score. A strong level of agreement was found between item scores from the two reviewers ($\kappa = 0.84$, SE = 0.025) (13).

Effect of exercise on AT mechanical properties. Of the 14 articles that assessed AT stiffness, six reported a significant decrease after exercise (10,26,28,29,36,39), one reported a significant increase (61), and the remaining articles reported no change (Fig. 2A). Seven out of nine articles that used an active exercise intervention recorded negative effect sizes, ranging from −0.02 (65) to −2.15 (26). Running and hopping interventions had no effect on AT stiffness, with all studies reporting nonsignificant changes postexercise and negative effect sizes ranging from −0.34 (16) to −0.02 (65). After concentric exercise, Kay and Blazevich (29) reported a significant reduction in AT stiffness (11.7%; $P < 0.01$) with a negative effect size of −1.08 , whereas Mademli et al. (47) reported no significant change and effect sizes ranging from −0.20 (low force) to 0.99 (high force). The four studies investigating isometric exercise all had negative effect sizes ranging from −0.1 (46) to −1.96 (47), although only two reported significant reductions postexercise (28,36), and the results of Mademli et al. (47) must be viewed with caution because it is not known what effect the preceding concentric exercise intervention had on their findings. Of the 10 studies that investigated the effect of sustained static

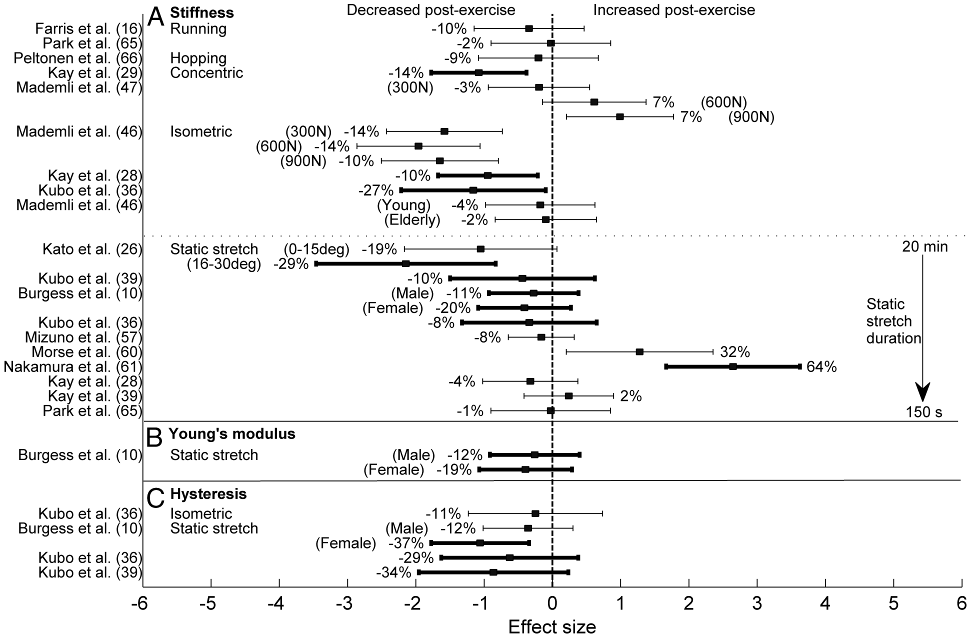

FIGURE 2—Forest plots (effect sizes and 95% CI) illustrating the immediate effect of a single exercise bout on AT (A) stiffness, (B) Young modulus, and (C) hysteresis. Numerical values adjacent to the error bar indicate percentage changes for postexercise relative to preexercise data. Bold error bars indicate significant differences in pre- and postexercise data as reported in the original article. All articles are listed alphabetically with the exception of those reporting static stretching interventions that are listed in descending order according to stretch duration. See Table 1 for a more detailed description of the exercise interventions used.

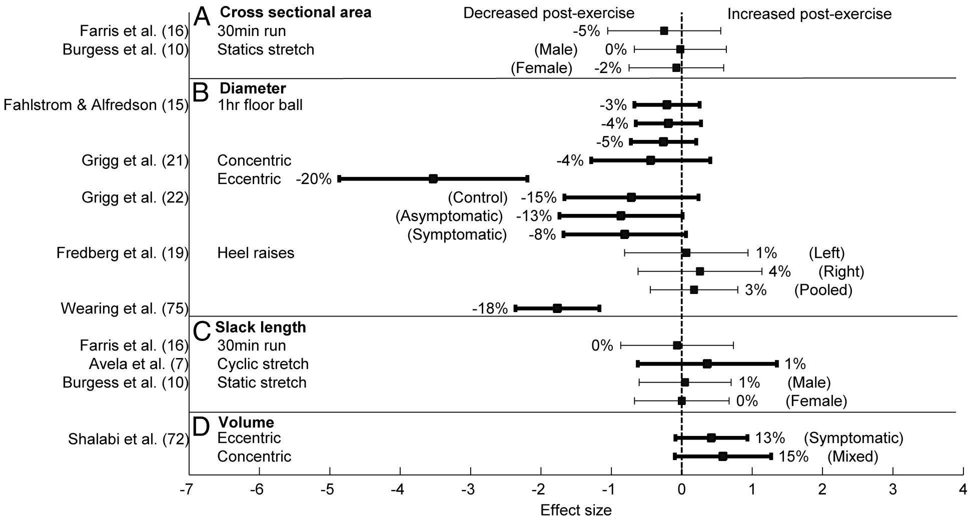

FIGURE 3—(A) Cross-sectional area (B) diameter, (C) slack length, and (D) volume. Numerical values adjacent to the error bar indicate percentage changes for postexercise relative to preexercise data. Bold error bars indicate significant differences in pre- and postexercise data as reported in the original article. See Table 1 for a more detailed description of the exercise interventions used.

stretching on AT stiffness, four reported a significant decrease (10,26,36,39), one reported a significant increase (61), and the remaining articles reported no change (28,30,57,60,65). Of these 10 studies, seven recorded negative effect sizes ranging from −0.02 (65) to −2.51 (26), and the remaining three recorded positive effect sizes ranging from 0.24 (29) to 2.65 (61). One study assessed Young modulus and reported a significant reduction after 5 min of sustained stretching in male and female participants with a negative effect size of −0.27 and −0.41, respectively, (10) (Fig. 2B). Three out of four studies reported significant reductions in AT hysteresis after exercise (10,36,39), with negative effect sizes ranging from −0.25 (36) to −1.06 (10) (Fig. 2C).

Effect of exercise on AT morphological properties. Both studies that assessed the effect of exercise on free AT CSA reported nonsignificant changes with negative effect sizes ranging from −0.02 (10) to −0.34 (16) (Fig. 3A). Four articles reported a significant decrease in free AT diameter (anterior-posterior) after exercise (15,21,22,75) (Fig. 3B). The two articles that evaluated the eccentric heel raise reported significant reductions in free AT diameter with negative effect sizes ranging from −0.72 (22) to −3.53 (21). Grigg et al. (21) also reported a significant reduction after concentric heel raises (effect size = −0.44), although the change was significantly smaller compared with the eccentric exercise. Of the two studies that investigated the effect of repeated concentric/eccentric heel raises on free AT diameter, one reported a significant decrease (75), whereas the other reported no change using a similar exercise dose and age group (19). Three articles reported data on AT slack length (7,10,16) (Fig. 3C). Avela et al. (7) reported a small (<1%) but significant increase in AT slack length after 1 h of repeated fast passive stretches of the triceps surae MTU. Conversely, Farris et al. (16) and Burgess et al. (10) reported no significant change in AT slack length after 30 min of running and 5 min of static stretching, respectively. Only one study investigated the effects of exercise on free AT volume and reported a significant reduction after eccentric and concentric heel raises in a group of symptomatic and mixed (i.e., symptomatic and asymptomatic) Achilles tendinosis participants, respectively (Fig. 3D) (72).

DISCUSSION

Twenty-one articles that assessed exercise modes ranging from prolonged passive stretching (static and cyclic) to active exercise involving controlled contractions of the triceps surae and functional activities including running and jumping of different durations were included in this review. The included articles were all published in the period 2001–2012, which to a large extent parallels the developments in the use of ultrasound for assessing tendon function *in vivo*. The review identified notable differences between included studies in participant characteristics (e.g., age, sex, and tendon health), as well as the mechanical and morphological properties that were assessed and how each property was quantified. There was also a clear lack of studies comparing exercise modes and doses, reporting both mechanical and morphological tendon measures and evaluating the mechanical properties of the free AT. The methodological quality of included articles was generally high and therefore unlikely to have had a substantial influence on the main conclusions of this review. Furthermore, the varied and inconsistent use of tendon preconditioning procedures identified in the quality assessment makes it impossible to speculate as to the effect of this covariate on the current findings. However, in spite of these limitations, some consistent findings were evident. Although the literature is sparse, the findings to date suggest that the mode and dose of exercise, as well as tendon health (i.e., healthy vs tendinopathy), may mediate the tendon mechanical and/or morphological response to a single exercise bout.

Immediate effect of exercise on AT mechanics. For exercise modes reliant on the SSC, such as running (16,65) and hopping (66), AT stiffness was relatively unchanged after exercise. In contrast, there was moderately consistent evidence for decreased AT stiffness after non-SSC exercise modes, such as isometric contractions (negative ES in four out of four studies [28,36,46,47]) and prolonged static stretching (negative ES in 7 out of 10 studies [10,26,28,36,39,57,65]) of the triceps surae. Although based on limited studies, the observed demarcation in AT stiffness response between SSC and non-SSC exercise may indicate that the AT is more resistant to fatigue during SSC activities, which it is more accustomed to and hence better suited to performing relative to non-SSC activities. This observation is supported by *in vitro* animal studies, which showed that tendons exhibit fatigue-resistant qualities that are specific to loads most frequently encountered during life (14,32,67). From a practical perspective, a transient reduction in AT stiffness immediately after exercise may expose the tendon to higher strains during subsequent exercise, thereby increasing the risk of strain-induced injury. Decreased tendon stiffness after exercise could also help explain recent evidence that maximum muscle performance is reduced immediately after a single bout of static stretching (30). For a given MTU length, a more compliant tendon would require muscle fibers to operate at relatively shorter lengths and require relatively more time to develop an equivalent tension in the absence of other adaptations, thereby reducing the magnitude and rate of force development during non-SSC exercise (8,52,62,73). In contrast, the finding of consistent evidence for decreased AT hysteresis after static stretching (negative ES in three out of three studies [10,36,39]) may be an advantage for exercise modes reliant on the SSC, such as running and hopping (73). A lack of association between immediate changes in AT stiffness after a single exercise bout and the reported long-term adaptations in AT stiffness with training was also identified. For example, both prolonged passive stretching and maximal isometric exercise were generally associated with immediate reductions in AT stiffness; however, only the latter training modality has been linked to long-term changes in AT stiffness (9,36). Although there is evidence that tendon metabolic activity is responsive to short-term mechanical loading (40), it is not yet understood to what extent these transient changes are reflected at the mechanical or morphological level and the relative of importance of such changes to long-term tendon adaptation.

The review also revealed evidence suggesting a dose response for the changes in AT mechanical properties after exercise. Significant reductions in AT stiffness were confined to studies using maximal voluntary contractions (MVC) (28,29,36) (i.e., relatively high force and short duration) or prolonged static stretching (10,26,36,39) (i.e., relatively low force and long duration). Despite very different tendon loading characteristics, these studies reported similar percentage reductions in AT stiffness, which would indicate that the change in AT stiffness after exercise is a combined function of the duration and magnitude of tendon loading. For example, the greatest percentage reduction in AT stiffness after maximal isometric exercise was reported in the study using the highest number of loading cycles (i.e., 50 × 3 s) and thus greatest total loading duration (i.e., 150 s) (36). Time-dependent effects were observed in the studies using comparable static stretching interventions of different durations, in which sustained bouts of 5 min or more were required to induce significant reductions in AT stiffness (10,26,36,39). In contrast, despite using similar total loading durations (i.e., 407 ± 129 s), Mademli and Arampatzis (46) found no change in AT stiffness after submaximal (i.e., 40% MVC) isometric exercise with an estimated AT strain (i.e., 2%–3%) below that required to cause permanent deformation in the relaxed tendon (11). Furthermore, prolonged running (16) and hopping (66) interventions that induce relatively high strains (i.e., 3.5%–5%) applied over much shorter durations (i.e., 0.2–0.25 s) compared with voluntary contractions had no effect on AT stiffness, suggesting that the loading frequency and the total loading duration are both important parameters in governing the response of the AT to exercise. Taken together, the abovementioned findings provide support to *ex vivo* studies on the human AT (76) and *in vivo* studies of the human vastus lateralis tendon (37,38,48) that demonstrate an interaction between tendon loading parameters and, in particular, strain duration and strain magnitude in determining the immediate response of the AT to loading *in vivo*. However, despite these findings, the relative importance of tendon strain characteristics of different exercise modes on the immediate changes in AT stiffness remains largely unknown. Furthermore, although the results of the majority of studies reporting AT stiffness appear consistent with the known viscoelastic behavior of tendons, two studies reported opposite findings demonstrating increased AT stiffness after 5 min of stretching (5 × 1 min) (60,61). It is difficult to reconcile the conflicting findings of Nakamura et al. (61) and Morse et al. (60) on the basis of methodological quality with both studies scoring well in areas with potential to confound their findings, such as controlling for covariates and rigor of experimental design. A possible explanation for these contrasting results is that AT stiffness was measured by these authors under passive compared with active conditions as used in the other studies, and thus, measurements were taken from a different portion of the tendon force–deformation curve. It is also known that muscles contribute up to half of the passive extensibility of an MTU (24,27,51), and it is possible that the relative contribution of muscle and tendon to the overall compliance of the MTU may differ under passive and active testing conditions (60). Furthermore, the findings of Nakamura et al. (61) that AT stiffness returned to within 1% of baseline within 10 min postexercise suggest that the observed increase in AT stiffness was transient and most likely reflects a proportionally larger decrease in triceps surae muscle stiffness immediately postexercise.

Immediate effect of exercise on AT morphology. The largest and most consistent (four out of five studies) finding for free AT morphology was decreased diameter (anterior-posterior) immediately after exercise. Three of the four studies that reported decreased free AT diameter investigated variations of the Alfredson heel raise protocol (1), and of these, the eccentric exercise produced the largest reduction (21,22). In contrast, tendon CSA and slack length were relatively unaffected by running or passive stretching interventions (7,10,16), and there was evidence of increased tendon volume after eccentric and concentric heel raises from one study (72).

It has been suggested that the decreased free AT diameter observed immediately after exercise reflects a net loss of fluid from the tendon proper to the peritendinous space and is because of increased hydrostatic pressure within the tendon due to mechanical loading. Although there is evidence of decreased diameter at discrete points along the free AT after exercise (15,21,22,75), it is not known whether these findings are coupled to changes in tendon dimensions beyond the measurement site and therefore to what extent diametral measurements are indicative of changes in the whole tendon morphology. Furthermore, it is currently difficult to reconcile the abovementioned findings and proposed mechanisms (21,22,75) with findings that free AT volume increased after eccentric heel raise exercise (72), and CSA was unchanged after 30 min of running (16) or 5 min of passive stretching (10) despite a significant decrease in Young modulus (10). It is also difficult to understand the significance of transient changes in free AT diameter after exercise with respect to injury risk or athletic performance without concomitant measures of tendon mechanical properties. Irrespective, the relatively larger reductions in free AT diameter after eccentric compared with concentric heel raises (21) and in diseased compared with healthy tendons (22) suggest that diametral changes may be an important stimulus or marker for tendon adaptation and may in part explain the superior results of eccentric training in the treatment of tendinopathies (21). Although there is evidence that free AT diameter/thickness is decreased after prolonged eccentric training (i.e., 12 wk) in patients with midportion tendinosis (64), it is not known to what extent these adaptations are correlated to the changes in tendon diameter immediately after a single bout of eccentric exercise. Furthermore, there is a lack of fundamental knowledge as to what mechanisms are responsible for the exercise mode- and dose-dependent changes in free AT diameter. It has been suggested that differences in the frequency content of AT tensile force–time histories during exercise may explain the differential effects of eccentric and concentric exercise on the AT (23,68). Because no studies that reported free AT diameter included estimations of tendon stress–strain during exercise, the relative contribution of these parameters to the immediate response of the AT remains unknown.

Limitations and future directions. Our current understanding of how exercise influences the *in vivo* mechanical and morphological properties of the AT is limited by a lack of studies that compare the effect of different exercise modes and doses, and in particular, eccentric exercise, in both healthy and degenerated tendons. At present, it is difficult to determine what combination of loading stimuli (e.g., stress–strain magnitude, rate, duration or frequency) are responsible for the immediate changes in AT properties identified in this review and to what extent these changes reflect a change at the material and/or structural level, predispose a tendon to strain-induced injury, affect the function of the MTU, or are a necessary stimulus to promote long-term adaptation. Attention to methodological issues such as how best to characterize tendon mechanical and morphological properties, assessing the validity and reliability of these measures, and controlling for covariates such as tendon preconditioning is also warranted. Future studies should simultaneously investigate mechanical and morphological responses of the AT to acute exercise with a particular focus on the free AT, the time course of recovery of these properties, and their relationship with the biological activity of the tendon. Reporting the stress–strain characteristics of the exercises under investigation will also be important for understanding the interaction and relative importance of mechanical stimuli in determining the short- and long-term changes in tendon properties.

CONCLUSIONS

There is evidence to suggest that the mechanical and morphological properties of the AT are affected by acute exercise in a mode- and dose-dependent manner. Of the exercises evaluated to date, prolonged stretching and repeated maximal isometric contractions of the triceps surae appear to cause the most consistent and pronounced reductions in AT stiffness and hysteresis. Transient reductions in tensile stiffness may expose the AT to increased risk of injury and have implications for the mechanical function of the MTU immediately after these modes of exercise. In contrast, stretch–shorten cycle exercises such as treadmill running and hopping do not appear to induce immediate mechanical or morphological changes in the AT. Although consistent reductions in free AT thickness after heel raise exercise have been reported and appear more pronounced after eccentric exercise, the immediate morphological response of the free AT to exercise remains poorly understood.

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REFERENCES

1. Alfredson H, Pietila T, Jonsson P, Lorentzon R. Heavy-load eccentric calf muscle training for the treatment of chronic Achilles tendinosis. *Am J Sports Med*. 1998;26(3):360–6.
2. Arampatzis A, De Monte G, Karamanidis K, Morey-Klapsing G, Stafilidis S, Bruggemann GP. Influence of the muscle–tendon unit's mechanical and morphological properties on running economy. *J Exp Biol*. 2006;209(17):3345–57.
3. Arampatzis A, Karamanidis K, Albracht K. Adaptational responses of the human Achilles tendon by modulation of the applied cyclic strain magnitude. *J Exp Biol*. 2007;210(15):2743–53.

4. Arampatzis A, Karamanidis K, Morey-Klapsing G, De Monte G, Stafilidis S. Mechanical properties of the triceps surae tendon and aponeurosis in relation to intensity of sport activity. *J Biomech*. 2007;40(9):1946–52.
5. Arampatzis A, Peper A, Bierbaum S, Albracht K. Plasticity of human Achilles tendon mechanical and morphological properties in response to cyclic strain. *J Biomech*. 2010;43(16):3073–9.
6. Arya S, Kulig K. Tendinopathy alters mechanical and material properties of the Achilles tendon. *J Appl Physiol*. 2009;108(3):670–5.
7. Avela J, Finni T, Liikavainio T, Niemela E, Komi PV. Neural and mechanical responses of the triceps surae muscle group after 1 h of repeated fast passive stretches. *J Appl Physiol*. 2004;96(6): 2325–32.
8. Barrett RS, Lichtwark GA. Effect of altering neural, muscular and tendinous factors associated with aging on balance recovery using the ankle strategy: a simulation study. *J Theor Biol*. 2008;254(3):546–54.
9. Burgess KE, Connick MJ, Graham-Smith P, Pearson SJ. Plyometric vs. isometric training influences on tendon properties and muscle output. *J Strength Cond Res*. 2007;21(3):986–9.
10. Burgess KE, Graham-Smith P, Pearson SJ. Effect of acute tensile loading on gender-specific tendon structural and mechanical properties. *J Orthop Res*. 2009;27(4):510–6.
11. Butler DL, Grood ES, Noyes FR, Zernicke RF. Biomechanics of ligaments and tendons. *Exerc Sport Sci Rev*. 1978;6:125–81.
12. Cohen J. A coefficient of agreement for nominal scales. *Educ Psychol Meas*. 1960;20(1):37–46.
13. Cohen J. *Statistical Power Analysis for the Behavioural Sciences*. 2nd ed. Hillsdale (NJ): Lawrence Erlbaum Associates; 1988. 567 p.
14. De Zee M, Bojsen-Moller F, Voigt M. Dynamic viscoelastic behavior of lower extremity tendons during simulated running. *J Appl Physiol*. 2000;89(4):1352–9.
15. Fahlstrom M, Alfredson H. Ultrasound and Doppler findings in the Achilles tendon among middle-aged recreational floor-ball players in direct relation to a match. *Br J Sports Med*. 2010;44(2):140–3.
16. Farris D, Trewartha G, McGuigan M. The effects of a 30-min run on the mechanics of the human Achilles tendon. *Eur J Appl Physiol*. 2012;112(2):653–60.
17. Foure A, Nordez A, Cornu C. Plyometric training effects on Achilles tendon stiffness and dissipative properties. *J Appl Physiol*. 2010;109(3):849–54.
18. Foure A, Nordez A, Cornu C. Effects of plyometric training on passive stiffness of gastrocnemii muscles and Achilles tendon. *Eur J Appl Physiol*. 2012;112(8):2849–57.
19. Fredberg U, Bolvig L, Lauridsen A, Stengaard-Pedersen K. Influence of acute physical activity immediately before ultrasonographic measurement of Achilles tendon thickness. *Scand J Rheumatol*. 2007;36(6):488–9.
20. Galna B, Peters A, Murphy AT, Morris ME. Obstacle crossing deficits in older adults: a systematic review. *Gait Posture*. 2009;30(3):270–5.
21. Grigg NL, Wearing SC, Smeathers JE. Eccentric calf muscle exercise produces a greater acute reduction in Achilles tendon thickness than concentric exercise. *Br J Sports Med*. 2009;43(4): 280–3.
22. Grigg NL, Wearing SC, Smeathers JE. Achilles tendinopathy has an aberrant strain response to eccentric exercise. *Med Sci Sports Exerc*. 2012;44(1):12–7.
23. Henriksen M, Aaboe J, Bliddal H, Langberg H. Biomechanical characteristics of the eccentric Achilles tendon exercise. *J Biomech*. 2009;42(16):2702–7.
24. Herbert RD, Moseley AM, Butler JE, Gandevia SC. Change in length of relaxed muscle fascicles and tendons with knee and ankle movement in humans. *J Physiol*. 2002;539(2):637–45.
25. Ishikawa M, Komi PV, Grey MJ, Lepola V, Bruggemann GP. Muscle–tendon interaction and elastic energy usage in human walking. *J Appl Physiol*. 2005;99(2):603–8.
26. Kato E, Kanehisa H, Fukunaga T, Kawakami Y. Changes in ankle joint stiffness due to stretching: the role of tendon elongation of the gastrocnemius muscle. *Eur J Sport Sci*. 2010;10(2):111–9.
27. Kawakami Y, Ichinose Y, Fukunaga T. Architectural and functional features of human triceps surae muscles during contraction. *J Appl Physiol*. 1998;85(2):398–404.
28. Kay AD, Blazevich AJ. Isometric contractions reduce plantar flexor moment, Achilles tendon stiffness, and neuromuscular activity but remove the subsequent effects of stretch. *J Appl Physiol*. 2009;107(4):1181–9.
29. Kay AD, Blazevich AJ. Concentric muscle contractions before static stretching minimize, but do not remove, stretch-induced force deficits. *J Appl Physiol*. 2010;108(3):637–45.
30. Kay AD, Blazevich AJ. Effect of acute static stretch on maximal muscle performance: a systematic review. *Med Sci Sports Exerc*. 2012;44(1):154–64.
31. Kay AD, Blazevich AJ, Kay AD, Blazevich AJ. Moderate-duration static stretch reduces active and passive plantar flexor moment but not Achilles tendon stiffness or active muscle length. *J Appl Physiol*. 2009;106(4):1249–56.
32. Ker RF, Wang XT, Pike AVL. Fatigue quality of mammalian tendons. *J Exp Biol*. 2000;203(8):1317–27.
33. Komi PV, Fukashiro S, Jarvinen M. Biomechanical loading of Achilles tendon during normal locomotion. *Clin Sports Med*. 1992;11(3):521–31.
34. Kongsgaard M, Aagaard P, Kjaer M, Magnusson SP. Structural Achilles tendon properties in athletes subjected to different exercise modes and in Achilles tendon rupture patients. *J Appl Physiol*. 2005;99(5):1965–71.
35. Kubo K, Kanehisa H, Fukunaga T. Effect of stretching training on the viscoelastic properties of human tendon structures in vivo. *J Appl Physiol*. 2002;92(2):595–601.
36. Kubo K, Kanehisa H, Fukunaga T. Effects of transient muscle contractions and stretching on the tendon structures in vivo. *Acta Physiol Scand*. 2002;175(2):157–64.
37. Kubo K, Kanehisa H, Fukunaga T. Influences of repetitive drop jump and isometric leg press exercises on tendon properties in knee extensors. *J Strength Cond Res*. 2005;19(4):864–70.
38. Kubo K, Kanehisa H, Kawakami Y, Fukunaga T. Effects of repeated muscle contractions on the tendon structures in humans. *Eur J Appl Physiol*. 2001;84(1–2):162–6.
39. Kubo K, Kanehisa H, Kawakami Y, Fukunaga T. Influence of static stretching on viscoelastic properties of human tendon structures in vivo. *J Appl Physiol*. 2001;90(2):520–7.
40. Langberg H, Skovgaard D, Petersen LJ, Bulow J, Kjaer M. Type I collagen synthesis and degradation in peritendinous tissue after exercise determined by microdialysis in humans. *J Physiol*. 1999; 521(1):299–306.
41. Lavagnino M, Arnoczky SP. In vitro alterations in cytoskeletal tensional homeostasis control gene expression in tendon cells. *J Orthop Res*. 2005;23(5):1211–8.
42. Lichtwark GA, Wilson AM. In vivo mechanical properties of the human Achilles tendon during one-legged hopping. *J Exp Biol*. 2005;208(24):4715–25.
43. Lichtwark GA, Wilson AM. Interactions between the human gastrocnemius muscle and the Achilles tendon during incline, level and decline locomotion. *J Exp Biol*. 2006;209(21):4379–88.
44. Lichtwark GA, Wilson AM. Is Achilles tendon compliance optimised for maximum muscle efficiency during locomotion? *J Biomech*. 2007;40(8):1768–75.
45. Lichtwark GA, Wilson AM. Optimal muscle fascicle length and tendon stiffness for maximising gastrocnemius efficiency during human walking and running. *J Theor Biol*. 2008;252(4):662–73.
46. Mademli L, Arampatzis A. Mechanical and morphological properties of the triceps surae muscle–tendon unit in old and young adults and their interaction with a submaximal fatiguing contraction. *J Electromyogr Kinesiol*. 2008;18(1):89–98.

47. Mademli L, Arampatzis A, Walsh M. Effect of muscle fatigue on the compliance of the gastrocnemius medialis tendon and aponeurosis. *J Biomech*. 2006;39(3):426–34.
48. Mademli L, Arampatzis A, Walsh M. Age-related effect of static and cyclic loadings on the strain-force curve of the vastus lateralis tendon and aponeurosis. *J Biomech Eng*. 2008;130(1):011007.
49. Maffulli N. Rupture of the Achilles tendon. *J Bone Joint Surg Am*. 1999;81(7):1019–36.
50. Maffulli N, Kader D. Tendinopathy of tendo achillis. *J Bone Joint Surg Br*. 2002;84(1):1–8.
51. Maganaris CN. Force-length characteristics of the in vivo human gastrocnemius muscle. *Clin Anat*. 2003;16(3):215–23.
52. Maganaris CN, Baltzopoulos V, Sargeant AJ, Maganaris CN, Baltzopoulos V, Sargeant AJ. Repeated contractions alter the geometry of human skeletal muscle. *J Appl Physiol*. 2002;93(6):2089–94.
53. Maganaris CN, Paul JP. Tensile properties of the in vivo human gastrocnemius tendon. *J Biomech*. 2002;35(12):1639–46.
54. Maganaris CN, Reeves ND, Rittweger J, et al. Adaptive response of human tendon to paralysis. *Muscle Nerve*. 2006;33(1):85–92.
55. Magnusson SP, Kjaer M. Region-specific differences in Achilles tendon cross-sectional area in runners and non-runners. *Eur J Appl Physiol*. 2003;90(5–6):549–53.
56. Mahieu NN, McNair P, De Muynck M, et al. Effect of static and ballistic stretching on the muscle–tendon tissue properties. *Med Sci Sports Exerc*. 2007;39(3):494–501.
57. Mizuno T, Matsumoto M, Umemura Y. Viscoelasticity of the muscle–tendon unit is returned more rapidly than range of motion after stretching. *Scand J Med Sci Sports*. 2013;23:23–30.
58. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Br. Med. J*. 2009;339:b2535.
59. Morrissey D, Roskilly A, Twycross-Lewis R, et al. The effect of eccentric and concentric calf muscle training on Achilles tendon stiffness. *Clin. Rehabil*. 2011;25(3):238–47.
60. Morse CI, Degens H, Seynnes OR, Maganaris CN, Jones DA. The acute effect of stretching on the passive stiffness of the human gastrocnemius muscle tendon unit. *J Physiol*. 2008;586(1):97–106.
61. Nakamura M, Ikezoe T, Takeno Y, Ichihashi N. Acute and prolonged effect of static stretching on the passive stiffness of the human gastrocnemius muscle tendon unit in vivo. *J Orthop Res*. 2011;29(11):1759–63.
62. Narici MV, Maffulli N, Maganaris CN. Ageing of human muscles and tendons. *Disabil Rehabil*. 2008;30(20–22):1548–54.
63. Narici MV, Maganaris CN, Reeves N. Muscle and tendon adaptations to ageing and spaceflight. In: *Proceedings of the European Symposium on Life in Space for Life on Earth*. Stockholm: European Space Agency; 2002. p. 69–70.
64. Ohberg L, Lorentzon R, Alfredson H. Eccentric training in patients with chronic Achilles tendinosis: normalised tendon structure and decreased thickness at follow up. *Br J Sports Med*. 2004;38(1):8–11.
65. Park DY, Rubenson J, Carr A, Mattson J, Besier T, Chou LB. Influence of stretching and warm-up on Achilles tendon material properties. *Foot Ankle Int*. 2011;32(4):407–13.
66. Peltonen J, Cronin NJ, Avela J, Finni T. In vivo mechanical response of human Achilles tendon to a single bout of hopping exercise. *J Exp Biol*. 2010;213(8):1259–65.
67. Pike AVL, Ker RF, Alexander RM. The development of fatigue quality in high- and low-stressed tendons of sheep (*Ovis aries*). *J Exp Biol*. 2000;203(14):2187–93.
68. Rees JD, Lichtwark GA, Wolman RL, Wilson AM. The mechanism for efficacy of eccentric loading in Achilles tendon injury; an in vivo study in humans. *Rheumatology*. 2008;47(10):1493–7.
69. Reeves ND, Maganaris CN, Ferretti G, Narici MV. Influence of 90-day simulated microgravity on human tendon mechanical properties and the effect of resistive countermeasures. *J Appl Physiol*. 2005;98(6):2278–86.
70. Reeves ND, Narici MV. Behavior of human muscle fascicles during shortening and lengthening contractions in vivo. *J Appl Physiol*. 2003;95(3):1090–6.
71. Rosager S, Aagaard P, Dyhre-Poulsen P, Neergaard K, Kjaer M, Magnusson SP. Load-displacement properties of the human triceps surae aponeurosis and tendon in runners and non-runners. *Scand J Med Sci Sports*. 2002;12(2):90–8.
72. Shalabi A, Kristoffersen-Wiberg M, Aspelin P, Movin T. Immediate Achilles tendon response after strength training evaluated by MRI. *Med Sci Sports Exerc*. 2004;36(11):1841–6.
73. Wang HK, Lin KH, Su SC, Shih TTF, Huang YC. Effects of tendon viscoelasticity in Achilles tendinosis on explosive performance and clinical severity in athletes. *Scand J Med Sci Sports*. 2012;22:e147–55.
74. Wang XT, Ker RF, Alexander RM. Fatigue rupture of wallaby tail tendons. *J Exp Biol*. 1995;198(3):847–52.
75. Wearing SC, Grigg NL, Hooper SL, Smeathers JE. Conditioning of the Achilles tendon via ankle exercise improves correlations between sonographic measures of tendon thickness and body anthropometry. *J Appl Physiol*. 2011;110(5):1384–9.
76. Wren TAL, Lindsey DP, Beaupre GS, Carter DR. Effects of creep and cyclic loading on the mechanical properties and failure of human Achilles tendons. *Ann Biomed Eng*. 2003;31(6):710–7.