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Altered Strength Profile in Achilles Tendinopathy: A Systematic Review and Meta-Analysis

Seán McAuliffe, PhD, BSc*; Ariane Tabuena, BSc†; Karen McCreesh, PhD, BSc†; Mary O'Keeffe, PhD, BSc†; John Hurley, BSc†; Tom Comyns, PhD, BSc‡; Helen Purtill, PhD, BSc§; Seth O'Neill, PhD, BSc||; Kieran O'Sullivan, PhD, BSc*†

*Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar; Departments of †Clinical Therapies, ‡Physical Education and Sports Science, and §Mathematics and Statistics, University of Limerick, Ireland; ||Department of Medical & Social Care Education, University of Leicester, United Kingdom

Background: Persistent strength deficits secondary to Achilles tendinopathy (AT) have been postulated to account for difficulty engaging in tendon-loading movements, such as running and jumping, and may contribute to the increased risk of recurrence. To date, little consensus exists on the presence of strength deficits in AT. Consequently, researchers are uncertain about the appropriate methods of assessment that may inform rehabilitation in clinical practice.

Objective: To evaluate and synthesize the literature investigating plantar-flexion (PF) strength in individuals with AT.

Study Selection: Two independent reviewers searched 9 electronic databases using an agreed-upon set of key words.

Data Extraction: Data were extracted from studies comparing strength measures (maximal, reactive, and explosive strength) between individuals with AT and healthy control participants or between the injured and uninjured sides of people with AT. The Critical Appraisal Skills Programme Case-Control Study Checklist was used to assess the risk of bias for the included studies.

Data Synthesis: A total of 19 studies were eligible. Pooled meta-analyses for isokinetic dynamometry demonstrated reductions in maximal strength (concentric PF peak torque [PT] slow [Hedges $g = 0.52$, 44% deficit], concentric PF PT fast [Hedges $g = 0.61$, 38% deficit], and eccentric PF PT slow [Hedges $g = 0.26$, 18% deficit]). Reactive strength, particularly during hopping, was also reduced (Hedges g range = 0.32–2.61, 16%–35% deficit). For explosive strength, reductions in the rate of force development (Hedges g range = 0.31–1.73, 10%–21% deficit) were observed, whereas the findings for ground reaction force varied but were not consistently altered.

Conclusions: Individuals with AT demonstrated strength deficits compared with the uninjured side or with asymptomatic control participants. Deficits were reported across the strength spectrum for maximal, reactive, and explosive strength. Clinicians and researchers may need to adapt their assessment of Achilles tendon function, which may ultimately help to optimize rehabilitation outcomes.

Key Words: tendon, strength spectrum, assessment

Key Points

- Traditional methods of strength assessment in patients with tendinopathy have focused on the heel-raise test.
- The heel-raise endurance test may not adequately quantify deficits across the entire strength spectrum.
- Individuals with Achilles tendinopathy displayed deficits in maximal, reactive, and explosive strength compared with the uninjured side or asymptomatic controls.
- The current focus on maximal strength during assessments and rehabilitation, with little emphasis on explosive or reactive strength, may not optimally match the entire strength spectrum and could explain why strengthening exercises are only moderately effective for reducing pain and disability in patients with Achilles tendinopathy.

The Achilles tendon is the largest and strongest tendon in the body.[1,2] Despite the relative strength of the Achilles musculotendinous unit, Achilles tendinopathy (AT) is a common musculoskeletal concern in both athletes and nonathletes.[3] In athletes, AT occurs most commonly among individuals participating in stretch-shortening–cycle (SSC) activities, such as running and jumping.[4–6] During such athletic endeavors, the Achilles tendon is subjected to loads as high as 6 to 12 times body weight (BW).[7,8] The high loads placed on the Achilles tendon require a considerable degree of strength and power from the plantar-flexor muscles to repeatedly generate appropriate force and enable the tendon to store and release energy for athletic movements.[9]

Individuals with AT often report impairments or an inability to engage in functional activities.[3] One possible explanation may relate to an altered strength profile or persistent weakness due to AT.[10–12] The mechanism behind strength deficits due to AT remains unclear; however, researchers have postulated that physiological alterations in the tendon, such as altered tendon mechanical properties,[13] pain inhibition, altered motor output,[14,15] or muscle disuse and atrophy,[16] may result in an inability to generate or tolerate the required loads.

In clinical environments, the most common method of quantifying tendon function in individuals with AT has been the calf-raise or heel-raise test. The calf-raise test involves repetitive concentric-eccentric action of the

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plantar-flexor muscles in a unipedal stance and is typically quantified by the total number of raises performed. This method reflects the ability to perform repeated submaximal contractions (ie, fatigue or endurance).[17] Consequently, the heel-raise test is frequently used in clinical practice to assist with diagnosis and to objectively assess the effects of exercise interventions on AT. Its use is based on the assumption that being able to perform pain-free heel raises using repetitions comparable with the uninjured side indicates functional restoration of strength. Despite the popularity of the heel-raise test in clinical practice, physiological or clinical evidence to support its use is limited.[18,19] The preference for using the number of raises as a primary outcome measure may be attributed to its practical and "user-friendly" clinical application. Yet such measures may not provide sufficient assessment of an athlete's entire strength profile. Consequently, the quantification of an individual's functional capabilities may be suboptimal, which may lead to persistent strength deficits[12] and inadequate rehabilitation programs, ultimately contributing to the high recurrence rates seen with AT.[20]

The lack of consensus on what exactly constitutes *strength* may be adding to the predominance of unidimensional measures for quantifying Achilles tendon function. To clarify this uncertainty, subcategories of strength have been proposed, including *maximal strength*, which involves maximal force development through high-load, low-velocity movements; *explosive strength*, which is the ability to rapidly produce muscle force through medium- to high-load, high-velocity movements (eg, rate of force development [RFD]); and *reactive strength*, which is the ability of the calf-muscle complex to store and release energy through sufficient function of the SSC through low-load, high-velocity exercises (eg, hopping, jumping).[21]

Little consensus exists on the presence of strength deficits in AT, so researchers are uncertain about the appropriate methods of assessment that may inform rehabilitation in clinical practice. Therefore, the purpose of our review was to evaluate and summarize the evidence regarding the plantar-flexor strength profile in individuals with AT.

METHODS

Search Strategy and Study Selection

The review was registered on the PROSPERO database (CRD42015025386) and has been reported in accordance with the PRISMA statement for systematic reviews.[22] The following databases were searched between February and April 2016 by 2 authors (S.M., J.H.) independently using an agreed-upon set of key words: Academic Search Complete, AMED, Biomedical Reference Collection, MEDLINE, CINAHL, SPORTDiscus, Web of Science, Embase, and Scopus. The search strings are shown in Table 1. The 2 reviewers conducted the database searches independently using prespecified inclusion and exclusion criteria. They independently compiled "short lists" of suitable abstracts and compared their respective short lists before reaching agreement on potentially relevant abstracts. A third reviewer (K.O.) reviewed the short-listed abstracts, and any disagreement was discussed among the 3 reviewers. The primary author (S.M.) screened the agreed-upon abstract list and obtained full texts of the studies that met the inclusion criteria to create a final list. The final list was confirmed by one of the authors (K.O.) to ensure that the studies met the inclusion criteria and did not meet the exclusion criteria.

Table 1. Key Words for Search Strategy

achill* OR calf* OR plantarflex* OR tendocalcan* OR heel* OR soleus OR gastroc* (Abstract)
AND
tendon* OR tendin* (Abstract)
AND
strength* OR weak* OR strong* OR power* OR force* OR isokinetic* OR muscle* OR concentric* OR eccentric* OR isometric* OR torque* OR jump* OR hop* OR muscular OR neuromuscular OR neuro-muscular OR function* OR land* OR drop* OR raise OR endurance OR fatigue* OR stiff* OR Hysteresis OR Rate of force development OR RFD OR Ground reaction force OR GRF OR stress OR Strain OR Kinetic* OR fluctuation* OR oscillation* OR vibration* (Abstract)
AND
non-injured OR noninjured OR asymptomatic OR contralat* OR opposite OR pain-free OR painfree OR control* OR healthy (Abstract)

Inclusion Criteria. Studies were included if

- the researchers compared plantar-flexion (PF) muscle strength between individuals with AT and asymptomatic control participants or between injured and uninjured sides within an AT population,
- data were cross-sectional or baseline data from prospective or intervention studies,
- articles were written in English and published in the 20 years before our review, and
- articles included participants of any age.

Exclusion Criteria. We excluded studies if

- the researchers investigated only kinematic variables,
- the researchers investigated PF muscle strength in asymptomatic populations only,
- participants with Achilles tendon rupture were explicitly included, or
- the researchers reported PF muscle strength only postoperatively or after a strengthening intervention.

Risk of Bias Assessment

The Critical Appraisal Skills Programme Case-Control Study Checklist was used to assess the risk of bias in the included studies.[23] This checklist contains 12 questions; questions 7 and 12 are guidance questions and were not rated. Therefore, the included studies were appraised using 10 questions. A list of criteria for each question and the justification for providing the indicated score are outlined in Supplemental Tables 1 and 2 (available online at http://dx.doi.org/10.4085/1062-6050-43-18.S1). Two authors (S.M., M.O.) scored the studies independently using the criteria outlined, with any disagreements in scoring mediated by a third reviewer (K.O.). Given that the Critical Appraisal Skills Programme checklist was originally designed as an educational tool in a workshop setting, no overall quality score was awarded to the included studies. Instead, the strengths and weaknesses of each study were noted based on these specific criteria.

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Data Extraction

The following data were extracted from each study by 2 reviewers (S.M., J.H.): characteristics of the participants (sample size, sex, and age) and details of the comparative assessment (groups compared, strength variable investigated, and summary of the results). Study results were extracted according to the subcategories for strength as outlined previously. This included data on (1) maximal strength (peak torque [PT], maximal voluntary isometric contraction, or peak force [in newtons]), (2) reactive strength (distance and height during hopping or jumping movements), and (3) explosive strength (RFD and ground reaction force [GRF]). Data relating to the mechanical properties of the tendon (eg, tendon stiffness, leg stiffness, tendon strain) or data on endurance (electromyography studies) or related concepts were not extracted.

Statistical Analysis

For all studies, where possible we computed the Hedges *g* effect size as a summary measure that is comparable across independent- and matched-groups study designs.[24] If the standard deviation of the differences was not reported in studies examining differences between the injured and uninjured limbs, it was estimated using the following formula[25]:

$$SD_{diff} = \sqrt{SD_1^2 + SD_2^2 - 2 \times r \times SD_1 \times SD_2},$$

where $r = 0.7$ was used as a conservative estimate of the within-participants correlation as recommended by Rosenthal.[26] Hedges *g* and associated 95% confidence intervals (CIs) were computed manually using the formulae provided by Borenstein et al.[24] A positive effect size indicated the investigated strength measure was greater for the uninjured limb or asymptomatic group. The magnitude of Hedges *g* effect sizes was interpreted using the Cohen[25] convention as *small* (0.2), *medium* (0.5), or *large* (0.8).

Studies were pooled for the meta-analysis according to similarities in study characteristics and methods. Given the range of variables used in isokinetic dynamometry, the results were further pooled according to the mode of contraction (eccentric or concentric) and speed of contraction (fast [>120°/s] or slow [≤120°/s]). Hedges *g* effect sizes were pooled using random-effects models. We selected random-effects models a priori to account for expected differences in study characteristics. Heterogeneity between studies was assessed using the I^2 statistic, which summarizes the percentage of total variation across studies due to differences between studies rather than chance. An I^2 value of 30% or less indicates *low heterogeneity*, with cutoffs of I^2 greater than 30% and I^2 greater than 50% indicative of *moderate* and *substantial heterogeneity*, respectively.[27] For some outcomes of interest, the data could not be pooled because of heterogeneity in the measures, the methods used, or only 1 study examined an outcome of interest (eg, eccentric PF PT as a percentage of BW [BW%]) at 180°/s). In these situations, such results are reported using weighted means. All meta-analyses were carried out using the Excel (version 2010; Microsoft Corp, Redmond, WA) spreadsheets of Neyeloff et al.[28]

RESULTS

Identification of Studies

The electronic search yielded a total of 7133 potentially relevant studies. After the title and abstract of each study were screened, 29 full-text studies were identified as potentially relevant (Figure 1). A total of 11 studies were removed after screening of the full texts.[3,29–38] Searching the reference lists of these full-text studies led to the addition of 1 study.[39] The final number of studies reviewed was 19.

Participants

A detailed description of the selected studies, listed alphabetically, is provided in Supplemental Table 3. The mean ages of the participants (range = 24–59 years) were similar among studies. A total of 13 studies[11,19,40–50] included both male and female participants, whereas 6 studies[13,39,51–54] included men only. The authors of 8 studies[13,39,42,43,48–51] compared strength measures between symptomatic and asymptomatic participants, the authors of 8 studies[11,40,41,44–47,52] compared strength values between injured and uninjured sides of the same participants, and the authors of 4 studies[48,53–55] compared strength variables between the injured and uninjured sides of the same participant and between the injured side and asymptomatic participants. Strength values between the "most" and "least" symptomatic sides were compared in 1 study.[19] In relation to the characteristics of the included studies comparing the injured limb with the asymptomatic controls, the control groups were generally similar with regard to sex and age; only Firth et al[43] reporting variability in sex between groups. The average duration of symptoms among participants (range = 5 weeks–37 months) was reported in 15 of 19 studies.

Outcome Measures

Maximal-strength values using isokinetic dynamometry were reported in 8 studies.[11,39–41,46,47,49,54] Large variations were present in the speed and mode of contraction. Researchers investigated PF PT at slow speeds (≤120°/s) in 7 studies[11,39–41,47,49,54] and at fast speeds (>120°/s) in 7 studies.[11,39–41,46,47,54] Maximal isometric-strength measures were reported in 3 studies[13,45,48] using various force apparatuses. Silbernagel et al[19] used a variety of heel-raise tests to quantify both concentric and eccentric PF strength and heel-raise–test outcomes using a customized spring-loaded linear encoder. Authors investigated explosive-strength variables in 7 studies,[42,45,49–53] reported values for RFD in 2 studies,[45,52] and addressed GRF in 5 studies.[42,49–51,53] For reactive-strength variables, various single-legged hop or jumping variables were compared in 4 studies.[19,43,44,52]

Risk of Bias

The risk of bias of the included studies using the Critical Appraisal Skills Programme checklist is shown in Table 2. One of the main weaknesses involved the reporting of statistical findings. Whereas most authors provided actual values with accompanying *P* values, few provided 95% CI statistics. A further limitation was the considerable

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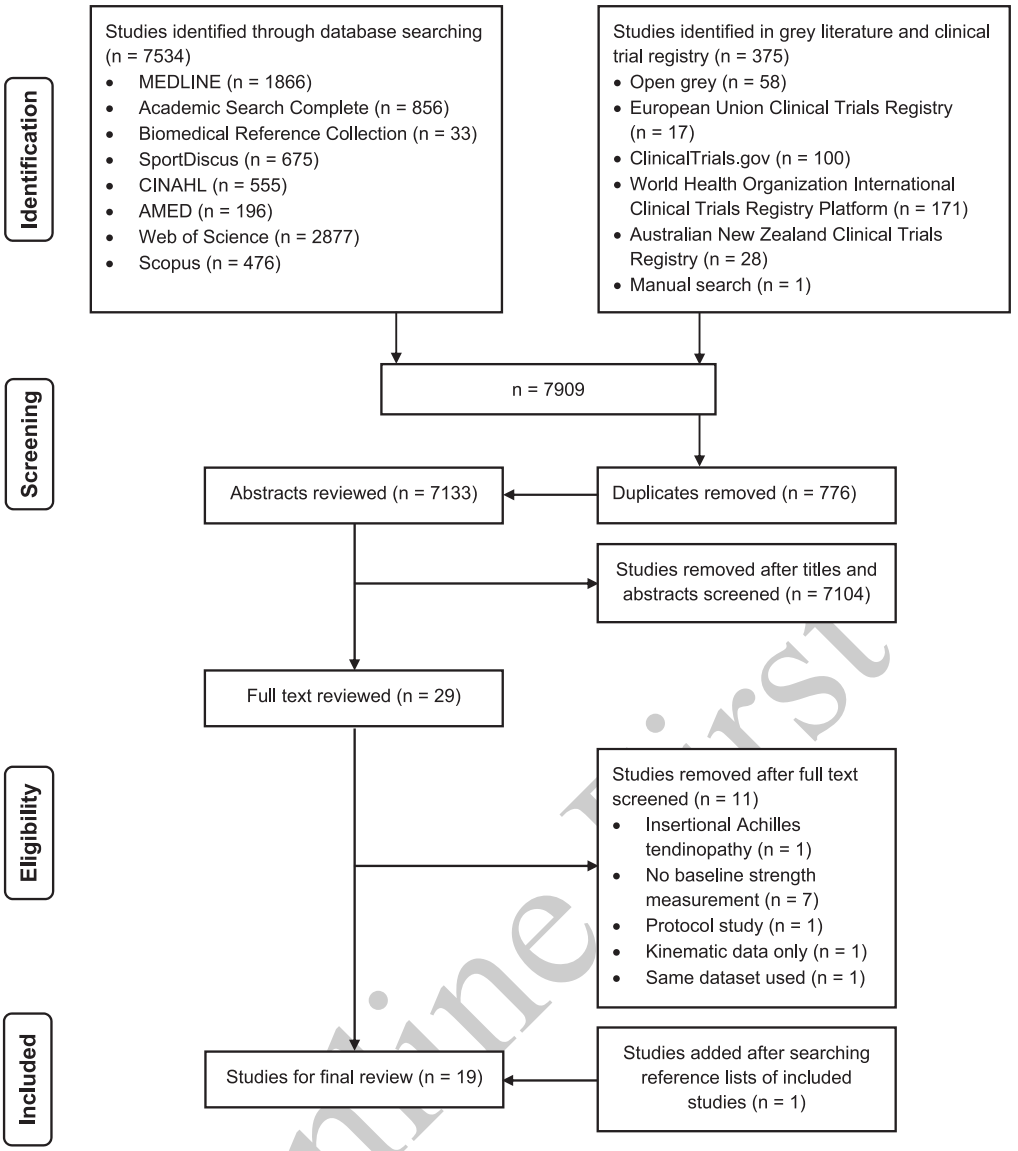


Figure 1. Literature search flowchart.

variation in the measurement techniques used by some researchers. Among the 4 studies[42,49,51,53] in which GRF was investigated, a large amount of variability was present in the methods used to measure GRF. For example, some authors used an instrumented treadmill to measure GRF, and others used force plates integrated in running tracks across a variety of capture distances. Furthermore, a large number of variables were reported for GRF across studies, such as horizontal braking force, vertical impact force, vertical loading rate, and vertical impulse. This variation in reported variables may have accounted for the variation in findings, leading to difficulty drawing conclusions from this outcome. Another limitation was the wide range of symptom durations. The variations in symptom duration suggested that considerable variation within the populations studied may have been present; however, this may also have had the advantage of increasing the generalizability of the findings. Whereas most researchers who compared strength between the injured limb and asymptomatic controls ensured matched control groups, Firth et al[43] included a control group that had more men than n the symptomatic group. Finally, several investigators[41,46,53] did not provide detailed inclusion criteria.

Maximal-Strength Profile

Isokinetic Dynamometry. The meta-analyses revealed moderate effect sizes for concentric PF PT fast (pooled Hedges $g = 0.61$; 95% CI = 0.43, 0.79; Figure 2) and concentric PF PT slow (pooled Hedges $g = 0.43$; 95% CI = 0.25, 0.62; Figure 3). However, effect sizes for eccentric PF PT slow were small (pooled Hedges $g = 0.25$; 95% CI = 0.09, 0.40; Figure 4). These differences reflected deficits of approximately 38%, 44%, and 18%, respectively, between the symptomatic and asymptomatic sides or between the symptomatic side and asymptomatic controls.

As outlined, the data are reported using weighted means when pooling was inappropriate because of heterogeneity in the measures, the methods used, or only 1 study examined an outcome of interest.

Isokinetic Strength. Large effect sizes were observed for eccentric PF PT fast (Hedges $g = 1.26$; 95% CI = 0.34,

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Table 2. Risk of Bias Assessment of Included Studies

Study	Focused Issue?	Appropriate Methodology?	Appropriate Recruitment of Patients?	Appropriate Recruitment of Controls?	Exposure Accurately Measured?	Control of Confounding Factors?	Precision of Results?	Statistics Clearly Reported?	Generalizability of Results?	Results Fit With Other Evidence?
Alfredson et al[11] (1998)	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Alfredson et al[40] (1998)	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Alfredson et al[41] (1998)	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Alfredson et al[46] (1996)	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Azevedo et al[42] (2009)	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Baur et al[53] (2004)	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Becker et al[50] (2017)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Child et al[13] (2010)	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Firth et al[43] (2010)	Yes	Yes	Yes	Yes	No	Yes	No	Yes	No	No
Grigg et al[51] (2013)	Yes	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes
Haglund-Åkerlind and Eriksson[39] (1993)	Yes	Yes	No	No	No	Yes	No	Yes	Yes	No
Maquirriain[44] (2012)	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No
Masood et al[48] (2014)	Yes	Yes	Yes	Yes	No	Yes	No	Yes	No	No
Mayer et al[54] (2007)	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No	Yes
McCrory et al[49] (1999)	Yes	Yes	Yes	No	No	Yes	No	No	Yes	No
Öhberg et al[47] (2001)	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Silbernagel et al[19] (2006)	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes
Wang et al[52] (2012)	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Wang et al[45] (2011)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No

2.18),[39] moderate effect sizes were observed for eccentric PF PT BW% at 180°/s (Hedges $g = 0.36$; 95% CI = –0.07, 0.79),[49] and small effect sizes were observed for eccentric PF PT BW% at 60°/s (Hedges $g = 0.24$; 95% CI = –0.19, 0.67[49]; Figure 5).

Isometric Strength. Small to moderate effect sizes were reported in 2 studies,[45,48] indicating reduced isometric PF strength in those with AT (Hedges $g = 0.46$–0.78). These effect sizes equated to a reduction of 5% to 12% between the symptomatic and asymptomatic sides or between the symptomatic side and asymptomatic controls. In contrast, Child et al[13] reported greater isometric strength in those with AT than controls (9% stronger; Hedges $g = –0.30$; 95% CI = –1.01, 0.41; Figure 5).

Isoinertial Strength. Silbernagel et al[19] investigated PF strength using a weighted eccentric-concentric calf-raise test and a concentric calf-raise test. The PF strength was reduced in in the most symptomatic side compared with the least symptomatic side (Hedges $g = 0.30$–0.60; Figure 5). The results equated to a difference ranging from 16% to 28% (mean difference = 39–83 W) between the most symptomatic and least symptomatic sides. The remaining calf-raise test, which was a traditional calf-raise test with the addition of 10% BW, indicated no difference ($P = .08$) in the number of repetitions performed between the least (n = 24) and most (n = 22) symptomatic sides.

Explosive-Strength Profile

Ground Reaction Force. Five studies[42,49,50,52,53] reported inconsistent results of both increased and decreased GRF in those with AT (Hedges g values = –0.73, 0.66; Figure 6).

Rate of Force Development. Small to large effect sizes indicated reduced RFD in those with AT across a variety of time intervals measured (Hedges $g = 0.42$–1.73; Figure 6).[45,52] These effect sizes equated to a reduction of 10% to 21% between the symptomatic and asymptomatic sides.

Reactive-Strength Profile (Hopping)

Small to large effect sizes were reported[19,43,44,52] for reduced hop performance in those with AT using a variety of hop tests (Hedges g range = 0.32–2.61; Figure 7). This reflected a difference of approximately 16% to 35% between the more and less symptomatic sides. The mean difference in distance hopped was 33% (43 cm) for the single-legged hop and 35% (151 cm) for the triple-legged hop. Average and maximal hop height during a single-legged hop demonstrated deficits of 18% (0.6 cm) and 16% (2.12 cm), respectively, on the symptomatic side. In addition, the hopping quotient (flight time/contact time) was reduced by 20% (0.1) on the symptomatic side during a single-legged hop.

Heterogeneity

Statistical analysis revealed the percentage of total variation across studies was low when comparing injured and uninjured sides versus injured sides and asymptomatic controls (Figures 2–4).

DISCUSSION

The results of this systematic review and meta-analysis demonstrated that individuals with AT displayed deficits in

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Study	Hedges *g*	Standard Error	Weight, %	Hedges *g* Inverse Variance, Random (95% CI)
Alfredson et al[46] (1996)	0.56	0.22	17.5	0.56 (0.13, 0.99)
Alfredson et al[11] (1998)	0.51	0.24	14.7	0.51 (0.04, 0.98)
Alfredson et al[40] (1998)	0.62	0.21	19.2	0.62 (0.21, 1.03)
Alfredson et al[41] (1998)	0.61	0.24	14.7	0.61 (0.14, 1.08)
Haglund-Åkerlind and Eriksson[39] (1993)	0.75	0.44	4.4	0.75 (−0.11, 1.61)
Öhberg et al[47] (2001)	0.67	0.17	29.4	0.67 (0.34, 1.00)
Total (95% CI)			100.0	0.61 (0.43, 0.79)

Heterogeneity: $\tau^2 = 0.00$; $\chi^2 = 0.45$, df = 5, $P = .99$, $I^2 = 0\%$
Test for overall effect: $Z = 6.65$ ($P < .001$)

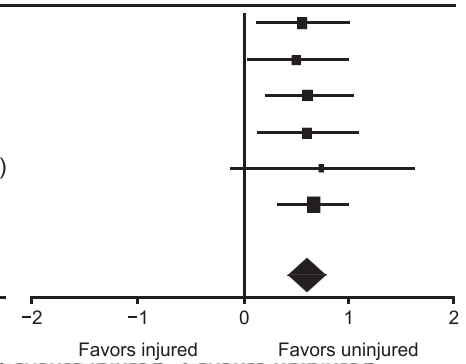


Figure 2. Meta-analysis of concentric plantar-flexion peak torque, fast. Abbreviation: CI, confidence interval.

Study	Hedges *g*	Standard Error	Weight, %	Hedges *g* Inverse Variance, Random (95% CI)
Alfredson et al[46] (1996)	0.36	0.21	14.8	0.36 (−0.05, 0.77)
Alfredson et al[11] (1998)	0.68	0.25	11.4	0.68 (0.19, 1.17)
Alfredson et al[40] (1998)	0.39	0.20	15.8	0.39 (−0.00, 0.78)
Alfredson et al[41] (1998)	0.75	0.25	11.4	0.75 (0.26, 1.24)
Haglund-Åkerlind and Eriksson[39] (1993)	0.67	0.44	4.3	0.67 (−0.19, 1.53)
Mayer et al[54] (2007)	0.08	0.16	21.2	0.07 (−0.24, 0.39)
Öhberg et al[47] (2001)	0.52	0.16	21.2	0.52 (0.21, 0.83)
Total (95% CI)			100.0	0.43 (0.25, 0.62)

Heterogeneity: $\tau^2 = 0.02$; $\chi^2 = 8.29$, df = 6, $P = .22$, $I^2 = 28\%$
Test for overall effect: $Z = 4.55$ ($P < .001$)

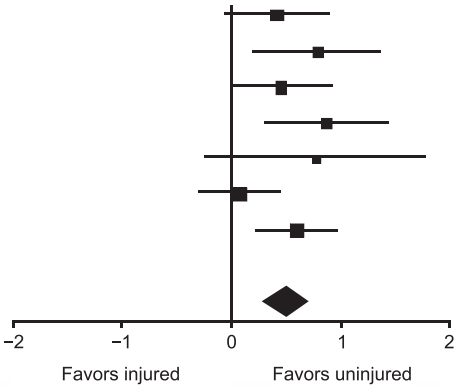


Figure 3. Meta-analysis of concentric plantar-flexion peak torque, slow. Abbreviation: CI, confidence interval.

Study	Hedges *g*	Standard Error	Weight, %	Hedges *g* Inverse Variance, Random (95% CI)
Alfredson et al[46] (1996)	0.10	0.20	15.3	0.10 (−0.29, 0.49)
Alfredson et al[11] (1998)	0.39	0.24	10.6	0.39 (−0.08, 0.86)
Alfredson et al[40] (1998)	0.34	0.20	15.3	0.34 (−0.05, 0.73)
Alfredson et al[41] (1998)	0.21	0.22	12.7	0.21 (−0.22, 0.64)
Haglund-Åkerlind and Eriksson[39] (1993)	0.95	0.45	3.0	0.95 (0.07, 1.83)
Mayer et al[54] (2007)	0.10	0.31	6.4	0.10 (−0.51, 0.70)
McCrory et al[49] (1999)	0.10	0.22	12.7	0.10 (−0.33, 0.53)
Öhberg et al[47] (2001)	0.27	0.16	24.0	0.27 (−0.04, 0.58)
Total (95% CI)			100.0	0.25 (0.09, 0.40)

Heterogeneity: $\tau^2 = 0.00$; $\chi^2 = 4.28$, df = 7, $P = .75$, $I^2 = 0\%$
Test for overall effect: $Z = 3.17$ ($P = .002$)

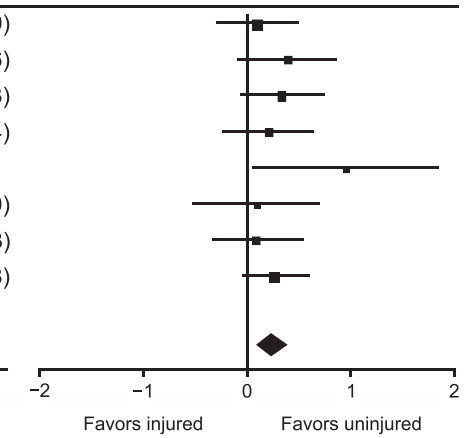


Figure 4. Meta-analysis of eccentric plantar flexion peak torque, slow. Abbreviation: CI, confidence interval.

Study	Hedges *g*	Standard Error	Hedges *g* Inverse Variance, Random (95% CI)
Isokinetic Dynamometry			
Haglund-Åkerlind and Eriksson[39] (1993)[a]	1.26	0.47	1.26 (0.34, 2.18)
McCrory et al[49] (1999)[a]	0.36	0.22	0.36 (−0.07, 0.79)
McCrory et al[49] (1999)[a]	0.24	0.22	0.24 (−0.19, 0.67)
Isometric Strength			
Child et al[13] (2010)[a]	−0.30	0.36	−0.30 (−1.01, 0.41)
Masood et al[48] (2014)[a]	0.78	0.43	0.78 (−0.06, 1.62)
Wang et al[45] (2011)[b]	0.46	0.21	0.46 (0.05, 0.87)
Isoinertial Strength			
Silbernagel et al[19] (2006)[c]	0.30	0.12	0.30 (0.06, 0.54)
Silbernagel et al[19] (2006)[c]	0.60	0.13	0.60 (0.35, 0.85)
Silbernagel et al[19] (2006)[c]	0.45	0.12	0.45 (0.21, 0.69)
Silbernagel et al[19] (2006)[c]	0.53	0.13	0.53 (0.28, 0.78)

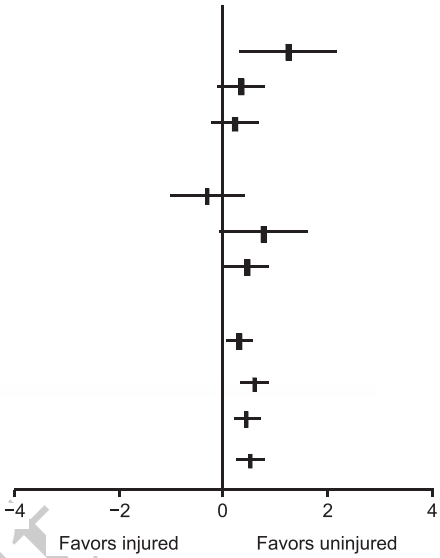


Figure 5. Effect sizes for maximal strength variables. [a] Injured side versus asymptomatic control. [b] Injured versus uninjured side. [c] Most versus least symptomatic side. Abbreviation: CI, confidence interval.

PF strength when the injured side was compared with the uninjured side or with asymptomatic controls. Deficits in maximal-, reactive-, and explosive-strength outcomes were reported across the strength spectrum.

Assessing Musculotendinous Function in AT

In clinical settings, the primary method used to assess PF function in individuals with AT has been the calf-raise or heel-raise test. The validity of the heel-raise test as an appropriate method for assessing PF strength in AT has been highlighted.[17] However, relying on such unidimensional measures to quantify PF function may hinder the appropriate identification of functional deficits in AT, which may lead to inadequate rehabilitation and persistent symptoms. Our findings highlight the potential scope of additional methods of quantifying PF strength in AT. Deficits in maximal strength ranging from 16% to 28% were reported using weighted concentric and eccentric calf-raise tests, whereas deficits of 18% to 44% were observed when using eccentric and concentric isokinetic PT assessments. Therefore, these assessment techniques may be more appropriate for identifying strength deficits than a BW maximal-repetition heel-raise test, in which deficits appear to be much less obvious (deficits of only 8% between sides for the traditional BW heel-raise test). Unfortunately, research comparing these deficits in maximal strength, particularly isokinetic variables, with other pathologic tendon conditions is limited. We reported deficits of 5% to 12% for maximal isometric strength, which is broadly comparable with the isometric-strength deficits reported (9%–32%) for both patellar and gluteus medius tendinopathy.[55–57]

Maximal-strength variables represent only 1 aspect of an individual's overall strength profile and crucially may not sufficiently assess the explosive-strength capabilities that are fundamental during sport movements, such as running or jumping. Our results also indicated a consistent trend toward reduced explosive strength (10%–21% deficit) in individuals with AT assessed by quantifying the RFD. Given that the RFD quantifies the ability to quickly produce muscle force,[58] identifying deficits may be important when assessing individuals with AT to help guide rehabilitation.

In addition to explosive strength, many athletic movements, such as running and jumping, also require substantial amounts of reactive strength to store and release energy and force. In AT, quantifying hopping ability (eg, hop distance, hop height) appears to be the most popular method of assessing reactive strength. Our results indicated deficits of 16% to 35% in individuals with AT, suggesting that these tests may be an appropriate way of assessing reactive-strength deficits in AT. Various hopping tasks have the advantage of being inexpensive, quick, and reliable in research and clinical settings[59]; however, in isolation, they may not discriminate between people using very different movement patterns to achieve hop distances, and hopping does not isolate the PF muscle group. Similar magnitudes of deficits in reactive strength have also been reported after ankle[60] and anterior cruciate ligament[58,61] injury. However, reactive strength requires considerable effort and functional demands, so assessing reactive strength may not always be appropriate, depending on an individual's loading demands and current capacity. The gross nature and variability of movement strategies possible during such tasks highlight the need to combine these assessment techniques with other functional measures.[62]

A further assessment technique that may complement the aforementioned functional outcome measures is evaluation of the tendon's mechanical properties. Achilles tendinopathy leads to alterations in the mechanical properties of the tendon, typically reduced tendon stiffness and increased strain.[51,52,63] Researchers[13,64,65] have postulated that such altered mechanical properties in AT may lead to increased strain on the Achilles tendon, contributing to the ongoing

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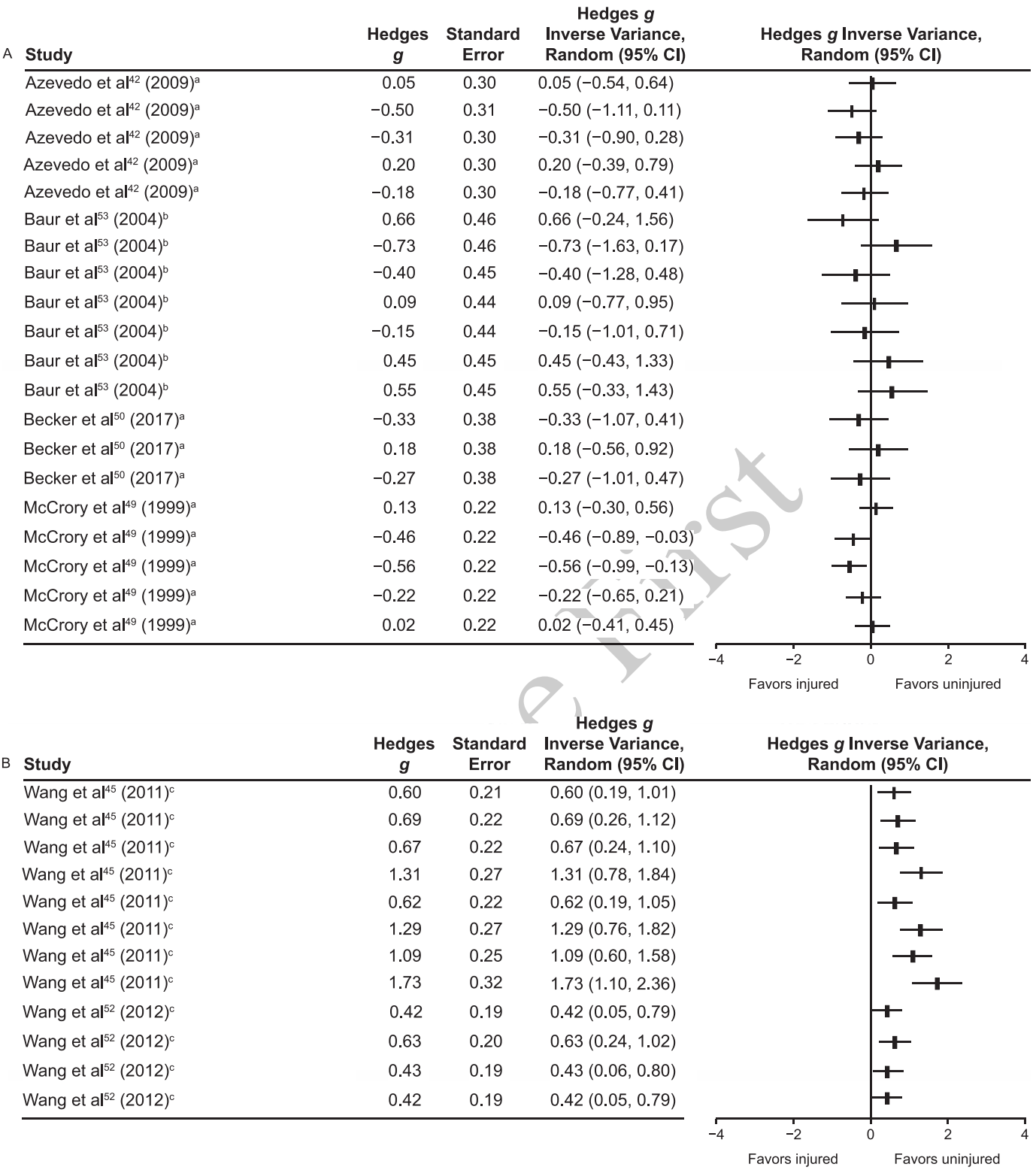


Figure 6. Effect sizes for explosive-strength variables. A, Ground reaction force. B, Normalized rate of force development. [a] Injured side versus asymptomatic controls. [b] Injured versus uninjured side versus asymptomatic controls. [c] Injured versus uninjured side. Abbreviation: CI, confidence interval.

recurrence of symptoms due to an inability to dissipate forces during SSC loading activities. An emerging body of literature[55,56,64] has indicated that the tendon's mechanical response to load may be quantified in individuals with AT using methods such as shear-wave elastography or ultrasound imaging combined with isokinetic dynamometry. Although it is beyond the scope of this review, correlating the tendon's mechanical properties using traditional functional measures may identify areas to be addressed during rehabilitation.

Study	Hedges *g*	Standard Error	Hedges *g* Inverse Variance, Random (95% CI)
Firth et al[43] (2010)[a]	1.44	0.20	1.44 (1.05, 1.83)
Maquirriain et al[44] (2012)[b]	0.32	0.11	0.32 (0.10, 0.54)
Silbernagel et al[19] (2006)[c]	0.33	0.12	0.33 (0.09, 0.57)
Silbernagel et al[19] (2006)[c]	0.48	0.12	0.48 (0.24, 0.72)
Wang et al[52] (2012)[b]	2.61	0.39	2.61 (1.85, 3.37)

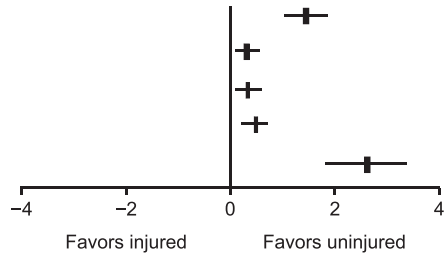


Figure 7. Effect sizes for reactive-strength variables (hopping). [a] Injured side versus asymptomatic controls. [b] Injured versus uninjured side. [c] Most versus least symptomatic side. Abbreviation: CI, confidence interval.

Appropriate Comparative Groups in Assessing Strength Variables

An area of debate in assessing strength outcomes among patients with tendinopathy centers on the suitability of the uninjured side as a comparison. In their systematic review, Heales et al[66] demonstrated motor deficits in the contralateral uninjured limb of patients with unilateral tendinopathy compared with asymptomatic controls, suggesting that the uninjured side may not be as "healthy" and unaffected as a pain-free matched control. In contrast, we did not find any differences in effect sizes when comparing the injured and uninjured sides or when comparing the injured side with asymptomatic matched controls. One potential explanation may relate to the characteristics of the studies included in the review by Heales et al[66]; researchers in 18 of the 20 studies investigated motor deficits in upper limb tendons, which may limit the generalizability to the lower limb. A further consideration is the influence of limb dominance in strength comparisons. In sport environments that require unilateral-dominant movements (eg, jumping in volleyball or basketball), athletes may have a favored jumping limb, which can complicate comparisons. Further research is warranted to improve our understanding of appropriate comparative groups when assessing strength in patients with tendinopathy.

Current Rehabilitation Programs and Adequately Addressing Deficits in Achilles Tendon Function

Exercise or strength interventions using repetitive concentric-eccentric PF muscle exercises have become the cornerstone of conservative treatment for AT.[67] The most popular exercise intervention has been the Alfredson heel-drop program, which is characterized by progressive, twice-daily, eccentric-only contractions over a 12-week period.[11] The popularity of other strengthening programs, most notably progressive mixed concentric-eccentric loading and mixed-contraction, heavy, slow resistance training, has grown.[12,38,55,68,69] Regardless of the mode of contraction, strength interventions have been reasonably effective in improving pain and disability in those with midportion AT; the average reduction in pain was approximately 55%.[34,68,70–78]

Despite the relative success of loading interventions for improving pain and disability, AT is associated with a high recurrence rate (27%).[20,35] One potential reason for the high recurrence rate and persistence of symptoms may be the nonresolution of the strength deficits associated with AT. The degree of improvement in PF strength (maximal-, explosive-, and reactive-strength outcomes) after loading interventions has been reported for only a few strengthening interventions for AT. Yu et al[79] and Alfredson et al[41] noted improvements in concentric PF PT of 10% to 15%, respectively, after the completion of a 12-week strengthening intervention. However, such reported improvements were less than the deficits we observed in isokinetic maximal-strength variables (up to 44%). Such nonresolution of deficits after strength interventions was reiterated by Silbernagel et al,[12] who demonstrated that full symptomatic recovery did not ensure full recovery of muscle-tendon function in patients with AT. Comparisons of outcomes at baseline and 1 year after a loading intervention revealed that only 4 (25%) of the 16 patients (67%) who had fully recovered had achieved an *acceptable level of muscle function*, which was defined as having normal (≥90%) capability across the test battery. These findings suggested that individuals with AT continued to display strength deficits despite reduced pain and disability. The persistence of strength deficits could be speculated to result in the tendon's inability to withstand the desired load, potentially accounting for the high recurrence rate associated with AT. In fact, the "one-size-fits-all" method of assessing and rehabilitating Achilles tendon function may fail to adequately address deficits not only in maximal-strength variables but also throughout the entire strength spectrum.[12,80] Alfredson eccentric loading has become the mainstay of conservative treatment for chronic AT.[67] The preference for eccentric-only interventions reflects the suggestion that eccentric training is more specific and provides a greater load via the force-velocity curve than concentric loading.[81] However, evidence to support these claims appears tenuous.[81] Training only 1 aspect of an individual's strength profile may not optimally improve performance across the entire strength spectrum. Few researchers have attempted to address the entire strength spectrum in an intervention study. Notably, Silbernagel et al[12] used a loading intervention aimed at improving functional outcomes across the entire strength spectrum by integrating plyometric exercises for longer than the traditional 12 weeks, which resulted in improvements in pain and disability at 1-year follow-up. This finding highlights the need for further research in this area.

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Mechanistic Effects of Strength Training in Tendinopathy

Numerous mechanistic theories have been proposed to explain improvements in pain and disability associated with strengthening interventions in AT. The term *mechanotherapy* has been used to describe how the body converts a mechanical stimulus into a cellular response,[82] which may influence structural alterations in the tendon due to AT (eg, disorganized collagen architecture, thinner collagen fibers, increased water content in the extracellular matrix). These structural alterations may alter a tendon's capacity to store and produce kinetic energy, affecting strength and functional performance.[13,83] Investigators[84,85] have suggested that the loading forces applied to the tendon will help stimulate the remodeling of the abnormal tendon structure. However, alterations in tendon structure may not be associated with improved clinical outcomes. In a systematic review, Drew et al[86] concluded that alterations in tendon structure did not adequately explain the response to loading interventions in tendinopathy, which is consistent with little turnover of collagen after puberty.[87] Nevertheless, tendon structure can be altered in young populations (<25 years) after loading interventions.[88,89] Whereas the evidence for the effect of loading interventions in altering abnormal tendon structure is conflicting, loading interventions may effectively improve the mechanical properties of the tendon, albeit in asymptomatic populations.[90]

LIMITATIONS

Our study had limitations. We pragmatically limited inclusion to studies published in the 20 years before our review. Another potential limitation relates to the exclusion of tendon mechanical properties. Originally, we planned to incorporate assessments of tendon mechanical properties (eg, stress, strain); however, the scope of the topic area became too broad, and these aspects were removed. The cross-sectional nature of the included studies led to difficulty in determining a causal relationship between strength and the development of AT symptoms, although the authors of 1 prospective study[10] reported that reduced PF strength predicted the onset of AT in military recruits. Finally, whereas pathologic tendon changes on the uninjured side or asymptomatic controls can potentially influence strength variables, few researchers provided information on the control side or a comparative group, making it difficult to investigate this phenomenon.

CONCLUSIONS

Individuals with AT displayed deficits in maximal, reactive, and explosive strength compared with the uninjured side or asymptomatic controls. Our focus on maximal strength during assessments and rehabilitation, with little emphasis on explosive or reactive strength, possibly did not optimally match the entire strength spectrum. This could also explain why strengthening exercises have had moderate effectiveness in reducing pain and disability in AT, yet residual deficits and high recurrence rates persisted even after strength training.

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Address correspondence to Seán McAuliffe, PhD, BSc, Aspetar Orthopaedic and Sports Medicine Hospital, Aspire Zone, Doha, Qatar, 29222. Address e-mail to sean.auliffe@aspetar.com.

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