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Review

Biomechanical alterations in individuals with Achilles tendinopathy during running and hopping: A systematic review with meta-analysis

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ABSTRACT

Introduction: Biomechanical alterations during running and hopping in people with Achilles tendinopathy (AT) may provide treatment and prevention targets. This review identifies and synthesises research evaluating biomechanical alterations among people with AT during running, jumping and hopping.
Method: MEDLINE, EMBASE, CiNAHL and SPORTDiscus were searched in July 2018 for case control, cross-sectional and prospective studies investigating kinematics, kinetics, plantar pressures and neuromuscular activity in AT participants during running or hopping. Study quality was assessed with a modified version of the Downs and Black quality checklist, and evidence grading applied.
Results: 16 studies reported 249 outcomes, of which 17% differed between groups. Reduced peroneus longus (standardized mean difference [95%CI]; −0.53 [−0.98, −0.09]) and medial gastrocnemius (−0.60 [−1.05, −0.15]) amplitude in AT runners versus control was found (limited evidence). Increased hip adduction impulse 1.62 [0.69, 2.54], hip peak external rotation moment (1.55 [0.63, 2.46] and hip external rotation impulse (1.45 [0.55, 2.35]) was found in AT runners versus control (limited evidence). Reduced anterior (−0.94 [−1.64, −0.24] and greater lateral (−0.92 [−1.61, −0.22]) displacement of plantar pressure preceded AT in runners (limited evidence). Delayed onsets of gluteus medius (1.95 [1.07, 2.83] and gluteus maximus (1.26 [0.48, 2.05] and shorter duration of gluteus maximus activation (−1.41 [−2.22, −0.61] was found during shod running in the AT group versus control (limited evidence). Earlier offset time of gluteus maximus (−1.03 [−1.79, −0.27] and shorter duration of activation of gluteus medius (−0.18 [−0.24, −0.12] during running in AT runners versus control was found (limited evidence). Reduced leg stiffness was found in the affected side during submaximal hopping (−0.39 [−0.79, −0.00]) (limited evidence).
Conclusion: This review identified potential biomechanical treatment targets in people with AT. The efficacy of treatments targeting these biomechanics should be assessed.
Systematic review registry: PROSPERO registration number: CRD42016048636.

1. Background

Achilles tendinopathy (AT) is characterised by localized pain, morning stiffness [1], and impaired function during activities such as running and hopping. AT is particularly prevalent among runners, accounting for 9–15% of total running injuries, but less active people can also be affected [2,3]. A Dutch general practice (GP) study reported an AT incidence of 2.35 per 1000 GP registered patients, and 65% did not involve sport, demonstrating the AT is not just a sports injury [4]. The aetiology is multifactorial, with both intrinsic and extrinsic factors proposed to contribute. These factors may vary between athletically active and sedentary people [5]. Common extrinsic factors may include training errors such as a change in training load [6–9] or training surface [6,7]. Proposed intrinsic risk factors include increasing age [10], increased BMI or body mass [11,12], decreased plantar flexor strength [13,14], systemic diseases such as type 2 diabetes [15],

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previous injuries [16], exposure to drugs (corticosteroids, quinolones) [17,18] and altered biomechanics [19,20].

Biomechanical alterations during running and hopping activities among people with AT have been investigated in numerous studies. These tasks are frequently investigated because they involve stretch-shortening cycle (SSC) plantarflexor loading, resulting in high Achilles tendon loads [21,22]. These activities are thought to be associated with a higher risk of developing Achilles tendinopathy [23], and returning to them after an episode of painful AT can be challenging [24]. Knowledge of biomechanical alterations during running and hopping that precede the onset, or are associated with the presence, of AT will inform rehabilitation as well provide insight relevant to aetiology and prevention.

Biomechanical alterations among people with AT during running have previously been reviewed [19,20]. In summary, these reviews confirmed the existence of biomechanical differences between runners with and without AT that may have implications for the prevention and management of the condition. However, both studies agreed that due to low source study quality, the results had to be interpreted cautiously. Since the search dates of these previous reviews (November 2010 and May 2016), new research investigating running biomechanics in people with AT has been published [25,26] alongside biomechanical studies of hopping, performed among people involved in dancing, ball-sports, and track and field athletics. Further, hopping studies have not been included in any previous reviews and are relevant because Achilles tendon loads during hopping are comparable to loads during running [24,27], and AT has been reported to be the most common running-associated tendinopathy in master runners [6]. Therefore, compared with walking, these high load activities (running and hopping) may be more suitable for identifying biomechanical alterations in people with AT, particularly in the more athletic sub-group. In support of this, studies have demonstrated biomechanical deficits in people with AT during sub-maximal hopping [28]. The aim of this review was to synthesise and evaluate reports of biomechanical alterations during running and hopping tasks among people with AT in order to guide assessment, rehabilitation and future research.

2. Methods

This systematic review was registered on PROSPERO International Prospective Register for Systematic Reviews (CRD42016048636) and conducted following the PRISMA statement guidelines [29].

2.1. Search criteria

MEDLINE (OVID), EMBASE (OVID), CiNAHL (EBSCO) and SPORTDiscus (EBSCO) electronic databases were searched in July 2018. A search strategy with keyword terms was formulated. Each term was mapped to specific subject headings within each database. In all the databases, the following four categories of keywords and related synonyms were used: biomechanical, running or hopping, tendinopathy and Achilles. Appropriate database-specific truncation was used to identify variations of the same search term. Within each keyword category, the different synonyms were combined using the Boolean command "OR" and categories were linked with the Boolean command "AND". The search terms for Medline (Ovid) database are reported in Table 1.

2.2. Selection criteria

Case-control, cross-sectional and cohort design studies of human participants which compared biomechanical factors between participants presenting with current, previous or subsequently developed AT and controls; during running or hopping activities were included. Biomechanical factors could include kinematics, joint moments, ground reaction forces (GRF), vertical or leg stiffness, plantar pressures or muscle activity (peak amplitude, onset, offset). Running at any speed, over ground or treadmill, and shod or barefoot conditions were included. Hopping included any double or single leg ballistic or plyometric activity.

Reviews, case-series, case studies, non-peer-reviewed publications, letters, opinion articles, abstracts, and non-English articles were excluded. Studies including participants with concomitant injury or pain arising from structures other than the Achilles tendon were also excluded.

Diagnosis of AT had to be based on established recommendations [30], including localised Achilles tendon pain (mid-portion and/or insertional, together or separately), and at least one of the following: pain during or after activities that load the tendon (e.g. walking, running), morning stiffness and tenderness on palpation.

2.3. Review process

Literature screening was performed independently by two authors (IS, PM). All titles and abstracts collected were downloaded into Endnote version x7 (Thomson Reuters, Philadelphia, USA) and duplicates removed. The title and abstract were evaluated using a checklist developed from the inclusion and exclusion criteria. Whenever there was lack of information from the title and abstract, the full text was obtained for adequate evaluation. The reference lists of included studies were hand searched for eligible studies. Google Scholar was used to identify any articles citing already retrieved manuscripts. Grey literature was not included.

2.4. Quality assessment

Two reviewers (IS and PM) independently assessed the quality of the included studies. Disagreements were resolved by consensus and the input of a third researcher (CB) was available if an agreement could not be reached, but was not needed. The methodological quality of each included study was assessed with a modified scale based on the Downs and Black Checklist for Measuring Quality [31]. This scale is a validated tool for both randomised and non-randomised controlled trials and has been broadly used to evaluate the quality of studies. The 27-item checklist was modified and targeted to the cohort and case-control designs in our yield. The reviewers also included a question (Q15) about effect size and estimates based on other quality assessment tools. The final quality scale, therefore, included 17 questions with a total score of 19 points (two questions scored up to two points) or 18 points for case-control and cohort studies where the question about follow-up time was not scored (Q16). Five quality components were evaluated: reporting 7 items; external validity (2 items), bias in measurements (3 items), confounding or bias in the selection of participants (4 items) and study power (1 item). Items were rated "yes = 1″, "no = 0″ and "unable to determine = 0″, aside from items 4 and 5 pertaining to distributions of principal confounders and exposure, that were rated "2 = all described, matched and adjusted", "1 = one not described, matched or adjusted" and "0 = two or more not described, matched or adjusted". Nine items (6, 8, 9,13, 14, 17, 19, 23 and 24) from the original Downs and Black questionnaire were excluded because they were related to interventions, overlapped with other criteria or were not relevant. The modified Downs and Black quality appraisal checklist is described in **Additional File 1.** Based on quality assessment scores studies were categorised as high quality (HQ, ≥70%), moderate quality (MQ, 69-40%) or low quality (LQ, < 40%) [32].

2.5. Data extraction and analysis

A predefined data extraction sheet was completed for all included studies. Sample size, demographics of participants, study design, characteristics of running or hopping, shoe condition (barefoot, shod type(s), whether participants currently had AT or a history of AT (for

Table 1
MEDLINE search terms and strategy.

Category	Terms
Biomechanical	Biomechanical phenomena (MESH), Biomechanic*, Kinematic*, Kinetic*, Kinetics (MESH), Motion (MESH), Temporospatial, Plantar pressure, Ground reaction force, GRF, Moment, Torque (MESH), Force, Stiffness, 3D Kinematics, Mechanic* / Mechanics (MESH), Neuromuscular, Neuromotor, Neuromotor control, Motor control, EMG, Electromyograph*, Electromyography (MESH), Muscle activit*
Running OR Hopping	Run*, Running (MESH), Gait (MESH), Running Gait, Gait-related, Locomotion(MESH), Hop*, Jump*, Bounc*, Plyometric*, Plyometric exercise (MESH)
Tendinopathy	Tendinopathy (MESH), Achilles tendinopathy (MESH), Tendinitis, Tenosynovitis (MESH), Tendinosis, Tenopathy, Tendonopathy, Partial rupture, Paratenonitis, Tendovaginitis, Peritendinitis, Achillodynia, Pain (MESH), Complaint*, Injur*, Tendon injuries(MESH)
Achilles	Achilles tendon (MESH), Achilles, Tendoachilles, Tendo-achilles, Triceps surae, Triceps sural
The four categories where linked with the Boolean command "AND"	

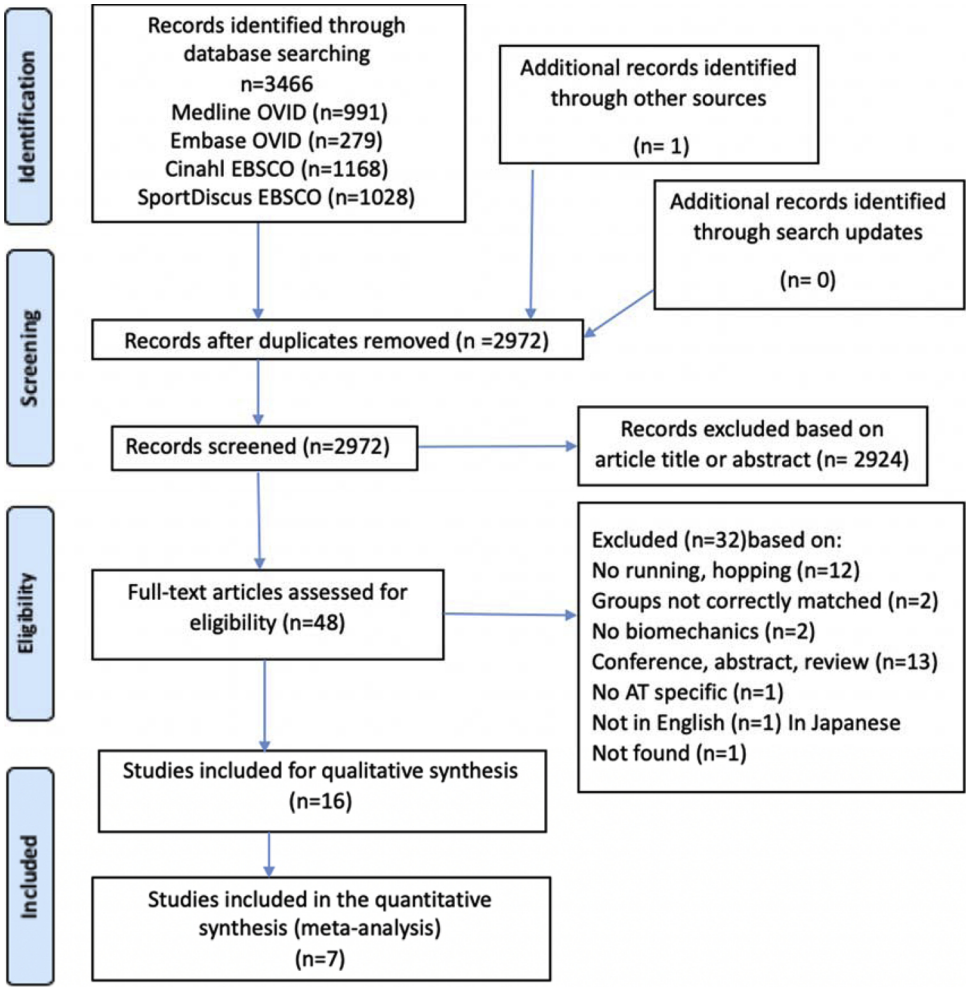


Fig. 1. PRISMA flow diagram of the search results.

cohort and cross-sectional studies), assessed biomechanical variables and the reported significant findings were extracted.

Statistical analyses were completed in Review Manager 5.3 (The Cochrane Collaboration, Copenhagen, Denmark) initially by one author (IS) and subsequently repeated independently by a second author (PM). Where inadequate data were available in original publications, authors were contacted for additional data. Studies where no data could be entered into the meta-analysis underwent narrative synthesis.

Dichotomous outcomes were expressed as relative risk (RR) with 95% confidence intervals. Continuous variables were expressed as standardised mean differences (SMD) (mean difference divided by pooled standard deviation) with 95% confidence intervals. Calculated individual or pooled SMDs were categorised as small (< 0.59), medium (0.60–1.19) or large (> 1.20) [33]. Meta-analyses were performed where two or more studies were investigating the same task and biomechanical outcome (i.e sufficient clinical homogeneity). The level of statistical heterogeneity for pooled data was established using I^2 statistics. For the I^2 statistic, we interpreted statistical heterogeneity as not important (< 50%), moderate (50–75%) and high (> 75%) [34]. We reported statistical heterogeneity but this did not inform the type of model used (fixed or random effects). A random-effects model was used for meta-analyses given typically small sample sizes and sample heterogeneity with selection bias being common in the literature [35]. Quality rating and SMDs were used to determine levels of evidence, based on a modified version of the van Tulder criteria [36]:

- Strong evidence: consistent findings among multiple studies including at least 3 high-quality studies
- Moderate evidence: consistent findings amongst multiple trials, including at least 3 moderate/high-quality studies or 2 high-quality

studies
- Limited evidence: pooled findings amongst multiple low/moderate quality studies, or 1 high-quality study
- Very limited evidence: findings from one 1 low/moderate quality study
- Conflicting evidence: one/some studies show significant effects and one/some studies show no significant effects while the CIs of the pooled effect size lead one to accept the null hypothesis.

3. Results

The final yield was 16 studies investigating biomechanical alterations during running or hopping among people with AT compared to controls, including 14 case-control and cross-sectional, and two prospective studies. 12 (75%) studies investigated participants during running [3,25,26,37–45] and four studies (25%) during hopping [28,46–48]. Two prospective studies (12%) evaluated biomechanics associated with the development of AT [3,41], three cross-sectional studies (19%) investigated asymptomatic people [44,46,48] and eleven cross-sectional studies (69%) investigated symptomatic people [25,26,28,37–40,42,43,45,47]. Fifteen studies (94%) included active participants (information obtained from the papers or contacting the authors) and one hopping study (6%) included sedentary and active participants [47]. Nine studies (56%) included participants with mid-portion AT, one study (6%) included participants with mid-portion and insertional AT [28] and three studies (19%) did not clarify location of pain [25,38,41]. No study reported differences apparent in findings for participants with mid-portion and insertional AT. Fig. 1 shows the search strategy process to identify included studies.

The mean quality score of the included studies was 57% (33%–89%) with four high quality studies [3,26,28,40] nine moderate quality studies [25,37,39,43–48] and three low quality studies [38,41,42]. Quality assessment of the studies is shown in Table 2. Data extraction is collated in Table 3.

3.1. Running studies

A summary of meta-analysis findings for kinematic, GRF, and neuromuscular outcomes are shown in Tables 4 and 5 respectively. Only pooled findings (significant and non-significant), and significant findings from single studies are summarised in the text. All biomechanical findings not included in meta-analysis are detailed in **Additional File 2**.

3.1.1. Prospective running studies

3.1.1.1. Plantar pressure distributions. One study [3] investigated six variables. Limited evidence indicates a significantly decreased total anterior displacement of the centre of force (medium SMD: -0.94 [-1.64, -0.24]) and a significantly more laterally directed force distribution underneath the foot at foot flat during running (medium SMD: -0.92 [-1.61, -0.22]) preceding AT development [3].

3.1.1.2. Kinematics. One study [41] investigated 12 variables. Very limited evidence indicates that decreased maximal ankle dorsiflexion during running preceded the development of AT (medium SMD: -1.15 [-2.23, -0.06]) [41].

3.1.2. Case-control and cross-sectional running studies

3.1.2.1. Kinematics. Ankle: Four studies [25,26,42,43] investigated a total of 29 variables during running, with six variables included in the meta-analyses. Based on meta-analysis, limited evidence indicates no between group differences for ankle dorsiflexion peak (1 shod and 1 barefoot) (small SMD: -0.10 [-0.56, 0.36] [26,43], ankle dorsiflexion ROM (1 shod and 1 barefoot) (small SMD: -0.13 [-0.59, 0.34] [26,43], ankle eversion peak (3 shod and 1 barefoot) (small SMD: -0.11 [-0.41, 0.18] [25,26,42,43] and maximum ankle eversion velocity (1 shod and 1 barefoot) (small SMD: -0.12 [-1.07, 0.83] [25,43]. Further, there was no pooled effect for timing to ankle peak eversion (2 shod and 1 barefoot) (small SMD: 0.24 [-0.39, 0.861]) [25,42,43] and ankle eversion ROM (3 shod and 1 barefoot) (small SMD: 0.18 [-0.39, 0.75]) [25,26,42,43] but evidence was conflicting between different studies (Table 4). Based on single studies, very limited evidence indicates that ankle rear foot eversion (negative values equate to more eversion) at heel-off (shod) (large SMD: -1.57 [-2.47, -0.68]) [25] and the duration of pronation (shod) (large SMD: 1.67 [0.76, 2.58]) [25] were increased; and ankle dorsiflexion maximum velocity was reduced (barefoot) (medium SMD: -0.61 [-1.19, -0.02]) [43] in the AT group compared to controls.

Knee: Three studies [37,43,44] investigated a total of 13 variables, but no data could be pooled in meta-analysis. Very limited evidence indicates people with AT had decreased knee ROM from heel strike to the mid-stance phase compared to controls during shod running (medium SMD: -0.88 [-1.52, -0.25]) [37].

Hip: Two studies [26,37] investigated eight variables, but no data could be pooled in the meta-analysis. Limited evidence indicates people with AT had increased hip internal rotation at peak vertical ground reaction force (vGRF) during shod running (medium SMD: 0.84 [0.01, 1.67]) [26].

3.1.2.2. Ground reaction forces. Four studies [25,37,38,42] investigated a total of 33 variables, with three variables included in the meta-analyses. Based on meta-analysis, limited evidence indicates peak vertical GRF (small SMD: 0.44 [-0.05, 0.92]) [25,37,42], horizontal breaking GRF (small SMD: -0.28 [-0.78, 0.22]) [37,38,42] and horizontal propulsive force (small SMD: 0.32 [-0.10, 0.74] [25,37,38,42] were not different between groups (Table 4).

3.1.2.3. Joint moments. Two studies [26,44] investigated a total of 13 variables and none could be included in the meta-analysis.

Knee: Very limited evidence indicates tibial external rotation external moment in asymptomatic runners with a history of at least one episode of AT was decreased during the stance phase of shod running compared to controls (large SMD: 1.29 [0.18, 2.39] [44].

Hip: Limited evidence indicates hip adduction impulse (large SMD: 1.62 [0.69, 2.54]), hip peak external rotation moment (large SMD: 1.55 [0.63, 2.46]) and hip external rotation impulse (large SMD: 1.45 [0.55, 2.35]) were increased in shod runners with AT compared to controls [26].

3.1.2.4. Plantar pressure distributions. One study [38] investigated four variables. Very limited evidence indicates that the lateral deviation of the center of pressure was decreased in relation to the plantar angle (longitudinal middle line of the foot) in the AT group compared to controls during barefoot running (medium SMD: -0.94 [-1.86, -0.02]) [38].

3.1.2.5. Neuromuscular activity

3.1.2.5.1. Tibialis anterior. Three studies [37–39] investigated a total of 18 variables, with two included in the meta-analyses. There was no pooled effect for tibialis anterior amplitude at weight acceptance between the groups (small SMD: 0.47 [-0.42, 1.37]) [38,39] but the evidence was conflicting between the two studies. There was limited evidence that tibialis anterior amplitude is not different at push-off phase (small SMD: 0.29 [-0.15, 0.73] [38,39] during shod running; and very limited evidence that tibialis anterior amplitude was decreased 100 ms prior to heel strike during shod running (medium SMD: -0.98 [-1.62, -0.34]) [37], and increased at push-off during barefoot running (large SMD: 1.86 [0.80, 2.92]) [38] when compared to control.

3.1.2.5.2. Peroneus longus. Three studies [37–39] investigated a total of 17 variables, with three included in the meta-analyses. Limited evidence indicates that during shod running, there were no

Table 2
Quality assessment of the studies.

Study	Hypothesis /aim/ objective clearly described	Main outcomes clearly described	Characteristics of patients clearly described	Confounders clearly described, matched, adjusted	Exposure clearly defined and matched	Estimates of the random variability for main outcomes	Probability values reported	Subjects asked to participate representative of the entire population	Subjects prepared to participate representative of the entire population
Azevedo et al [37]	1	1	1	1	1	1	1	0	0
Baur et al [38]	1	1	0	0	2	0	0	0	0
Baur et al [39]	1	1	1	2	1	1	1	1	0
Becker et al [25]	1	1	0	0	0	1	1	1	0
Chang et al [46]	1	1	1	0	1	1	1	0	0
Creaby et al [26]	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**
Debenham et al [47]	1	1	1	0	0	1	1	0	0
Franettovich et al [40]	**1**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**0**
Hein et al [41]*	1	1	0	2	1	1	0	0	0
Kulig et al [48]	1	1	1	1	2	1	1	1	1
Maquirriain et al [28]	**1**	**1**	**1**	**2**	**2**	**1**	**1**	**1**	**1**
McCrory et al [42]	0	1	0	1	0	1	1	0	0
Ryan et al [43]	1	1	1	1	1	1	1	1	0
Van Ginckel et al [3]*	**1**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**
Williams et al [44]	1	1	0	2	1	1	1	1	0
Wyndow et al [45]	1	1	1	2	1	1	1	1	0

Study	Blindness of assessors	Data dredging clear	Appropiate statistical tests	Cases & controls recruited at same period	Adequate adjustment for confounding	Effect size estimate and confidence intervals calculated	Losses to follow-up considered	Sufficient power to detect a clinically important effect	Rate	Percentage (%)
Azevedo et al [37]	0	1	1	0	1	0	N/A	0	10	56
Baur et al [38]	0	1	1	0	0	0	N/A	0	6	33
Baur et al [39]	1	1	1	0	0	0	N/A	0	12	67
Becker et al [25]	0	1	1	0	1	1	N/A	1	10	56
Chang et al [46]	0	1	1	0	1	0	N/A	0	9	50
Creaby et al [26]	**1**	**1**	**1**	**0**	**1**	**1**	N/A	**1**	**14**	**78**
Debenham et al [47]	0	1	1	0	1	0	N/A	0	8	44
Franettovich et al [40]	**0**	**1**	**1**	**0**	**1**	**1**	N/A	**0**	**13**	**72**
Hein et al [41]*	1	1	0	0	0	0	0	0	8	37
Kulig et al [48]	0	1	0	0	0	0	N/A	0	11	61
Maquirriain et al [28]	**0**	**0**	**1**	**0**	**0**	**0**	N/A	**1**	**13**	**72**
McCrory et al [42]	0	1	1	0	0	0	N/A	0	6	33
Ryan et al [43]	0	1	1	0	0	1	N/A	0	11	61
Van Ginckel et al [3]*	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**17**	**89**
Williams et al [44]	0	0	0	0	0	0	N/A	0	8	44
Wyndow et al [45]	0	1	1	0	0	1	N/A	0	12	67

The final quality scale included 17 items with a total score of 19 points for prospective studies (*) or 18 points for case control and cohort studies where the item about follow-up time was not applicable (N/A). Items were rated “yes = 1”, “no = 0” and “unable to determine = 0”, aside from items 4 and 5 pertaining to distributions of principal confounders and exposure, that were rated “2 = all described, matched and adjusted”, “1 = one not described, matched or adjusted” and “0 = two or more not described, matched or adjusted”. In bold high quality studies.

Table 3
Study characteristics and reported findings.

Study Authors, quality level & study type	Sample Group and number/male-female/age (years)/ mass (kg), height (cm), BMI (kg/m$^{2)}$ Years of sporting activity/ training per week/ symptoms	Activity characteristics and shoe condition	Biomechanical variables	Reported significant findings (AT vs CO) ($p < 0.005$)	P-value
Azevedo et al. [37] MQS 56% Case control	AT 21 / 16m5f / 41.8 ± 9.7 / 77.6, 177.8, NR 3/ > 15 km/ symptomatic CO 21/ 16m5f / 38.9 ± 10.1 / 70.2, 174.3, NR 3/ > 15 km	Run / self-selected speed / 10 m pathway heel strike pattern Neutral running shoes (Rainha Athens, Alpargatas inc; Shore A40)	Kinematics: sagittal plane hip, knee and ankle joints Kinetics: antero-posterior and vertical ground reaction forces Temporo-spatial parameters: speed, stride length, stride time and stride frequency EMG: tibilalis anterior, peroneus longus, lateral gastrocnemius, rectus femoris, biceps femoris and gluteus medius	Knee ROM (between heel-stike and middstance) Tibialis anterior pre-heel strike Rectus femoris post-heel strike Gluteus maximus post-heel strike	0.011 0.003 0.000 0.004
Baur et al. [38] LQS 33% Case control	AT 8 / NR / 36 ± 9 / 73, 179, NR NR/ 5 ± 2 units/ symptomatic CO 14/ NR / 36 ± 9 / 73, 179, NR NR/ 5 ± 2 units	Run / 12 km/h / treadmill / rear foot striking technique Gymnastic shoe that simulates barefoot condition and standard marketed reference running shoe	Kinetics: antero-posterior and vertical ground reaction forces EMG: tibialis anterior, peroneus, gastrocnemius lateralis, gastrocnemius medialis and soleus Plantar pressure distribution	*"The amplitude of the EMG in the extensor loop in the phase of weight acceptance both barefoot, and shod is significantly higher in the healthy control group than in the runners with Achilles tendon complaints"* Lateral deviation of the center of pressure in relation to the plantar angle (Alat) in barefoot condition	0.000 0.000
Baur et al. [39] MQS 67% Case control	AT 30 / 19m10f / 41 ± 7 / 72, 175, NR NR/ 45 ± 21 km/ symptomatic CO 30 / 20 m10f / 37 ± 10 / 67, 174, NR NR/ 42 ± 14kms	Run / 12 km/h / treadmill Neutral running shoes	EMG: tibialis anterior, peroneus longus and gastrocnemius medialis (Plantar pressure distribution to calculate touch down/take off time)	*Bilaterally pooled data (AT vs CO):* Peroneus longus weight acceptance Gastrocnemius medialis weight acceptance Gastrocnemius medialis push-off *Unilateral data (AT affected extremity vs CO extremity):* Gastrocnemius medialis weight acceptance	 0.006 0.001 0.04 0.04
Becker et al. [25] MQS 56% Case control	AT 13/ 9m4f / 37.6 ± 15.9 / NR, NR, NR NR/ 50.1 ± 15.1miles/ symptomatic CO 13 / 9m4f / 32.6 ± 12.4 / NR, NR, NR NR/ 52.32 ± 14.7 miles	Run / Self-selected pace / 5 m straight section / subjects matched on foot strike pattern Own training shoes	3D rear foot kinematics Ground reaction forces	Period of pronation Eversion at heel-off	< 0.001 < 0.001
Chang et al. [46] MQS 50% Case control	AT 9 / NR / 46.8 ± 6.3 / 74.1, 170, NR NR /4720 MET-min asymptomatic (history of pain) CO 10 / NR / 48.7 ± 4.4 / 84.9, 170, NR NR/ 3983 MET-min	Hop / 20 submaximal single leg hops / frequency: 2.2 Hz / Own shoes	EMG: tibialis anterior, medial gastrocnemius, soleus and peroneal longus (Ground reaction forces to calculate touch down/ take off time)	*"Muscular preactivation between sides differences between groups"* *"Individuals with Achilles tendinosis exhibit an earlier preactivation of the medial gastrocnemius on the involved side"*	< 0.001 < 0.001
Creaby et al. [26] HQS 78% Case control	AT 14 / 14 m0f / 43 ± 8 / 82.3, 179, 25.73 NR/ 38.1 ± 13.2 km/ symptomatic CO 11 / 11m10f / 37 ± 9 / 73.5, 177, 23.5 NR/ 35.9 ± 13.6 km	Run / 4 m/s (± 10%) / 25 m walkway Nike Strap runner IV running sandals	3D kinematics: hip and ankle Kinetics: hip and ankle joint moments	Hip rotation at peak vGRF Hip adduction impulse Hip peak external rotation Hip external rotation impulse	0.042 0.0005 0.0006 0.0001
Debenham et al. [47] MQS 44% Case control	AT 15/ 9m6f / 41.2 ± 12.7 / 82, 174.1, NR NR/ NR/ symptomatic CO 11 / 5 m6f / 23.2 ± 6.7 / 70.7, 170.1, NR NR/NR	Hop/ 15 sub-maximal single leg hops on a Sledge Jump System (knee fully extended) Barefoot	Kinematics: sagittal plane of the ankle joint EMG: tibialis anterior and soleus Stiffness	Ankle stretch amplitude Ankle hopping range Soleus onset Tibialis anterior peak Tibialis anterior offset Stiffness	< 0.001 < 0.001 < 0.001 0.026 < 0.001 < 0.001
Franettovich et al. [40] HQS 72% Case control	AT 14 / 14 m0f / 43 ± 8 / 82.3, 179, NR NR/ 38.1 ± 13.2 km/ symptomatic CO 19 / 19m0f / 37 ± 8 / 77.4, 179, NR NR/ 37.6 ± 16.4 km	Run / 4 m/s (± 10%) / 25 m walkway Nike Strap runner IV running sandals	EMG: gluteus maximus and gluteus medius (Vertical ground reaction forces were used to establish heel strike and toe-off)	Gluteus medius onset Gluteus medius activity time Gluteus maximus onset Gluteus maximus activity time Gluteus maximus offset	< 0.001 < 0.001 0.008 0.002 0.001
Hein et al. [41] LQS 37% Prospective	AT 10 / 8m2f / 45 ± 5 / 72, 177, 23 NR/ 33 ± 15 km/ asymptomatic (healthy participants)	Run / controlled speed of 12 km/h (SD 5%) / 13 m runway Barefoot	3D kinematics in hip, knee and ankle joints	*"it can be concluded that AT also show a more extended knee joint, a lower dorsiflexed ankle joint and a more everted rearfoot at touchdown compared with CO"*	NR

(*continued on next page*)

Table 3 (*continued*)

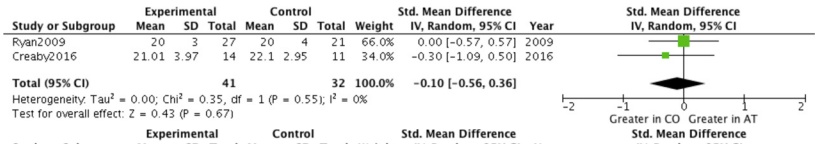
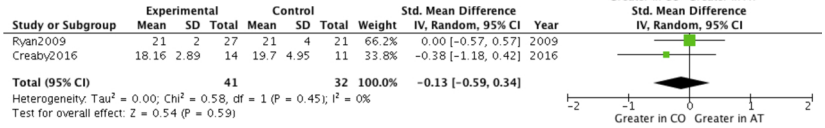
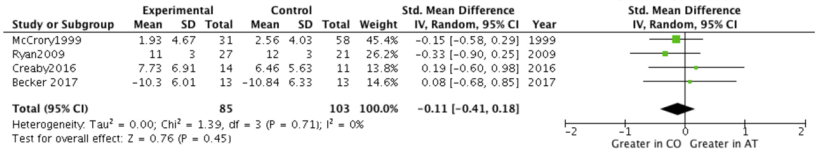
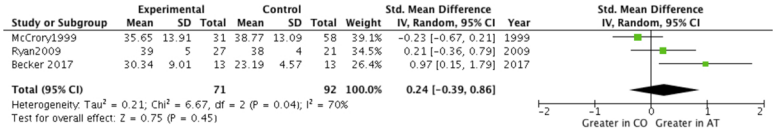
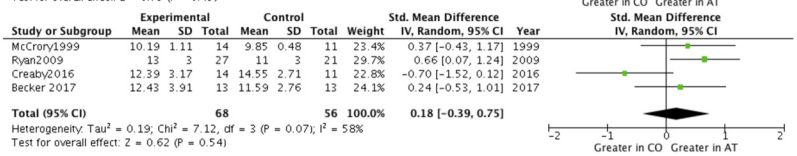
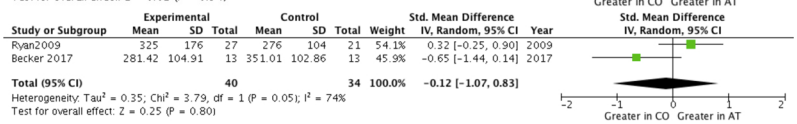
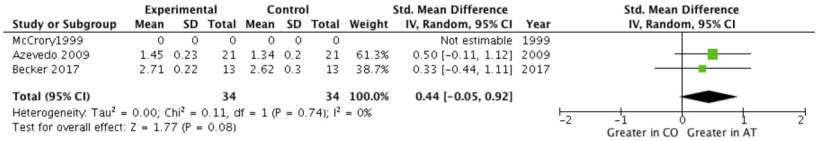
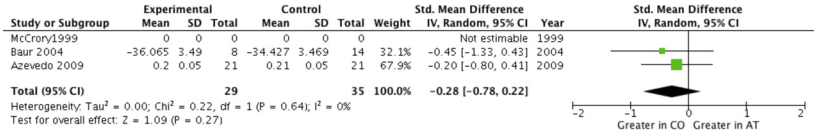
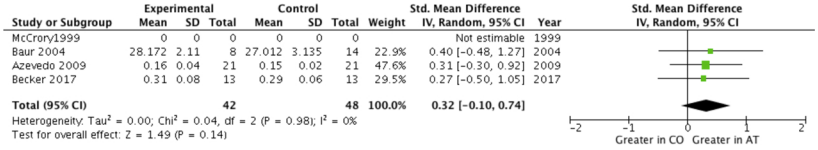
Study Authors, quality level & study type	Sample Group and number/male-female/age (years)/ mass (kg), height (cm), BMI (kg/m$^{2)}$ Years of sporting activity/ training per week/ symptoms	Activity characteristics and shoe condition	Biomechanical variables	Reported significant findings (AT vs CO) ($p < 0.005$)	P-value
	CO 10 / 8m2f / 40 ± 7 / 72, 177, 23 NR/ 32 ± 20 km				
Kulig et al. [48] MQS 61% Case control	AT 8 / 0m8f / 18.5 ± 1.1 / 57.3, 164, NR NR/ 30 to 35 h of formal training/ asymptomatic (history of pain) CO 8 / 0m8f / 19.0 ± 1.3 / 54.3, 164, NR NR /30 to 35 h of formal training	Hop / *saut de chat* jump* Barefoot	3D kinematics in hip, knee and ankle (Ground reaction forces were used to establish heel strike and toe-off)	Hip adduction at braking phase Knee internal rotation at push-off phase	0.046 0.024
Maquirriain et al. [28] HQS 72% Cross sectional	AT 51 / 40m11f / 39.82 ± 11.80 / 77.46, 173.05, 25.82 NR/ > 15 h of training for high performance athletes NR for the rest of participants/symptomatic/ CO same participants' contralateral leg	Hop / 3 maximal single leg hops / 10" single leg hopping on the place / self-selected frequency Own shoes	Leg mechanical values (jump height, flight time, contact time, velocity, performance) Leg stiffness	Stiffness	0.04
McCrory et al. [42] LQS 33% Case control	AT 31 / NR / 38.4 ± 1.8 / 71.4, 174.5, NR 11.9 ± 1.4/ 52.1 ± 4.68 km/NR CO 58 / NR / 34.5 ± 1.2 / 70.03, 174.5, NR 9.6 ± 0.8/ 44.5 ± 2.85 km	Run/ self-selected training pace / rear foot motion analysis on a treadmill / kinetics analysis on 22.75 m runway Shoes in which they became injured for AT / regular training shoes for CO	Rear foot 2D kinematics Kinetics: antero-posterior, mediolateral and vertical ground reaction forces	Maximum pronation Time to maximum pronation Calcaneus to vertical touch down angle Maximum pronation velocity	NR
Ryan et al. [43] MQS 61% Case control	AT 27 / 27m0f / 40 ± 7 / 78, 181, NR NR/ > 30 km/ symptomatic "negligible pain" CO 21 / 21m0f / 40 ± 9 / 71, 177, NR NR/ > 30 km	Run / self-selected pace / 13 m padded runway Barefoot	Kinematics: frontal and sagittal plane ankle and transverse plane tibia	Ankle eversion ROM	0.04
Van Ginckel et al. [3] HQS 89% Prospective	AT 10 / 2m8f / 38 ± 11.35 / 69.8, 167,1, 24.95 / NR **/ 7.7 ± 103 h of walk + run/ asymptomatic (healthy participants) CO 53 / 8m45f / 40 ± 9 / 69.95, 168.34, 24.69 / NR **/ 7.8 ± 1.24 h of walk + run	Run / self-selected speed / 15 m runway Barefoot	Plantar dynamic force distribution	Total posterior–anterior displacement of the centre of force Laterally directed force distribution underneath the forefoot at 'forefoot flat'	0.015 0.016
Williams et al. [44] MQS 44% Case control	AT 8 / 6m2f / 36.0 ± 8.2 / 67.3, 176, NR 19.1 ± 7.7/ 41.3 ± 20.8 km/ asymptomatic (history of pain) CO 8 / 5 m3f / 31.8 ± 9.3 / 65.6, 170, NR 11 ± 9.1/ 35.3 ± 23.1 km	Run / 3.35 m/s (± 5%) / 20 m runway /rear foot strike pattern Saucony neutral running shoes	3D Kinematics and moments in transverse plane tibia relative to foot (tibial motion) and tibia relative to femur (knee motion)	Peak internal rotation motion Peak tibial external rotation moment	0.05 0.01
Wyndow et al. [45] MQS 67% Case control	AT 15 / 15 m0f / 42 ± 7 / 80, 177, NR NR/ maximum of 43 ± 15 km/ symptomatic CO 19 / 19m0f / 36 ± 8 / 77, 179, NR NR/ maximum of 40 ± 16 km	Run / 4 m/s (± 100 ms) / 25 m walkway Nike Strap runner IV running sandals	EMG: soleus, lateral head of gastrocnemius and medial head of gastrocnemius (Vertical ground reaction forces to establish heel strike and toe-off times were used)	Offset timing between soleus and lateral gastrocnemius	0.02

Age, mass, height, BMI, years of sporting activity and training per week in mean and standard deviation values. Abbreviations: AT participants with Achilles tendinopathy, CO control participants, kg kilograms, cm centimetres, m meter, m^2 squared meter, km kilometres, NR not reported, m male, f female, EMG electromyography, MET-min* MET, metabolic equivalent of task per minute, Hz hertz, 3D three dimensional, 2D two dimensional, MQS moderate quality study, LQS low quality study, HQS high quality study.

**Saut de chat* jump is a leap common in ballet. Its goal is to launch from 1 foot, gain as much height as possible, attain a fully extended split-legs posture at the peak of the airborne period, and then land on the opposite foot.

**Participants in this study were novice runners.

Table 4
Meta-analysis of kinematic and GRF outcomes in running studies.

Outcome	Evidence	
Ankle peak dorsiflexion	Limited 1MQS [43] 1HQS [26]	
Ankle dorsiflexion ROM	Limited 1MQS [43] 1HQS [26]	
Ankle peak eversion	Limited 1LQS [42] 1MQS [43] 1HQS [26] 1MQS [25]	
Timing to ankle peak eversion	Conflicting 1LQS [42] 1MQS [43] 1MQS [25]	
Ankle eversion ROM	Conflicting 1LQS [42] 1MQS [43] 1HQS [26] 1MQS [25]	
Maximum velocity in ankle eversion	Limited 1MQS [43] 1MQS [25]	
Peak vertical force	Limited 1LQS [42] 1MQS [37] 1MQS [25]	
Horizontal breaking force	Limited 1LQS [42] 1LQS [38] 1MQS [37]	
Horizontal propulsive force	Limited 1LQS [42] 1LQS [38] 1MQS [37] 1MQS [25]	

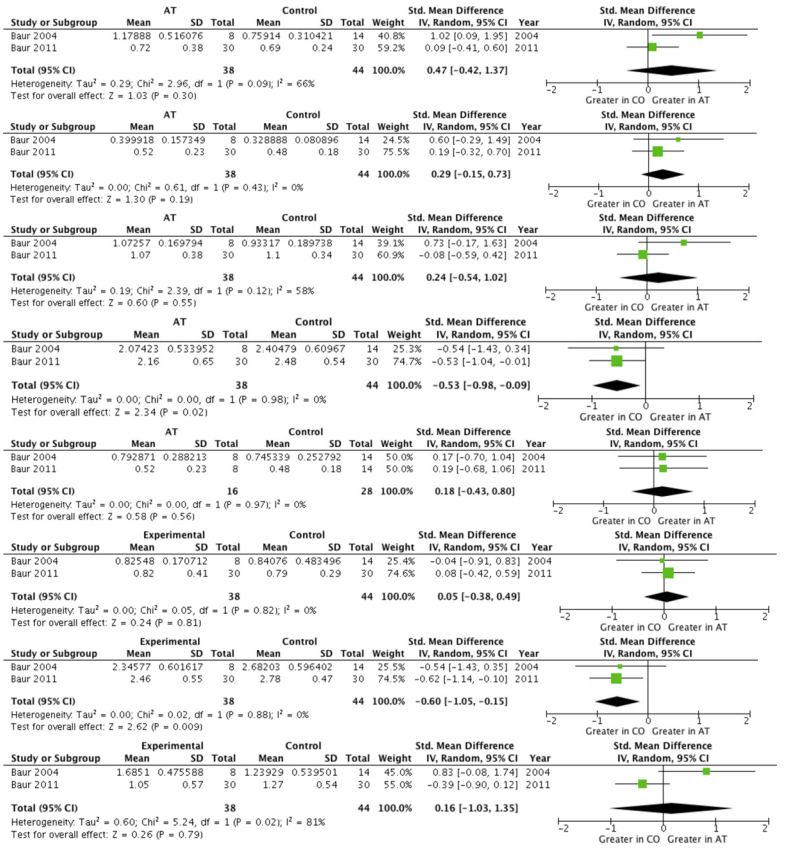
Abbreviations: Std standard, IV inverse variance, CI confidence interval, ROM range of motion, HQS high quality study, MQS moderate quality study, LQS low quality study.

differences between groups for peroneus longus amplitude at pre-activation (small SMD: 0.24 [-0.54, 1.02]) [38,39] and at push-off (small SMD: 0.18 [-0.43, 0.80]) [38,39], but at weight acceptance phase, the amplitude was decreased in the AT group compared to the control group (small SMD: -0.53 [-0.98, -0.09]) [38,39]. Very limited evidence indicates peroneus longus activity 100 ms post heel strike was decreased in the affected limb of the AT group in comparison to controls for shod running (medium SMD: -0.65 [-1.28, -0.03]) [37].

3.1.2.5.3. Gastrocnemius. Four studies [37–39,45] investigated a total of 33 variables during running, with three included in the meta-analyses. Based on the meta-analysis, limited evidence indicates that during shod running, medial gastrocnemius amplitude at pre-activation (small SMD: 0.05 [-0.38, 0.49]) [38,39] and at push-off (small SMD: 0.16 [-1.03, 1.35]) [38,39] was not different between groups; but at weight acceptance the amplitude was decreased in the AT group (medium SMD: -0.60 [-1.05, -0.15]) [38,39]. Very limited evidence indicates lateral gastrocnemius amplitude was decreased at weight acceptance phase during barefoot (large SMD: -2.36 [-3.53, -1.20]) and shod running (large SMD: -1.44 [-2.43, -0.45]), but increased at push-off time during barefoot running (large SMD: 1.22 [0.26, 2.17]) when comparing the AT group to controls [38]. Additionally, very limited evidence indicates that total lateral gastrocnemius activity duration during barefoot running was increased in individuals with AT compared to controls (medium SMD: 1.17 [0.22, 2.12]) [38].

3.1.2.5.4. Soleus. Two studies [38,45] investigated a total of 14 variables, but none could be included in the meta-analysis. Very limited evidence indicates soleus amplitude pre-heel strike for shod running (large (SMD: -1.43 [-2.41, -0.44) and at weight acceptance phase for

Table 5
Meta-analysis of neuromuscular outcomes in running studies.

Outcome	Evidence	
Tibialis anterior A-wa (S)	Conflicting 1LQS [38] 1MQS [39]	
Tibialis anterior A-po (S)	Limited 1LQS [38] 1MQS [39]	
Peroneus longus A-pre (S)	Limited 1LQS [38] 1MQS [39]	
Peroneus longus A-wa (S)	Limited 1LQS [38] 1MQS [39]	
Peroneus longus A-po (S)	Limited 1LQS [38] 1MQS [39]	
Medial gastrocnemius A-pre (S)	Limited 1LQS [38] 1MQS [39]	
Medial gastrocnemius A-wa (S)	Limited 1LQS [38] 1MQS [39]	
Medial gastrocnemius A-po (S)	Limited 1LQS [38] 1MQS [39]	

Abbreviations: Std standard, IV inverse variance, CI confidence interval, S shod, B barefoot, LQS low quality study, MQS moderate quality study, T ini time of start of activation, T max time of maximum activation, T tot total time of activation, A-pre pre-activation (period from onset of electromyographic activity to initial touchdown), A-wa weight acceptance (period between initial contact and the following 20% of the stride period), A-po push-off (period from 20% of stride to toe off). Neuromuscular activity compared among means of right and left side for both groups.

barefoot running (large SMD: -1.44 [-2.43, -0.45]) were decreased; but at push-off for barefoot running (large SMD: 1.91 [0.84, 2.98]) was increased when compared to the control group [38]. Additionally, the AT group had increased duration of soleus activity (medium SMD: 0.92 [0.00, 1.84]) [38], and an earlier offset timing relative to lateral gastrocnemius (medium SMD: -0.88 [-1.59, -0.17]) [45] during shod running when compared to the control group.

3.1.2.5.5. Thigh muscles. One study [37] investigated four variables. Very limited evidence indicates that rectus femoris activity 100 ms post heel strike was reduced in the AT group compared to controls during shod running (large SMD: -1.37 [-2.05, -0.69]) [37].

3.1.2.5.6. Hip muscles. Two studies [37,40] investigated eight variables and none could be included in the meta-analysis. Limited evidence indicates the AT group has delayed onset of gluteus medius (1.95 [1.07, 2.83]) and gluteus maximus (1.26 [0.48, 2.05]), an earlier offset time of the gluteus maximus (-1.03 [-1.79, -0.27]), and shorter duration of activation of gluteus medius (-0.18 [-0.24, -0.12]) and gluteus maximus (-1.41 [-2.22, -0.61]) compared to controls during shod running [40]. Very limited evidence indicates that gluteus medius activity at 100 ms post heel strike was decreased in the AT group compared to the control group during shod running (medium SMD: -1.03 [-1.68, -0.38]) [37].

3.2. Studies in hopping

No biomechanical findings in the hopping studies could be included in the meta-analysis. In the text, only significant findings from single studies are summarised. All the biomechanical findings from hopping studies are detailed in **Additional File 3**.

3.2.1. Kinematics

Three studies [28,47,48] investigated a total of 29 variables and none could be included in the meta-analysis.

3.2.1.1. During submaximal hops in standing. Limited evidence indicates people with AT had reduced leg stiffness in the affected limb compared to the unaffected limb during 10 s of single legged submaximal hopping (own shoes) (small SMD: -0.39 [-0.79, -0.00]) [28].

3.2.1.2. During a saut de chat jump. Very limited evidence indicates peak internal rotation of the knee was increased during the push-off phase of the *saut de chat jump* in dancers with a history of AT, but without current symptoms, compared to controls (barefoot) (medium SMD: 1.18 [0.09, 2.27]) [48].

3.2.1.3. During submaximal hops on a horizontal sledge. Very limited evidence indicates ankle dorsiflexion peak (medium SMD: 0.84 [0.02,

1.65]) and lower limb stiffness (large SMD: 2.14 [1.13, 3.14]) were increased in the AT group compared to controls during submaximal single-legged barefoot hopping on a customised sledge designed to minimise knee movement [47].

3.2.2. Neuromuscular activity

Two studies [46,47] investigated a total of eight variables and none could be included in the meta-analysis.

3.2.2.1. During 20 submaximal single leg hops. Very limited evidence indicates onset time of medial gastrocnemius was earlier at the involved side of individuals with a history of unilateral Achilles discomfort compared to controls during 20 single leg hops at 2.2 Hz (large SMD: 3.36 [1.86, 4.87]), and this pre-activation of the AT group occurred earlier on the involved side compared to the uninvolved side (large SMD: 3.04 [1.59, 4.50]) [46].

4. Discussion

This review has synthesised evidence investigating the relationship between biomechanical variables and AT presence, and it is important to note that a majority of the investigated biomechanical factors were not different between AT and control groups. Among 249 biomechanical variables investigated, only 44 (17%) were reported to be different between groups and evidence supporting these relationships was in most cases limited or very limited. Further, only seven variables (3%) were identified in prospective studies and preceded the onset of AT, making it difficult to establish a causal relationship between impaired biomechanics and AT onset. It is unclear if the majority of factors found to be associated with AT in this review are related to development or if they occur as a result of the condition and/or contribute to persistence.

4.1. Biomechanics during running

4.1.1. Kinematics were rarely associated with AT

Only 10% percent of the investigated kinematic outcomes (three in the foot and ankle, one in the knee and one in the hip) were different between groups. In the sagittal plane, meta-analysis indicates limited evidence of no differences between runners with AT and controls for ankle peak dorsiflexion or ankle dorsiflexion ROM during the stance phase of running [26,43]. This finding is interesting considering both reduced and increased ankle dorsiflexion available range of motion have been reported to be associated with greater risk of developing AT among military recruits when measuring dorsiflexion clinically [13,49,50]. Further, healthy runners who had decreased ankle dorsiflexion range during the stance phase of running had a greater likelihood of developing AT pain, but the confidence intervals [-2.23, -0.06] indicate wide participant variability. Very limited evidence from cross-sectional studies indicates runners with symptomatic AT may run with reduced maximum ankle dorsiflexion velocity [43] which could be a protective mechanism in an attempt to restrict Achilles tendon loading [51].

Further, ankle rearfoot eversion at heel-off and the duration of pronation (time during which the foot is in a pronated position) during running were reported to be increased in the AT group compared to controls [25]. However, meta-analysis indicated limited evidence of no differences between groups for ankle peak eversion, maximum velocity in ankle eversion movement, timing to ankle peak eversion and ankle eversion ROM [25,26,42,43]. Together, these findings do not support Clement et al.'s "whiplash theory", where excessive pronation of the foot has been proposed to play a role in the aetiology of AT by creating 'wringing' or twisting forces in the Achilles tendon [52]. Further, our findings are consistent with the absence of an effect for AT seen in a high-quality clinical trial [53] testing efficacy of pronation control orthotics. However, all the reviewed studies are cross-sectional so biomechanical alterations may either be a result of, or precede, the onset of AT. Nonetheless, prospective studies are needed to refute or confirm the apparent lack of relationship between foot pronation and AT.

4.1.2. Ground reaction forces do not identify individuals with AT

Current research indicates that people with AT do not run with higher overall ground reaction forces indicating that symptoms may relate to the ability to attenuate load and /or other factors unrelated to biomechanics. Therefore, people with AT might develop compensatory strategies such as increased hip forces as observed by Creaby et al. (2016) [26] without resulting in a net change in GRF.

4.1.3. Plantar pressure alterations vary pre and post onset of AT

One prospective study found decreased anterior displacement of the centre of pressure and a more laterally directed force distribution at foot flat gait position (i.e. midstance) among novice runners who subsequently developed AT [3]. These biomechanical alterations would be likely to reduce the external moment acting on the ankle joint centre and thereby reduce peak Achilles tendon load [54], although other factors such as loading *rate* may be increased [55]. Interestingly, cross-sectional research findings conflict with these prospective findings. Specifically, very limited evidence indicates that people with symptomatic AT present a more medially deviated centre of pressure at the stance phase compared to controls during barefoot running [38]. The difference in running speed of the studies (comfortable self-selected pace for novice runners [3] vs 12 km/h for symptomatic runners [38]) could explain these findings, considering a slower pace would most likely lead to increased contact times. Alternatively, people with symptomatic AT could also run with greater contact time due to reduced lower limb spring efficiency. Greater contact time has been reported among people with AT during hopping [28]. Lastly, the difference in shoe condition (shod vs barefoot) of participants in these studies could also be associated with the outcomes. Further research is needed to understand the relationship of plantar pressure alterations with both the development and persistence of AT.

4.1.4. Joint moments could be altered proximally in the presence of AT

One study investigating runners with AT and controls reported greater external hip frontal and transverse plane moments (hip adduction impulse, peak hip external rotation moment and hip external rotation impulse) in runners with AT compared with control, but no differences between groups in ankle moments and kinematics [26]. A separate investigation indicates reduced internal tibial external rotation moment, but no difference in tibial transverse plane motion relative to the rearfoot [44]. As the calcaneus is relatively fixed to the ground during running, it has been suggested that excessive tibial transverse plane motion will introduce a "wringing" of the Achilles tendon [52]. Thus, the elevated frontal and transverse plane hip external moments may represent a consequence or compensation for reduced moments at the knee and lack of changes of the lower leg to control the transverse plane motion of the tibial rotation on the fixed calcaneus in presence of AT. Importantly, data from both of these studies [26,44] are cross-sectional in nature. In the presence of ongoing Achilles tendon pain, runners may shift frontal and transverse plane loads from the lower leg and ankle to the more proximal hip to reduce loads on the Achilles tendon. While hip strengthening does not appear to alter hip kinematics [56], it does appear to reduce hip frontal plane moments [57]. Therefore, hip strengthening may be considered in runners with AT. Nevertheless, caution is urged as these data are from cross-sectional observational studies and direct measures of ankle, knee and hip moments were not included in the same study. Importantly, further research is needed to determine if these mechanics were present before the development of AT or become apparent once symptoms develop.

4.1.5. Neuromuscular alterations throughout the running gait cycle

Neuromuscular activity findings around the ankle indicate reduced muscle activity around heel strike and mid-stance [37–39,45]. This

could reflect the inability to attenuate loads or inhibition related to the presence of pain in people with AT.

Tibialis anterior, lateral gastrocnemius and soleus amplitude at the push-off phase were not different between groups during shod running but were increased in the AT group when running barefoot [38]. Barefoot running is more demanding for the plantarflexors when compared with shod running [58], and deficits are more likely to be revealed in more demanding activities. Reduced feed forward muscle activity is potentially related to muscle inhibition, pain or even tissue pathology that influences Golgi tendon organ function [51,59]. In contrast, increased muscle activity occurred during the propulsive phase when the plantar flexor and Achilles tendon loads are highest [55]. This could be a compensation for reduced passive tendon recoil contribution [60,61] or reduced calf neuromuscular capacity [13] reported in AT or response to impaired function of the hip extensors reported in this review. For example, greater neural drive and activation of plantar flexors may be required to compensate for an Achilles tendon that returns less energy in the runner with AT. Future studies are required to explore this hypothesis as this finding may have implications for AT rehabilitation.

At the hip, limited evidence indicates reduced and delayed gluteal muscle activity around heel strike (pre-contact and at weight acceptance phases). Given the gluteal muscles are hip stabilizers and important hip extensors, altered gluteal activation may be related to the increased hip internal rotation range during mid-stance at peak vGRF also found in this review. Delayed and reduced gluteal muscle activation has previously been noted in runners with patellofemoral pain [62], a population in which altered proximal mechanics and hip weakness are often observed [63,64]. It is possible that the gluteal muscles are inhibited or underutilised in the presence of painful AT and this may contribute to hip muscle weakness reported in people with AT [65]. Change in hip moments and biomechanics may be secondary to changes in gluteal muscle activation patterns, although this needs to be investigated in prospective studies. Based on these limited data, it seems reasonable to further consider hip kinematics and gluteal muscle function in the assessment and rehabilitation of runners with AT.

4.2. Biomechanics during hopping

4.2.1. Upright hopping less efficient in the presence of AT

Limited evidence indicates that people with unilateral AT demonstrate reduced leg stiffness on the affected side during single-legged hopping. This possibly reflects poorer lower limb spring efficiency due to painful AT and associated reduced plantar flexor muscle capacity and/or fear/apprehension. Interestingly, one study reported increased lower limb stiffness among subjects with AT during sub-maximal hopping on a customised sledge designed to minimise knee movement and constrain knee flexion. It is possible that forcing subjects with AT to hop with an ankle strategy may increase apprehension and result in a stiffer strategy and increased leg stiffness.

5. Limitations

There are several limitations of the literature included in this review that affect the strength of the findings. A paucity of prospective data prevents the identification of causal risk factors for AT. Further, considering the evidence in this review was generally limited or very limited (with only 17 outcomes included in the meta-analysis) our findings should be interpreted with caution and need to be confirmed or refuted in future high quality, adequately powered studies. Additionally, very few studies described participants' experience with running and hopping, limiting the external validity of findings. A limitation to external validity based on demographic details provided could be that most participants in the included studies were long distance runners, and/or remained physically active, so the results may not be generalizable to other subgroups. There was notable heterogeneity between studies about methods, including footwear condition, participants' activity level and the inconsistent use of either a random or dominant limb from control participants. Further, the fact that three studies [25,38,41] did not specify the location of pain means it is difficult to apply these findings to the clinical context of managing subjects with insertional or midportion AT. There were also limitations related to our review methods. We were unable to confidently calculate the SMD for GRF from one study [42] because of uncharacteristically low SD when calculated from the SE (confirmed by the authors). However, no significant differences were reported between groups, so this study is unlikely to have changed the review findings. Further, several instances where unreported data could not be received from authors limited data pooling. The exclusion of non-English studies is not expected to be a limitation as we only found one paper, in Japanese, that did not meet inclusion criteria based on abstract screening.

6. Future directions

Given some factors were reported in previously symptomatic cohorts, the extent to which pain has influenced the biomechanical findings in this review is difficult to determine. Alterations of the muscular activity have been reported during the whole running gait cycle, but it is unclear whether cross-sectional findings are a cause or effect of the condition. Further research should investigate whether pain, or threat of pain [66,67], could cause protective strategies that might explain the biomechanical findings in this review, such as decreased and delayed muscle activation [51]. We could hypothesise longer testing periods inducing muscle fatigue may highlight other biomechanical issues with relevance for distance runners [68–70].

Few biomechanical alterations were found to be present during running and hopping among people with AT in this review. Further, biomechanical alterations associated with AT may persist even in the absence of symptoms. Future studies should investigate whether addressing changeable biomechanical factors (i.e. reduced muscular activity or increased hip moments) could benefit the recovery of AT. A potential barrier to clinical translation is that the biomechanical alterations identified in this review are difficult to assess in regular clinical practice i.e. plantar pressure distributions, joint moments and neuromuscular activity are not measurable without expensive devices and advanced clinical expertise.

This systematic review and meta-analysis indicate the existence of few biomechanical alterations in people with AT during running and hopping, in the context of a large body of research, therefore suggesting that either the right biomechanical questions have not been answered or that biomechanical factors play a relatively minor role in the development and treatment of AT. Alternatively, it is possible that the main biomechanical findings have been identified from a comprehensive search – and now require confirmatory, prospective study. It is likely that other factors such as structure, genetics, load management, co-morbidities, cardio-metabolic factors, low-grade traumatic injury, psychosocial factors, health literacy, inflammation and as yet unidentified causal factors play a relatively major role. To address this, cohort studies of high-risk groups are required, albeit these would be expensive and a major logistical challenge. An interim alternative may be to assess these factors in a large scale cohort study of people with AT to determine outcome prediction models containing multiple variables.

7. Conclusion

This systematic review and meta-analysis indicate that potential biomechanical treatment targets in people with AT may include hip joint moments, plantar pressures, lower limb muscle activation and timing during running and vertical stiffness during hopping. Although the strength and quality of the evidence are somewhat limited, further research to determine the efficacy of treatments targeting these biomechanical factors is warranted.

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Authors' contributions

IS, DM, and PM conceptualised the study. IS, CB, RW, DM, and PM developed the study design and protocol. All the authors contributed and agreed on the final manuscript.

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Declaration of Competing Interest

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2019.07.121.

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