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SYSTEMATIC REVIEW

# What are the Benefits and Risks Associated with Changing Foot Strike Pattern During Running? A Systematic Review and Meta-analysis of Injury, Running Economy, and Biomechanics

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## Abstract

**Background** Running participation continues to increase. The ideal strike pattern during running is a controversial topic. Many coaches and therapists promote non-rearfoot strike (NRFS) running with a belief that it can treat and prevent injury, and improve running economy.

**Objective** The aims of this review were to synthesise the evidence comparing NRFS with rearfoot strike (RFS) running patterns in relation to injury and running economy (primary aim), and biomechanics (secondary aim).

**Design** Systematic review and meta-analysis. Consideration was given to within participant, between participant, retrospective, and prospective study designs.

**Data Sources** MEDLINE, EMBASE, CINAHL, and SPORTDiscus.

**Results** Fifty-three studies were included. Limited evidence indicated that NRFS running is retrospectively associated with lower reported rates of mild (standard mean difference (SMD), 95% CI 3.25, 2.37–4.12), moderate (3.65, 2.71–4.59) and severe (0.93, 0.32–1.55) repetitive stress injury. Studies prospectively comparing injury risk between strike patterns are lacking. Limited evidence indicated that running economy did not differ between habitual RFS and habitual NRFS runners at slow (10.8–11.0 km/h), moderate (12.6–13.5 km/h), and fast (14.0–15.0 km/h) speeds, and was reduced in the immediate term when an NRFS-running pattern was imposed on habitual RFS runners at slow (10.8 km/h; SMD = − 1.67, − 2.82 to − 0.52) and moderate (12.6 km/h; − 1.26, − 2.42 to − 0.10) speeds. Key biomechanical findings, consistently including both comparison between habitual strike patterns and following immediate transition from RFS to NRFS running, indicated that NRFS running was associated with lower average and peak vertical loading rate (limited-moderate evidence; SMDs = 0.72–2.15); lower knee flexion range of motion (moderate-strong evidence; SMDs = 0.76–0.88); reduced patellofemoral joint stress (limited evidence; SMDs = 0.63–0.68); and greater peak internal ankle plantar flexor moment (limited evidence; SMDs = 0.73–1.33).

**Conclusion** The relationship between strike pattern and injury risk could not be determined, as current evidence is limited to retrospective findings. Considering the lack of evidence to support any improvements in running economy, combined with the associated shift in loading profile (i.e., greater ankle and plantarflexor loading) found in this review, changing strike pattern cannot be recommended for an uninjured RFS runner.

**PROSPERO Registration** CRD42015024523.


## 1 Introduction

With an increase in running participation, the prevalence of running-related injuries is on the rise. Up to 79% of runners report lower extremity injuries each year [1], with a large variation in reported incidence and prevalence likely to be due to varying definitions for injury and populations studied. The most frequent running-related injuries reported are medial tibial stress syndrome, Achilles tendinopathy, plantar fasciopathy and patellofemoral pain [2]. Reported findings related to potential biomechanical risk factors for running-related injury development are inconsistent [3], but a number of individual biomechanical variations regarding kinetics (forces), kinematics (movements), and muscle function have been reported and proposed [3, 4]. Given the potential association between altered biomechanics during running and

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**Key Findings**

Despite frequent suggestions in the literature that non-rearfoot strike running is associated with reduced injury risk, the relationship between strike pattern and injury risk could not be determined from current evidence.

There is currently no evidence to support transitioning from rearfoot strike to non-rearfoot strike to reduce injury risk or improve running economy.

Transition from a rearfoot strike to a non-rearfoot strike will reduce running economy and increase loads at the ankle plantarflexor moments.

Transition from a rearfoot strike to a non-rearfoot strike will reduce knee flexion peak and range of motion, patellofemoral joint stress, and vertical loading rates.

injury risk, it is plausible that changing running technique may be either beneficial or detrimental in the prevention and management of running-related injuries.

Identifying running biomechanical variables that could be changed to help prevent or manage injury presents a great challenge [4]. It is well documented that the majority of shod runners habitually run with a rearfoot strike (RFS) pattern when running longer distances [5–7]. Changing the running strike pattern of distance runners from RFS to non-rearfoot strike (NRFS) is a commonly used intervention by clinicians, coaches and runners in an attempt to prevent and manage injuries [4, 8]. Transitioning to an NRFS has been reported to reduce pain in runners with patellofemoral pain [9] and anterior exertional lower leg pain [10, 11]. However, a key consideration is that changing one variable of running technique, such as foot strike, will result in significant changes to a number of biomechanical variables, which may also increase risk of injury to other tissues [4].

Running coaches commonly encourage the adoption of an NRFS running pattern in an attempt to improve running economy. This is often based on the proposed theory that NRFS running allows greater storage and return of elastic energy from the plantar fascia and tendons of the foot and ankle [12]; and research indicating that a greater proportion of elite runners, compared to non-elite runners, tend to run with an NRFS [6, 12, 13]. However, there appears to be no consensus in the literature regarding the influence of strike pattern on running economy. In addition, altering strike pattern in an attempt to improve running economy is also likely to alter tissue loading, and may have implications on injury risk [4], which could impair participation and ability to train.

To our knowledge, no review has been conducted to date that has synthesised findings related to the effects of different foot strike patterns on injury, alongside running economy. The primary aim of this systematic review and meta-analysis was to synthesise the evidence relating to the differences between RFS and NRFS in relation to (1) injury and (2) running economy. Considering the potential influence of biomechanics on tissue stress, injury and economy, a secondary aim of this review was to synthesise the evidence relating to the differences between RFS and NRFS in relation to kinetics, kinematics, muscle function, and other gait parameters.

## 2 Methods

The protocol was prospectively registered on the PROSPERO International Prospective Register for Systematic Reviews website (Registration #: CRD42015024523) in August 2015. Design and reporting of this review have followed the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) statement.

### 2.1 Literature Search Strategy

Using guidelines provided by the Cochrane Collaboration, a comprehensive search strategy was devised and applied to the following electronic databases in the 4th week of April 2019 with no date restrictions: (1) MEDLINE via OVID; (2) EMBASE via OVID; (3) CINAHL via EBSCO; and (4) SPORTDiscus. The search strategy was developed to optimise identification of relevant papers, with all terms searched as free text and keywords (where applicable). Concept 1, Foot strike pattern (foot strik* OR strik* pattern OR forefoot strik* OR midfoot strik* OR rearfoot strik* OR heel strik* OR first contact OR initial contact OR ground contact) AND Concept 2, Running (run* OR jog* OR treadmill OR overground OR marathon). The primary search strategy included a search for original publications comparing the influence of strike pattern on injury, running economy, biomechanics, and temporospatial parameters. All potential references were imported into Endnote X7 (Thomson Reuters, Carlsbad, California, USA) and duplicates were removed. Two reviewers (LMA & DRB) reviewed all titles returned by the database searches and retrieved suitable abstracts. Where abstracts suggested that papers were potentially suitable, the full-text versions were screened and included in the review if they fulfilled the selection criteria. A third reviewer was consulted in case of disagreements (CJB). Additional searching included reference list screening and citation tracking (Google Scholar) of all included studies.

## 2.2 Selection Criteria

Studies comparing RFS and NRFS pattern whilst running were considered for inclusion.

### 2.2.1 Inclusion Criteria

1. Studies comparing RFS and NRFS pattern whilst running, regardless of surface, whether on treadmill (excepting curved treadmills) or overground.
2. Studies comparing habitual and imposed foot strike patterns.
3. Studies of participants running barefoot, in their own shoes, or in standardised shoes, as long as comparisons between different strike patterns are made in the same footwear condition.

### 2.2.2 Exclusion Criteria

4. Case reports.
5. Non-English studies.
6. Studies with less than ten participants in the cohort or each group. We excluded studies with less than ten participants in a cohort or group to minimise the risk of potentially false-positive or false-negative findings influencing the evidence synthesis.
7. Studies that include other running retraining strategies (e.g., increased step rate) in addition to changing strike pattern.
8. Running on uneven surfaces (e.g., downhill running).

## 2.3 Reported Methodological Quality Assessment

Two independent reviewers (LMA and DRB) rated the quality of included studies using the Downs and Black Quality Index [14]. Any inter-rater discrepancies were resolved by consensus, with a third reviewer (CJB) available if needed. All items were scored as ‘Yes’ (score = 1), ‘No’ (score = 0) or ‘Unclear’ (score = 0), except item 5, which was scored as ‘Yes’ (score = 2), ‘Partial’ (score = 1), ‘No’ (score = 0) or ‘Unclear’ (score = 0). Based on assessment scores, studies were categorised as high quality (≥ 20 out of maximum possible score 28), moderate quality (17–19) or low quality (≤ 16). Cut points for quality were determined following discussion between three people in the research team who were experienced in the completion of similar systematic reviews (DB, HH, CB) [4].

## 2.4 Data Management

Data (means and standard deviations) pertaining to participant and study characteristics were extracted and entered into an Excel spreadsheet. If sufficient data (mean and standard deviation) were not reported in the published article or supplementary material provided, corresponding authors were contacted via email to request further data.

### 2.4.1 Variable Classifications

Within this review, RFS was classified as making initial contact with the heel, and a NRFS includes both midfoot and forefoot strike patterns. In cases where both midfoot and forefoot strike pattern data were reported, only forefoot strike data was extracted for synthesis. Toe running was not included in NRFS pattern classification, since this is a rare running pattern, and studies including this condition also contained forefoot strike pattern running which was used for NRFS data. Methods for strike pattern determination could be any (e.g., video, three-dimensional kinematics, plantar pressure), and were documented in Table 1 of results.

‘Running economy’ is defined by the steady-state oxygen consumption whilst running at a constant submaximal speed, reflecting the energy demand of running at a given velocity [15]. Running economy is a complex measure representing the multifactor interplay of metabolic, cardiopulmonary, biomechanical, and neuromuscular function [15]. Runners with a superior running economy use less oxygen when at the same steady-state speed as runners with inferior running economy [15]. Given this, superior economy has been shown to be predictive of endurance running performance, even in athletes with a similar $VO_2$max (which is a measure of aerobic capacity) [16, 17].

### 2.4.2 Statistical Analysis

Means and standard deviations were used to calculate the standardised mean difference (SMD) with 95% confidence intervals (CI) for variables of interest. Data were pooled where possible. Data were pooled separately for comparisons between (1) habitual RFS and habitual NRFS; and (2) habitual RFS and imposed NRFS. Data for all speeds and footwear (including barefoot) conditions were extracted and considered in our synthesis of findings. If multiple speeds were evaluated in the same study, only the speed reflecting normal running speed, or a speed similar to that used in other studies, was included in data pooling. If multiple footwear conditions were evaluated in the same study, the condition reflecting traditional running shoes or the participants own running shoes, or a footwear most similar to other studies, was included for data pooling. In these cases, findings for other speeds and other footwear conditions were still reported and SMDs calculated where possible. Meta-analysis was performed using the Cochrane Collaboration Review Manager 5.3 software. A random-effects meta-analysis was used due to differences between studies in relation to outcome measures, strike pattern differentiation,

**Table 1** Characteristics of the included studies

| Study | Study design | Sample | Comparison | Strike pattern assessment method | Outcome measures |
|---|---|---|---|---|---|
| Bowersock (2017) [36] | Participants ran on an instrumented treadmill at a self-selected speed in standardised footwear | 19 runners (ran minimum 16 km/week)<br>9 males (age, 23 ± 3 years; mass, 80 ± 8 kg)<br>10 females (age, 23 ± 3 years; mass, 58 ± 7 kg) | Habitual RFS vs imposed NRFS | Foot strike validated visually during data collection and cross-validated post-processing using foot strike index<br>*No further details provided | GRF<br>Tibiofemoral joint contact force: peak force, loading rate, impulse/step, impulse/km<br>Medial tibiofemoral joint compartment contact force: peak force, loading rate, impulse/step, impulse/km<br>Muscle force: hamstring, quadriceps, gastrocnemius |
| Boyer (2014) [58] | Participants ran overground at a self-selected speed in standardised footwear | 30 competitive runners<br>15 habitual NRFS (age, 20 ± 2 years; mass, 64 ± 9 kg; females, 3)<br>15 habitual RFS (age, 21 ± 2 years; mass, 66 ± 8 kg; females) | RFS (habitual and imposed) vs NRFS (habitual and imposed) | Force platform<br>SI was calculated as the average center-of-pressure location during the first 2.5 ms of stance and reported as a percentage of foot length from the posterior calcaneus. Participants were categorised as habitual RFS (SI < 33.3%) or habitual FFS (SI > 33.3%) | GRF (medial–lateral and anterior–posterior)<br>Loading rate |
| Boyer (2015) [59] | Participants ran overground at 3.4 m/s in their own footwear | 42 runners<br>21 habitual RFS (age, 21 ± 6 years; mass, 72 ± 10 kg; females, 1)<br>21 habitual FFS/MFS (age, 22 ± 4 years; mass, 67 ± 11 kg; females, 7) | RFS (habitual and imposed) vs NRFS (habitual and imposed) | Force platform<br>Kinetic data were collected at 1600 Hz by an in-ground force platform (AMTI) and filtered at 50 Hz<br>SI was calculated as the average center-of-pressure location during the first 10 ms of stance and reported as a percentage of foot length from the posterior calcaneus. Participants were categorised as habitual RFS (SI < 33.3%) or habitual FFS (SI > 33.3%) | Gait: stride length, step width<br>Iliotibial band strain, iliotibial band strain rate<br>Joint kinematics: hip, knee, ankle, pelvis |

**Table 1** (continued)

| Study | Study design | Sample | Comparison | Strike pattern assessment method | Outcome measures |
|---|---|---|---|---|---|
| Boyer (2018) [60] | Participants ran overground (30 m runway) at 3.4 m/s in their own footwear | 38 recreational or competitive runners (ran minimum 16 km/week)<br>19 habitual RFS (age, 21 ± 6 years; mass, 72 ± 11 kg)<br>19 habitual FFS (age, 22 ± 3 years; mass, 66 ± 10 kg) | RFS (habitual and imposed) vs NRFS (habitual and imposed) | Force platform<br>SI was calculated after each trial as the average initial center-of-pressure location, as a percentage of foot length. Participants were categorised as habitual RFS (SI < 33.3%) or habitual FFS (SI > 33.3%)<br>Kinematic data were collected at 200 Hz with an 8-camera<br>Vicon system (Vicon MX, Vicon, Centennial, CO, USA). Kinetic data were collected at 1600 Hz by an in-ground force platform (AMTI, Watertown, MA, USA) | Joint kinetics: hip, knee, patellofemoral, ankle |
| Breine (2017) [21] | Participants ran overground (25 m runway) at 3.2 m/s in standardised footwear | 52 recreational or competitive runners (ran minimum 15 km/week)<br>39 males (age, 29 ± 8 years; mass, 72 ± 6 kg)<br>13 females (age, 28 ± 8 years; mass, 58 ± 5 kg) | Habitual RFS vs habitual NRFS | Force platform<br>Definition of strike based on a combination of strike index, time of 1st metatarsal contact, qualitative assessment of center-of-pressure pattern<br>GRFs (1000 Hz) and plantar pressures (500 Hz) were measured with a 2-m force plate (AMTI, Watertown, MA, USA) with a 2-m pressure plate mounted on top (Footscan, RSscan International, Paal, Belgium) | Gait: contact time, flight time, step frequency, step length<br>Kinematics: thigh, knee, shank, ankle, foot<br>Kinetics: knee, ankle<br>GRF |
| Breine (2017) [22] | Participants ran overground (25 m runway) at 3.2 m/s in standardised footwear | 49 runners (ran minimum 15 km/week)<br>37 males (age, 29 ± 8 years; mass, 72 ± 6 kg)<br>12 females (age, 28 ± 8 years; mass, 59 ± 5 kg) | Habitual RFS vs habitual NRFS | Shoe surface pressure<br>(500 Hz, Footscan®, RSscan International, Olen, Belgium)<br>Definition of strike based on a combination of SI, time of first metatarsal contact, and qualitative assessment of center-of-pressure pattern | GRF<br>Loading rates: vertical instantaneous |

**Table 1** (continued)

| Study | Study design | Sample | Comparison | Strike pattern assessment method | Outcome measures |
|---|---|---|---|---|---|
| Bruening (2018) [61] | Participants ran overground (20 m runway) at 3.7 m/s in standardised footwear | 18 female recreational runners (ran minimum 16 km/week)<br>Age, 25 ± 4 years; mass, 61 ± 7 kg) | RFS (habitual and imposed) vs NRFS (habitual and imposed) | A visual check of the positioning of the GRF vector at initial contact relative to the tracking foot markers<br>A SI was also calculated post hoc for comparison purposes<br>Force platform (Bertec Corp., Columbus OH, USA) | Joint kinematics: ankle, midtarsal, metatarsophalangeal<br>Joint kinetics: knee, ankle, midtarsal, metatarsophalangeal |
| Chen (2016) [37] | Participants ran on an instrumented treadmill at 2.5 m/s in standardised footwear | 14 experienced runners (females, 7), all habitual RFS<br>Age, 35 ± 6 years; mass, 64 ± 11 kg | Habitual RFS vs imposed NRFS | Not clearly stated | Loading rates: vertical average, vertical instantaneous<br>Joint kinetics: ankle<br>Peak tibial strain |
| Daoud (2012) [33] | Not applicable, as retrospective study collecting injury data over years 2006–2011 | 52 middle-long distance runners from the same collegiate cross-country team<br>36 habitual RFS (age, 20 ± 1 years; BMI, 20 ± 1 kg/m$^2$; females, 18)<br>16 habitual FFS (age, 20 ± 2 years; BMI, 21 ± 2 kg/m$^2$; females, 5) | Habitual RFS vs habitual NRFS | 500 Hz video camera | Strike pattern<br>Injury rate |
| Delgado (2013) [62] | Participants ran barefoot on an instrumented treadmill at a self-selected speed | 43 runners (females, 19)<br>Age, 24 ± 2 years; mass, 57 ± 19 kg | RFS (habitual and imposed) vs NRFS (habitual and imposed) | Visual<br>Foot strike patterns were classified visually on the basis of foot segment inclination relative to the support surface | Shock attenuation<br>Leg acceleration<br>Lumbar spine motion |
| Dos Santos (2016) [52] | Participants ran on a treadmill at a self-selected speed in standardised footwear standardised footwear | 31 recreational runners (females, 11), all habitual RFS<br>Age, 28 ± 5 years; mass, 72 ± 14 kg | Habitual RFS vs imposed NRFS<br>Habitual RFS + 10% increase in step rate<br>Habitual RFS + forward trunk lean | Real-time visual analysis of plantar pressure distribution using insole sensors (Novel, Munich, Germany) | Joint kinematics: ankle, knee, hip, trunk |
| Dos Santos (2019) [51] | Participants ran on an instrumented treadmill at a self-selected (footwear details not specified) | 19 recreational runners (females, 11)<br>Age, 28 ± 5 years; mass, NR kg | Habitual RFS vs imposed NRFS | High-speed camera | Joint kinematics: knee<br>Joint kinetics: patellofemoral, knee, ankle, hip<br>GRF |

**Table 1** (continued)

| Study | Study design | Sample | Comparison | Strike pattern assessment method | Outcome measures |
|---|---|---|---|---|---|
| Futrell (2018) [23] | Participants ran on an instrumented treadmill at a self-selected speed<br>Injured participants ran in their own footwear<br>Healthy participants were provided with footwear similar to their usual running footwear | 32 recreational runners<br>19 habitual RFS (age, 31 ± 9 years; mass, 72 ± 10 kg; females, 6)<br>13 habitual FFS (age, 33 ± 9 years; mass, 74 ± 12 kg; female, 1) | Habitual RFS vs habitual NRFS | High-speed video | GRF<br>Loading rates: vertical average, vertical instantaneous<br>Gait: cadence |
| Gruber (2013) [63] | Participants ran on a treadmill at 3.0, 3.5 and 4.0 m/s in standardised footwear | 37 experienced runners<br>19 habitual RFS (age, 26.7 ± 6.1 years; mass, 70.1 ± 10 kg; females, 7)<br>18 habitual FFS (age, 25.6 ± 6.4 years; mass, 68.7 ± 9.8 kg; females, 4) | RFS (habitual and imposed) vs NRFS (habitual and imposed) | Force platform and motion analysis<br>Habitual foot strike pattern of each participant was determined using a combination of the SI, the characteristics of the vertical ground reaction force, and the sagittal plane ankle angle at touchdown | Oxygen consumption<br>Carbohydrate contribution to total energy expenditure<br>Joint kinematics: ankle<br>Gait: stride length, stride frequency, contact time |
| Gruber (2014) [24] | Participants ran on treadmill at 3.5 m/s in standardised footwear | 38 experienced runners (minimum 16 km/week, speed 3.5 m/s)<br>19 habitual RFS (age, 27 ± 6 years; mass, 70 ± 10 kg; females, 7)<br>19 habitual FFS (age, 25 ± 6 years; mass, 69 ± 10 kg; females, 5) | Habitual RFS vs habitual NRFS | Force platform and motion analysis<br>The participants' habitual footfall pattern was determined by assessing the SI, vertical GRF profile, and sagittal plane angle ankle at touchdown, whilst the participants ran at their preferred speed over a force platform (OR 6–5; AMTI, Watertown, MA, USA) | Joint kinematics: ankle<br>Tibial acceleration<br>Head acceleration<br>Frequency content of impact shock at the tibial and head<br>Signal magnitude of impact shock at the tibial and head<br>Shock attenuation |
| Gruber (2017) [25] | Participants ran overground at a self-selected speed in standardised footwear (racing flats) | 40 competitive and/or recreational runners<br>20 habitual RFS (age, 26 ± 6 years; mass, 70 ± 10 kg; females, 7)<br>20 habitual NRFS (age, 26 ± 6 years; mass, 70 ± 11 kg; females, 5) | Habitual RFS vs habitual NRFS | Force platform and motion capture system<br>Footfall pattern was classified using the SI and sagittal plane foot segment angle at initial ground contact | GRF<br>Gait: stance time; horizontal distance from heel to whole body center-of-mass at initial contact |

**Table 1** (continued)

| Study | Study design | Sample | Comparison | Strike pattern assessment method | Outcome measures |
|---|---|---|---|---|---|
| Hamill (2014) [64] | Participants ran overground at 3.5 m/s in standardised footwear | 40 experienced runners (ran minimum 16 km/week, minimum speed 3.5 m/s)<br>20 habitual RFS (females, 7)<br>20 habitual FFS (females, 6)<br>Age, 26 ± 6 years; mass, 70 ± 10 kg | RFS (habitual and imposed) vs NRFS (habitual and imposed) | Not stated | Joint kinetics: ankle and knee |
| Hashizume (2017) [57] | Participants ran barefoot overground (15 m runway) at 3.3 m/s | 10 male recreational runners<br>Age, 21 ± 2 years; mass, 63 ± 5 kg | RFS vs NRFS (unclear if habitual or imposed) | Force platform and motion analysis<br>The ratio of the foot length and the heel-to-GRF application point length at the instance of foot contact defined foot strike patterns | GRF<br>Achilles tendon force<br>Joint reaction force<br>Moment of the GRF<br>Moment of the Achilles tendon force<br>Moment of the foot weight<br>GRF moment arm<br>Achilles tendon moment arm<br>Foot weight moment arm |
| Hayes (2012) [26] | Participants were filmed 15 m from the finish line during 800 m and 1500 m races (footwear details not specified) | 181 runners (females, 58) from 22 middle distance races at competitive athletics meetings (800 m and 1500 m races) | Habitual RFS vs habitual NRFS | High-speed video | Foot strike<br>Gait: contact time |
| Hazzaa (2018) [34] | Participants ran barefoot on a treadmill at 11, 13 and 15 km/h | 52 male runners (minimum 3 runs/week)<br>26 habitual FFS (age, 27 ± 4 years; mass, 80 ± 9 kg)<br>26 habitual RFS (age, 27 ± 4 years; mass, 79 ± 9 kg) | Habitual RFS vs habitual NRFS | Not clearly stated<br>"During the acclimatization, the foot strike pattern was re-<br>corded and estimated using the measuring software" | Gait: step rate, step length<br>Heel pressure<br>Plantar pressure |
| Huang (2019) [65] | Participants ran on an instrumented treadmill at a self-selected speed in standardised footwear | 19 male runners (minimum 10 km/week for at least 6 months)<br>Age, 22 ± 3 years; mass, 68 ± 6 kg | RFS (habitual and imposed) vs NRFS (habitual and imposed) | SI was computed in real time via a customised Matlab program (The Mathworks Inc, Natick, MA, USA) and was calculated as a measurement of the initial center of pressure position relative to the foot length | Loading rates: vertical average, vertical instantaneous, vertical impact<br>Peak tibial acceleration |

**Table 1** (continued)

| Study | Study design | Sample | Comparison | Strike pattern assessment method | Outcome measures |
|---|---|---|---|---|---|
| Kelly (2018) [38] | Participants ran barefoot on an instrumented treadmill at 2.8 m/s | 30 (females, 5) recreational habitual RFS runners<br>Age, 24 ± 6 years; mass, 72 ± 12 kg | Habitual RFS vs imposed NRFS | Visual analysis | Gait: contact time, stride duration<br>GRF<br>Joint kinematics: ankle, rearfoot, midfoot<br>Joint kinetics: ankle, rearfoot, midfoot<br>Muscle activation: abductor hallucis, flexor digitorum brevis, medial gastrocnemius, soleus |
| Kernozek (2016) [39] | Participants ran overground (20 m runway) at a self-selected speed in standardised footwear | 23 female habitual RFS runners (age, 22 ± 2 years; mass, 64 ± 7 kg) | Habitual RFS vs imposed NRFS | In-sole pressure sensor | Gait: contact time<br>Peak force<br>Force time integral<br>Peak pressure<br>Pressure time integral |
| Kernozek (2018) [28] | Participants ran overground (20 m runway) at 3.3 m/s in standardised footwear | 35 female runners (minimum 10 miles per week over the past 6 months)<br>17 habitual RFS (age, 22 ± 2 years; mass, 59 ± 7 kg)<br>18 habitual NRFS (age, 22 ± 1 years; mass, 61 ± 7 kg) | Habitual RFS vs habitual NRFS | Force platform<br>The runners' foot strike pattern was established based on the location of the center-of-pressure relative to their foot at the point of initial contact with the force plate during the running trials | Achilles tendon stress |
| Knorz (2017) [66] | Participants ran on an instrumented treadmill at 3.0 m/s in their own footwear | 22 male runners (minimum 1 h or 10 miles per week)<br>11 habitual RFS (age, 31 ± 7 years; mass, 85 ± 11 kg)<br>11 habitual FFS (age, 29 ± 8 years; mass, 79 ± 9 kg) | RFS (habitual and imposed) vs NRFS (habitual and imposed) | Motion camera analysis and force Plates in an instrumented treadmill | Joint kinetics: ankle, knee, hip |

**Table 1** (continued)

| Study | Study design | Sample | Comparison | Strike pattern assessment method | Outcome measures |
|---|---|---|---|---|---|
| Kubo (2015) [27] | Participants ran on a treadmill at 14, 16 and 18 km/h. Participants were shod, but footwear details were not specified | 41 highly trained long-distance runners<br>17 habitual RFS (age, 20 ± 1 years; mass, 57 ± 5 kg; females, 0)<br>12 habitual MFS (age, 21 ± 1 years; mass, 57 ± 4 kg; females, 0)<br>12 habitual FFS (age, 21 ± 1 years; mass, 59 ± 4 kg; females, 0) | Habitual RFS vs habitual NRFS | High-speed video camera | Maximal Achilles tendon elongation<br>Maximal Achilles tendon strain<br>Stiffness of tendon structures<br>Cross-sectional area of tendon |
| Kuhman (2016) [40] | Participants ran overground (20 m runway) at two speeds (3.4 and 4.5 m/s) in their own footwear | 16 competitive male habitual RFS runners (mass, 72 ± 11 kg) | Habitual RFS vs imposed NRFS | Visually (initially)<br>Force platform and motion analysis system (post-hoc)<br>Foot strike pattern was initially confirmed visually during over-ground running trials at the start of the testing session and was confirmed post-hoc using<br>the SI defined as the ratio of the center-of-pressure location at foot strike relative to the length of the foot | GRF<br>Loading rates<br>Joint kinetics: ankle, knee<br>Joint kinematics: ankle, knee |
| Kulmala (2013) [29] | Participants ran overground (15 m runway) at 4.0 m/s. Participants were shod, but footwear details were not specified | 38 female athletes<br>19 habitual RFS (age, 18 ± 4 years; mass, 63 ± 9 kg; females, 19)<br>19 habitual FFS (age, 19 ± 5 years; mass, 63 ± 9 kg; females, 19) | Habitual RFS vs habitual NRFS | Not stated<br>Force platform and motion analysis system | Joint kinematics: hip, knee, ankle<br>Joint kinetics: hip, knee, ankle<br>GRF<br>Gait: cadence, contact time, step length, step width, center-of-mass to heel distance at initial contact |
| Landreneau (2014) [67] | Participants ran on a treadmill at 8.9 km/h in their own footwear | 14 individuals (female, 8)<br>Age, 24 ± 1 years; mass, 70 ± 11 kg | RFS (habitual and imposed) vs NRFS (habitual and imposed) | Foot strike on the treadmill was defined as the forward most position of the right MTP marker and was used to define the beginning and end of each stride | Joint kinematics: hip, knee, ankle<br>Muscle activation: tibialis anterior, medial gastrocnemius, lateral gastrocnemius, soleus, vastus medialis, rectus femoris, semi-tendinosis, bicep femoris |

**Table 1** (continued)

| Study | Study design | Sample | Comparison | Strike pattern assessment method | Outcome measures |
|---|---|---|---|---|---|
| Laughton (2003) [41] | Participants ran overground at 3.7 m/s in standardised footwear | 15 habitual RFS runners (age, 22 ± 4 years; mass, 66 ± 9 kg; females, NR) | Habitual RFS vs imposed NRFS | Force platform and motion analysis system | GRF: vertical, anterior–posterior<br>Loading rates: vertical average, vertical instantaneous, anterior–posterior<br>Kinematics: rearfoot, ankle, knee<br>Kinetics: leg, ankle, knee<br>Tibial acceleration |
| Lyght (2016) [68] | Participants ran overground (20 m runway) at 3.5 m/s in standardised footwear | 19 females<br>Age, 22 ± 1 years; mass, 60 ± 9 kg | RFS (habitual and imposed) vs NRFS (habitual and imposed) | In-shoe pressure system (Novel GMBH, Munich, Germany) | Achilles tendon peak stress<br>Achilles tendon strain<br>Achilles tendon strain rate<br>Achilles tendon peak force<br>Gait: center-of-mass to heel distance at initial contact<br>Joint kinematics: ankle, knee<br>Joint kinetics: ankle |
| Melcher (2017) [42] | Participants ran overground (25 m runway) at a self-selected speed in their own footwear | 13 habitual RFS runners (minimum 30 miles per week)<br>Age, 32 ± 9 years; mass, 74 ± 12 kg | Habitual RFS vs imposed NRFS | Not stated | Joint kinematics: ankle, knee<br>Joint kinetics: ankle, knee<br>Running economy<br>Gait: cadence |
| Mercer (2015) [56] | Participants ran overground at a self-selected speed in standardised footwear | 10 physically active males (habitual foot strike not reported)<br>Age, 25 ± 6 years; mass, 70 ± 12 kg | RFS vs NRFS (unclear if habitual or imposed) | Visually | GRF<br>Gait: stance time<br>Impact force |
| Nishida (2017) [69] | Participants ran on an instrumented treadmill at 5, 7, 9, 12 and 15 km/h. Participants were shod, but footwear details were not specified | 10 male runners<br>Age, 21–25 ± NR years; mass, 62 ± 4 kg | RFS (habitual and imposed) vs NRFS (habitual and imposed) | Motion analysis system<br>Foot strike angle determined by kinematic data collected by three-dimensional optical motion capture system (OptiTrack V100, NaturalPoint Inc., OR, USA) | Muscle activation: ankle, knee, hip |

**Table 1** (continued)

| Study | Study design | Sample | Comparison | Strike pattern assessment method | Outcome measures |
|---|---|---|---|---|---|
| Nunns (2013) [70] | Participants ran barefoot overground at 3.6 m/s | 1026 male Royal Marine recruits<br>823 habitual RFS (age, 22 ± 3 years; mass, 76 ± 7 kg)<br>88 habitual MFS (age, 21 ± 3 years; mass, 75 ± 7 kg)<br>71 habitual FFS (age, 22 ± 4 years; mass, 76 ± 7 kg)<br>44 habitual toe running (age, 21 ± 3 years; mass, 78 ± 8 kg) | RFS (habitual and imposed) vs NRFS (habitual and imposed) | Plantar pressure profile | Foot strike<br>Gait: contact time<br>Kinematics: rearfoot, ankle, knee<br>Peak plantar pressure<br>Peak plantar impulse |
| Ogueta-Alday (2014) [30] | Incremental Test: Participants ran on treadmill at 1% slope at 6 km/h (increasing in speed by 1 km/h every 1 min) in standardised footwear km/h ↑ 1 km/h every 1 min<br>Sub Max Test: 6 min of running at 11, 13 and 15 km/h—5 min rest between | 20 male sub-elite long-distance runners (average 91 ± 24 km/week), all had a half marathon time between 1 h 05 min–1 h 15 min<br>10 habitual RFS (age, 26 ± 7 years; mass, 68 ± 5 kg)<br>10 habitual MFS/FFS (age, 29 ± 7 years; mass, 66 ± 6 kg) | Habitual RFS vs habitual NRFS | High-speed video camera | Oxygen consumption<br>Running economy<br>Gait: cadence, step length |
| Paquette (2017) [31] | Participants ran on a treadmill at 75% of their self-reported 10 km personal best time (i.e., running speed) in their own footwear | 21 runners (females, 7)<br>Age, 32 ± 8 years; mass, 70 ± 11 kg | Habitual RFS vs habitual NRFS | Kinematic data were collected for 10 s using an 8-camera three-dimensional motion<br>Capture system (240 Hz; Qualisys AB, Goteborg, Sweden) | Foot contact angle and foot contact angle variability |
| Perl (2012) [73] | Participants ran on a treadmill at 3.0 m/s in standardised footwear (both standard and minimal) | 15 runners (females, 2)<br>Age, NR years; mass, 73 ± 11 kg | Habitual NRFS vs imposed RFS | Not stated | Running economy<br>Arch strain<br>Joint kinematics: knee<br>Joint kinetics: ankle |
| Peters (2017) [55] | Participants ran barefoot overground (10 m runway) at 3.3 m/s | 12 active individuals (females, 7)<br>Age, 24 ± 4 years; BMI, 22 ± 2 $kg/m^2$ | RFS vs NRFS (unclear if habitual or imposed) | Force plate and plantar pressure platform | Gait: stride time, stance time, swing time<br>Joint kinematics: shank-calcaneus, calcaneus–midfoot, midfoot–metatarsus |

**Table 1** (continued)

| Study | Study design | Sample | Comparison | Strike pattern assessment method | Outcome measures |
|---|---|---|---|---|---|
| Pohl (2008) [54] | Participants ran barefoot overground at a self-selected speed | 12 active participants (females, 6), habitual foot strike NR<br>Age, 21 ± 2 years; mass, 68 ± 13 kg | RFS vs NRFS (unclear if habitual or imposed) | Vertical positioning of a calcaneal marker during ground contact was assessed retrospectively | Joint kinematics: rearfoot, shank, forefoot |
| Rice (2017) [43] | Participants ran overground (30 m runway) at 3.1 m/s in standardised footwear (both standard and minimal) | 22 habitual RFS runners (minimum 30 min of vigorous activity/day)<br>11 males (age, 23 ± 3 years; mass, 74 ± 13 kg)<br>11 females (age, 23 ± 4 years; mass, 61 ± 9 kg) | Habitual RFS vs imposed NRFS | High-speed video camera | GRF: vertical, anterior–posterior, medial–lateral<br>Loading rates: vertical instantaneous, anterior–posterior, medial–lateral |
| Rooney (2013) [72] | Participants ran overground at a self-selected speed in standardised footwear | 30 competitive runners<br>15 habitual RFS (age, 21 ± 2 years; mass, 66 ± 8 kg; females, NR)<br>15 habitual FFS (age, 22 ± 2 years; mass, 64 ± 9 kg; females, NR) | RFS (habitual and imposed) vs NRFS (habitual and imposed) | Force platform and motion analysis system<br>The initial point of contact was calculated as an average of the center of pressure values over the first five data points of stance. Reflective markers were used to express this location as a percentage of the foot length measured relative to the heel (heel strike index) | Joint kinetics: ankle, knee, hip<br>Muscle activation: ankle, knee, hip |
| Santos-Concejero (2014) [35] | Participants ran on a treadmill at different velocities in their own footwear (road race shoes < 300 g) | 30 experienced male runners (best 10 km time of 32.9 ± 2.7 min)<br>Age, 32 ± 8 years; mass, NR; peak $VO_2$ of 63.1 ± 5.0 ml·kg·min | Habitual RFS vs habitual NRFS | High-speed camera | Gait: stride length, stride frequency, stride angle<br>Running economy |
| Shih (2013) [44] | Participants ran on a treadmill at 9.0 km/h in standardised footwear and barefoot | 12 male habitual RFS runners<br>Age, 24 ± 1 years; mass, 69 ± 8 kg | Habitual RFS vs imposed NRFS (barefoot and shod) | High-speed camera | Loading rates<br>Gait: stance time, flight time, cadence<br>Joint kinematics: ankle, knee, hip<br>Lower extremity stiffness<br>Landing point to center-of-mass<br>Vertical displacement of center-of-mass<br>Lateral displacement of center-of-mass<br>Muscle activation: ankle, knee |

**Table 1** (continued)

| Study | Study design | Sample | Comparison | Strike pattern assessment method | Outcome measures |
|---|---|---|---|---|---|
| Stackhouse (2004) [45] | Participants ran overground at 3.7 m/s in standardised footwear | 15 habitual RFS runners<br>Age, 18 and 45 years; mass, NR; females, NR | Habitual RFS vs imposed NRFS | Force platform and motion analysis software | Joint kinematics: rearfoot, knee |
| Sun (2018) [45] | Participants ran overground (20 m runway) at 3.0 m/s in standardised footwear | 12 male recreational runners<br>Age, 21 ± 1 years; mass, 68 ± 7 kg) | Habitual RFS vs imposed NRFS | Not stated | GRF<br>Plantar pressure<br>Gait: contact time |
| Valenzuela (2015) [71] | Participants ran overground (no further details provided) | 21 runners (able to run 5 km in 30 min or less)<br>Age, 22.86 ± 2.20 years; mass, 71.7 ± 14.5 kg; height = 1.75 ± 0.08; females, 10 | RFS (habitual and imposed) vs NRFS (habitual and imposed) | Video camera | GRF<br>Joint kinematics: ankle, knee, hip<br>Joint kinetics: ankle, knee, hip |
| Vannatta (2015) [47] | Participants ran overground (20 m runway) at 3.5–3.9 m/s in standardised footwear | 16 female habitual RFS runners (weekly running distance 33.2 ± 14.7 km)<br>Age, 22 ± 3 years; mass, 64 ± 5 kg | Habitual RFS vs imposed NRFS | In-sole pressure sensors (Novel GmbH, Munich, Germany) | Joint kinematics: knee<br>Joint kinetics: knee, ankle, patellofemoral<br>GRF<br>Gait: step length |
| Vannatta (2017) [48] | Participants ran overground (20 m runway) at 3.5–3.9 m/s in standardised footwear | 25 female runners (minimum 10 miles per week)<br>age 27 ± 2 years; mass, 60 ± 13 kg | Habitual RFS vs imposed NRFS | In-sole pressure sensors (Novel GMBH, Munich, Germany, Minneapolis/St. Paul, USA) | Muscle forces: hip<br>Joint kinematics: hip; pelvis<br>Gait: contact time, center-of-mass to heel distance |
| Williams (2012) [49] | Participants ran overground (20 m runway) at 3.5 m/s in standardised footwear | 20 habitual RFS runners (minimum 6 miles/week)<br>10 males (age, 25 ± 2 years; mass, 80 ± 10 kg)<br>10 females (age, 24 ± 1 years; mass, 59 ± 6 kg) | Habitual RFS vs imposed NRFS | Not clearly stated<br>Force platform and motion analysis system | Joint kinematics: ankle, knee, hip<br>Joint kinetics: ankle, knee, hip |
| Willson (2015) [53] | Participants ran on a treadmill at a self-selected speed. Participants wore ‘conventional footwear’, but no further details were provided | 20 runners (minimum 16 km/h per week)<br>10 females (age, 23 ± NR years; mass, 58 ± NR kg<br>10 males (age, 23 ± NR years; mass, 81 ± NR kg | RFS vs NRFS (unclear if habitual or imposed) | Visually<br>Foot strike pattern was evaluated visually during data collection and cross-validated<br>during post-processing using the foot SI to ensure the appropriate foot strike pattern was utilised during each condition | Joint kinetics: patellofemoral |

**Table 1** (continued)

| Study | Study design | Sample | Comparison | Strike pattern assessment method | Outcome measures |
|---|---|---|---|---|---|
| Yong (2014) [32] | Participants ran on a treadmill at 4.0 m/s in their own footwear | 22 experienced long-distance runners (minimum 25 km/week)<br>12 habitual RFS (age, 28 ± 5 years; mass, 64 ± 11 kg; females, NR)<br>10 habitual FFS (age, 29 ± 6 years; mass, 65 ± 8 kg; females, NR) | Habitual RFS vs habitual NRFS | Shoe makers and motion analysis | Joint kinematics: knee, ankle<br>GRF<br>Muscle activation: ankle, knee, hip |
| Yong (2018) [50] | Participants ran on a treadmill at a self-selected speed in standardised footwear | 17 recreational habitual RFS runners (minimum 10 km/week)<br>Age, 32 ± 10 years; mass, 65 ± 13 kg; females, 11 | Habitual RFS vs imposed NRFS | High-speed camera and pressure insoles | GRF<br>Loading rate<br>Joint kinematics: hip, knee, ankle<br>Peak tibial acceleration |

*RFS* rearfoot strike, *FFS* forefoot strike, *MFS* midfoot strike, *NRFS* non-rearfoot strike, *SI* strike index, *GRF* ground reaction force, *BMI* body mass index, *NR* not reported, *TR* toe running, *BW* body weight

participants, and research settings. Statistical heterogeneity of the included studies was calculated using the $I^2$ statistic [18]. For the primary aim (injury and running economy), all SMD calculations, including from single studies, were included in our data synthesis. For the secondary aim (biomechanics) only SMD calculations from data pooling (i.e., 2 or more studies) were included in our data synthesis.

#### 2.4.3 Data Synthesis

Levels of evidence were determined using a modified version of the van Tulder criteria [19]: (1) strong evidence provided by consistent findings amongst multiple studies, including at least three high quality studies; (2) moderate evidence provided by consistent findings amongst multiple studies, including at least three moderate or high quality studies or two high-quality studies; (3) limited evidence provided by consistent findings amongst multiple low- or moderate-quality studies, or one high-quality study; (4) very limited evidence provided by findings from one low- or moderate-quality study; and (5) conflicting evidence provided by pooled results insignificant and derived from multiple studies, regardless of quality, which are statistically heterogeneous. Definition of consistent findings (i.e., statistical homogeneity) was based on an $I^2$ of 50% or less. $I^2$ values greater than 50% were classified as inconsistent (i.e., statistical heterogeneity), with level of evidence downgraded one level if pooled results were significant. Calculated SMD magnitudes were classified as small ($\leq$ 0.59), medium (0.60–1.19), or large ($\geq$ 1.20) [20].

## 3 Results

### 3.1 Search Strategy and Reported Quality

Search results are summarised in Fig. 1. The search (4th week of April 2019) identified 3109 titles. Following removal of duplicate publications, titles of 1397 publications were evaluated. The full text of 60 articles was retrieved, and 53 studies were identified for inclusion. The primary reasons for exclusion of studies were a participant number less than ten and running gait modifications in addition to a change in foot strike, such as Chi or Pose technique. Refer to Fig. 1 for a flow diagram of the study selection process.

Characteristics of the 53 included studies are provided in Table 1. Fifteen [21–35] of the included studies compared habitual RFS runners and habitual NRFS runners; 17 studies [36–52] compared habitual RFS runners running with an imposed NRFS pattern; five studies [53–57] compared RFS and NRFS patterns without comment regarding habitual foot strike; 15 studies [58–72] included both habitual RFS and habitual NRFS runners and compared both habitual and imposed strike patterns; and one study compared habitual NRFS runners running with an imposed RFS pattern [73]. Results of reported quality assessment and individual study Downs and Black Quality Index scores are presented in Table 2. Of the 53 included studies, 16 were high quality [33, 36, 39, 40, 42, 48, 49, 52–54, 57, 62, 63, 65, 67, 70], 35 were moderate quality [21, 22, 24–32, 34, 35, 37, 38, 41, 43–47, 50, 51, 55, 58–61, 64, 66, 68, 69, 71–73], and two were low quality [23, 56].

## 3.2 Primary Outcomes

### 3.2.1 Injury

One high-quality retrospective study [33] indicated limited evidence that runners with a habitual NRFS pattern had a significantly lower rate of previous repetitive stress injuries compared to runners with a habitual RFS per 10,000 miles of running, when injuries were categorised as mild (SMD, 95% CI 3.25, 2.37–4.12), moderate (3.65, 2.71–4.59) and severe (0.93, 0.32–1.55) (see Fig. 2).

### 3.2.2 Running Economy

Five studies [30, 35, 42, 63, 73] were identified comparing running economy between strike patterns in 'experienced' or 'well trained' recreational runners.

*Habitual foot strike pattern* Pooled data from three (2 MQ [30, 35] and 1 HQ [63]) studies provided conflicting evidence of differences in running economy between habitual RFS and habitual NRFS runners at slow (10.8–11.0 km/h), medium (12.6–13.5 km/h) [30, 35] and fast (14.0–15.0 km/h) speeds [30, 63] (see Fig. 3).

*Imposed foot strike pattern* When habitual RFS runners transitioned to NRFS, moderate evidence indicated decreased running economy at a medium speed (2 HQ [42, 63]; 12.6 km/h: − 0.55, − 1.05 to − 0.05; $I^2 = 0\%$); and limited evidence indicated decreased running economy at a slow speed (1 HQ [63]; 10.8 km/h: − 0.90, − 1.57 to − 0.23); but no change in running economy at a fast speed (1 HQ [63]; 14.0 km/h) (see Fig. 3). In addition, when habitual RFS runners transitioned to NRFS, limited evidence indicated no

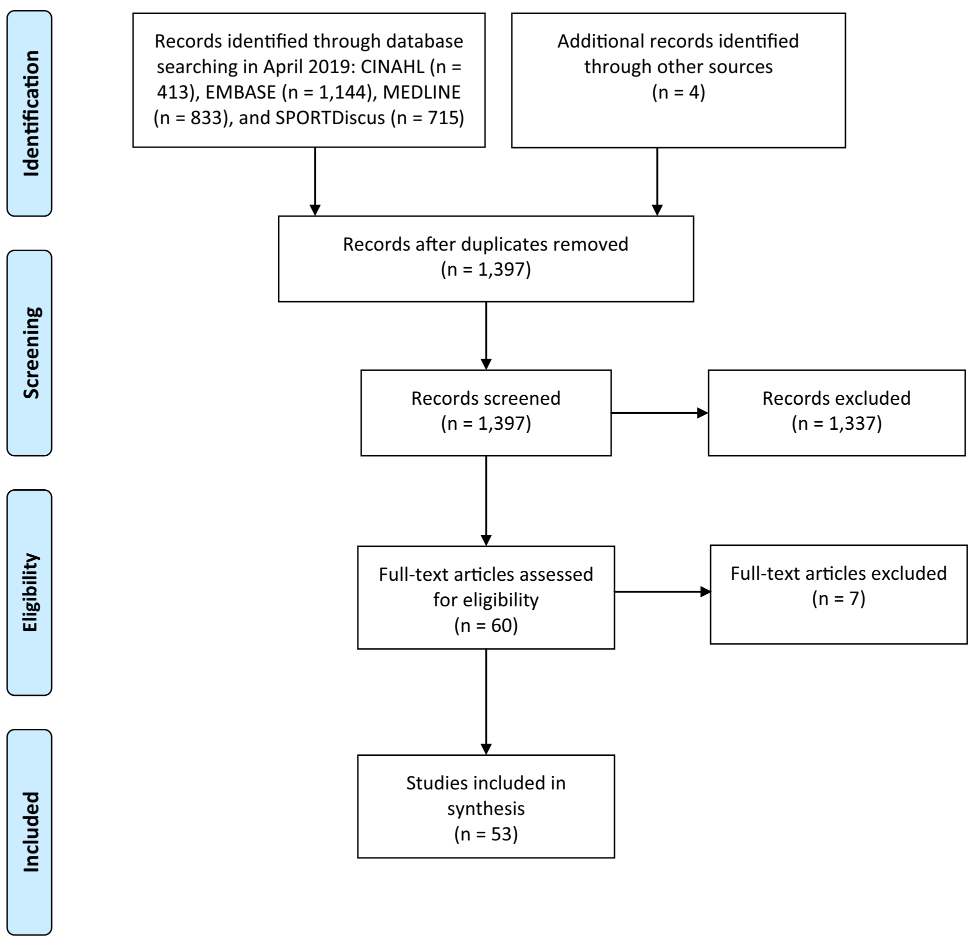


**Fig. 1** PRISMA flow diagram for the selection of studies

**Table 2** Downs and Black Quality Index results for each study

| | 1. Clear aim/hypothesis | 2. Outcome measures described | 3. Patient characteristics described | 4. Intervention clearly described | 5. Principal confounders | 6. Findings clearly described | 7. Random variability | 8. Adverse events | 9. Lost to follow-up | 10. Probability values reported | 11. Asked subjects representative | 12. Inc. subjects representative | 13. Staff and facilities representative | 14. Attempt blinding participants |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Daoud 2012 [33] | 1 | 1 | 1 | 0 | 2 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 |
| Delgado 2013 [62] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Bowersock 2017 [36] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Dos Santos 2016 [52] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Gruber 2013 [63] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Hashizume 2017 [57] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Huang 2019 [65] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Kernozek 2016 [39] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Kuhman 2016 [40] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Landreneau 2014 [67] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |
| Melcher 2017 [42] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Nunns 2013 [70] | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 |
| Pohl 2008 [54] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | U | U | 0 | 0 |
| Vannatta 2017 [48] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Williams 2012 [49] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Willson 2015 [53] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Boyer 2018 [60] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |

**Table 2** (continued)

| | 1. Clear aim/hypothesis | 2. Outcome measures described | 3. Patient characteristics described | 4. Intervention clearly described | 5. Principal confounders | 6. Findings clearly described | 7. Random variability | 8. Adverse events | 9. Lost to follow-up | 10. Probability values reported | 11. Asked subjects representative | 12. Inc. subjects representative | 13. Staff and facilities representative | 14. Attempt blinding participants |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bruening 2018 [61] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Chen 2016 [37] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Dos Santos 2019 [51] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Gruber 2014 [24] | 1 | 1 | 1 | 0 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Hayes 2012 [26] | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 |
| Hazzaa 2018 [34] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | U |
| Kernozek 2018 [28] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Knorz 2017 [66] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Lyght 2016 [68] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Ogueta-Alday 2014 [30] | 1 | 1 | 1 | 0 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Paquette 2017 [31] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | U |
| Peters 2017 [55] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Rice 2017 [43] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Rooney 2013 [72] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 0 | U | U | 0 | 0 |
| Vannatta 2015 [47] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Yong 2014 [32] | 1 | 1 | 1 | 0 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Yong 2018 [50] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |

**Table 2** (continued)

| | 1. Clear aim/hypothesis | 2. Outcome measures described | 3. Patient characteristics described | 4. Intervention clearly described | 5. Principal confounders | 6. Findings clearly described | 7. Random variability | 8. Adverse events | 9. Lost to follow-up | 10. Probability values reported | 11. Asked subjects representative | 12. Inc. subjects representative | 13. Staff and facilities representative | 14. Attempt blinding participants |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boyer 2014 [58] | 1 | 1 | 1 | 1 | 2 | 1 | 0 | 0 | 1 | 1 | U | U | 0 | 0 |
| Breine 2017 (JSS) [21] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | U |
| Breine 2017 (JAB) [22] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 0 | U | U | 0 | U |
| Gruber 2017 [25] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 0 | U | U | 0 | U |
| Hamill 2014 [64] | 1 | 1 | 1 | 1 | 2 | 1 | 0 | 0 | 1 | 1 | U | U | 0 | 0 |
| Kelly 2018 [38] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Kubo 2015 [27] | 1 | 1 | 1 | 1 | 2 | 1 | 0 | 0 | 1 | 1 | U | U | 0 | 0 |
| Kulmala 2013 [29] | 1 | 1 | 1 | 0 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Perl 2012 [73] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Santos-Concejero 2014 [35] | 1 | 1 | 1 | 0 | 2 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Stackhouse 2004 [45] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| Sun 2018 [45] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Valenzuela 2015 [71] | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 | 1 | 0 | U | U | 0 | 0 |
| Boyer 2015 [59] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Laughton 2003 [41] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |

**Table 2** (continued)

| | 1. Clear aim/hypothesis | 2. Outcome measures described | 3. Patient characteristics described | 4. Intervention clearly described | 5. Principal confounders | 6. Findings clearly described | 7. Random variability | 8. Adverse events | 9. Lost to follow-up | 10. Probability values reported | 11. Asked subjects representative | 12. Inc. subjects representative | 13. Staff and facilities representative | 14. Attempt blinding participants |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nishida 2017 [69] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Shih 2013 [44] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | 0 |
| Mercer 2015 [56] | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | U | U | 0 | 0 |
| Futrell 2018 [23] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | U | U | 0 | U |

| | 15. Attempt blinding clinicians | 16. Data dredging | 17. Analysis adjust for follow-up | 18. Statistics appropriate | 19. Compliance with intervention | 20. Outcome measures accurate | 21. Recruited same population | 22. Recruited same period of time | 23. Randomised to groups | 24. Randomisation concealed | 25. Adjustment for confounding | 26. Accounted for lost to follow-up | 27. Power to detect clinical effect | Total (score out of 28) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Daoud 2012 [33] | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 21 |
| Delgado 2013 [62] | 1 | 1 | 1 | 1 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 21 |
| Bowersock 2017 [36] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 20 |
| Dos Santos 2016 [52] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 20 |
| Gruber 2013 [63] | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 20 |
| Hashizume 2017 [57] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 20 |
| Huang 2019 [65] | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 20 |
| Kernozek 2016 [39] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 20 |
| Kuhman 2016 [40] | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 20 |
| Landreneau 2014 [67] | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 20 |
| Melcher 2017 [42] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 20 |

**Table 2** (continued)

| | 15. Attempt blinding clinicians | 16. Data dredging | 17. Analysis adjust for follow-up | 18. Statistics appropriate | 19. Compliance with intervention | 20. Outcome measures accurate | 21. Recruited same population | 22. Recruited same period of time | 23. Randomised to groups | 24. Randomisation concealed | 25. Adjustment for confounding | 26. Accounted for lost to follow-up | 27. Power to detect clinical effect | Total (score out of 28) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nunns 2013 [70] | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 20 |
| Pohl 2008 [54] | 0 | 1 | 1 | 0 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 20 |
| Vannatta 2017 [48] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 20 |
| Williams 2012 [49] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 20 |
| Willson 2015 [53] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 20 |
| Boyer 2018 [60] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 19 |
| Bruening 2018 [61] | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 19 |
| Chen 2016 [37] | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 19 |
| Dos Santos 2019 [51] | 0 | 1 | 1 | 0 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 19 |
| Gruber 2014 [24] | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 19 |
| Hayes 2012 [26] | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 19 |
| Hazzaa 2018 [34] | U | 1 | 1 | 1 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 19 |
| Kernozek 2018 [28] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 19 |
| Knorz 2017 [66] | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 19 |
| Lyght 2016 [68] | 0 | 1 | 1 | 0 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 19 |
| Ogueta-Alday 2014 [30] | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 19 |
| Paquette 2017 [31] | U | 1 | 1 | 1 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 19 |

**Table 2** (continued)

| | 15. Attempt blinding clinicians | 16. Data dredging | 17. Analysis adjust for follow-up | 18. Statistics appropriate | 19. Compliance with intervention | 20. Outcome measures accurate | 21. Recruited same population | 22. Recruited same period of time | 23. Randomised to groups | 24. Randomisation concealed | 25. Adjustment for confounding | 26. Accounted for lost to follow-up | 27. Power to detect clinical effect | Total (score out of 28) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Peters 2017 [55] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 19 |
| Rice 2017 [43] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | U | U | 1 | 1 | 1 | 19 |
| Rooney 2013 [72] | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 19 |
| Vannatta 2015 [47] | 0 | 1 | 1 | 0 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 19 |
| Yong 2014 [32] | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 19 |
| Yong 2018 [50] | 0 | 1 | 1 | 0 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 19 |
| Boyer 2014 [58] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 18 |
| Breine 2017 (JSS) [21] | U | 1 | 1 | 0 | 1 | 1 | U | 1 | U | U | 1 | 1 | 1 | 18 |
| Breine 2017 (JAB) [22] | U | 1 | 1 | 0 | 1 | 1 | 1 | 1 | U | U | 1 | 1 | 1 | 18 |
| Gruber 2017 [25] | U | 1 | 1 | 1 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 18 |
| Hamill 2014 [64] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 18 |
| Kelly 2018 [38] | 0 | 1 | 1 | 0 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 18 |
| Kubo 2015 [27] | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 18 |
| Kulmala 2013 [29] | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 18 |
| Perl 2012 [73] | 0 | 1 | 1 | 0 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 18 |

**Table 2** (continued)

| | 15. Attempt blinding clinicians | 16. Data dredging | 17. Analysis adjust for follow-up | 18. Statistics appropriate | 19. Compliance with intervention | 20. Outcome measures accurate | 21. Recruited same population | 22. Recruited same period of time | 23. Randomised to groups | 24. Randomisation concealed | 25. Adjustment for confounding | 26. Accounted for lost to follow-up | 27. Power to detect clinical effect | Total (score out of 28) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Santos-Concejero 2014 [35] | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 18 |
| Stackhouse 2004 [45] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 18 |
| Sun 2018 [45] | 0 | 1 | 1 | 0 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 18 |
| Valenzuela 2015 [71] | 0 | 1 | 1 | 1 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 18 |
| Boyer 2015 [59] | 0 | 0 | 1 | 1 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 17 |
| Laughton 2003 [41] | 0 | 1 | 1 | 0 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 17 |
| Nishida 2017 [69] | 0 | 1 | 1 | 0 | 1 | 1 | U | 1 | U | U | 1 | 1 | 1 | 17 |
| Shih 2013 [44] | 0 | 1 | 1 | 0 | 1 | 1 | U | 1 | 0 | 0 | 1 | 1 | 1 | 17 |
| Mercer 2015 [56] | 0 | 1 | 1 | 0 | 1 | 1 | U | 1 | 1 | 0 | 1 | 1 | 1 | 16 |
| Futrell 2018 [23] | U | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 16 |

Item 5 is assessed as yes = 2, partial = 1, no = 0, U = unclear. All other items are assessed as yes = 1, no = 0, U = unclear

High quality scores ≥ 20 out of maximum possible score 28, moderate quality scores = 17–19, and low quality scores ≤ 16

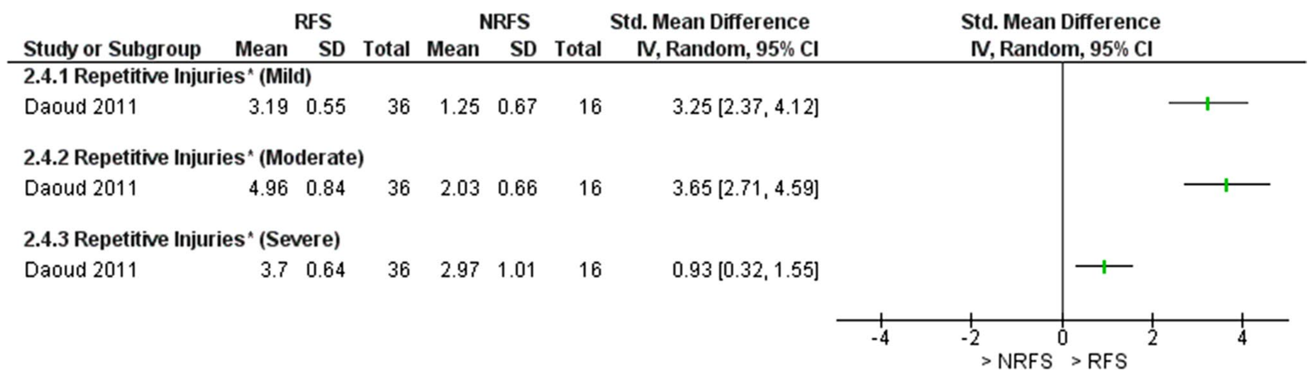


**Fig. 2** Forrest plot for retrospective association between injury and strike pattern. > NRFS = greater rate of injuries per 10,000 miles in non-rearfoot strike runners; > RFS = greater rate of injuries per 10,000 miles in rearfoot strike runners

difference in running economy at the end of a long run at a medium speed (1 HQ [44]; 12.6 km/h) (see Fig. 3).

When habitual NRFS runners transitioned to RFS, limited evidence indicated no change in running economy at slow (1 MQ [73] and 1 HQ [63]; 10.8 km/h), medium (1 HQ [63]; 12.6 km/h), and fast speeds (1 HQ [63]; 14.0 km/h) (see Fig. 3). In addition, when habitual NRFS runners transitioned to RFS whilst wearing minimalist footwear, very limited evidence indicated no difference in running economy at a slow speed (1 MQ [73]; 10.8 km/h).

## 3.3 Secondary Outcomes

### 3.3.1 Biomechanical Studies Overview

Forty-nine studies were identified evaluating biomechanical differences between strike patterns, and included a total of 220 variables. In the main manuscript, only the pooled results for biomechanical findings (i.e. secondary aim) are presented. Pooling was possible for 49 separate variables, with a summary provided in Table 3 (gait parameter and ground reaction force findings) and Table 4 (kinetic, kinematic and muscle function findings). All SMDs for pooled and individual biomechanical findings, and associated forest plots are presented in supplementary file 1.

### 3.3.2 Gait Parameters

*Habitual foot strike pattern* When comparing habitual NRFS runners with habitual RFS runners, moderate evidence indicated NRFS runners had a shorter stance contact time (4 MQ [21, 25, 29, 46]; 1.28, 0.90–1.66; $I^2=0\%$); and limited evidence indicated no difference in step rate (2 HQ [42, 52]; −0.17, −0.66 to 0.32; $I^2=0\%$), no difference in step length (4 MQ [21, 28, 29, 34]; 0.06, −0.26 to 0.37; $I^2=0\%$), and no difference in step width (2 MQ [29, 59]; −0.17, −0.61 to 0.27; $I^2=0\%$).

*Imposed foot strike pattern* When habitual RFS runners transitioned to NRFS, moderate evidence indicated no difference in stance contact time (2 HQ [36, 48] and 2 MQ [38, 44]; 0.23, −0.11 to 0.56; $I^2=0\%$), no difference in centre of mass vertical displacement (3 MQ [21, 41, 44]; 0.24, −0.19 to 0.67; $I^2=0\%$), no difference for step rate (1 MQ [34] and 1 LQ [23]; −0.31, −0.64 to 0.01; $I^2=4\%$), and no difference for step length (3 MQ [43, 47, 51]; 0.39, −0.07 to 0.86; $I^2=36\%$); and limited evidence indicated reduced heel-to-centre of mass distance (2 MQ [25, 29]; 2.00, 1.45–2.56; $I^2=0\%$). Inconsistent findings were identified when habitual RFS runners transitioned to NRFS for leg stiffness (2 MQ [41, 44]; −0.63, −1.86 to 0.60; $I^2=79\%$).

### 3.3.3 Ground Reaction Forces

*Habitual foot strike pattern* When comparing habitual NRFS runners with habitual RFS runners, moderate evidence indicated that NRFS runners had a higher peak vertical GRF (5 MQ [21, 25, 29, 32, 71]; −0.67, −1.00 to −0.34; $I^2=0\%$); limited evidence indicated that NRFS runners had a lower peak vertical loading rate (2 MQ [21, 58] and 1 LQ [23]; 0.72, 0.23–1.22; $I^2=50\%$); and very limited evidence indicated that NRFS runners had a lower average vertical loading rate (1 MQ [29] and 1 LQ [23]; 1.81, 0.81–2.81, $I^2=78\%$) and lower vertical impact peak (2MQ [29, 58]; 1.76, 0.57–2.94; $I^2=76\%$). Inconsistent findings were identified when comparing habitual NRFS runners with habitual RFS runners for peak anterior–posterior GRF (2 MQ [25, 58]; −1.84, −4.61 to 0.94; $I^2=94\%$).

*Imposed strike pattern* When habitual RFS runners transitioned to NRFS, moderate evidence indicated higher peak vertical GRF (2 HQ [40, 47] and 5 MQ [38, 41, 46, 51, 71]; −0.89, −1.18 to −0.60; $I^2=0\%$); and limited evidence indicated reduced peak vertical loading rate (6 MQ [37, 41, 43, 44, 50, 58]; 1.77, 0.81–2.73; $I^2=87\%$) and average vertical loading rate (4 MQ [37, 41, 44, 50]; 2.15,

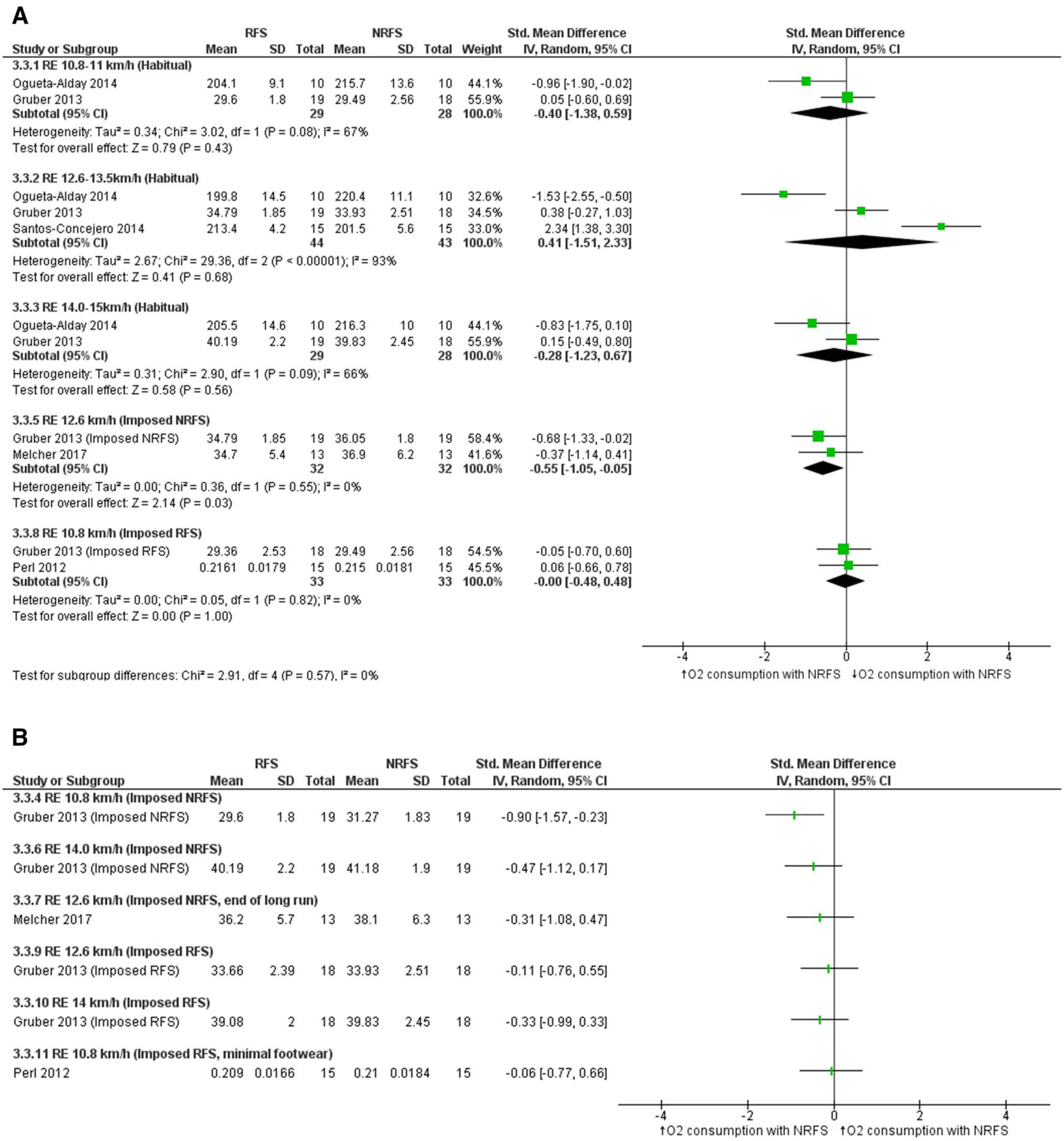


**Fig. 3** Forrest plots running economy. > NRFS = greater oxygen consumption in non-rearfoot strike runners or condition (i.e., reduced economy); > RFS = greater oxygen consumption in rearfoot strike runners or condition (i.e., reduced economy)

0.72–3.58; $I^2 = 89\%$). Inconsistent findings were identified when habitual RFS runners transitioned to NRFS for vertical impact peak (1 HQ [58] and 1 MQ[58]; 0.81, −1.63 to 3.25; $I^2 = 95\%$) and anterior–posterior GRF (2 MQ [41, 58]; −2.64; −5.60 to 0.33; $I^2 = 93\%$).

### 3.3.4 Trunk and Pelvis

*Habitual foot strike pattern* No data pooling was possible for any trunk or pelvis kinematic and kinetic findings comparing habitual strike patterns.

**Table 3** Summary of pooled findings for gait parameters and ground reaction force findings

| Variable | Habitual RFS vs habitual NRFS (pooled standard mean difference) | Habitual RFS vs imposed NRFS (pooled standard mean difference) |
|---|---|---|
| **Gait parameters** | | |
| Stance contact time | ↓ (**1.28**) | **No difference** (**0.23**) |
| Step rate (cadence) | ***No differences*** (***–0.17***) | No difference (–0.31) |
| Step length | ***No difference*** (***0.06***) | **No difference** (**0.39**) |
| Step width | ***No difference*** (***–0.17***) | – |
| Center of mass vertical displacement | – | **No difference** (**0.24**) |
| Heel to center of mass distance | ↓ (***2.00***) | – |
| **Ground reaction forces** | | |
| Peak vertical ground reaction force | ↑ (**–0.67**) | ↑ (**–0.89**) |
| Peak vertical loading rate | ↓ (***0.72***) | ↓ (***1.77***) |
| Average vertical loading rate | ↓ (1.81) | ↓ (***2.15***) |
| Vertical impact peak | ↓ (1.76) | Inconsistent |
| Anterior–posterior ground reaction force | Inconsistent | Inconsistent |

Bold = moderate evidence; bold italic = limited evidence; normal text = very limited evidence; ↑ = greater in NRFS condition; ↓ = lower in NRFS condition

*Imposed foot strike pattern* When habitual RFS runners transitioned to NRFS, moderate evidence indicated no change in peak lumbar flexion (1 HQ [52] and 1 MQ [51]; 0.02, –0.37 to 0.42; $I^2 = 0\%$).

#### 3.3.5 Hip

*Habitual foot strike pattern* When comparing habitual NRFS runners with habitual RFS runners, moderate evidence indicated no difference in peak hip flexion (2 HQ [48, 52]; 0.03, –0.34 to 0.40; $I^2 = 0\%$); and limited evidence indicated no difference in peak hip extension moment (2 MQ [29, 71]; 0.02, –0.49 to 0.53; $I^2 = 0\%$), and NRFS runners had reduced peak hip adduction (2 MQ [29, 58]; 0.58, 0.04–1.12; $I^2 = 31\%$)

*Imposed foot strike pattern* When habitual RFS runners transitioned to NRFS, moderate evidence indicated no change in hip flexion at initial contact (2 HQ [49, 52] and 1 MQ [44]; 0.00, –0.35 to 0.35; $I^2 = 0\%$), and no change in peak hip adduction (2 HQ [48] and 2 MQ [50, 59]; 0.21, –0.07 to 0.50; $I^2 = 0\%$); and limited evidence indicated no change in peak hip extension moment (2 MQ [51, 71]; –0.04, –0.55 to 0.47; $I^2 = 0\%$), greater hip sagittal plane range of motion during stance (2 MQ [44, 71]; 0.73, 0.12–1.34; $I^2 = 0\%$), and no change in peak contralateral pelvic drop (1 HQ [48] and 1 MQ [59]; 0.04, –0.37 to 0.45). Inconsistent findings were identified when habitual RFS runners transitioned to NRFS for peak hip internal rotation (2 HQ [48, 52]; 0.11, –0.78 to 1.01; $I^2 = 82\%$).

#### 3.3.6 Knee

*Habitual foot strike pattern* When comparing habitual NRFS runners with habitual RFS runners, moderate evidence indicated NRFS runners had lower knee flexion range of motion (4 MQ [21, 29, 32, 71]; 0.88, 0.48–1.27; $I^2 = 0\%$); limited evidence indicated no difference in peak knee extension moment (2 MQ [29, 71]; 0.48, –0.04 to 1.00; $I^2 = 0\%$), NRFS runners had lower patellofemoral joint stress (2 MQ [29, 60]; 0.68, 0.21–1.14; $I^2 = 0\%$) and patellofemoral joint contact force (2 MQ [29, 60]; 0.75, 0.25–1.25; $I^2 = 12\%$); and very limited evidence indicated NRFS runners had greater knee joint stiffness (2 MQ [21, 64]; –1.77, –2.98 to –0.57; $I^2 = 78\%$). Inconsistent findings were identified when comparing habitual NRFS runners with habitual RFS runners for knee flexion angle at initial contact (3 MQ [29, 32, 71]; –0.29, –1.11 to 0.52; $I^2 = 68\%$), and peak knee flexion (2 MQ [29, 32]; 0.48, –0.63 to 1.58; $I^2 = 68\%$)

*Imposed foot strike pattern* When habitual RFS runners transitioned to NRFS, strong evidence indicated reduced knee flexion range of motion (3 HQ [40, 42, 52] and 5 MQ [41, 44, 45, 47, 71]; 0.76, 0.45–1.07; $I^2 = 28\%$), and moderate evidence indicated reduced peak quadriceps force (2 HQ [36, 48]; 1.54, 1.01–2.07; $I^2 = 0\%$), reduced hamstring force (2 HQ [36, 48]; 0.92, 0.40–1.45; $I^2 = 28\%$), and reduced peak knee flexion (2 HQ [40, 52] and 3 MQ [45, 47, 51]; 0.28, 0.00–0.58; $I^2 = 0\%$); and limited evidence indicated reduced peak knee extension moment (1 HQ [42] and 2 MQ [51, 71]; 0.65, 0.21–1.09; $I^2 = 1\%$), reduced patellofemoral joint stress time integral (1 HQ [47] and 1 MQ [51]; 0.63, 0.16–1.11; $I^2 = 0\%$), no difference in knee joint stiffness (2 MQ [41,

**Table 4** Summary of pooled findings for lower limb kinetics, kinematics and muscle function

| Variable | Habitual RFS vs habitual NRFS (pooled standard mean difference) | Habitual RFS vs imposed NRFS (pooled standard mean difference) |
|---|---|---|
| **Trunk and pelvis** | | |
| ***Kinematics:*** | | |
| Peak lumbar flexion | – | **No change (0.02)** |
| **Hip** | | |
| ***Kinetics:*** | | |
| Peak hip extension moment | **No difference (0.02)** | ***No change (− 0.04)*** |
| ***Kinematics:*** | | |
| Hip flexion at initial contact | – | **No change (0.00)** |
| Peak hip flexion | – | **No difference (0.03)** |
| Hip sagittal plane range of motion | – | ↓ (***0.73***) |
| Peak hip internal rotation | – | Inconsistent |
| Peak hip adduction | ↓ (***0.58***) | **No change (0.21)** |
| Peak contralateral pelvic drop | – | ***No change (0.04)*** |
| **Knee and thigh** | | |
| ***Kinetics:*** | | |
| Peak knee extension moment | ***No difference (0.48)*** | ↓ (***0.65***) |
| Patellofemoral joint stress | ↓ (***0.68***) | Inconsistent[a] |
| Patellofemoral joint stress time integral | – | ↓ (***0.63***) |
| Patellofemoral contact force | ↓ (***0.75***) | ***No difference (− 0.13)*** |
| Knee joint stiffness | ↑ (− 1.77) | ***No difference (− 0.51)*** |
| ***Kinematics:*** | | |
| Knee flexion angle at initial contact | Inconsistent | Inconsistent |
| Peak knee flexion | Inconsistent | ↓ (**0.28**) |
| Knee flexion range of motion | ↓ (**0.88**) | ↓ (**0.76**) |
| ***Muscle function:*** | | |
| Quadriceps force | – | ↓ (**1.54**) |
| Rectus femoris activation during stance | – | ***No difference (− 0.08)*** |
| Rectus femoris activation during terminal swing | – | ↑ (***− 0.63***) |
| Hamstring force | – | ↓ (**0.92**) |
| Lateral hamstring activation during stance | – | **No difference (− 0.41)** |
| **Foot, ankle and tibia** | | |
| ***Kinetics:*** | | |
| Peak internal plantarflexion moment | ↑ (***− 1.30***) | ↑ (***− 1.33***) |
| Peak rearfoot plantarflexion moment | – | Inconsistent |
| Peak negative ankle power | – | ↑ (***− 1.88***) |
| Achilles tendon force | ↑ (***− 1.10***) | – |
| Ankle joint stiffness | ↓ (1.53) | ↓ (1.79) |
| Posterior ankle joint contact force | – | ***No difference (0.00)*** |
| Posterior ankle joint contact force | – | ***No difference (0.30)*** |
| Peak tibial acceleration | – | Inconsistent |
| ***Kinematics:*** | | |
| Ankle dorsiflexion at initial contact | ↓ (***3.48***) | ↓ (***3.92***) |
| Foot angle (plantarflexion) | ↓ (3.37) | – |
| Ankle dorsiflexion range of motion | ↑ (***− 1.20***) | ↑ (***− 2.22***) |
| Peak ankle dorsiflexion during stance | – | ↓ (**0.90**) |
| ***Muscle function:*** | | |
| Gastrocnemius muscle activation | ↑ (***− 0.82***) | – |
| Soleus muscle activation | ↓ (***0.69***) | – |
| Tibialis anterior activation during terminal swing | – | ↓ (2.38) |
| Tibialis anterior activation during stance | – | Inconsistent (0.42) |

Bold underline = strong evidence; bold = moderate evidence; bold italic = limited evidence; normal text = very limited evidence; ↑ = greater in NRFS condition; ↓ = lower in NRFS condition

[a]Inconsistent findings approaches significance (0.78, − 0.05 to 1.61)

42]; − 0.51, − 1.03 to 0.02; $I^2$ = 0%), and no difference in peak knee contact force (1 HQ [36] and 1 MQ [72]; − 0.13, − 0.60 to 0.35; $I^2$ = 0%). Inconsistent findings were identified when habitual RFS runners transitioned to NRFS for patellofemoral joint stress (1 HQ [48] and 2 MQ [51, 60]; 0.78, − 0.05 to 1.61; $I^2$ = 76%), and knee flexion angle at initial contact (2 HQ [49, 52] and 3 MQ [44, 47, 71]; − 0.15, − 1.21 to 0.92; $I^2$ = 91%).

### 3.3.7 Foot, Ankle, and Tibia

*Habitual foot strike pattern* When comparing habitual NRFS runners with habitual RFS runners, limited evidence indicated NRFS runners had a greater peak internal plantarflexion moment (2 MQ [29, 71]; − 1.30, − 1.87 to − 0.73); $I^2$ = 0%), greater Achilles tendon force (2 MQ [28, 29]; − 1.10, − 1.59 to − 0.60; $I^2$ = 0%), lower peak tibial acceleration (1 HQ [62] and 1 MQ [24]; 1.03, 0.66–1.41; $I^2$ = 0%), less ankle dorsiflexion at initial contact (2 MQ [21, 29]; 3.48, 2.57–4.39; $I^2$ = 32%), and less ankle dorsiflexion range of motion (4 MQ [21, 28, 67, 71]; − 1.20, − 2.05 to − 0.35; $I^2$ = 77%); and very limited evidence indicated NRFS runners had lower ankle joint stiffness (2 MQ [21, 64]; 1.53, 0.62–2.44; $I^2$ = 65%), and lower foot angle (more plantarflexed) at initial contact (2 MQ [21, 31]; 3.37, 2.02–4.73; $I^2$ = 71%).

*Imposed foot strike pattern* When habitual RFS runners transitioned to NRFS, moderate evidence indicated reduced peak ankle dorsiflexion during stance (1 HQ [52] and 2 MQ [38, 43]; 0.90, 0.54–1.26; $I^2$ = 0%); limited evidence indicated increased peak internal plantarflexion moment (1 HQ [42] and 4 MQ [38, 43, 71]; − 1.33, − 2.18 to − 0.48; $I^2$ = 81%), increased peak negative ankle power (1 HQ [38] and 1 MQ [49]; − 1.88, − 2.47 to − 1.29; $I^2$ = 0%), no difference in peak ankle joint posterior contact force (2 MQ [37, 60]; 0.00, − 0.48 to 0.48; $I^2$ = 0%), no difference in peak ankle joint medial contact force (2 MQ [37, 60]; 0.30, − 0.35 to 0.95; $I^2$ = 42%), reduced ankle dorsiflexion at initial contact (2 HQ [49, 52] and 2 MQ [43, 44]; 3.92, 3.08–4.77; $I^2$ = 56%), and reduced ankle dorsiflexion range of motion (1 HQ [42] and 3 MQ [41, 45, 71]; − 2.22, − 3.04 to − 1.39; $I^2$ = 63%); and very limited evidence indicated reduced ankle joint stiffness (1 HQ [42] and 1 MQ [41]; 1.79, 0.65–2.93; $I^2$ = 69%). Inconsistent findings were identified when habitual RFS runners transitioned to NRFS for peak rearfoot plantarflexor moment (2 MQ [38, 74]; − 0.72, − 1.56 to 0.12; $I^2$ = 63%), and peak tibial acceleration (1 HQ [62] and 2 MQ [41, 50]; 0.28, − 0.72 to 1.29; $I^2$ = 88%).

### 3.3.8 Electromyography (EMG)

*Habitual foot strike pattern* No data pooling were possible for any EMG findings comparing habitual strike patterns.

*Imposed foot strike pattern* When habitual RFS runners transitioned to NRFS, limited evidence indicated increased gastrocnemius average activation (2 MQ [38, 44]; − 0.82, − 1.44 to − 0.20; $I^2$ = 10%), reduced soleus average EMG (2 MQ; 0.69, 0.10–1.28; $I^2$ = 0%), no difference in rectus femoris activation during stance (2 MQ [32, 44]; − 0.08, − 0.64 to 0.49; $I^2$ = 0%), greater rectus femoris activation during terminal swing (2 MQ [32, 44]; − 0.63, − 1.22 to − 0.05; $I^2$ = 0%), no difference in lateral hamstring activation during stance (2 MQ [32, 44]; − 0.41, − 1.00 to 0.17; $I^2$ = 0%); and very limited evidence indicated reduced tibialis anterior activation during terminal swing (2 MQ [32, 44]; 2.38, 0.93–3.83; $I^2$ = 70%). Inconsistent findings were identified when habitual RFS runners transitioned to NRFS for tibialis anterior activity during stance (2 MQ [32, 44]; 0.42, − 0.88 to 1.71; $I^2$ = 79%)

## 4 Discussion

This systematic review highlights insufficient evidence to conclusively determine the benefits or harms of transitioning from RFS to NRFS during running. However, there is a large body of work which provides some insight to guide current clinical practice and future research. Although limited evidence indicated that an NRFS pattern may be retrospectively associated with lower rates of previous injury [33], a causal relationship of strike pattern with injury risk cannot be determined. Importantly, no prospective evidence supported one strike pattern being associated with reduced likelihood of future injury development, meaning claims that NRFS runners are less likely to be injured than RFS runners [4, 8] have not been adequately tested in research. Limited evidence indicated no difference in running economy between habitual RFS and habitual NRFS runners, and transitioning from RFS to NRFS at slow and medium speeds reduces running economy in the immediate term. Research evaluating changes in running economy following a period transition from RFS to NRFS was not identified. Thus, recommendation to transition from RFS to NRFS to improve running economy [12, 13] lacks supporting evidence at this time.

### 4.1 Injury

No study of adequate sample size ($n \geq 10$) evaluating the effects of transitioning from RFS to NRFS in isolation when managing running related injuries was identified. Previous small randomised trials and cohort studies have reported that transitioning from a RFS to an NRFS as part of a running retraining intervention may reduce pain in runners with patellofemoral pain [9, 75] and anterior exertional lower leg pain [10, 11]. Studies related to patellofemoral pain [9, 75] were excluded from this review, because they included less than ten participants in the retraining group or cohort, whilst studies related to exertional lower leg pain [10, 11] were excluded due to the concurrent use of other retraining strategies, including increased step rate [11] and proximal cues (increasing hip flexion, promoting more push off and running more upright) [10]. The use of concurrent retraining strategies means it is not possible to determine how much the change in strike pattern may have contributed to reductions in pain. Considering frequent recommendations provided by experts in the field to transition from RFS to NRFS to manage running related injuries [4], adequately powered high quality randomised controlled trials are urgently needed.

## 4.2 Running Economy

Limited-moderate evidence indicated that transitioning a RFS runner to NRFS during slow and medium speeds would reduce running economy in the immediate term in experienced recreational runners. Additionally, limited evidence from this review indicated transitioning an NRFS runner to RFS running at slow, medium and fast speeds did not detrimentally affect running economy. Thus, current evidence does not support the commonly proposed theory that NRFS running is more economical compared to RFS running due to greater storage and return of elastic energy at the foot and ankle [12, 76]. The greater proportion of elite distance runners adopting an NRFS compared to non-elite runners [6, 12, 13] may reflect this group's capacity to run with an NRFS pattern to absorb greater loads at faster speeds, rather than being a feature of improved running economy. However, the effect of foot strike pattern on running economy has not been investigated among elite runners, and requires further research.

Findings in this review were limited to comparison of habituated strike patterns, which identified no difference in running economy, and immediate effects of transitioning to an imposed NRFS or RFS on running economy. Further research to evaluate the influence of transition following a longer period of adaption is needed. Limited evidence does indicate running economy improves when transitioning to minimalist footwear over a number of weeks [77–80], with these transitions often accompanied by preparatory exercise and adoption of NRFS running [80]. However, with lighter footwear known to improve running economy [81], it is unclear from this research whether transition from RFS to NRFS alone can influence running economy following a period of transition. Although some evidence indicates footwear weight is likely to have a stronger influence on running economy than strike pattern [82], further research evaluating the influence of strike pattern on running economy following a period of adaptation is encouraged. In light of the evidence related to economy and shifts in load associated with an NRFS, if the goal is to improve running economy, building capacity to run with an NRFS (e.g. plyometrics, skipping) may be safer and more important during training than focussing on transitioning strike pattern specifically. Indeed, current evidence supports the use of resistance training and plyometric exercise programs to improve running economy [83].

## 4.3 Biomechanics

Consistent with previous systematic reviews evaluating the influence of strike pattern on biomechanics [84, 85], we identified evidence that NRFS when imposed on habitual RFS runners led to greater ankle plantar flexion at foot strike and reduced vertical loading rates. Our review is the most comprehensive synthesis of research comparing biomechanical outcomes between RFS and NRFS running to date, allowing data pooling of 26 variables when comparing habitual RFS and NRFS, and 42 variables when comparing habitual RFS with imposed NRFS. Where overlap occurred between these two comparisons (21 variables), the direction of findings differed 38% (8 occasions) of the time. This indicates pooling data for different methods of comparing strike pattern (i.e., habitual and imposed) may not be valid and justifies our decision to split the analysis.

Shorter stance contact time was identified in habitual NRFS compared to habitual RFS runners, but no difference occurred when an NRFS pattern was imposed on habitual RFS runners. This may indicate a need for adaptation when adopting an NRFS running pattern if targeting a reduction in contact time for potential performance gains. Although reduced contact time associated with NRFS compared to RFS running has been hypothesised by some researchers to improve running economy [86], our review findings do not support this. The only other difference in gait parameters identified was a reduction in distance from the heel to centre of mass at foot strike when imposing an NRFS on habitual RFS runners. The implications of this difference to injury and running economy remain unclear, and requires further research.

An NRFS running pattern was associated with reduced peak and average vertical loading rate, regardless of whether comparisons were made between habitual strike patterns, or a habitual RFS and imposed NRFS pattern. Additionally, vertical impact peak was also lower in habitual NRFS compared to habitual RFS runners. A reduction in vertical loading rate associated with an NRFS pattern is sometimes used to justify transition to an NRFS pattern to reduce injury risk [4, 8]. Indeed, reviews by both van der Warp et al. [87]

and Zadpoor et al. [88] have reported that patients with a history of stress fracture (tibial and metatarsal) run with higher vertical loading rates [87, 88]. However, further research is needed to understand whether reductions in vertical loading rates and impact peaks associated with NRFS running are beneficial to managing or preventing injury.

At the hip and trunk, eight of the ten biomechanical comparisons where data pooling was possible indicated no difference between RFS and NRFS patterns, meaning strike pattern may have little influence on proximal biomechanics. One exception was increased hip sagittal plane range of motion when NRFS running was imposed on habitual RFS runners. Considering evidence for this finding was limited, and the same data was not available comparing habitual strike patterns, the clinical significance of this finding is unclear. Limited evidence of reduced peak hip adduction with NRFS running when comparing habitual strike patterns, but not when NRFS running was imposed on habitual RFS runners, indicates potential changes in hip mechanics may take a period of habituation. Theoretically, reduced peak hip adduction in NRFS runners may help treat or prevent proximal running injuries (e.g., patellofemoral pain, gluteal tendinopathy), but further research is required to confirm this.

At the knee, moderate-strong evidence was identified that NRFS running was associated with a lower knee flexion range of motion for both habitual and imposed comparisons. In addition, NRFS was generally associated with reduced loading at the knee, including lower patellofemoral joint stress and contact force when habitual strike patterns were compared, and reduced peak knee extension moment and patellofemoral joint stress time integral when NRFS running was imposed on habitual RFS runners. Additionally, imposing NRFS running on habitual RFS runners appears to reduce peak knee flexion and quadriceps muscle force. These biomechanical differences provide possible mechanistic explanations for the previously reported benefits of transitioning from RFS to NRFS in runners with patellofemoral pain [9, 75].

Our meta-analysis indicated limited evidence of large increases in peak internal ankle plantarflexion moment and peak negative ankle power when NRFS running was imposed on habitual RFS runners. Furthermore, limited evidence indicated greater peak internal plantarflexion moment, gastrocnemius muscle activation, and Achilles tendon force in habitual NRFS compared to habitual RFS runners. The relationship of increased ankle and plantarflexor complex loading with injury is currently unclear. However, Roper et al. [9] did report running-related ankle pain at 1-month follow-up in two of eight (25%) runners with patellofemoral pain who transitioned from RFS to NRFS [9], attributing this to increased ankle loads associated NRFS running [9]. In addition, running in minimalist footwear, which is often used to facilitate a transition to an NRFS [80], increases foot bone marrow oedema [89] and the risk of pain and injury [90] in the short term, particularly in experienced [91] or heavier [92] runners. This suggests there may be a risk of injury if foot strike changes are not implemented gradually alongside consideration of tissue capacity.

Other noteworthy findings at the ankle included lower soleus muscle activation in habitual NRFS runners, and reduced peak ankle dorsiflexion when NRFS running was imposed on habitual RFS runners. Both lower soleus activity and reduced peak ankle dorsiflexion are associated with lower Achilles tendon strain during running [93–95]. The potential benefits of this to people with Achilles tendinopathy requires further research, and should also be considered alongside evidence for greater peak Achilles tendon force in habitual NRFS compared to RFS runners found in this review. Very limited evidence indicated that imposing NRFS running on habitual RFS runners reduced tibialis anterior activation during terminal swing, which may provide some biomechanical explanation for the benefits of a multifaceted gait retraining program including transition from RFS to NRFS in runners with anterior exertional lower leg pain [10, 11]. Further research to establish the influence of different strike patterns on foot and ankle loading alongside injury in the longer term is needed.

### 4.4 Limitations and Future Directions

Although limited evidence indicates history of injury may be less likely in an NRFS compared with a RFS runner, it is unclear whether strike pattern changes injury risk profile, or if in fact, history of injury itself may influence habitual strike pattern. Further prospective research is required to explore this question. Running economy and biomechanical findings related to the influence of strike pattern synthesised in this review are limited to comparisons of habitual strike patterns, and immediate changes (i.e., imposed). The effects of transitioning to NRFS following habituation may differ. For example, findings of our review indicate that running economy is reduced in the short term by transitioning to a NRFS pattern at slower running speeds. However, it is possible that running economy may return to normal or improve in the longer term in response to adaptation to an NRFS pattern. Further research including long-term follow-up evaluating injury, biomechanics and running economy is urgently needed.

Several limitations must be considered in relation to our review methodology. We excluded studies that applied other interventions in addition to changing strike pattern. Importantly, it must be acknowledged that choice to change strike pattern in research and practice may be accompanied by other gait retraining strategies (e.g., increased step rate) or interventions (e.g., change in footwear). This combination would ultimately influence injury, efficiency and biomechanical outcomes. Thus, our conclusions may apply only in cases where changing strike pattern is the sole intervention. We also excluded non-English studies, and studies including less than ten participants per group or cohort, which may lead to the omission of potentially relevant data. The latter exclusion was applied to minimise the risk of potentially false-positive or false-negative findings influencing the evidence synthesis.

Findings of this review must be interpreted in the context of reported methodological limitations of the included studies. Only one included study [62] attempted to blind assessors, and only one study [96] reported adverse events. Documentation of adverse events should be ensured as it is of particular interest when considering the shifts in loading profiles highlighted by this review, combined with a potential increase in injury risk associated with running retraining interventions [4]. Study designs varied in relation to footwear, habitual strike pattern, foot strike assessment methods, and definition of NRFS. Some studies compared RFS to NRFS patterns of both midfoot strike and forefoot strike. Importantly, findings related to injury, biomechanics and running efficiency may differ dependent on type of NRFS pattern adopted, and may be influenced by method of strike pattern assessment, which varied greatly (see Table 1). Future research is needed to better understand these possible differences. A final consideration related to biomechanical findings is that most studies included in the meta-analysis of this review evaluated asymptomatic populations. Therefore, caution is needed when attempting to apply these findings to symptomatic running populations.

## 5 Conclusions

Since current evidence related to injury rates and strike pattern is limited to retrospective findings, the relationship between strike pattern and injury risk cannot be determined. Considering the lack of evidence to support any improvements in running economy, combined with the associated shift in loading profile, changing strike pattern cannot be recommended for an uninjured RFS runner.

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### Compliance with Ethical Standards

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