# Effects of Foot Strike Techniques on Running Biomechanics: A Systematic Review and Meta-analysis

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**Content:** Distance running is one of the most popular physical activities, and running-related injuries (RRIs) are also common. Foot strike patterns have been suggested to affect biomechanical variables related to RRI risks.

**Objective:** To determine the effects of foot strike techniques on running biomechanics.

**Data Sources:** The databases of Web of Science, PubMed, EMBASE, and EBSCO were searched from database inception through November 2018.

**Study Selection:** The initial electronic search found 723 studies. Of these, 26 studies with a total of 472 participants were eligible for inclusion in this meta-analysis.

**Study Design:** Systematic review and meta-analysis.

**Level of Evidence:** Level 4.

**Data Extraction:** Means, standard deviations, and sample sizes were extracted from the eligible studies, and the standard mean differences (SMDs) were obtained for biomechanical variables between forefoot strike (FFS) and rearfoot strike (RFS) groups using a random-effects model.

**Results:** FFS showed significantly smaller magnitude (SMD, −1.84; 95% CI, −2.29 to −1.38; $P < 0.001$) and loading rate (mean: SMD, −2.1; 95% CI, −3.18 to −1.01; $P < 0.001$; peak: SMD, −1.77; 95% CI, −2.21 to −1.33; $P < 0.001$) of impact force, ankle stiffness (SMD, −1.69; 95% CI, −2.46 to −0.92; $P < 0.001$), knee extension moment (SMD, −0.64; 95% CI, −0.98 to −0.3; $P < 0.001$), knee eccentric power (SMD, −2.03; 95% CI, −2.51 to −1.54; $P < 0.001$), knee negative work (SMD, −1.56; 95% CI, −2.11 to −1.00; $P < 0.001$), and patellofemoral joint stress (peak: SMD, −0.71; 95% CI, −1.28 to −0.14; $P = 0.01$; integral: SMD, −0.63; 95% CI, −1.11 to −0.15; $P = 0.01$) compared with RFS. However, FFS significantly increased ankle plantarflexion moment (SMD, 1.31; 95% CI, 0.66 to 1.96; $P < 0.001$), eccentric power (SMD, 1.63; 95% CI, 1.18 to 2.08; $P < 0.001$), negative work (SMD, 2.60; 95% CI, 1.02 to 4.18; $P = 0.001$), and axial contact force (SMD, 1.26; 95% CI, 0.93 to 1.6; $P < 0.001$) compared with RFS.

**Conclusion:** Running with RFS imposed higher biomechanical loads on overall ground impact and knee and patellofemoral joints, whereas FFS imposed higher biomechanical loads on the ankle joint and Achilles tendon. The modification of strike techniques may affect the specific biomechanical loads experienced on relevant structures or tissues during running.

**Keywords:** foot strike pattern; distance running; impact load; joint biomechanics

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Distance running is one of the most popular physical activities, and it is associated with a high rate of running-related injuries (RRIs). The rate of RRIs is reported to be 19.4% to 79.3%,[44] and 56% of runners with overuse injuries sustain multiple injuries at least once during a 2-year observation.[31] Furthermore, a recent meta-analysis showed that the incidence of RRIs per 1000 hours of running ranged from 2.5 to 33.0.[47]

Given the high prevalence and incidence, various biomechanical variables have been investigated to reveal the underlying mechanisms of RRIs. Among these variables, high and repetitive applied impact load, including the magnitude and loading rate of impact force (the vertical ground-reaction force [VGRF] during the deceleration phase of running), has been implicated as an important etiologic factor for RRI.[23] A prospective study by Bredeweg et al[3] found that the impact force loading rate was the only predictor of all RRI types in novice male runners. Increased impact force loading rate was reported to contribute to the development of lower limb stress fracture,[42,52] plantar fasciitis,[35] and all RRI types.[23,42] Also, the excessive biomechanical demands directly imposed on local structures and tissues may contribute to RRIs. For example, an increase in patellofemoral joint stress (PFJS) has been proposed to cause patellofemoral pain (PFP).[9,17]

The relationship between biomechanical variables and risks for RRI has prompted numerous running injury reduction strategies, such as modification of running techniques and control of running distance.[4] Among running technique modifications, special attention has been given to foot strike techniques. A retrospective study reported that rearfoot strike (RFS) induced a significantly higher rate of stress injury compared with forefoot strike (FFS).[13] RFS results in a significant increase in magnitude[33] and loading rate[11,51] of impact force, knee eccentric power,[24,40,49] and PFJS[15,45] compared with FFS. Furthermore, a recent running retraining study revealed that converting from RFS to a non-RFS could alleviate the symptoms of runners with PFP.[12] However, FFS increases ankle eccentric power,[40,49] and peak Achilles tendon (AT) stress[29] and force[36] when compared with RFS, which may be responsible for higher risk of ankle injuries. Taken together, these findings indicate that different foot strike techniques may impose various effects on structures or tissues and further influence risks for RRI.

Although there was 1 review in which the biomechanical differences of foot strike techniques were examined, several confounding factors were not well controlled in the specific meta-analyses.[1] Data from studies on running barefoot or with shoes, such as ankle angle and VGRF, were pooled in specific meta-analyses. However, recent evidence indicates significant interaction in certain biomechanical variables between foot strike technique and footwear.[36] The potential confounder can substantially reduce the quality of evidence if not controlled. Furthermore, there is a paucity of reviews examining the effects of foot strike techniques on relevant biomechanical risk factors of RRI, such as knee moments[40] and PFJS.[9,17] Therefore, the purpose of this systematic review and meta-analysis is to, independently and comprehensively, determine effects of foot strike techniques on ground-reaction force and biomechanical joint variables during running.

## METHODS

### Search Strategy

Relevant articles were searched using the databases of Web of Science, PubMed, EMBASE, and EBSCO online from inception through November 2018. Combinations of the following keywords were used: run* OR jog*; foot strik* OR foot land* OR foot fall* OR forefoot strik* OR rearfoot strik* OR mid-foot strik* OR heel strik* OR toe strik*; lower extremit* OR lower limb* OR ankle OR knee OR hip; and biomechanic* OR kinematic* OR kinetic* OR ground reaction force OR impact force OR collision force OR mechanical loading OR loading rate OR moment OR torque OR power OR electromyography OR EMG OR muscle activ*.

### Study Selection

Two reviewers independently identified the relevant studies after the selection process. Initially, the titles and abstracts of the relevant studies were screened against the inclusion criteria. Next, if sufficient information was not included in the title and abstract to determine inclusion, the full text was examined. The following inclusion criteria were applied: (1) studies that assessed healthy adult runners participating in distance running, (2) FFS and RFS were compared and must have been performed by participants from the same group, (3) participants had to wear shoes while running over ground or on a treadmill without slope, (4) the evaluated variables had to be those that relate to running biomechanics, and (5) the studies had to be peer-reviewed and written in English.

### Data Extraction

Two reviewers extracted the characteristics and outcomes of each eligible study, including first author, publication year, methods, sample size, participant characteristics, natural foot strike pattern, foot strike comparison, and other variables. Relevant outcomes included ground-reaction force variables (magnitude and loading rate of impact force and VGRF) and biomechanical joint variables (ankle, knee, and hip angle; excursion; moment; eccentric power and axial contact force; ankle and knee stiffness and negative work; and PFJS).

### Assessment of Risk of Bias

The modified version of the Downs and Black Quality Index was used to assess the risk of bias of the eligible studies.[16] The scale, which was previously applied to running-related reviews,[1,19] consisted of 20 items. Studies with scores of 0 to 6 were categorized as high risk of bias, 7 to 13 as moderate risk of bias, and 14 to 20 as low risk of bias.[1]

### Data Analysis

While there are typically 3 categorical classifications of foot strike techniques, participants from natural FFS and natural midfoot strike (MFS) are often combined into the FFS group.[6,7,8,18,33] Therefore, the meta-analyses were performed on biomechanical outcomes for 2 classifications: FFS (FFS or FFS/MFS) and RFS. The data, which came from 2 natural foot strike techniques[6,7,8,18,37,40] or speeds,[24] were respectively pooled with formulae previously reported by Wang et al.[48] The data captured at preferred step length and frequency and medium speed were included when there were more than 2 step length, step frequency, and speed conditions.[18,29,50] Also, the data collected before a long run were analyzed to avoid the effect of fatigue.[30]

### Statistical Analysis

Inverse variance with the random-effects model was used to calculate the standard mean difference (SMD) using Review Manager (RevMan 5.3). The effect size of each eligible study was presented as SMD with 95% CI. The statistical heterogeneity among studies was identified using the chi-square and $I^2$ statistics (heterogeneity defined as $P < 0.05$ and/or $I^2 > 75\%$).[22] A $P$ value <0.05 was accepted as statistically significant for the overall effect.

## RESULTS

### Search Results

A total of 36 articles met the inclusion criteria, and 10 studies were further excluded from quantitative synthesis due to insufficient data. Finally, 26 studies with 472 participants were eligible for inclusion in this meta-analysis (Figure 1).[5-8,10,11,14,15,18,20,24,27,29,30,33,34,36,37,39-41,45,46,49-51]

### Study Characteristics

Sample sizes of the included studies varied from 9 participants[1] to 42.[6] The participants' natural foot strike pattern was RFS in 13 studies,[5,11,14,15,24,27,30,36,39,45,46,49,51] and FFS in only 1 study.[34] Of the studies, 11 included 2 groups of runners (those whose natural strike pattern was RFS and those whose natural strike pattern was FFS/MFS),[6-8,10,18,20,29,37,40,41,50] while there was only 1 study in which the natural foot strike pattern of participants was FFS/MFS or RFS.[33] Running speed ranged from 2.5 m/s[11,39] to 4.55 m/s.[24] The characteristics of the eligible studies are summarized in Table A1 in the Appendix (available in the online version of this article).

### Risk of Bias

All 26 studies were classified as moderate risk of bias, and the mean risk of bias score for the included studies was 11.35 out of 20 (range, 10-13) (Table A2 in the Appendix, available online).

### Ground-Reaction Force Variables

FFS was found to be associated with significantly smaller peak impact force ($P < 0.001$)[8,33] as well as average ($P < 0.001$)[11,24,27,39,51] and peak impact force loading rate ($P < 0.001$)[11,36,39,51] compared with RFS (Table 1 and Figures A1a-A1c in the Appendix, available online). On the contrary, FFS was associated with significantly greater peak VGRF compared with RFS ($P < 0.001$) (Table 1 and Figure A1d in the Appendix, available online).[15,24,27,41,45]

### Biomechanical Joint Variables

FFS was associated with a more plantarflexed ankle at initial contact (IC) ($P < 0.001$),[14,18,29,36,39,49] smaller peak ankle dorsiflexion angle ($P < 0.001$),[5,14,24,36] and greater ankle excursion ($P = 0.01$)[24,30,39,41] compared with RFS (Table 1 and Figures A2a-A2c in the Appendix, available online).

There were no significant differences between FFS and RFS for knee flexion angle at IC ($P = 0.66$)[14,29,39,45,49] and peak knee flexion angle ($P = 0.09$)[5,14,15,24,45] (Table 1 and Figures A3a and A3b in the Appendix, available online). However, FFS significantly decreased knee flexion excursion compared with RFS ($P < 0.001$) (Table 1 and Figure A3c in the Appendix, available online).[24,27,30,34,39,41,45]

No significant differences were observed between FFS and RFS on hip flexion angle at IC ($P = 0.99$)[14,39,49] and peak hip flexion angle ($P = 0.35$)[5,14,46] and adduction angle ($P = 0.14$)[5,14,46,51] (Table 1 and Figures A4a-A4c in the Appendix, available online). FFS significantly decreased hip flexion excursion compared with RFS ($P = 0.04$) (Table 1 and Figure A4d in the Appendix, available online).[39,41]

It was found that FFS was associated with significantly greater peak ankle plantarflexion moment ($P < 0.001$),[15,24,30,36,40,41] eccentric power ($P < 0.001$),[24,40,49] negative work ($P = 0.001$),[10,40] and axial contact force ($P < 0.001$)[7,11,37] compared with RFS (Table 1 and Figure A5a-A5d in the Appendix, available online). However, FFS decreased ankle stiffness significantly compared with RFS ($P < 0.001$) (Table 1 and Figure A5e in the Appendix, available online).[20,30]

FFS significantly reduced peak knee extension moment ($P < 0.001$),[15,24,30,40,41] eccentric power ($P < 0.001$)[24,40,49] and negative work ($P < 0.001$)[10,40] as well as peak ($P = 0.01$)[7,15,45,50] and integral PFJS ($P = 0.01$)[15,45] compared with RFS (Table 1 and Figures A6a-A6e in the Appendix, available online). In addition, no significant differences were found between FFS and RFS for peak knee axial contact force ($P = 0.07$)[7,37] and stiffness ($P = 0.15$)[20,30] (Table 1 and Figures A6f and A6g in the Appendix, available online).

No significant differences were found between FFS and RFS for peak hip extension moment ($P = 0.31$),[15,40,41] eccentric power ($P = 0.07$),[40,49] and axial force ($P = 0.58$)[7,37] (Table 1 and Figures A7a-A7c in the Appendix, available online).

## DISCUSSION

FFS has lower magnitude and loading rate of impact force compared with RFS. The difference in impact load between FFS and RFS is likely attributed to vertical compliance, as a more compliant joint absorbs greater impact energy than a stiffer

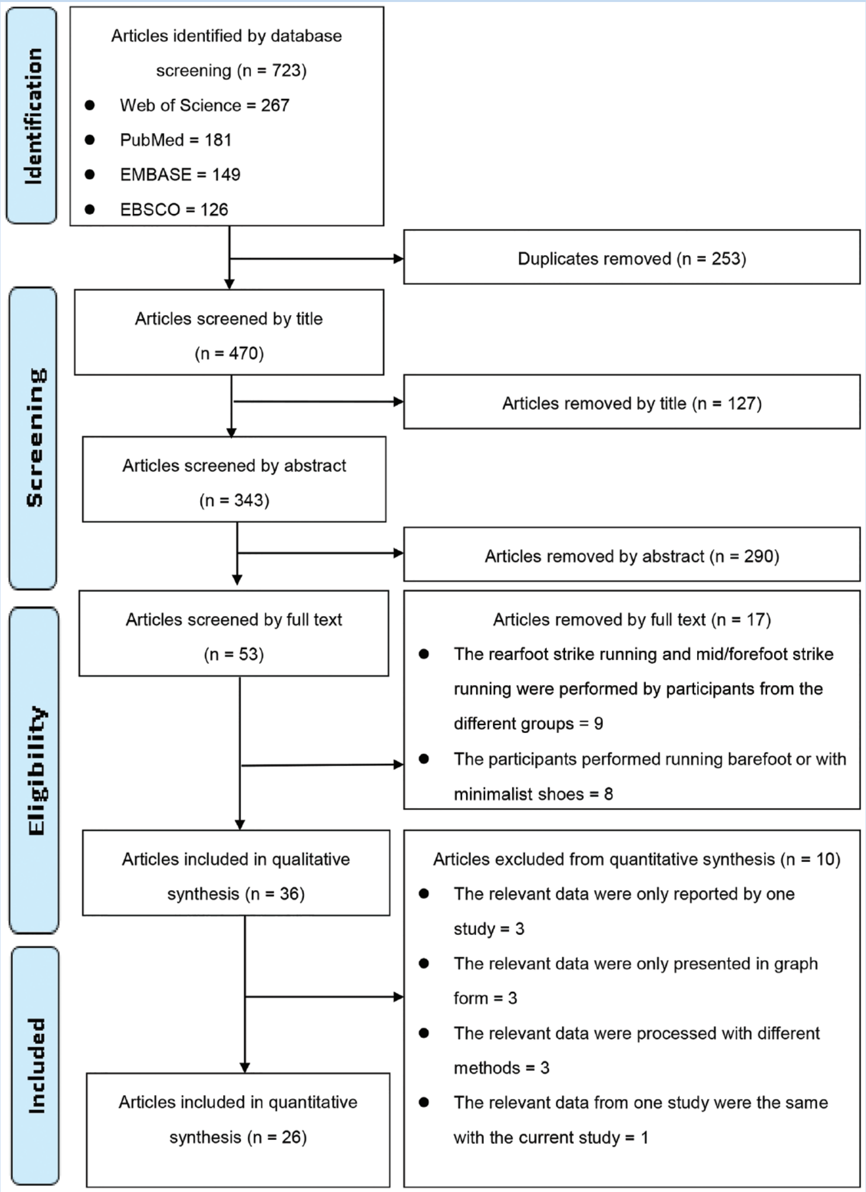


Figure 1. Flowchart of the study screening process.

joint.[20,28,31] Running with FFS increases vertical compliance, and vertical compliance negatively correlates with average impact force loading rate.[28] The ankle can be considered one of the primary joints to reduce impact load during foot-ground contact. It converts part of the translational kinetic energy into rotational kinetic energy when running with FFS,[28] which can be achieved by increased ankle motion[25] and plantarflexor force.[45] Current evidence indicates that the higher impact force loading rate may influence the risks of stress fracture,[42,52] plantar fasciitis,[35] and all RRI types.[23,42] Taken together, RFS may potentially increase the risk of RRI, in particular stress fractures and plantar fasciitis. Moreover, FFS was also found to associate with greater peak VGRF compared with RFS in this review. The greater plantarflexor force over greater ankle excursion is responsible for the increased peak VGRF when running with FFS.[5,45] The greater peak VGRF is likely not the primary contributor to the risk of RRI,[23,42] and the relationship between peak VGRF and RRI requires further investigation.

FFS significantly increased ankle eccentric power and negative work compared with RFS. It was supported by the finding that FFS was associated with significantly smaller ankle stiffness compared with RFS. As mentioned previously, FFS with a more compliant ankle joint can absorb higher impact energy at the ankle compared with RFS.[20,28,31] The eccentric contraction of the plantarflexors is the primary contributor to ankle joint negative work.[21,53] Greater impact energy absorbed at the ankle joint is

Table 1. Pooled effects of the foot strike techniques on ground-reaction force and biomechanical joint variables

| Variables | No. of Related Studies | SMD (95% CI)[a] | *P* |
|---|---|---|---|
| Ground-reaction force variables | | | |
| Peak impact force | 2 | −1.84 (−2.29, −1.38) | <0.001* |
| Average impact force loading rate | 5 | −2.1 (−3.18, −1.01) | <0.001* |
| Peak impact force loading rate | 4 | −1.77 (−2.21, −1.33) | <0.001* |
| Peak VGRF | 5 | 0.84 (0.52, 1.15) | <0.001* |
| Biomechanical joint variables | | | |
| Ankle angle at IC | 6 | −4.16 (−4.83, −3.49) | <0.001* |
| Peak ankle dorsiflexion angle | 4 | −0.83 (−1.14, −0.52) | <0.001* |
| Ankle excursion on sagittal plane | 4 | 1.41 (0.29, 2.54) | 0.01* |
| Knee flexion angle at IC | 5 | 0.23 (−0.79, 1.25) | 0.66 |
| Peak knee flexion angle | 5 | −0.24 (−0.52, 0.03) | 0.09 |
| Knee flexion excursion | 7 | −0.78 (−1.09, −0.47) | <0.001* |
| Hip flexion angle at IC | 3 | 0 (−0.35, 0.35) | 0.99 |
| Peak hip flexion angle | 3 | −0.15 (−0.48, 0.17) | 0.35 |
| Peak hip adduction angle | 4 | −0.19 (−0.45, 0.07) | 0.14 |
| Hip flexion excursion | 2 | −0.55 (−1.09, −0.02) | 0.04* |
| Peak ankle plantarflexion moment | 6 | 1.31 (0.66, 1.96) | <0.001* |
| Peak ankle eccentric power | 3 | 1.63 (1.18, 2.08) | <0.001* |
| Peak ankle negative work | 2 | 2.60 (1.02, 4.18) | 0.001* |
| Peak ankle axial contact force | 3 | 1.26 (0.93, 1.6) | <0.001* |
| Peak ankle stiffness | 2 | −1.69 (−2.46, −0.92) | <0.001* |
| Peak knee extension moment | 5 | −0.64 (−0.98, −0.3) | <0.001* |
| Peak knee eccentric power | 3 | −2.03 (−2.51, −1.54) | <0.001* |
| Peak knee negative work | 2 | −1.56 (−2.11, −1.0) | <0.001* |
| Peak PFJS | 4 | −0.71 (−1.28, −0.14) | 0.01* |
| Integral PFJS | 2 | −0.63 (−1.11, −0.15) | 0.01* |
| Peak knee axial contact force | 2 | 0.35 (−0.03, 0.72) | 0.07 |
| Peak knee stiffness | 2 | 1.45 (−0.51, 3.4) | 0.15 |
| Peak hip extension moment | 3 | 0.19 (−0.18, 0.57) | 0.31 |
| Peak hip eccentric power | 2 | −0.8 (−1.66, 0.06) | 0.07 |
| Peak hip axial contact force | 2 | 0.1 (−0.24, 0.43) | 0.58 |

IC, initial contact; PFJS, patellofemoral joint stress; VGRF, vertical ground-reaction force.
[a]In the SMD column, positive values indicate that forefoot strike (FFS) is larger than rearfoot strike (RFS), and negative values indicate that RFS is larger than FFS.
*Statistical significance between FFS and RFS.

transmitted to AT,[32] which can increase AT load. Furthermore, FFS was associated with increased ankle excursion and reduced knee flexion excursion in this review, which indicates that more energy is likely absorbed at the ankle than the knee. However, lesser knee flexion excursion during running may be a risk factor for AT injuries.[2] Also, FFS is linked to higher ankle axial contact force in this review. Joint contact force is primarily composed of muscle forces and joint reaction forces across the joint during normal range of movement, and muscle forces are the major contributor to joint contact force compared with joint reaction forces.[38] Higher ankle axial contact force indicates greater plantarflexor force, which likely contributes to the increased AT stress and strain and further to the pathomechanics of AT injuries when running with FFS.[26] This review shows that FFS imposes higher biomechanical loads on the ankle joint (including AT) and potentially increases the risks of RRI at the ankle joint, in particular AT injuries, compared with RFS.

On the contrary, RFS is associated with greater knee eccentric power and negative work compared with FFS. More energy is absorbed at the knee than at the ankle when running with RFS,[10,20] which can be attributed to a more compliant knee and stiffer ankle.[20,30] RFS significantly elevates peak and integral PFJS compared with FFS, which may potentially contribute to PFP based on the relationship between the etiology of PFP and PFJS.[9,17] The difference in PFJS between RFS and FFS is likely attributed to the differential knee extension moment and quadriceps force.[15,43,45] Combining these findings, the current review suggests that RFS may increase the biomechanical loads experienced at the knee joint (including patellofemoral joint) and potentially elevate the risk of RRI at knee, particularly PFP, compared with FFS.

Seven hip joint–related variables were included in the meta-analysis. Hip flexion excursion was the only variable that was significantly influenced by the foot strike pattern. FFS was associated with increased ankle excursion and reduced hip and knee excursion on the sagittal plane compared with RFS. The various motion patterns across the lower limb joints can help control the movement of the body center of mass in the vertical direction aimed to modify energy absorption at different joints.[28,40] However, this review found no significant differences in hip kinetic variables between FFS and RFS, indicating that foot strike pattern has little biomechanical effect on hip joint kinetics during running.

## CONCLUSION

Running with RFS was linked to the increasing impact loads and placed higher biomechanical loads on structures or tissues around the knee and patellofemoral joints. However, running with FFS placed higher biomechanical loads on more distal structures, such as the ankle joint and Achilles tendon. The influence of foot strike techniques on running biomechanics indicates that the foot strike techniques are likely used to modulate the biomechanical loads of various structures or tissues during running.

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