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Footstrike Patterns in Runners: Concepts, Classifications, Techniques, and Implications for Running-Related Injuries

Fußaufsatz bei Läufern: Konzepte, Klassifikationen, Techniken und Implikationen für laufbedingte Verletzungen

REVIEW

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Summary

› **The footstrike pattern** of an athlete is understood as the way the foot touches the ground. Over the years, several definitions and techniques to classify and quantify footstrike patterns have been described. Therefore, this narrative review summarizes the existing classifications of footstrike patterns, gives suggestions for further use of these classifications, and provides a summary of the relationship between footstrike patterns and the occurrence of overuse injuries.

› **Footstrike patterns are classified** by using nominal (e.g. forefoot strike, midfoot strike, rearfoot strike) or continuous variables (e.g. footstrike angle). Possible assessments include visual, video-based, 3D-biomechanical, force plate-based or inertial measurement unit-based analysis.

› **Scientists, coaches, and clinicians** can choose between different methods to analyze footstrike patterns in runners. All approaches to classify footstrike patterns have advantages and limitations. In certain situations, it might be beneficial to combine these methods. Despite great efforts in analyzing footstrike patterns, relationships between footstrike patterns and running-related injuries are mostly unclear at present. Based on the current literature, causal links to overuse injuries, recommendations to change running technique, and other simplifications solely based on the footstrike pattern must be considered critically.

KEY WORDS:
Running, Biomechanics, Overuse Injuries

Zusammenfassung

› **Seit langem ist die biomechanische Analyse** des Fußaufsatzes bei Läufern Bestandteil zahlreicher wissenschaftlicher Untersuchungen. Über die Jahre wurden jedoch verschiedene Klassifikationen und Techniken zur Messung des Fußaufsatzes bei Sportlern beschrieben und verwendet. Aus diesem Grunde erfolgt im Rahmen dieser narrativen Übersichtsarbeit eine zusammenfassende Darstellung aller gängigen Verfahren unter Einbeziehung neuer technischer Entwicklungen der letzten Jahre. Zusätzlich wird ein Überblick über entsprechende Assoziationen zwischen Fußaufsatz und Überlastungsverletzungen gegeben.

› **Grundsätzlich** ist zwischen nominalen Klassifikationen (z. B. Vorfuß-, Mittelfuß-, und Fersenlauf) und kontinuierlichen Variablen (z. B. Fußwinkel) zu unterscheiden. Die Analyse kann visuell, per Kamera, per 3D-Bewegungsanalyse, auf der Basis von Kraftmessplatten oder mittels Inertialsensoren erfolgen.

› **Wissenschaftler, Trainer und Therapeuten** können sich hierbei auf reliable und validierte Verfahren stützen, wenngleich alle Herangehensweisen individuelle Vor- und Nachteile aufweisen. In bestimmten Situationen kann es hilfreich sein, mehrere Methoden zu kombinieren. Trotz großer wissenschaftlicher Anstrengungen in der letzten Zeit bleiben Zusammenhänge zwischen Fußaufsatz und laufassoziierten Überlastungsverletzungen überwiegend unklar. Basierend auf der aktuellen Literatur sollten aktuell sowohl kausale Verknüpfungen zwischen Fußaufsatz und Überlastungsverletzungen als auch Empfehlungen zur Änderung des Fußaufsatzes kritisch hinterfragt werden.

SCHLÜSSELWÖRTER:
Laufen, Biomechanik, Überlastungsverletzungen

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Introduction

Biomechanical running gait analysis in athletes has been reported to be a crucial part of improving running style (9, 13). Clinicians commonly analyze running gait patterns to prevent or treat injuries that are related to a poor alignment or possibly damaging biomechanics (27). Besides the clinical significance of an appropriate running gait analysis, scientists also assess the biomechanics of athletes, mostly runners, to ensure an efficient running technique (41).

A common component of analyzing running technique is the determination of footstrike patterns in athletes (9, 11, 22). Typically, the footstrike pattern is defined as a biomechanical analysis of the way the foot touches the ground (35), A common interpretation of this definition uses the distinction of three footstrike patterns (Fig. 1): forefoot strike (FFS), midfoot strike (MFS), rearfoot strike (FRS). Several modifications have been made to this popular classification. For instance, some authors ›

Figure 1

Rearfoot strike (RFS): The rearfoot contacts the ground first (A); Midfoot strike (MFS): simultaneous landing of forefoot and rearfoot (B); Forefoot strike (FFS): The forefoot contacts the ground first (C).

differentiate between an FFS where the toe touches the ground before the heel and an FFS (so-called toe strike) where the heel never touches the ground (35). It is therefore hardly surprising that several authors mention and criticize the coexistence of different footstrike pattern classifications (4, 9, 16, 20, 22, 35, 47, 48). Thus, the main purpose of this paper is to narratively review the literature and to summarize the existing classifications and techniques of footstrike patterns in runners. To provide readers with information for everyday clinical practice, we additionally summarize the relationship between footstrike patterns and the occurrence of overuse injuries.

Classifications and Techniques

Nominal (Visual) Classification

A nominal (visual) classification of footstrike patterns usually requires a lateral view on the runner's foot (12, 46). Sometimes the attempt is made to identify the footstrike pattern of an athlete without a video recording. However, not only for research purposes, a lateral video recording is recommended and often necessary to avoid misinterpretation (46). To analyze the footstrike accurately, a high-speed camera (preferably more than 120 frames per second, but there are no specific recommendations) with slow motion or frame-by-frame analysis should be used (16).

A commonly used footstrike pattern classification is the differentiation of RFS, MFS, and FFS as compiled by Lieberman (35):

1. Rearfoot strike: A rearfoot strike is sometimes called a "heel-toe-run" or "heel strike", meaning that the heel of the foot contacts the ground first, whereas the forefoot contacts the ground later.
2. Midfoot strike: Technically, a midfoot strike is defined as simultaneous landing of forefoot and rearfoot, often meaning that the runner contacts the ground with the outside edge of the foot or shoe.
3. Forefoot strike: In a forefoot strike, the forefoot contacts the ground first, usually followed by the heel touching the ground.

However, there is no consensus on how to define and classify footstrike patterns yet. Hasegawa et al. (25) introduced the following definition: If footstrike initially contacts the ground with the posterior third (heel) of the foot only, it is termed an RFS. If the footstrike initially is the front half (the ball) of the foot only, it is termed an FFS. Otherwise, it is termed an MFS.

Additionally, some authors differentiate between an FFS where the ball touches the ground before the heel and an FFS (so-called toe strike) where the heel never touches the ground (35, 37). According to Hamill & Gruber (22), the toe strike can only be defined as an FFS whereas an initial touchdown of the forefoot with subsequent ground contact of the rearfoot can be seen as MFS. Other authors combined an MFS and an FFS to a non-rearfoot strike (27, 31). This might be due to difficulties in the correct determination of "simultaneous" landing of forefoot and rearfoot, due to low occurrences of MFS and FFS patterns, but also due to similar biomechanical characteristics of ankle joint kinetics and muscle activation (1, 16, 24, 27, 34). Instead of referring to a non-RFS, some authors just refer to FFS – the latter also including MFS (1, 25, 34, 37).

Generally speaking, the visual and video-based classification is an easy and cheap method that is frequently used in research and training routine. However, it is often argued that foot striking of an athlete differs individually as runners use various forms of touching the ground. By differentiating just three types of foot striking (FFS, MFS, RFS), biomechanics of running might be over-simplified (39). For instance: RFS includes both, extreme landing on the heel as well as a situation where the heel lands just right before the forefoot. From a biomechanical standpoint, those two conditions might affect running technique, muscle activity, ground reaction forces, or force absorption (39). Under the traditional classification, both types of foot striking are classified the same (as RFS). Hence, clinicians should take into consideration that footstrike patterns, even if grouped the same way, differ individually. Finally, it should be mentioned that this method of classifying footstrike patterns relies on subjective decisions, especially when considering that exact simultaneous landing of fore- and rearfoot rarely exists. However, when performed by experienced reviewers, agreement was reported to be >99% and reliability (weighted kappa κ=0.96; n=28) is excellent (43). The accuracy of this method was shown to be 75-91% (compared to footstrike angle) or 77-92% (compared to foot strike index), respectively (2, 40).

Footstrike Angle

The footstrike angle (FSA) is a measurement of the angle between foot and ground at initial contact (2, 37). Technically, the FSA is similar to the Nominal (Visual) Classification described above. To determine the FSA, a lateral view is required if no indirect measurement is made using wearable technology. Instead of classifying nominal variables (FFS, MFS, RFS), the exact angle at footstrike is measured (continuous variable). Two markers can be placed on the athlete's shoe or foot, respectively: (A) calcaneus and (B) 5th metatarsal head (37). The vector AB is formed and the angle between AB and the ground is measured during stance as well as during initial ground contact while running. It is, of course, possible to form vectors without previous marker placement by just evaluating a video recording (43).

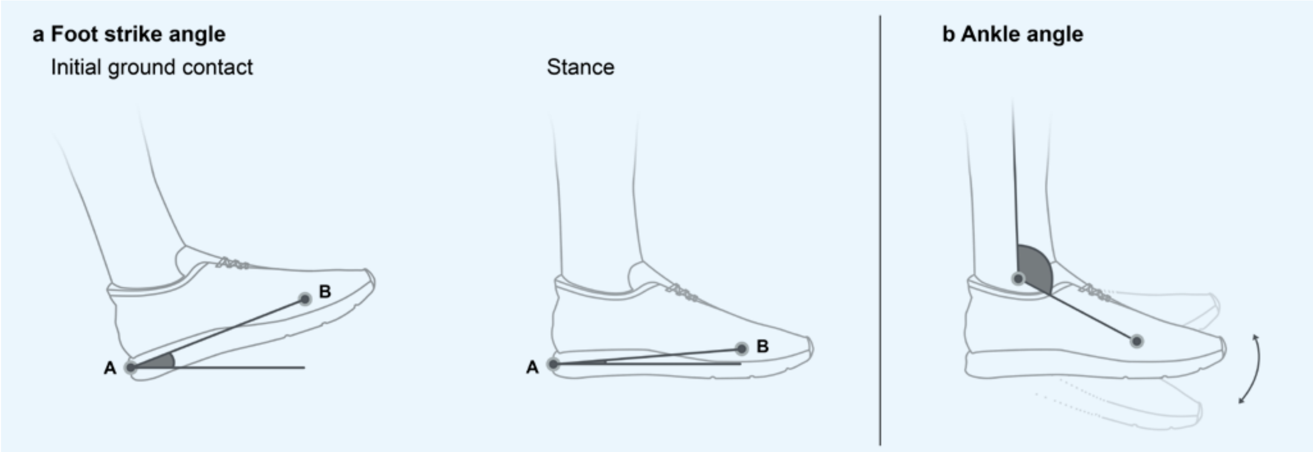

Figure 2

a) The vector AB is formed by calcaneal marker A and metatarsal 5 head marker B. The angle ∡AB represents the angle between AB and the earth horizontal. Finally, the foot strike angle can be calculated: Foot strike angle = ∡ABinitial ground contact - ∡ABstance. Modified from (2). b) Negative ankle angles indicate plantarflexion, positive angles indicate dorsiflexion. Forefoot and midfoot striking are associated with a more plantarflexed foot position. Rearfoot striking is associated with a more dorsiflexed position.

In these cases, the (sole) angle between ground and sole of the running shoe at initial ground contact can be used to determine FSA (43).

It is not always easy to find the exact moment of initial contact. In daily clinical practice, it might be appropriate to evaluate the moment of foot striking by visually analyzing the video records. However, for research purposes the exact moment of foot striking is often determined by using data from force plates, pressure plates or a three-dimensional motion capture system (15). Once the time point of initial ground contact has been identified, the FSA can be calculated (Fig. 2a):

$$FSA = ∡AB_{initial\ ground\ contact} - ∡AB_{stance}$$

To classify FSA under the traditional footstrike definitions (FFS, MFS, RFS), Altman & Davis (2) used the following conversion:

FFS: FSA < -1.6°
MFS: -1.6° < FSA < 8.0°
RFS: FSA > 8.0°

The limits, especially the angles corresponding to an MFS, can also be chosen more strictly (36, 47, 49). In short, the FSA is seen as a valid (R^2=0.85; correlated to foot strike index) and reliable (intraclass correlation coefficient=0.88 based on a 2-way mixed-effects single measurement model; typical error=2.5°; coefficient of variation=17.6%; n=28) method for evaluating footstrike patterns (2, 43). However, just like other two-dimensional techniques, the FSA does not reflect the three-dimensional anatomy of the foot.

Ankle Angle and Ankle Moment

As mentioned above, the FSA is calculated by a foot segment and the earth horizontal. By contrast, determination of the ankle angle uses a foot vector relative to a shank vector (Fig. 2b). Measurements of the ankle angle commonly require – like the FSA – at least two-dimensional sagittal plane kinematics (21). FFS and MFS are characterized by a more plantarflexed foot position (e.g. ankle angle below 0° relative to a neutral standing position) at touchdown whereas RFS is characterized by a more dorsiflexed position (e.g. ankle angle above 0°) of the foot (20, 21, 33). Taking an intraclass correlation coefficient and a coefficient of multiple correlation of >0.90 and within- and inter-assessor errors <3° into consideration, the determination of the ankle angle in runners may be assumed to be reliable (38). However, to the best of our knowledge, this approach was not proven to be valid to classify footstrike patterns yet. The examiner should be experienced as marker placement is prone to errors.

Garofolini et al. (18) described a new classification that combines the measurement of vertical ground reaction force (vGRF) and joint kinetics. During a phase of initial contact, defined by an increase of vGRF, the ankle moment was determined. In RFS, touchdown of the foot occurs with the rearfoot. After initial contact the forefoot moves down towards a flat foot position (plantarflexion movement). The external plantarflexion moment is balanced with an early internal dorsiflexion moment (32). Consequently, athletes with mainly internal dorsiflexion moments were classified as RFS. In FFS, touchdown of the foot occurs with the forefoot. After initial contact the rearfoot commonly moves down towards a flat foot position (dorsiflexion movement). The external dorsiflexion moment is balanced with an internal plantarflexion moment. Consequently, athletes with mainly internal plantarflexion moment were classified as FFS. The advantage of this classification might be that it better reflects force vectors during footstrike and the individual anatomy of the foot (18).

Foot Strike Index

Besides the footstrike classifications described above, another approach is frequently used to describe footstrike patterns. The "foot strike index" (FSI) does not primarily focus on the visible ground contact of the foot, but rather on measuring forces that occur during footstrike (2). Using this approach, the footstrike pattern can be determined by the location of the center of pressure (COP) relative to the foot during ground contact (6). An instrumented treadmill or a sensor insole is usually required to apply the FSI as this method relies on force/pressure data. However, indirect measurements with inertial measurement units (IMUs) have been a promising approach lately (3). Based on the FSI, an RFS can be determined when the COP is located between 0% and 33% of the total foot length (Fig. 3). A COP between 34% and 67% indicates an MFS and a COP between 68% and 100% quantifies an FFS (2). The FSI is commonly used for evaluation of shod and barefoot runners (2, 20, 30).

The importance of the FSI is that this technique can indicate how the ground reaction force vector acts on the foot. Repetitive forces that are applied to the human body are considered a ›

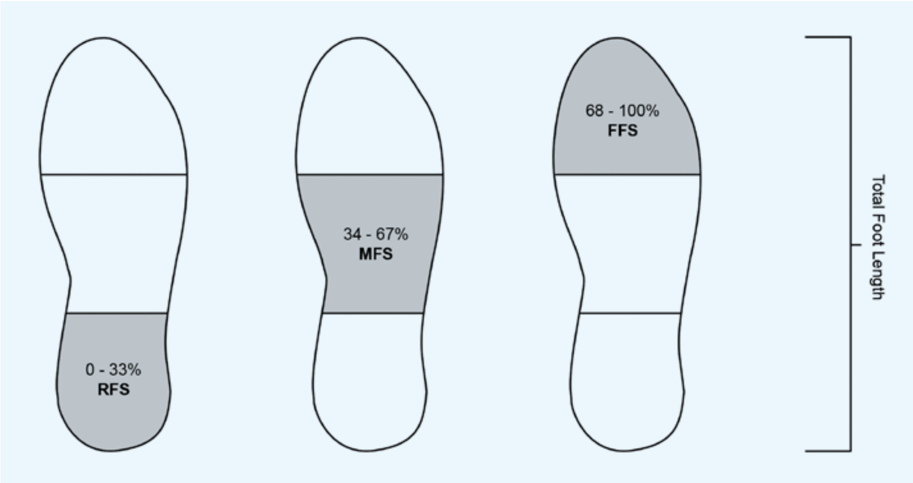

Figure 3
Center of pressure at initial contact determines the foot strike (Rearfoot strike: 0-33%; Midfoot strike: 34-67%, Forefoot strike: 68-100%). Modified from (2).

major contributor to running-related overuse injuries (17, 50). Not only for this reason, the FSI might be considered the "gold standard" in the analysis of footstrike patterns (2). However, the FSI is, just like other classifications, still far from entirely addressing the musculoskeletal system of the foot during foot striking (18). Therefore, few researchers proposed to rely on more values than just the COP (18, 20). Besides the anatomical situation of the ankle, they recommended to take the vGRF into consideration. This idea is based on the assumption that RFS runners often experience a higher impact peak than MFS/FFS runners (37). However, determination of footstrike patterns depending on impact peaks cannot be regarded as a standard procedure. Nowadays, instrumented treadmills are expensive and limited to a biomechanical laboratory setting – and therefore limited in a practical setting. This may change as wearable technology (e.g. shoe insoles with the feature to measure plantar pressure) is getting increasing attention.

Additional Parameters and Techniques

It was reported that more than one parameter might be useful to classify footstrike patterns (20, 21, 23). Besides ankle and footstrike angles, athletes with different footstrikes differ in many other kinetic and kinematic parameters. As mentioned above, it has been indicated that the occurrence of a visible impact peak shortly after initial ground contact correlates with the type of foot striking (37). A high impact peak in vGRF can often be observed in RFS running (20). Therefore, spatio-temporal, kinematic, and kinetic parameters, such as vGRF, may additionally be used to distinguish between footstrike patterns (21). Other parameters, which are known to be influenced by footstrike patterns, include cadence, stride length, contact time as well as hip, knee, and foot characteristics (7, 14, 17, 25, 33, 42, 52). To measure biomechanical parameters outside the lab, the use of IMUs is regarded as a promising technology (27). Usually, IMUs are devices that commonly combine accelerometers, gyroscopes, and occasionally magnetometers. Regarding footstrike, it was already shown that IMUs are valid to detect footstrike patterns (19).

Overuse Injuries and Practical Implications

When it comes to the relationship between footstrike patterns and overuse injuries, scientists have dealt with two major questions. One question concerns the possible correlation between injury occurrence and habitual footstrike pattern (11). In particular, do runners with a certain kind of footstrike pattern have an increased risk of developing running-related injuries, such as runner's knee, Achilles tendinopathy, plantar fasciitis, iliotibial band syndrome, or bone stress injuries (i.e. stress fractures)? The other question concerns the issue of whether a change of footstrike patterns could reduce the incidence of running-related injuries (22). In particular, should runners be advised to change their type of foot striking?

Some studies, mainly retrospective, directly investigated the relationship between footstrike pattern and injury occurrence. Daoud et al. (9) reported a lower overall incidence of running injuries in forefoot runners. By contrast, other studies showed that the individual footstrike patterns do not correlate with injury occurrence (45, 51). Just recently, a systematic review by Anderson et al. (4) highlighted the lack of prospective studies investigating the relationship between footstrike patterns and injury risk. A similar situation with conflicting study results arises when comparing injury risk with kinematic, kinetic, and electromyographic parameters (44). It has been known that the likelihood of occurrence of a visible impact peak shortly after initial ground contact depends on the type of foot striking (37). A high impact peak in vGRF can often be observed in RFS runners. Absence or unidentifiability of such an impact peak in MFS and FFS runners was assumed to be protective against overuse injuries (37). However, this finding is not supported by other studies (48, 53). More generally, it was shown that FFS (compared to RFS) is associated with a higher ankle plantarflexion angles at ground contact, higher knee flexion angles at ground contact, lower knee range of motion, and lower peak and average vertical loading rates (4, 11). Individual studies reported more parameters, though they failed to attain significance in the systematic review by de Almeida et al. (11). Besides knee angle, ankle angle, and vertical loading rates, transition from rearfoot towards forefoot/midfoot striking was mainly assumed to change stride length, contact time, and step frequency as well as hip, foot, and leg characteristics (4, 7, 14, 25, 33, 42, 52).

Among all kinetic and kinematic variables, the investigation of vertical loading rates during running has gained high attention within the last years (5, 10). For instance, vertical loading rates are seen as an import factor contributing to the development of running-related injuries, especially bone stress injuries (50, 53). A study by Davis et al. (10) reported that female runners with a diagnosed injury showed higher vertical average loading rates compared with "non-injured" runners. Remarkably, a recent study showed a non-linear (cubic) relationship between FSA and vGRF (47). This finding questions the frequent gait retraining advice of changing an RFS towards an MFS/FFS. Furthermore, this study corroborates the idea that footstrike patterns should be measured as continuous variables when looking at vGRF (48). Besides vertical loading rates, many other biomechanical parameters are assumed to be linked to running-related injuries. For instance, stride length, cadence and rearfoot eversion were discussed as contributing to injury risk in runners (11). It was noted that forefoot runners exhibit higher mechanical loading characteristics on ankle structures whereas rearfoot runners show a higher loading of the knee joint (7, 13). One possible conclusion of this fact is that forefoot runners are more prone to ankle and foot injuries and rearfoot runners more prone to knee injuries (32). The injury patterns of the human foot may also differ as MFS/FFS running could possibly increase the risk for metatarsal, plantar, and submetatarsal skin injuries (42). By contrast, RFS could possibly increase the risk for injuries of the calcaneus, cartilage, tibialis anterior tendon, and heel soft tissue (42).

To ensure relevance of the data, prevalence of footstrike patterns among runners should be taken into consideration. Rearfoot striking is by far the most common footstrike pattern in (shod) running (24, 27). The prevalence of rearfoot striking may be influenced by running velocity (8), footwear (8, 28), habituation to footwear (30), running distance (26), competition level (25), age (29), and fatigue (9). As a higher running speed seems to make it necessary to change the footstrike pattern towards the forefoot, MFS and FFS are commonly seen in sprinting and middle-distance running (26). In long-distance running, a greater percentage of RFS in recreational runners (compared to competitive or elite runners) was reported (25). Nevertheless, there is evidence that even competitive runners prefer using an RFS during running (24, 25, 27). Beyond that, it is uncertain if and to what extent MFS/FFS could give a performance advantage to the athlete (4).

This narrative review highlights a lack of evidence linking footstrike patterns to biomechanics, running-related injuries, and running performance. The increasing popularity of IMUs, other wearable technology, big data analysis, or indirect stress measurements such as finite element modelling could create new opportunities in the field of running gait analysis and the identification of predisposing factors for overuse injuries.

Conclusions

In daily clinical practice, there is a variety of options to detect footstrike patterns. Nominal classifications as well as continuous variables are frequently used. Possible assessments include visual, video, 3D-biomechanical, force plate-based, or IMU-based analysis. Even for research purposes, most classifications and techniques have been proven reliability and validity, including visual assessment and measurement of the footstrike angle. However, the foot strike index is often seen as the "gold standard," but it can be assumed that IMUs and other wearables will gain more attention. Further research of comparing classifications of footstrike pattern and validity of IMU-based footstrike pattern determination is recommended. Until more evidence is available on this subject, we recommend the continued use of the well-established classification systems and techniques. Scientists should be aware that there is no consensus on how footstrike patterns are defined. In the literature, terms are used interchangeably. We advise scientists to pay more attention on describing the methodology of footstrike pattern analysis as well as using concrete definitions. Finally, despite the relatively high number of studies on footstrike patterns and injury risk, it needs to be mentioned that the evaluation of a footstrike pattern is far from entirely describing the musculoskeletal function of the foot during running. Clinicians should be aware that biomechanical characteristics such as a footstrike pattern may increase the risk of some running-related injuries but reduce the risk in others. At present, recommendations to change the running technique, relationships to overuse injuries, and other simplifications solely based on the footstrike pattern must be considered critically.

Conflict of Interest

The authors have no conflict of interest.

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