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Original Research

Agreement between 2D Visual- and 3D Motion Capture-based Assessment of Foot Strike Pattern

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Keywords: foot strike pattern, forefoot strike, midfoot strike, non-rearfoot strike, rearfoot strike, strike angle, strike index

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Background

Foot strike patterns during running are typically categorized into two types: non-rearfoot strike (NRFS) and rearfoot strike (RFS), or as three distinct types: forefoot strike (FFS), midfoot strike (MFS), and RFS, based on which part of the foot lands first. Various methods, including two-dimensional (2D) visual-based methods and three-dimensional (3D) motion capture-based methods utilizing parameters such as the strike index (SI) or strike angle (SA), have been employed to assess these patterns. However, the consistency between the results obtained from each method remains debatable.

Hypothesis/Purpose

The purpose of this study was to examine the agreement for assessing foot strike patterns into two (NRFS and RFS) or three types (FFS, MFS, and RFS) between 2D visual- and 3D motion capture-based methods. The authors hypothesized that using two description types (NRFS and RFS) would have high inter-method reliability; however, using three description types (FFS, MFS and RFS) would have lower inter-method reliability because of the difficulty in distinguishing between FFS and MFS.

Study design

Controlled Laboratory Study

Methods

Overall, 162 foot strikes from four healthy runners with various foot strike patterns were analyzed. Running kinematics and kinetics were recorded using a 3D motion capture system with a force platform. Each foot strike was filmed at 240 fps from the sagittal perspective. The visual, SI, and SA methods were used, and the kappa values for each method were calculated.

Results

An assessment of the two types of foot strike: NRFS and RFS, revealed almost perfect kappa values (κ = 0.89–0.95) among the visual, SI, and SA methods. In contrast, an assessment of the three types: FFS, MFS, and RFS, revealed relatively low kappa values (κ = 0.58–0.71). Kappa values within the NRFS category, which includes MFS and FFS, ranged from fair to slight (κ = 0.08–0.33).

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Conclusion

Previous laboratory findings that categorized foot strike patterns into two distinct types may be applied in observational studies, clinical practice, and training situations.

Level of evidence

Level 2

INTRODUCTION

Foot strike patterns during running are classified into two or three types depending on the specific part of the foot that makes initial contact with the ground. A forefoot strike (FFS) occurs when the ball of the foot or the front third part of the foot lands before the heel. Midfoot strike (MFS) involves the simultaneous landing of the whole foot, and rearfoot strike (RFS) is characterized by the heel or rear third of the foot landing first.[1,2] In certain studies, FFS and MFS have been classified together as one group: non-rearfoot strike (NRFS), in which the heel does not land first.[3] RFS runners have demonstrated higher initial vertical loading rates than NRFS runners; thus, RFS runners were considered to have a higher risk of running-related injury (RRI) such as stress fracture of the lower extremities or plantar fasciitis.[4-7] In contrast, NRFS runners demonstrated higher force applied around the ankle joint than RFS runners; thus, they were considered to have a higher risk of RRI occurring in the Achilles tendon or lower leg.[8,9]

The strike index (SI), initially proposed by Cavanagh and Lafortune[1] approximately 40 years ago, has become the gold standard method for assessing foot strike patterns. They measured the location of the center of pressure (COP) at initial contact relative to the foot length as the SI, and then, classified it into three patterns as follows: 66.7–100 % from the heel as FFS, 33.4–66.6 % as MFS, and 0–33.3 % as RFS. Many previous studies have used three-dimensional (3D) motion capture systems with force platforms[1,10] or pressure plate systems[11,12] in laboratories to measure the COP location and then calculated the SI for assessing foot strike patterns.

The strike angle (SA), which is the angle between the foot and the running surface at initial contact relative to static posture, is also commonly used for assessing foot strike patterns.[13-15] A negative SA value indicates that the ankle joint is more plantar flexed, whereas a positive SA value indicates that it is more dorsiflexed. Altman and Davis[13] previously proposed specific cut-off values of -1.6° to differentiate between FFS and MFS and 8.0° to distinguish MFS from RFS. These values were calculated based on kinematic data collected via a 3D motion capture system. Thus, the SI and SA settled each value on a certain figure, and assessment results of those methods were highly correlated.[13] Consequently, SA is primarily used in laboratory-based research, similar to the SI.

While two laboratory 3D motion capture-based methods exist for evaluating foot strike patterns, there is also a visual classification method available for assessing foot strike patterns *in situ*.[2,3] Using a high-speed digital video camera at 240 or 180 frames per second (fps), foot strike patterns were visually classified into two or three types based on the initial contact point of the foot with the surface. Visual classification is predominantly utilized in field-based observational studies to assess the incidence of RRI for each foot strike pattern type,[16,17] or to analyze step variables in track events or road races.[2,3] In these earlier studies, participants were filmed from a sagittal perspective, often from outside the running track, and foot strike patterns were assessed using two-dimensional (2D) images. Intra- and inter-rater reliabilities of the visual classification results were excellent or very good on a treadmill or overground.[18,19] However, the categorization of foot strike patterns into two (NRFS and RFS) or three types (FFS, MFS, and RFS) has been inconsistent, and there is no consensus regarding whether NRFS should be further subdivided into FFS and MFS.

Although the basics of the theory of classification methods are the same for the SI, SA, and visual classification, studies examining the agreement among them are limited. For example, in certain observational studies that examined the agreement among the SI, SA, and visual classification involving overground running, the camera's frame rate was only 30 fps,[20] or the pressure plate had a low sampling frequency compared with the 3D motion capture systems used in previous studies.[1,13,21] These limitations can result in an unclear representation of the foot touchdown during running. Consequently, the consistency between the results of each classification method remains debatable, and it remains uncertain whether the findings from laboratory-based studies can be readily applied to observational *in situ* studies. Previous observational studies, which used 2D visual classification for foot strike patterns, have revealed differences in the type of RRI between foot strike patterns.[16,17] While these studies referenced the aforementioned 3D motion capture-based investigations in their discussions, it is worth noting that the methods used for foot strike pattern assessments varied across the studies. Therefore, it is essential to clarify the degree of agreement between the SI, SA, and visual methods for foot strike assessment to apply laboratory findings to visual-based observational studies or clinical practice.

The present study aimed to examine the agreement for assessing foot strike patterns into two (NRFS and RFS) or three types (FFS, MFS, and RFS) between 2D visual- and 3D motion capture-based methods. The authors hypothesized that classifying foot strike patterns into two types (NRFS and RFS) have high inter-method reliability; however, using three description types (FFS, MFS and RFS) would have lower inter-method reliability because of the difficulty in distinguishing between FFS and MFS using 2D methods.

MATERIALS AND METHODS

PARTICIPANTS

Four healthy recreational male runners without lower-extremity injuries in the prior six months participated in the study. Their age, height, and monthly running mileage were verbally confirmed and entered into a Microsoft Excel (Microsoft Corp., Washington, USA) file on site. The study was approved by the Ethics Committee of Waseda University (#2021-384) and was conducted in accordance with the tenets of the Declaration of Helsinki. All participants provided written informed consent before participation.

DATA COLLECTION

During all data collecting trials, participants used their own running shoes. All of their shoes were standard running shoes, and there were no low drop shoes or minimal footwear. Before the data collection, participants had 15–30 min for both warm up, including static and/or dynamic stretching and familiarization trial for running in their preferred speeds. Ten reflective markers (three tracking markers with red boundaries and seven anatomical markers) were attached to the bottom and middle of the heel; upper heel; lateral heel; first, third, and fifth metatarsal heads; toe; medial and lateral malleolus of the right shoes; and toes[10,13] (Figure 1).

Prior to the running trial, a static standing calibration trial was performed for at least 2 sec. Subsequently, the running trial was performed on a 20 m runway using a 3D motion capture system and force platforms (Figure 2). The participants were instructed to run at their preferred running speeds and land on one of the force platforms with their right foot under the following four conditions: uncontrolled habitual foot strike; FFS, to land with the third part of the foot; MFS, to land with the mid-third part of the foot or simultaneously land the whole foot; and RFS, to land with the rear third part of the foot. The sequence of the conditions was randomized, and the participants ran 10 trials for each condition. If participants stepped force platforms twice by their right feet in one trial, the analysis included both steps.

The marker trajectories and ground reaction force were recorded using a seven-camera 3D motion capture system (T40-S, Vicon, Oxford, UK; 250 Hz) and three built-in force platforms (9287C, Kistler Instrumente AG, Winterthur, Switzerland; 1000 Hz, 0.9 m × 0.6 m), respectively. The x-, y-, and z-axes of the global coordination system were defined as the medial-lateral, anterior-posterior, and vertical directions of the participants, respectively.

A high-speed digital video camera (GC-LJ25BM, Sports Sensing, Fukuoka, Japan; 240 fps) was mounted on a stationary tripod at a height of 0.8 m perpendicular to the runway. All running trials were filmed from the participants' sagittal perspective. Photocells (NT7728A, NISHI Sports, Tokyo, Japan; 100 Hz) were placed at 15 m intervals along the center of the runway to capture running times. Trials were rejected if the participant obviously targeting the force platforms, or if the participant accelerated or decelerated during a trial.

DATA PROCESSING – KINEMATIC AND KINETIC DATA

The marker trajectories were reconstructed and labeled using Vicon Nexus 2.11 (Vicon Motion System Limited, Oxford, UK). The marker trajectories and ground reaction force data were filtered using a fourth-order low-pass Butterworth filter at 8 and 50 Hz, respectively.[10] The body weights (BW) of the participants were calculated using the ground reaction force in a static standing calibration trial. The point of initial contact was defined as the moment at which the ground reaction force exceeded 20 N.[20] All foot strikes were classified as RFS, MFS, or FFS using the SI and SA methods.

The SI was calculated using the location of the COP at the initial contact relative to the foot length, which is the distance between the heel and toe. Subsequently, foot strike patterns were classified into three types: FFS, 66.7–100%; MFS, 33.4–66.6%; and RFS, 0–33.3%.[1,12] Furthermore, FFS and MFS were combined as NRFS: SI of 33.3–100%.

The SA was calculated by subtracting the foot angle during the static standing trial from that at the initial contact during the running trial in sagittal plane. The foot was defined as the line connecting the third metatarsal and bottom of the heel, with the foot angle representing the angle between the foot and the ground. Foot strike patterns were classified into three types: FFS, <-1.6°; MFS, between -1.6° and 8.0°; and RFS, >8.0°.[13] Furthermore, FFS and MFS were combined into the NRFS category, defined as SA <8.0°.

All calculations were performed using Microsoft Excel and MATLAB R2021b (MathWorks Inc., Natick, MA, USA).

DATA PROCESSING – HIGH-SPEED MOVIE AND RUNNING SPEED

All images filmed during data collection were processed using QuickTime for Windows (Apple Inc., CA, USA), and an experienced researcher performed visual classification into the following three types according to which part of the foot landed first: RFS, the rear-third part of the foot lands first; MFS, the mid-third part of the foot lands first or whole foot lands simultaneously; and FFS, the front third part of the foot lands first.[2] NRFS was defined as FFS and MFS (Figure 3).[3]

The running time to pass the runway was measured using photocells, which were placed at 15 m intervals. This time was then converted to running speed using the following formula:

$$Running\ speed\ (m/sec) = \frac{photocell\ interval\ (m)}{running\ time\ (sec)}$$

STATISTICAL ANALYSIS

Prior to the analysis, a weighted kappa was computed for the visual foot strike assessment to evaluate inter-rater reliability. This involved assessing 30 randomly selected foot

Figure 1. Ten reflective markers (three tracking markers with red boundaries and seven anatomical markers) on the right shoes of the participant: A. lateral view and B. medial view.

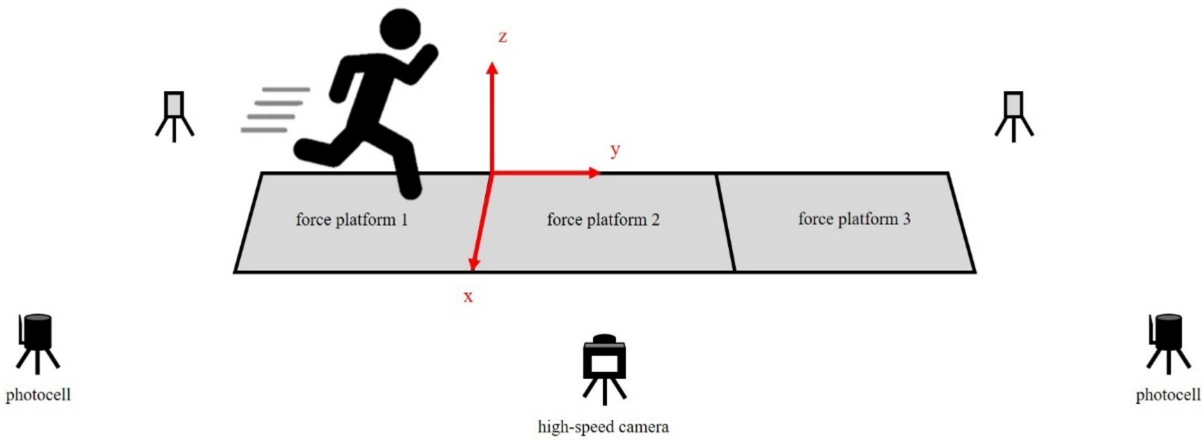

Figure 2. Data collection arrangement.

strikes three times. The resulting value was 0.933, indicating almost perfect reliability.

Afterward, a simple kappa value along with a 95% confidence interval (95%CI) was calculated to confirm the reliability between the SI and visual methods, as well as between the SA and visual methods, for assessing foot strike patterns. This analysis was performed for both two type classification (NRFS and RFS), three type classification (FFS, MFS, and RFS), and within the NRFS (FFS and MFS). Kappa values were categorized as almost perfect when > 0.81, substantial from 0.61 to 0.80, moderate from 0.41 to 0.60, fair from 0.21 to 0.40, and slight when < 0.20. All statistical analyses were performed using IBM SPSS Statistics for Windows version 28 (IBM Corp., Armonk, NY, USA).

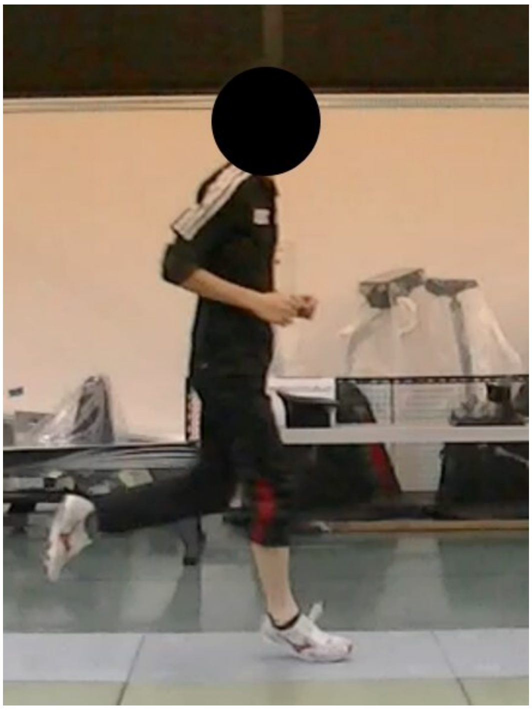

Figure 3A. Examples of 2D visual assessments for each foot-strike pattern: Forefoot strike (FFS).

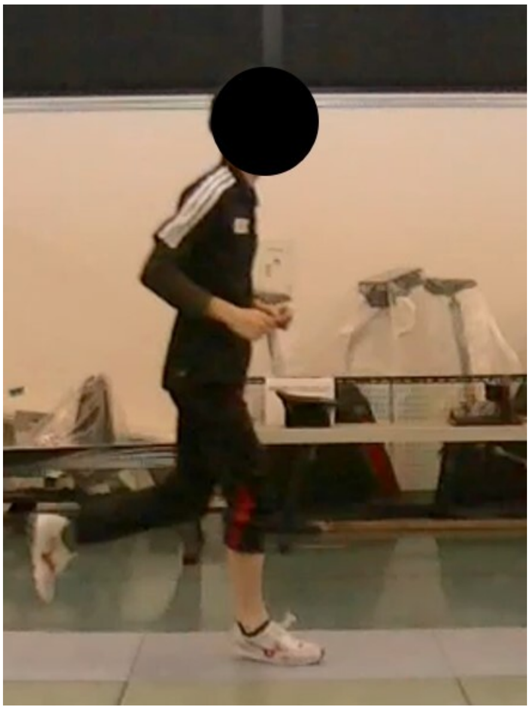

Figure 3B. Examples of 2D visual assessments for each foot-strike pattern: Midfoot strike (MFS).

RESULTS

The participants' characteristics and running speeds during data collection are presented as means ± standard deviations in Table 1. Overall, 162 foot strikes from four runners were analyzed, including two trials of two steps in one trial.

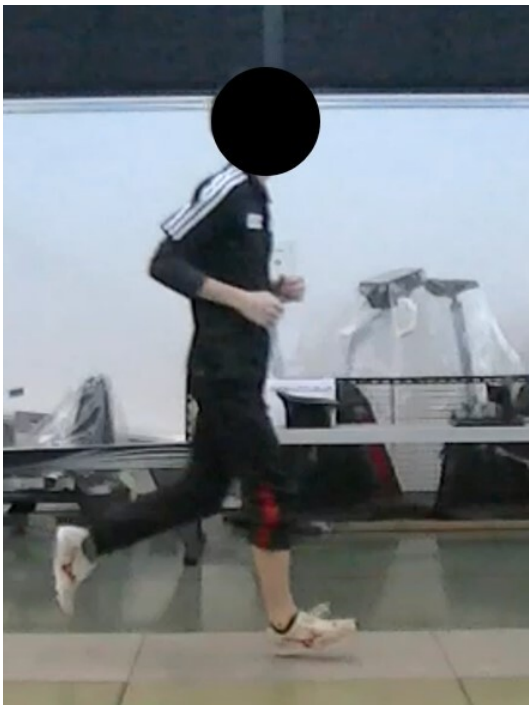

Figure 3C. Examples of 2D visual assessments for each foot-strike pattern: Rearfoot strike (RFS).

The number and values of each foot strike assessment are presented as means ± standard deviations in Table 2.

In the foot strike assessment using SI, there were 44 instances of FFS (SI, 78.0 ± 8.4%), 38 instances of MFS (SI, 55.3 ± 9.8%), and 80 instances of RFS (SI, 15.9 ± 8.1%). In the foot strike assessment using SA, there were 40 instances of FFS (SA, -5.2 ± 2.6°), 39 instances of MFS (SA, 1.7 ± 2.6°), and 83 instances of RFS (SA, 21.8 ± 7.7°). For the foot strike patterns obtained through 2D visual assessment, there were 43, 37, and 82 instances of FFS, MFS, and RFS, respectively. The SI and SA values for FFS, MFS, and RFS based on 2D visual assessment were as follows: FFS, 71.1 ± 8.4% and -5.2 ± 2.6°; MFS, 55.3 ± 9.8% and 1.7 ± 2.6°; RFS, 15.9 ± 8.1% and 21.8 ± 7.7° (Figures 4A and B).

For foot strike classification into two types (NRFS and RFS), kappa values and 95%CI between the visual and both SI and SA methods were almost perfect (κ = 0.90 [0.82, 0.98] and 0.95 [0.90, 1.00], respectively) (Table 3A and B). The kappa value and 95%CI between the SI and SA methods were almost perfect (κ = 0.91 [0.85, 0.98]).

In the classification of foot strike patterns into three types (FFS, MFS, and RFS), kappa values and 95%CI between the visual and SI or SA methods ranged from moderate to substantial (κ = 0.58 [0.48, 0.68] or κ = 0.71 [0.62, 0.80]) (Tables 4A and B). In particular, kappa values and 95%CI between the methods for FFS and MFS were found to be fair or slight (κ = 0.08 [-0.15, 0.31] or κ = 0.33 [0.11, 0.54]) (Tables 5A and B).

DISCUSSION

To the best of the authors' knowledge, this study represents the first attempt to analyze the concordance between foot

Table 1. Means ± standard deviations for the participants' characteristics and running speeds during data collection.

Participant	Age [years]	Height [cm]	Weight [kg]	Monthly running mileage [km]	Running speed during data collection [m/s]
A	31	168.2	52.3	100	3.0
B	25	176.5	65.2	200	3.5
C	28	171.9	61.9	150	2.1
D	29	168.7	63.7	100	2.6
Mean	28.3 ± 2.5	171.3 ± 3.8	60.8 ± 5.8	137.5 ± 47.9	2.7 ± 0.5

Table 2. Number and values of each foot strike pattern assessment.

	FFS	MFS	RFS
SI [N (%)]	44 (78.0 ± 8.4)	38 (55.3 ± 9.8)	80 (15.9 ± 8.1)
SA [N (degrees)]	40 (-5.2 ± 2.6)	39 (1.7 ± 2.6)	83 (21.8 ± 7.7)
Visual [N]	43	37	82

FFS: forefoot strike, MFS: midfoot strike, RFS: rearfoot strike, SI: strike index, SA: strike angle

strike assessments utilizing both a high-speed video camera and a 3D motion capture system. The agreement among the visual, SI, and SA classification methods was investigated for evaluating foot strike patterns. Overall, 162 foot strikes, including various foot strike patterns, were analyzed. In the running trials, participants were asked to use uncontrolled habitual foot strike, FFS, MFS, and RFS, and the numbers of NRFS and RFS were nearly the same, regardless of the assessment method.

As hypothesized, the kappa values of the agreement between the visual and both SI and SA methods for the two types of foot strike patterns, NRFS and RFS, were almost perfect (κ = 0.89 and 0.95, respectively). In contrast, the kappa values of the agreement between those methods for the three types of foot strike patterns, FFS, MFS, and RFS, were relatively low compared with those for the two types (κ = 0.58–0.71). Particularly among NRFS, between FFS and MFS, the kappa values indicating agreement between those methods were fair or slight (κ = 0.08–0.33).

In a prior study, the assessment of the two types of foot strike patterns, NRFS and RFS, demonstrated both validity and reliability when using a visual method with a standard video camera capturing footage at 30 fps, as well as the SA method during overground running.[20] Another study indicated high agreement between the visual method using a high-speed video camera and the SI method with a pressure plate of 120 Hz.[21] However, in those studies, the frame rate of the video camera or sampling frequency of the pressure plate system was lower than that of previous studies.[2,10,22] This reduced frame rate or sampling frequency was considered insufficient to capture the timing of foot strikes accurately.[20,23] In this study, a 240 fps high-speed video camera, equivalent to those employed in previous analyses of athletic events,[2,3] was utilized alongside a 3D motion capture system operating at 250 Hz. This sampling frequency significantly surpassed that of earlier studies with lower sampling rates.[20,21] The findings imply that foot strike assessment in NRFS and RFS demonstrates a rational approach to the methods, and the laboratory-based evaluations of foot strike patterns for these two types can be extrapolated to observational studies or clinical practice.

Previous observational studies have revealed that NRFS runners are three times more likely to experience RRI at their Achilles tendon than RFS runners[17] and that RFS runners have a two-fold higher rate of RRI than NRFS runners.[16] These studies utilized 2D visual-based methods for assessing foot strike patterns via high-speed movies, while also referencing 3D motion capture-based studies in their discussions. NRFS runners exhibited greater force applied around the Achilles tendon and triceps surae compared to RFS runners in those studies, suggesting a heightened risk of Achilles tendinopathy. The current findings reinforce their conclusions by elucidating the consistency of assessment methods, indicating the potential extension of laboratory-based findings regarding the disparity between NRFS and RFS to observational *in situ* studies. Consequently, physiotherapists and athletic trainers might be able to evaluate the risk of RRI according to the foot strike patterns using high-speed movies. This could eliminate the need for time- and cost-consuming 3D motion capture systems.

When assessing the three types of foot strike: FFS, MFS, and RFS, relatively lower agreement was noted compared with that observed for the two types, as previously mentioned. Specifically, when comparing the 2D visual method with the SI as the gold standard, the kappa value for the three types was moderate (κ = 0.58), whereas for the two types, it was nearly perfect (κ = 0.90). A previous study, which examined the intra- and inter-rater reliability of foot strike pattern assessment across various types of foot strike patterns, demonstrated a high level of reliability, particularly for two types: NRFS and RFS (κ > 0.80); however, there was relatively low reliability for classifying foot strike patterns into three or more types (κ = 0.41–0.69).[24] The pre-

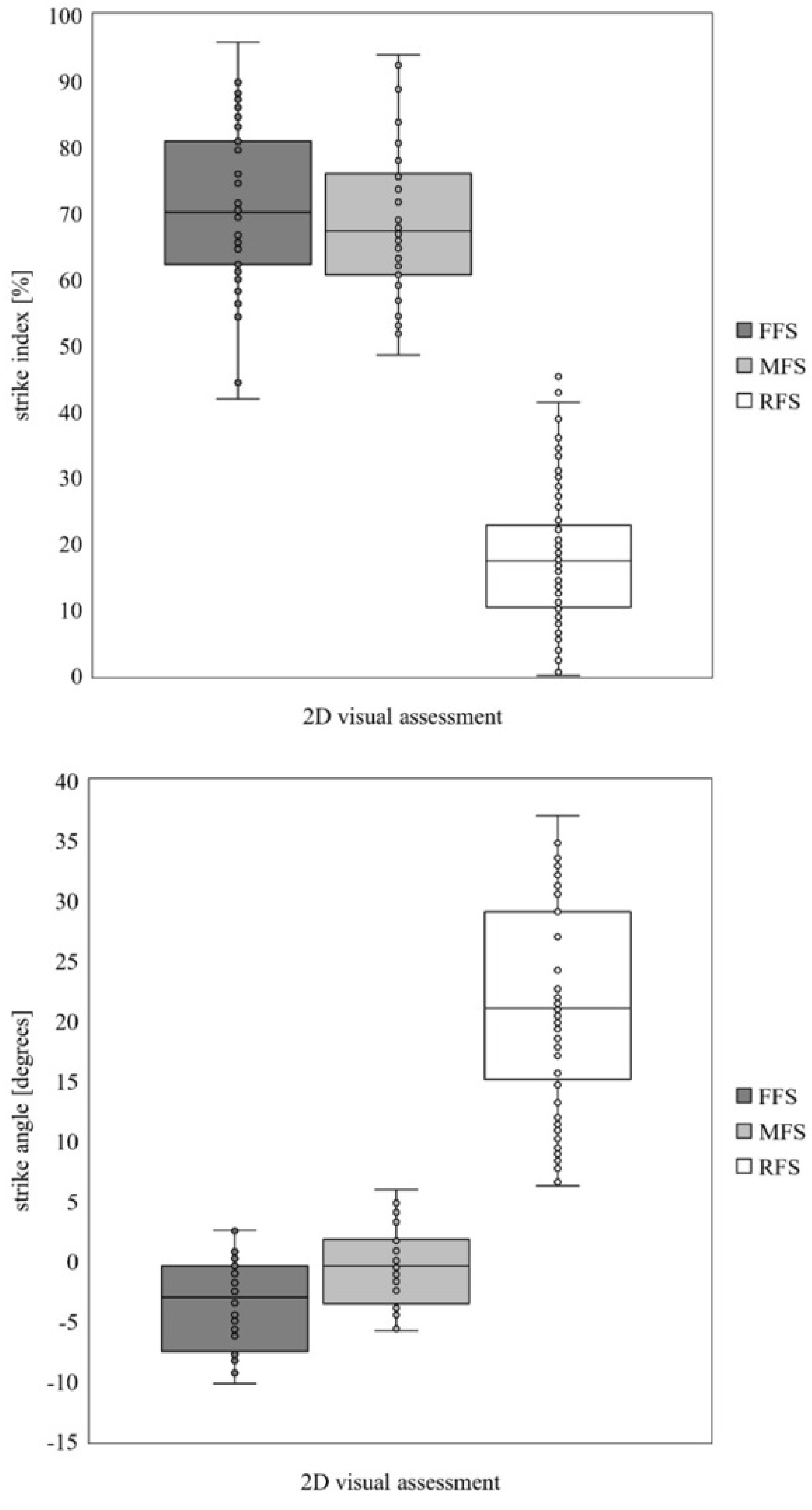

Figure 4. SI and SA for each foot strike pattern using 2D visual assessment. A: Strike index for each foot-strike pattern using 2D visual assessment. B: Strike angle for each foot strike pattern using 2D visual assessment.

FFS, forefoot strike; MFS, midfoot strike; RFS, rearfoot strike.

sent study also exhibited low agreement among the three types. The discrepancy in actual values between FFS and MFS, with an SI of 78.0% vs. 55.3%, translates to a 5 cm difference, assuming a foot size of 26 cm. Alternatively, for SA, the difference was only 6.9°. This subtle distinction can pose challenges in visual discernment, particularly when capturing the entire body; therefore, identifying FFS and MFS may be difficult, irrespective of the methods or devices employed. Thus, assessing the three types of foot strike patterns might not be appropriate when applying these findings to *in situ* studies or clinical practice.

Table 3. Contingency table of agreement for foot strike pattern for two types—NRFS and RFS. A: strike index and 2D visual assessment, B: strike angle and 2D visual assessment.

A		SI		
		NRFS	RFS	Total
Visual	NRFS	74	1	75
	RFS	8	79	87
	Total	82	80	162
κ = 0.90 [0.82, 0.98], p < 0.001				

B		SA		
		NRFS	RFS	Total
Visual	NRFS	75	0	75
	RFS	4	83	87
	Total	79	83	162
κ = 0.95 [0.90, 1.00], p < 0.001				

NRFS: non-rearfoot strike, RFS: rearfoot strike, SA: strike angle

Table 4. Contingency table of agreement for foot strike pattern for three types. A: strike index and 2D visual assessment, B: strike angle and 2D visual assessment.

A		SI			
		FFS	MFS	RFS	Total
Visual	FFS	27	16	0	43
	MFS	17	14	1	32
	RFS	0	8	79	87
	Total	44	38	80	162
κ = 0.58 [0.48, 0.68], p < 0.001					

B		SA			
		FFS	MFS	RFS	Total
Visual	FFS	29	14	0	43
	MFS	11	21	0	32
	RFS	0	4	83	87
	Total	40	39	83	162
κ = 0.71 [0.62, 0.80], p < 0.001					

FFS: forefoot strike, MFS: midfoot strike, RFS: rearfoot strike, SI: strike index

A previous study that classified foot strike patterns into three types by the visual method indicated that MFS runners had a higher prevalence of Achilles tendon injury and FFS runners had a higher prevalence of posterior lower leg injuries.[25] The force applied around the ankle joints, such as the Achilles tendon and triceps surae, has been reported to be higher for NRFS runners, including both FFS and MFS,[8,9] and this might increase the risk for both Achilles tendon and lower leg injury. In the present study, foot strike patterns were classified into three types by visual method with 125 fps high-speed movies.[25] However, categorizing foot strike patterns into three types may have lacked reliability, and it is important to note that a previous study might not have accurately distinguished between FFS and MFS. Consequently, caution is warranted when applying the results of studies that classify foot strike patterns into three types, particularly in observational studies and training scenarios. In the contemporary context, the widespread availability of smartphones and tablets enables the convenient capture of high-speed movies at 240 fps. Scientific discoveries are frequently utilized by physiotherapists, athletic trainers, and coaches to mitigate RRI or improve performance, extending to clinical practice and training alike. Notably, the current findings indicate that classifying foot strike patterns into two types, NRFS and RFS, is more suit-

Table 5. Contingency table of agreement for foot strike pattern for two types—FFS and MFS. A: strike index and 2D visual assessment, B: strike angle and 2D visual assessment.

A		SI		
		FFS	MFS	Total
Visual	FFS	27	16	43
	MFS	17	14	31
	Total	44	30	74
κ = 0.08 [-0.15, 0.31], p < 0.001				

B		SA		
		FFS	MFS	Total
Visual	FFS	29	14	43
	MFS	11	21	32
	Total	40	35	75
κ = 0.33 [0.11, 0.54], p < 0.001				

FFS: forefoot strike, MFS: midfoot strike, SI: strike index

able when utilizing high-speed movies in clinical practice and/or training settings.

The present study has some limitations. The participants ran at their preferred speeds, and the velocity of their feet might have influenced the assessment of foot strike patterns if the sampling frequency was inadequate. Nonetheless, it is crucial to highlight that in this study, the video camera operated at a high frame rate of 240 fps. This is akin to the video cameras typically used in analyzing athletic events, which are marked by faster running speeds than those observed in the present study.[3] Thus, the running speed of the participants might have a limited impact on the results of the present study. Another limitation is that the results of the present study is based on a small and homogenous sample from the participants of four male runners. The number of foot strikes allowed for statistical analysis, however, a wider range of participants' demographics or running experience might lead to more robust results.

CONCLUSION

For foot strike assessments for NRFS and RFS, the kappa values of agreement between the visual, SI, and SA methods were nearly perfect. However, agreement values for the three types (FFS, MFS, and RFS) was relatively low, especially between FFS and MFS. The laboratory findings that assessed foot strike patterns for NRFS and RFS can be applied to observational studies or clinical and coaching situations; however, caution is advised when applying the findings of foot strike patterns for the three types.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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REFERENCES

1. Cavanagh PR, Lafortune MA. Ground reaction forces in distance running. *J Biomech*. 1980;13(5):397-406. doi:10.1016/0021-9290(80)90033-0

2. Hasegawa H, Yamauchi T, Kraemer WJ. Foot strike patterns of runners at the 15-km point during an elite-level half marathon. *J Strength Cond Res*. 2007;21(3):888-893. doi:10.1519/R-22096.1

3. Hanley B, Tucker CB, Bissas A, Merlino S, Gruber AH. Footstrike patterns and race performance in the 2017 IAAF World Championship men's 10,000 m final. *Sports Biomech*. 2024;23(3):314-323. doi:10.1080/14763141.2020.1856916

4. Pohl MB, Hamill J, Davis IS. Biomechanical and anatomic factors associated with a history of plantar fasciitis in female runners. *Clin J Sport Med*. 2009;19(5):372-376. doi:10.1097/JSM.0b013e3181b8c270

5. Zadpoor AA, Nikooyan AA. The relationship between lower-extremity stress fractures and the ground reaction force: a systematic review. *Clin Biomech*. 2011;26(1):23-28. doi:10.1016/j.clinbiomech.2010.08.005

6. Hamill J, Gruber AH. Is changing footstrike pattern beneficial to runners? *J Sport Health Sci*. 2017;6(2):146-153. doi:10.1016/j.jshs.2017.02.004

7. Futrell EE, Jamison ST, Tenforde AS, Davis IS. Relationships between habitual cadence, footstrike, and vertical load rates in runners. *Med Sci Sports Exerc*. 2018;50(9):1837-1841. doi:10.1249/MSS.0000000000001629

8. Kulmala JP, Avela J, Pasanen K, Parkkari J. Forefoot strikers exhibit lower running-induced knee loading than rearfoot strikers. *Med Sci Sports Exerc*. 2013;45(12):2306-2313. doi:10.1249/MSS.0b013e31829efcf7

9. Kuhman D, Melcher D, Paquette MR. Ankle and knee kinetics between strike patterns at common training speeds in competitive male runners. *Eur J Sport Sci*. 2016;16(4):433-440. doi:10.1080/17461391.2015.1086818

10. Mo S, Huang M, Ng L, Cheung RTH. Footstrike angle cut-off values to classify footstrike pattern in runners. *Res Sports Med*. 2023;31(2):181-191. doi:10.1080/15438627.2021.1954516

11. Hatala KG, Dingwall HL, Wunderlich RE, Richmond BG. Variation in foot strike patterns during running among habitually barefoot populations. *PLOS ONE*. 2013;8(1):e52548. doi:10.1371/journal.pone.0052548

12. Breine B, Malcolm P, Frederick EC, De Clercq D. Relationship between running speed and initial foot contact patterns. *Med Sci Sports Exerc*. 2014;46(8):1595-1603. doi:10.1249/MSS.0000000000000267

13. Altman AR, Davis IS. A kinematic method for footstrike pattern detection in barefoot and shod runners. *Gait Posture*. 2012;35(2):298-300. doi:10.1016/j.gaitpost.2011.09.104

14. Lieberman DE. Strike type variation among Tarahumara Indians in minimal sandals versus conventional running shoes. *J Sport Health Sci*. 2014;3(2):86-94. doi:10.1016/j.jshs.2014.03.009

15. Forrester SE, Townend J. The effect of running velocity on footstrike angle—a curve-clustering approach. *Gait Posture*. 2015;41(1):26-32. doi:10.1016/j.gaitpost.2014.08.004

16. Daoud AI, Geissler GJ, Wang F, Saretsky J, Daoud YA, Lieberman DE. Foot strike and injury rates in endurance runners: a retrospective study. *Med Sci Sports Exerc*. 2012;44(7):1325-1334. doi:10.1249/MSS.0b013e3182465115

17. Goto H, Torii S. Foot strike patterns and running-related injuries among high school runners: a retrospective study. *J Sports Med Phys Fitness*. 2022;62(12):1668-1674. doi:10.23736/S0022-4707.22.13445-6

18. de Oliveira FCL, Fredette A, Echeverría SO, Batcho CS, Roy JS. Validity and reliability of 2-dimensional video-based assessment to analyze foot strike pattern and step rate during running: A systematic review. *Sports Health*. 2019;11(5):409-415. doi:10.1177/1941738119844795

19. Murray L, Beaven CM, Hébert-Losier K. Reliability of overground running measures from 2D video analyses in a field environment. *Sports*. 2018;7(1):8. doi:10.3390/sports7010008

20. Esculier JF, Silvini T, Bouyer LJ, Roy JS. Video-based assessment of foot strike pattern and step rate is valid and reliable in runners with patellofemoral pain. *Phys Ther Sport*. 2018;29:108-112. doi:10.1016/j.ptsp.2016.11.003

21. Santuz A, Ekizos A, Arampatzis A. A pressure plate-based method for the automatic assessment of foot strike patterns during running. *Ann Biomed Eng*. 2016;44(5):1646-1655. doi:10.1007/s10439-015-1484-3

22. Pipkin A, Kotecki K, Hetzel S, Heiderscheit B. Reliability of a qualitative video analysis for running. *J Orthop Sports Phys Ther*. 2016;46(7):556-561. doi:10.2519/jospt.2016.6280

23. de Almeida MO, Saragiotto BT, Yamato TP, Lopes AD. Is the rearfoot pattern the most frequently foot strike pattern among recreational shod distance runners? *Phys Ther Sport*. 2015;16(1):29-33. doi:10.1016/j.ptsp.2014.02.005

24. Damsted C, Larsen LH, Nielsen RO. Reliability of video-based identification of footstrike pattern and video time frame at initial contact in recreational runners. *Gait Posture*. 2015;42(1):32-35. doi:10.1016/j.gaitpost.2015.01.029

25. Hollander K, Johnson CD, Outerleys J, Davis IS. Multifactorial determinants of running injury locations in 550 injured recreational runners. *Med Sci Sports Exerc*. 2021;53(1):102-107. doi:10.1249/MSS.0000000000002455