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Validation of Foot-Strike Assessment Using Wearable Sensors During Running

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Wearable sensors are capable of capturing foot-strike positioning, which lends insight into landing biomechanics during running. The purpose of our study was to assess the relationship between foot-strike categorization and foot-strike angle during running to validate the sensor-derived foot-strike outcome. Twenty collegiate cross-country athletes (12 females, 8 males) ran at 2 speeds on an instrumented treadmill. RunScribe sensors were used to determine foot-strike categorizations (1–5 = *rearfoot*, 6–10 = *midfoot*, 11–16 = *forefoot*), and foot-strike angles were simultaneously assessed with 3-dimensional motion capture bilaterally. We calculated Pearson *r* correlation coefficients to compare foot-strike categorizations and angles at initial contact over 800 steps as well as sensor foot-strike identification accuracy. A strong, inverse correlation between foot-strike categorizations and foot-strike angles was present ($r = -0.86$, $P < .001$). Overall, the sensors demonstrated 78% accuracy (rearfoot = 72.5%, midfoot = 55.3%, forefoot = 95.4%). These results support the concurrent validity of the sensor-derived foot-strike measures.

Key Words: gait analysis, wearable technology, validity

Key Points

- Foot-strike measures obtained from RunScribe wearable sensors were strongly correlated with sagittal-plane angles at initial contact, thereby demonstrating concurrent validity.
- The RunScribe sensors accurately predicted foot-strike type 78% of the time and performed the best in runners categorized as using forefoot-strike patterns.
- Clinicians may consider using wearable sensors to assess foot-strike patterns for running-gait analyses in natural training settings.

Wearable technology to assess athletes in natural training environments is becoming increasingly popular in sports medicine. Though wearable sensors have been primarily used in team-based sports,[1] there has been a push to use wearable sensors during individual activities, particularly running-gait analyses.[2] The benefits of wearable sensors in lieu of traditional indoor running assessments lie in both the quantity of steps that can be obtained in a single assessment period and the generalizability of the data to typical training.[2]

Wearable sensors for running assessments often consist of triaxial accelerometers and gyroscopes capable of capturing spatiotemporal and biomechanical outcomes. One commercially available sensor is the RunScribe (Scribe Labs, Inc, Half Moon Bay, CA). The RunScribe sensors consist of small foot pods secured bilaterally on runners' shoes that can collect spatiotemporal, kinematic, and kinetic outcomes continuously throughout activity. Previous authors[3,4] have confirmed that the RunScribe sensors are a valid means of assessing spatiotemporal outcomes, including cadence, stride length, cycle time, and foot-contact time (intraclass correlation coefficients [ICCs] = 0.86–0.94), and kinematic outcomes, particularly pronation excursion, and maximum pronation velocity (ICCs = 0.57 and 0.74, respectively). Additionally, these outcomes have demonstrated face validity with respect to expected changes in running speed and surface[5] and in response to ankle-bracing and -taping interventions.[6] However, foot-strike patterns measured by the RunScribe sensors have not been previously validated. Earlier researchers[7] assessed foot-strike patterns using sensor raw accelerometry data, and a similar approach is warranted to assess the concurrent validity and accuracy of this commercially available sensor.

Foot-strike position is a clinically meaningful measure to capture in the field, given the relationship between foot-strike type and lower extremity loading elucidated in previous research.[8] Investigators[8,9] have found that rearfoot-strike patterns consistently resulted in increased tibial shock and ground reaction forces compared with forefoot-strike patterns in which loading was attenuated by dynamic soft tissue structures. To ensure that this metric can be incorporated into future research and clinical practice, this outcome must strongly relate to criterion-standard motion-capture measures. Laboratory-based gait assessments[10] showed that the sagittal-plane angle between the foot and the ground was an appropriate surrogate measure of foot-strike indices (termed the *foot-strike angle*), such that forefoot strikes were associated with increased ankle plantar flexion and, conversely, that rearfoot strikes related to increased dorsiflexion. Foot-strike angles can therefore be considered 1 approach for assessing the concurrent validity of sensor-derived foot-strike outcomes. Specific

Table 1. Participant Demographics, Mean ± SD

Characteristic	Females (n = 12)	Males (n = 8)
Age, y	20 ± 2	20 ± 2
Height, cm	166.78 ± 5.11	176.53 ± 5.47
Mass, kg	57.91 ± 7.79	66.79 ± 7.17
Running experience, y	7 ± 2	8 ± 3
Weekly running distance, mi	47.25 ± 13.78	79.25 ± 5.92
Average pace, min/mi	7.35 ± 0.29	6.58 ± 0.31

foot-strike angle ranges have appropriately identified foot-strike types (>8° of dorsiflexion = *rearfoot*, 1.6° of plantar flexion–8° of dorsiflexion = *midfoot*, >1.6° of plantar flexion = *forefoot*).[10] These reference values can be used to determine the accuracy of sensor-derived foot-strike identification.

The primary purpose of our study was to assess the correlation between the foot-strike metrics derived from RunScribe sensors and software algorithm and the foot-strike angles simultaneously recorded during treadmill running at 2 standardized speeds in a cohort of healthy runners. Based on previous findings,[10] we hypothesized that foot-strike patterns would be strongly inversely related to foot-strike angles. Our secondary purpose was to characterize the accuracy of RunScribe foot-strike identification using predefined foot-strike angle cutoff values.

METHODS

Participants

From a convenience sample in a larger study, 20 National Collegiate Athletic Association Division I collegiate cross-country athletes (12 females, 8 males) reported to a university laboratory for a single session of data collection (Table 1). The athletes were currently participating in varsity cross-country practices and were free of any lower extremity musculoskeletal injuries at the time of the study. All participants provided informed consent before the trial began, and the study was approved by the university's institutional review board.

Instrumentation

We used a 12-camera motion-capture system (model 1.8.5; Vicon Motion Systems, Inc, Lake Forest, CA) sampled at 250 Hz and synchronized with a dual-belt instrumented treadmill (model 1.0.1; Bertec Corp, Columbus, OH) sampled at 1000 Hz in conjunction with MotionMonitor software (version 9.32; Innovative Sports Training, Chicago, IL) to collect foot-strike angles during running.

RunScribe Plus wearable sensors were used to assess foot-strike patterns during running assessments. Each sensor consisted of a triaxial accelerometer and gyroscope that collected kinematic and kinetic data at a 200-Hz sampling rate, with onboard processing and memory capabilities.

Procedures

Participants had right and left RunScribe sensors secured in the lace cradles on the dorsum of their typical training shoes and were outfitted with 8 clusters containing 34 retroreflective markers placed bilaterally on the participants' dorsal feet, lateral calf, lateral thigh, and on the sacrum and upper back. An examiner used a stylus to indicate the bony landmarks for joint-center identification in the MotionMonitor software in order to digitize participants for gait analysis. After a 10-second static recording to obtain resting joint position measures, all participants completed a 5-minute warmup on the treadmill at a standardized speed of 2.68 m/s.

For data collection, 3 sets of 30-second motion-capture trials were recorded at the 2.68 m/s running speed simultaneously with the sensor data to obtain continuous, representative running samples from each participant. Although the 2 measurement systems are not currently able to synchronize electronically, the same researcher who controlled the systems set the technologies to record at the same time to ensure that the 2 datasets could be directly compared.[3] Next, the treadmill speed was increased to a standardized 3.60 m/s running speed, and participants were given a 1-minute adjustment period so their running patterns could stabilize in response to the new pace. Three additional 30-second data recordings were then obtained at the faster speed. Data were collected at 2 speeds to provide more data points for the analyses.

Data Processing

Foot-strike angle, defined as the sagittal-plane angle between the foot segment and the ground, along with ground reaction force data were exported for data reduction from all gait trials for each participant. We normalized foot-strike angles by subtracting the foot angle at initial contact from the foot-angle positioning during quiet stance; positive values were defined as *ankle dorsiflexion* and negative values as *ankle plantar flexion*. Ground reaction force data were used to identify initial contact timing for data reduction using a 20-N threshold. The central 20 steps (10 left and 10 right) of the cleanest running trial (ie, trial with no artifact) from the 30 seconds of data recording in which participants landed with 1 foot on each force plate were analyzed to determine foot-strike angles at initial contact.

We downloaded the RunScribe data from each trial to an iPad (Apple, Cupertino, CA) via the sensors' mobile application and then extracted them from the company's online dashboard to obtain step-by-step datasheets for analysis. As the data were recorded synchronously, timestamps were used to match the steps from the motion-capture system with the sensor data to ensure that the same steps were included for data reduction. Foot-strike metrics were calculated via the RunScribe sensors' algorithms on a scale from 1 to 16 based on the location of loading on the foot at initial contact: 1 through 5 indicated *rearfoot* strike; 6 to 10, *midfoot* strike; and 11 to 16, *forefoot* strike.

Statistical Analysis

Pearson *r* correlation coefficients were calculated to assess the relationship between foot-strike angle at initial contact and the foot-strike categories, with α set a priori to .05. Correlation coefficients were interpreted as 0–0.39 = *weak*, 0.40–0.59 = *moderate*, and 0.60–1.0 = *strong*.[11] Means and standard deviations of the ankle angles were computed for the 3 foot-strike categories (rearfoot, midfoot,

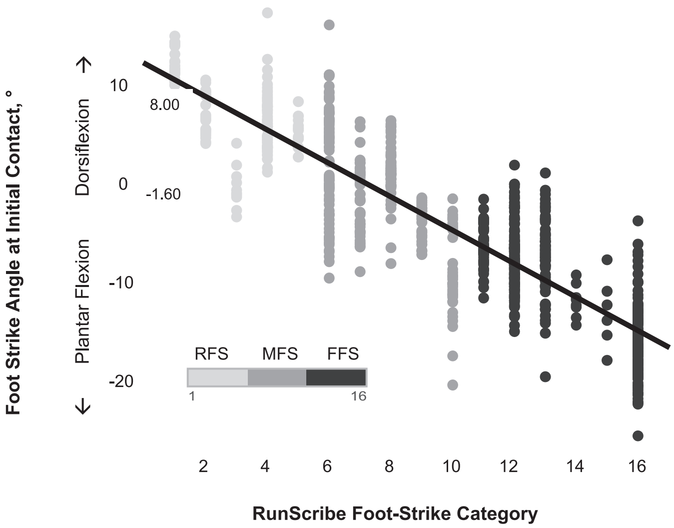

Figure. Foot-strike type by foot-strike angle at initial contact.

and forefoot). To assess sensor accuracy, we determined the percentage of each RunScribe category that fell within the previously published foot-strike category ranges[10] using Equation 1. This process was repeated for all foot-strike categories (1–16), broad categories (rearfoot, midfoot, forefoot), and overall sensor accuracy.

$$\frac{\text{No. of Steps Identified Correctly}}{\text{No. of Total Steps Taken}} \times 100. \qquad (1)$$

RESULTS

A total of 800 steps were analyzed, and all foot-strike types were represented in the dataset. A strong negative correlation was present between sagittal-plane ankle kinematics and foot-strike types, such that increases in ankle plantar flexion were associated with forefoot-strike patterns and, conversely, that increases in ankle dorsiflexion were associated with rearfoot-strike patterns ($r = -0.86$, $P < .001$; Figure). Mean sagittal-plane ankle motion by strike type is shown in Table 2.

Overall, the RunScribe sensors accurately classified foot-strike outcomes for 78% of all steps (Figure; Table 2). Forefoot strikes were classified most accurately (95.4%), followed by rearfoot (72.5%) and midfoot (55.3%) strikes. Rearfoot-strike categories 3 to 5 were least accurate (0%–38.5%) and instead fell in the midfoot foot-strike angle range. Similarly, midfoot strike categories 9 to 10 were least accurate (3.6%–14.3%) and instead fell in the forefoot-strike range.

DISCUSSION

These results supported our primary hypothesis. The foot-strike metrics obtained from RunScribe wearable sensors during treadmill running across speeds were strongly inversely correlated with foot-strike angles. These findings align with a previous assessment[10] of foot-strike angles and running landing patterns using criterion-standard 3-dimensional motion-capture systems. Therefore, the concurrent validity of the RunScribe foot-strike metrics for running-gait assessment is supported.

Table 2. Foot-Strike Angles by Foot-Strike Type

Foot-Strike Type	Category (n)	Foot-Strike Angle, ° (Mean ± SD)	Accuracy, %
Rearfoot strike (n = 91)		10.9 ± 2.2	72.5
	1 (49)	12.6 ± 1.6	100
	2 (14)	7.4 ± 2.1	64.3
	3 (9)	0.1 ± 2.2	0
	4 (13)	6.6 ± 2.9	38.5
	5 (6)	1.0 ± 1.7	33.3
Midfoot strike (n = 295)		3.0 ± 2.7	55.3
	6 (151)	2.6 ± 5.6	60.3
	7 (39)	−1.2 ± 3.6	87.2
	8 (63)	1.6 ± 2.8	55.6
	9 (14)	−3.7 ± 1.9	14.3
	10 (28)	−8.9 ± 4.4	3.6
Forefoot strike (n = 414)		−9.1 ± 5.0	95.4
	11 (26)	−5.9 ± 2.2	96.2
	12 (190)	−7.1 ± 3.3	92.6
	13 (61)	−7.1 ± 4.0	93.4
	14 (10)	−11.5 ± 1.7	100
	15 (6)	−12.6 ± 3.6	100
	16 (121)	−15.5 ± 3.8	100

Our secondary outcomes indicated that the RunScribe sensors were accurate (78%) but that adjustments to the algorithm cutoff values may be needed. Specifically, we found that extremes in the strike types (categories 1 and 16) were 100% accurate in detecting strike types, whereas categories closer to the midranges performed worse. Based on our data, we recommend grouping sensor categories 3 through 5 in the midfoot-strike category because these outcomes fell within the midfoot foot-strike angle range for 65% to 100% of participants. Additionally, we recommend shifting sensor categories 9 and 10 to the forefoot-strike range because they fell within the forefoot-strike angle range for about 95% of runners. Although the sensors currently have reasonable accuracy, these suggested algorithm shifts may more adequately capture strike types. Clinicians should consider the current outcomes in contextualizing sensor outcomes and proceed cautiously when using the broad sensor-derived strike-type categories.

At this stage we are unable to extrapolate these laboratory-based findings to the field, yet future researchers should investigate foot-strike outcomes to determine the approximate ankle positioning at initial contact during outdoor running assessments. Foot-strike patterns are particularly important to incorporate into clinical gait assessments, as rearfoot-strike impact patterns have been associated with running-related lower extremity injuries, such as tibial stress fractures and patellofemoral pain.[12] Further, rearfoot-strike patterns have been linked with higher average and peak vertical ground reaction forces.[8,9,13] Previous researchers[14] who evaluated rearfoot-strike patterns also found decreased overall motion at the ankle throughout the entire running gait, or a "stiffer" overall motion pattern, which supports our finding of increased foot-strike angle at initial contact. Additional work is still needed to fully elucidate the relationships between foot-strike patterns and specific lower extremity injuries and foot-strike patterns and running performance. Wearable sensors may provide an economical means of continuing this line of research in the field to prospectively track injury and performance outcomes.

Clinical Implications

Our results in conjunction with those of earlier validation studies support the use of RunScribe sensors for assessing running-gait biomechanics. Although the sensors were adequate overall, we advocate for a slight shift in the RunScribe foot-strike algorithm classifications to more adequately capture strike types. Future authors may consider incorporating the foot-strike metric along with spatiotemporal, kinetic, and kinematic measures into running assessments to determine prospective relationships between sensor-derived metrics and running-related injuries.[2] Foot-strike measures may be considered for tracking the adherence to or efficiency of gait-training interventions if runners are being trained to adopt new landing patterns during injury recovery or as a preventive measure.[13]

Limitations

Our study had several limitations. All analyses were performed during treadmill running, which may have influenced landing patterns and sagittal-plane foot strike angles when compared with overground running.[15] Whereas all foot-strike type categories were represented, this cohort presented with more forefoot- and midfoot-strike patterns than rearfoot-strike patterns, which may have influenced the findings. Runners did not receive instructions on foot-strike patterns and, therefore, foot-strike patterns were not controlled. Instead, the purpose of the study was to determine if the RunScribe sensor measures would coincide with foot-strike angles during preferred running patterns. Future investigators should determine how instructed landing patterns influence the sensor-derived foot-strike outcome measure. Finally, at this point, it is not possible for the RunScribe and MotionMonitor systems to be electronically synchronized for data collection. We used timestamps to ensure that the same steps were included in all analyses; however, this is a limitation of the current technology.

CONCLUSIONS

The foot-strike metrics obtained from the RunScribe wearable sensors and software algorithm were strongly correlated with foot-strike angles at initial contact during running and were accurate in capturing foot-strike types across running strides. These outcomes reinforce the use of sensor-derived outcome measures as a valid surrogate for strike indices. Clinicians and researchers may consider incorporating foot-strike assessments into field-based running, given the importance of foot-strike patterns in lower extremity loading.

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