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Impact Sound Across Rearfoot, Midfoot, and Forefoot Strike During Overground Running

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Context: Three foot-strike techniques are common in runners. If these techniques generate different sounds at the point of impact with the ground, lower limb kinetics may be influenced. No previous authors have determined whether such relationships exist.

Objectives: To determine foot-ground impact sound characteristics and compare the impact-sound characteristics across foot-strike techniques and the relationships between impact-sound characteristics and vertical loading rates.

Design: Cross-sectional study.

Setting: Gait analysis laboratory.

Patients or Other Participants: A total of 30 runners (15 women, 15 men; age = 23.5 ± 4.0 years, height = 1.67 ± 0.1 m, mass = 58.1 ± 8.2 kg) completed overground running trials with rearfoot-strike, midfoot-strike (MFS), and forefoot-strike (FFS) techniques in a gait analysis laboratory.

Main Outcome Measure(s): Impact sound was measured using a shotgun microphone, and the peak sound amplitude, median frequency, and sound duration were analyzed. Separate linear regressions, clustering participants due to repeated measures, were used to compare the sound characteristics across foot-strike techniques. Kinetic data were collected from a force plate, and the vertical loading rates were calculated. Pearson correlation was used to determine the relationship between sound characteristics and kinetics.

Results: Landing with an MFS or FFS resulted in greater peak sound amplitude ($P < .001$) and shorter sound duration ($P < .001$) than a rearfoot strike. The MFS exhibited the highest median frequency among the 3 foot-strike patterns, followed by the FFS ($P < .001$). We did not find a significant relationship between vertical loading rates and any impact sound characteristics ($P > .115$).

Conclusions: The results suggest that impact-sound characteristics may be used to differentiate foot-strike patterns in runners. However, these did not relate to lower limb kinetics. Therefore, clinicians should not solely rely on impact sound to infer impact loading.

Key Words: locomotion, biomechanics, running technique, landing pattern, audible feedback

Key Points

- Across the 3 foot-strike techniques, the midfoot strike showed the loudest impact sound and the highest pitch during running.
- The pitches generated during the impact of each foot-strike technique were within the audible range of the average human; clinicians and runners could potentially use an existing sound-detecting device to assess foot-strike technique.
- None of the investigated sound characteristics were associated with vertical loading rates, which are injury-related kinetic factors.

During running, the foot can strike the ground with the heel first, referred to as a *rearfoot strike* (RFS); with the whole foot, a *midfoot strike* (MFS); or with the ball of the foot first, a *forefoot strike* (FFS).[1] Different foot-strike techniques have been suggested, although not proven, to affect injury location,[2] economy,[3] and performance in running.[4] Researchers[5] have identified that nearly 90% of recreational runners naturally adopt an RFS, 6.9% adopt an MFS, and only 3.5% adopt an FFS. Two groups[6,7] reported that between 32% and 68% of runners were unable to correctly self-report their own foot-strike technique. This surprisingly large number of incorrect responses may have implications for footwear choice, training activities, and specific joint loadings that could potentially lead to an increased risk of injury. Therefore, a real-time feedback mechanism that assists runners and clinicians in correctly identifying the foot-strike technique could prove useful. One such method may be simply listening to the sound of the foot-ground impact.

Relationships between the sound of impact and different running techniques have been identified.[1,8] After instructing healthy male athletes to run quietly, Phan et al[1] found that impact-sound amplitude was reduced by 9.1 dB and 16 of the 22 habitual RFS runners instinctively changed to a non-RFS technique. Tate and Milner[8] observed that runners who received real-time sound-intensity feedback could reduce their vertical impact forces, vertical instantaneous loading rate (VILR) and vertical average loading rate (VALR).

Examination of the ground reaction force curves in this study revealed that some runners who underwent training experienced a loss of vertical impact peak, which may suggest that these runners changed their foot strike from RFS to non-RFS techniques.[8] However, running quietly may not necessarily be due to a change in the foot-strike pattern. Instead, a lower foot-ground impact sound can be a consequence of other gait modifications, such as vertical body stiffness adjustment.[9] Whether differences in sound amplitude exist between RFS and MFS or FFS is unknown. Furthermore, running foot-strike sound characteristics such as frequency, which represents the pitch of the sound, and sound duration have not been investigated.

The primary aim of our study was to compare the differences in sound amplitude among foot-strike techniques. The secondary aims were to explore the differences in sound frequency and duration among different foot-strike techniques and to determine the relationships among the sound characteristics (ie, sound amplitude, frequency, and duration) of the 3 foot-strike techniques and kinetics (VALR and VILR). Based on previous findings,[8] we hypothesized that the RFS technique would have a higher sound amplitude than the non-RFS techniques and the sound amplitude would show a positive relationship with the running kinetics (VALR and VILR). If identifiable differences in sound characteristics exist among the 3 techniques, clinicians and runners may be better able to assess foot-strike techniques with a relatively low-cost sound detective device.

METHODS

In this cross-sectional, within-subject laboratory study, a convenience sample of male and female regular distance runners was recruited from community running groups between October 2017 and February 2018. Participants were included if they had run a minimum of 15 km per week in the 6 months before testing. Volunteers were excluded if they had ever undergone surgery to the lower limbs or had a musculoskeletal injury that affected their running in the 6 weeks before testing. An a priori power calculation showed that a sample size of 24 participants would provide 96% power to detect a significant difference in sound amplitude between the RFS and non-RFS runners, with the α level set at .05 based on Phan et al.[1]

Thirty runners, 15 men and 15 women, with a mean age of 23.5 ± 4.0 years, height of 1.67 ± 0.1 m, and body mass of 58.1 ± 8.2 kg participated in the study. These runners ran a median of 35 km (range = 15–130 km) a week and had 7 years (range = 1–14 years) of running experience. Ethics approval was obtained from the relevant institutional human research ethics committee, and all participants provided written informed consent before testing.

Kinetic data were collected using an in-ground force plate (Advanced Medical Technology, Inc) sampling at 1000 Hz, and kinematic data were collected using a 10-camera motion-analysis system (Vicon Nexus) at 200 Hz. Sound data were collected using a unidirectional shotgun microphone (Azden Corp) at 21.6 kHz. All 3 data-collection instruments were connected to Vicon Nexus software (version 2.6). The tip of the microphone was positioned 350 mm to the left and 200 mm above the force plate. This microphone setup was used in previous studies.[1,10] A pair of remote timing units (Fusion Sport) were placed 1.5 m in front of and behind the force plate to monitor running speed.

Participants were asked to attend 1 data-collection session at the institution's motion-analysis laboratory. They completed a screening questionnaire that contained questions regarding sex, date of birth, running history, and relevant injury history to determine eligibility. Height and mass were measured using a stadiometer (model 206; SECA) and a scale (Tanita Corp), respectively, and foot length was measured using a standard tape measure. Four 14-mm retroreflective markers were then placed on the posterior calcaneus and second metatarsal heads of the 2 lower limbs. Individuals were fitted with standardized running shoes (model Gel Feather Glide 3; Asics America Corp) according to their measured foot lengths before completing a 10-minute warm-up jog in the laboratory.

Participants were then asked to run multiple times along a 20-m runway in the laboratory at a speed of 3.5 m/s ± 5% using 3 foot-strike techniques: RFS, MFS, and FFS. They were instructed to run in each foot-strike technique multiple times, and the order of the techniques was randomized using online software (http://www.random.org). Videos of the 3 foot-strike techniques were shown to the participants beforehand and practice time was given until they felt confident to run with the designated technique. Ten successful trials of each foot-strike technique were included in data analyses, and a running trial was deemed *successful* if the whole foot landed on the force platform while the individual was running at the designated speed. No feedback was given to the participants regarding the success of the trial; however, they were told to adjust their speed or run-up distance accordingly. They were allowed a 30-second rest between trials.

Foot-strike technique was classified by deriving the foot-strike angle using the motion-analysis system according to Altman and Davis.[11] Marker trajectories and ground reaction force data were filtered by a fourth-order Butterworth recursive low-pass filter, with cutoff frequencies set at 8 Hz and 50 Hz, respectively. The initial contact of foot strike was identified by a cutoff threshold of 10 N based on the vertical ground reaction force. The *foot-strike angle* is the angle between the imaginary line joining the second metatarsal head and heel markers and the ground. We calculated the exact value by subtracting the angle at static standing position from the angle at the initial contact of foot strike. This angle was $>8.0°$ for RFS, $-1.6°$ to $8°$ for MFS, and $<-1.6°$ for FFS.[11]

The VILR and VALR were calculated according to the method previously described.[12] The *VALR* was the average slope of the line from the 20% point to the 80% point of the vertical impact peak, whereas the *VILR* was the maximal slope of the vertical ground reaction force curve during the same period. In the absence of vertical impact peak, a set value of 13% stance was used as a surrogate for the time to vertical impact peak.[13] The loading rates were correspondingly normalized by the body mass of the participant.

The sound data were first exported to WAV files from the C3D files using a custom-written program (LabVIEW 2017 SP1, National Instruments Corp). Each sound file was opened in Audacity 2.4.0 for Windows and cropped to contain only the foot strike of interest. This was accomplished by visualizing each individual sound wave in each trial. These cropped sound files were then analyzed using a second custom-written program that was used in a previous study.[1] Sound was filtered using a second-order 50-Hz high-pass Butterworth filter to remove low-frequency sounds unrelated to the impact. Sound onset and offset were detected using an integration protocol.[14,15] *Sound duration* was defined as the difference between onset and offset times. Sound data were then smoothed using a 100-millisecond moving average, and the minimal value in the first 100 milliseconds after onset was identified as the end of the initial phase of impact sound. The peak within the initial phase of impact sound was the maximal amplitude of sound. The median frequency of the initial impact sound was also determined by computing the normalized cumulative sum of the single-sided power spectrum and finding the frequency corresponding to the cumulative sum of 0.5.

Statistical analysis was carried out using Stata/IC (version 15.1 for Windows; StataCorp LP). The data were tested for normality using histogram plots. The peak sound amplitude and median frequency were nonnormally distributed and, therefore, we applied logarithmic transformation. This was determined to be the best transformation according to the statistical software package after different transformation procedures (eg, log, 1/sqrt, inverse, 1/square, 1/cubic, cubic, square) were presented. Separate linear regressions for logarithmic transformed peak sound amplitude and median frequency, clustering participants due to repeated measures, were used to compare the sound characteristics among the 3 foot-strike patterns. The results were retransformed by exponentiation in the results and for graphic presentation. A separate linear regression for raw sound duration, clustering participants due to repeated measures, was used to compare sound characteristics among the 3 foot-strike patterns. We calculated the Pearson correlation to determine the relationship between sound characteristics and kinetics. A Pearson correlation >0.90 is considered a *very strong correlation*; 0.70 to 0.89, a *strong correlation*; 0.40 to 0.69, a *moderate correlation*; 0.10 to 0.39, a *weak correlation*; and 0 to 0.10, a *negligible correlation*.[16] The α level was set to $P < .05$. None of the demographic variables (ie, sex, age, height, and weight) were found to be covariates.

RESULTS

The mean peak sound amplitudes for RFS, MFS, and FFS were 0.154 mV, 0.384 mV, and 0.351 mV, respectively (Table 1). The peak sound amplitudes for each person in the 3 sound conditions are presented in the Figure. A significant strong association was found ($F_{2,29} = 136.96$, $P < .0001$), with an R^2 of 0.499 for peak sound amplitude among the FFS, MFS, and RFS techniques. Pairwise comparisons of the peak sound amplitude among the 3 foot-strike techniques indicated that the peak sound amplitude of RFS was quieter than that of FFS and MFS and the peak sound amplitude of the MFS was louder than that of FFS.

The median frequencies of initial impact sound for RFS, MFS, and FFS were 513.8 Hz, 849.3 Hz, and 770.7 Hz, respectively (Table 1). The median frequencies for each participant in the 3 sound conditions are displayed in the Figure. A moderate association was present ($F_{2,29} = 32.62$, $P < .0001$), with an R^2 of 0.322 for the median frequency

Table 1. Sound Characteristics of the 3 Foot-Strike Techniques With Predicted Marginal Means Between the Foot Strikes and 95% CIs

Variable Foot-Strike Pattern	Mean (SE)	95% CI	*P* Values With MFS	 With RFS
Peak sound amplitude, mV				
RFS	0.154 (1.061)	0.136, 0.174	<.001[a]	
MFS	0.384 (1.053)	0.345, 0.427	NA	<.001[a]
FFS	0.351 (1.059)	0.311, 0.394	.048[a]	<.001[a]
Median frequency, Hz				
RFS	513.8 (1.063)	453.9, 581.7	<.001[a]	NA
MFS	849.3 (1.035)	790.8, 912.1	NA	<.001[a]
FFS	770.7 (1.029)	726.2, 817.9	.002[a]	<.001[a]
Sound duration, s				
RFS	0.069 (0.002)	0.065, 0.074	<.001[a]	NA
MFS	0.055 (0.001)	0.053, 0.058	NA	<.001[a]
FFS	0.053 (0.002)	0.050, 0.057	0.188	<.001[a]

Abbreviations: FFS, forefoot strike; MFS, midfoot strike; NA, not applicable; RFS, rearfoot strike.

[a] Denotes a significant difference between a sound characteristic variable and foot-strike technique.

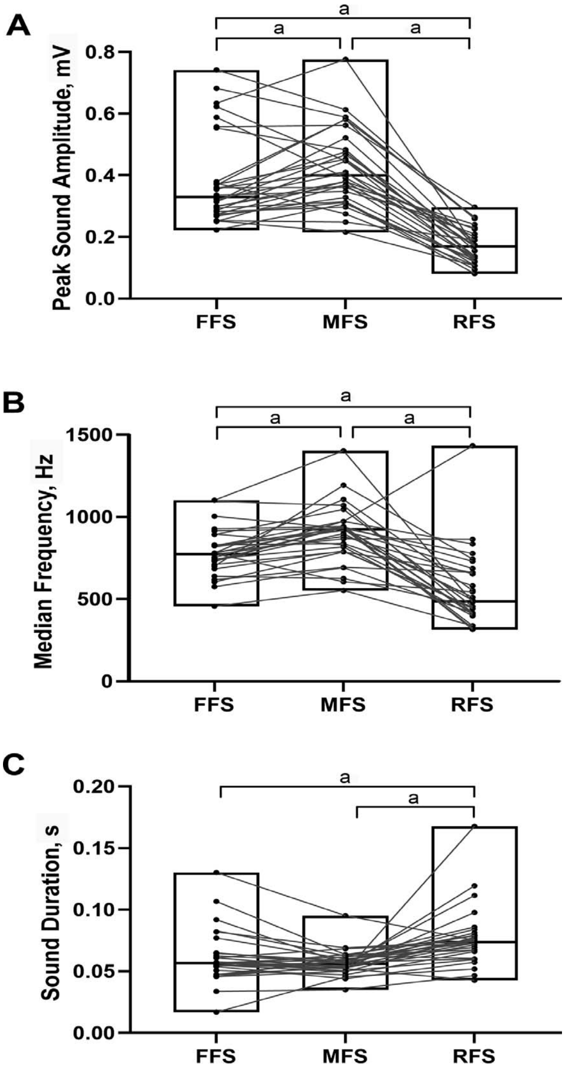

Figure. A, Mean peak sound amplitude (mV); B, median frequency (Hz); and C, sound duration (s) of the forefoot strike (FFS), midfoot strike (MFS), and rearfoot strike (RFS) running techniques for each individual runner. [a] Denotes a difference between a sound characteristic variable and foot-strike technique.

Table 2. Pearson Correlations and P Values Between Sound Characteristics and Running Kinetics

	R Value (P Value)		
Vertical Loading Rate	Peak Sound Amplitude	Median Frequency	Sound Duration
Average	−0.065 (.115)	0.029 (.483)	0.064 (.120)
Instantaneous	−0.016 (.690)	0.060 (.141)	0.058 (.159)

among the RFS, MFS, and FFS techniques. Pairwise comparisons of the median frequencies of initial impact sound among the 3 foot-strike techniques demonstrated that RFS had a lower sound frequency than FFS and MFS and MFS had a higher sound frequency than FFS and RFS.

The sound duration was longest in RFS, averaging 0.069 seconds, whereas MFS and FFS averaged 0.055 and 0.053 seconds, respectively (Table 1). The sound durations for each individual in the 3 sound conditions are shown in the Figure. A moderate association was found ($F_{2,29} = 28.09$, $P < .0001$), with an R^2 of 0.168 for the sound duration among RFS, MFS, and FFS techniques. Pairwise comparisons showed that the sound duration of RFS was longer than that of FFS or MFS.

No significant relationships were noted between sound characteristics and running kinetics (VALR and VILR; Table 2).

DISCUSSION

Our results showed that some sound characteristics differed among the RFS, MFS, and FFS techniques. Peak sound amplitude of RFS was quieter ($P < .001$) than that of MFS and FFS, and peak sound amplitude of MFS was louder ($P = .048$) than that of FFS. Median frequency of the MFS was higher ($P = .002$) than that of FFS and both values were higher ($P < .001$) than that of RFS. The sound duration of RFS was longer ($P < .001$) than that of MFS and FFS. Sound characteristics were not significantly associated with VALR or VILR.

The MFS and FFS were louder than the RFS, which is contrary to the findings of Phan and colleagues.[1] Phan et al reported that when asked to run "quietly," participants switched to an MFS or FFS technique, which resulted in a quieter sound amplitude than their initial RFS. This suggests that an MFS or FFS technique produces a quieter sound on impact. The conflicting results are most likely attributed to the different instructions in the 2 studies, as we instructed participants to run with different foot-strike techniques rather than to run quietly. Compared with the previous findings, our data may better represent the isolated effects of foot-strike patterns over impact sound amplitude. In practice, therefore, runners with experience in different types of foot-strike patterns could make use of the loudness differences to assist in switching the foot-strike pattern.

The MFS and FFS runners contacted the ground at higher median frequencies than did the RFS runners. Although sound frequency has not been investigated in running, it has been studied in walking. Ekimov and Sabatier[17] concluded that the higher sound frequency (>500 Hz) was the result of the tangential force (governed by the horizontal motion: eg, sliding between shoes and the ground) or frictional forces in normal walking. The high-frequency sound we recorded during MFS and FFS running may also be due to more tangential force (sliding) between the shoes and the ground than in RFS runners. Boyer et al[18] observed that posterior and medial ground reaction forces were greater in habitual MFS and FFS runners than in habitual RFS runners. The higher posterior and medial shear forces may, in turn, generate a higher-frequency sound in MFS and FFS runners and explain the difference we documented. Given that an adult with normal hearing can discriminate frequencies on the order of 0.2% to 0.3% between 250 and 4000 Hz,[19] it is reasonable to hypothesize that these significant differences in median frequency are detectable by the human ear. Future researchers may be able to combine sound amplitude and frequency to assist foot-strike analyses of runners in a controlled overground setting.

Our results indicated that sound duration was longer for RFS than for MFS and FFS. Although sound duration of foot strike during running has not previously been assessed, it may be related to the duration of the stance phase or ground contact time. Evidence surrounding the duration of the stance phase among RFS, MFS, and FFS runners is contradictory.[3,20] Gruber et al[3] found nonsignificant differences in stance-phase duration between habitual RFS (0.247 seconds) and MFS and FFS (0.214 seconds) when participants ran at 3.5 m/s, whereas Stearne et al[20] determined that RFS runners had a longer stance phase ($P = .013$) when running at 4.5 m/s (RFS = 0.23 seconds, FFS = 0.20 seconds). However, we evaluated sound duration only at impact. On separate analysis, the associated between sound duration and ground contact time was significant but weak ($r = .088$, $P = .032$). This indirectly suggests that other factors (eg, materials of different parts of the shoes and their mechanical property) are contributing to sound duration. Because the difference in sound duration for RFS and non-RFS runners is typically minimal, it is unlikely that sound duration could be used to distinguish between an RFS and non-RFS running pattern.

We did not find any significant relationship between vertical loading rates (VALR and VILR) and the selected sound characteristics. Hence, assessing foot-strike impact sound might not be a viable method of estimating runners' vertical loading rates. Clinicians should consider other equipment (eg, accelerometer) to estimate vertical loading rates[21]; however, the sound characteristics we evaluated did not provide insights into these measures.

We acknowledge that, because the characteristics of impact sound during running (such as frequency) have not previously been investigated, our data analyses were based on observation of raw data and discussion with experts in physics, biomechanics, and physiotherapy. One limitation of our work was that the participants were not habituated to all 3 foot-strike techniques. Even though practice time was given, habituation of the foot-strike technique may affect the impact-sound characteristics. Also, the usual foot-strike types of the participants were not identified in the laboratory environment; therefore, the habitual and non-habitual foot-strike types were not compared. Moreover, we presented the peak sound amplitudes in millivolts because we used a sound-level meter (Rion Co Ltd) and the conversion from millivolts to decibels at a logarithmic scale would have introduced a source of error. We also acknowledge individual differences in sound characteristics with foot-strike changes as seen in the Figure. Certain people have a higher peak sound amplitude in MFS, whereas others have a higher median frequency and longer duration in RFS. This is likely due to differences in individual running patterns, even with the same foot-strike techniques.[21]

The practical implications of these results are that using impact sound as a method of determining differences in running techniques may be feasible for runners and clinicians assessing shod, overground running. Runners could make use of this information to adjust their race strategy, arrange their training program, and choose footwear; clinicians could help runners design rehabilitation protocols according to their foot-strike techniques. Further investigation into shoe design (outsole material and thickness) and running surface should also be conducted to increase the generalizability of the application. However, the result may not be generalizable in treadmill running because the impact sound would be mixed with mechanical noises. Audio feedback as a real-time mechanism to correctly recognize the foot-strike technique being adopted may assist runners in changing running techniques, which has the potential for injury management.

CONCLUSIONS

We found that runners who were instructed to adopt an MFS had a louder impact sound and higher pitch (median frequency) than with either RFS or FFS during overground shod running. No relationship was identified between sound characteristics and VALR or VILR, which are kinetic factors with implications for running injuries. This study provided information about sound characteristics across foot-strike techniques, which may be a basis for future research to assist in low-cost clinical assessments of runners' foot-strike techniques.

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