Foot Strike and Injury Rates in Endurance Runners: A Retrospective Study

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ABSTRACT

DAOUD, A. I., G. J. GEISSLER, F. WANG, J. SARETSKY, Y. A. DAOUD, and D. E. LIEBERMAN. Foot Strike and Injury Rates in Endurance Runners: A Retrospective Study. *Med. Sci. Sports Exerc.*, Vol. 44, No. 7, pp. 1325–1334, 2012. **Purpose**: This retrospective study tests if runners who habitually forefoot strike have different rates of injury than runners who habitually rearfoot strike. **Methods**: We measured the strike characteristics of middle- and long-distance runners from a collegiate cross-country team and quantified their history of injury, including the incidence and rate of specific injuries, the severity of each injury, and the rate of mild, moderate, and severe injuries per mile run. **Results**: Of the 52 runners studied, 36 (69%) primarily used a rearfoot strike and 16 (31%) primarily used a forefoot strike. Approximately 74% of runners experienced a moderate or severe injury each year, but those who habitually rearfoot strike had approximately twice the rate of repetitive stress injuries than individuals who habitually forefoot strike. Traumatic injury rates were not significantly different between the two groups. A generalized linear model showed that strike type, sex, race distance, and average miles per week each correlate significantly ($P < 0.01$) with repetitive injury rates. **Conclusions**: Competitive cross-country runners on a college team incur high injury rates, but runners who habitually rearfoot strike have significantly higher rates of repetitive stress injury than those who mostly forefoot strike. This study does not test the causal bases for this general difference. One hypothesis, which requires further research, is that the absence of a marked impact peak in the ground reaction force during a forefoot strike compared with a rearfoot strike may contribute to lower rates of injuries in habitual forefoot strikers. **Key Words:** RUNNING FORM, INJURY RATE, INJURY PREVENTION, REPETITIVE STRESS, FOREFOOT STRIKE, REARFOOT STRIKE

Distance running causes high rates of running injuries, variously estimated to be between 30% and 75% per year (38,39). Although comparisons of injury rates among studies are complicated by different methods used to define and measure injuries and by differences between the populations studied, there is general agreement that running injury rates are unacceptably high, with no significant decline during the last 30 yr despite considerable efforts to reduce them. The causal bases for running injuries are obviously multifactorial and are often thought to include both intrinsic factors such as biomechanical abnormalities, previous injury, sex, and body mass index (BMI), as well as extrinsic factors such as shoes, flexibility, core strength, or the intensity duration and frequency of training (3,6,15,19,22,37–39). Many studies, however, have found that efforts to mitigate the effect of these factors on injury using either graded training programs (6,44) or prescriptions of shoes and orthotics have either modest or nonsignificant effects (14,18,23,33,34).

Because a runner's kinematics affects how external and internal forces are generated and withstood by the body, this study considers how differences in general running form may influence overall injury rates. Although running form has many components, we focus on just one major aspect of running form, foot strike pattern, whose effect on injury rates has not been previously studied. Foot strikes vary, and there is no consensus on how to define and measure them (see Cavanagh and Lafortune [8] and Lieberman et al. [21]). Here, we define three categories of strike types that are prevalent among distance runners: rearfoot strikes (RFS), in which the heel contacts the ground first (heel–toe running); forefoot strikes (FFS), in which the ball of the foot contacts the ground before the heel (toe–heel–toe running); and midfoot strikes (MFS), in which the heel and ball of the foot contact the ground simultaneously. Note that we do not consider toe strikes, in which the heel never contacts the ground because this is a rare strike pattern among distance runners. We also

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Submitted for publication June 2011.
Accepted for publication December 2011.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.acsm-msse.org).

0195-9131/12/4407-1325/0
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DOI: 10.1249/MSS.0b013e3182465115

note that strike pattern depends to some extent on speed, surface, footwear, and fatigue, but FFS gaits are generally more common at higher speeds, and among unshod or minimally shod runners, especially on hard surfaces (12,21,36).

There are three major reasons to test for a relationship between strike pattern and injury rates. First, how the foot strikes the ground involves disparate kinematics of the lower extremity. During a RFS, a runner usually lands with the foot in front of the knee and hip, with a relatively extended knee, and with a dorsiflexed, slightly inverted and abducted ankle; the runner then plantarflexes rapidly as the ankle everts just after impact (Fig. 1A). In contrast, a FFS runner lands with a more flexed knee and plantarflexed ankle (Fig. 1B), usually making ground contact below the fourth or fifth metatarsal heads; the runner then simultaneously everts and dorsiflexes the foot during the brief period of impact, usually with more ankle and knee compliance (21). MFS landings are highly variable, but generally intermediate in terms of kinematics. Second, different strike patterns generate contrasting kinetics, especially at impact. As Figure 1 shows, RFS landings typically generate a rapid, high-impact peak in the ground reaction force (GRF) during the first part of stance; FFS also must generate an impact, but they usually cause no clear and marked impact peak (4,12,20,21,27,41). MFS can cause a broad range of impact peaks, from high to low, depending on ankle and knee compliance (12,21). Strike pattern also affects lower extremity joint moments, with FFS landings causing higher net moments around the ankle in the sagittal plane and lower net moments around the knee and hip in both the sagittal and transverse planes (11,41). A final reason to study the relationship between foot strike pattern and injury rates is the growing popularity of running either barefoot or in minimal shoes that lack an elevated heel, contain no arch support, and have a thin, flexible sole. All humans ran either barefoot or in minimal shoes before the invention of the modern running shoe in the 1970s. Habitually barefoot and minimally shod runners commonly FFS or MFS (21,37), and habitually shod runners asked to run barefoot instinctively land more toward the ball of the foot (12). These and other sources of information, such as old coaching manuals (e.g., Wilt [42]), lead to the hypothesis that FFS running may have been more common for most of human evolution. This hypothesis is relevant to the issue of running injury because if the foot evolved via natural selection to cope primarily with movements and forces generated during mostly forefoot rather than rearfoot strikes, then it follows that the body may be better adapted to FFS running.

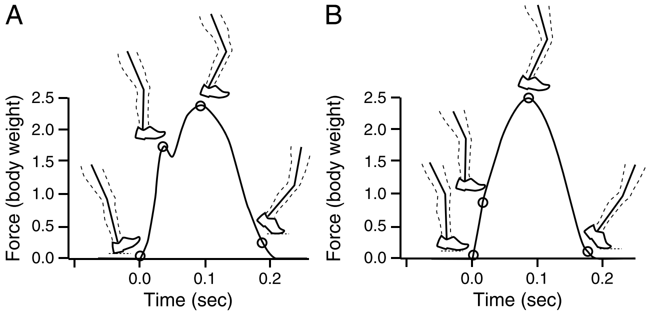

FIGURE 1—*Top*, GRF and kinematics (traced from a high-speed video) for the same runner at 3.5 m·s^{-1} wearing standard running shoes during a RFS (A) and a FFS (B). *Circles* on the force trace indicate the instant of the kinematic trace.

Another motivation for this study is that a growing number of runners are adopting FFS or MFS landings in minimal shoes or sometimes even barefoot, many because of unsubstantiated claims that this sort of form can prevent injuries, as well as increase speed and improve endurance. These claims are problematic because they have not been tested. However, there are two major reasons to predict that strike type affects injury rates. First, as noted above, studies of GRF have shown that RFS landings typically generate a marked, substantial impact peak (Fig. 1A), defined as a brief, high spike of force that is superimposed on the upslope of the vertical GRF immediately after the foot's initial contact with the ground. The impact peak in a typical barefoot RFS has a rate of loading of 400–600 body weights per second and a magnitude of 1.5–2.5 body weights but is usually dampened by a shoe heel to a loading rate of 70–100 body weights per second, with a 10% reduction in magnitude (21,30,35). In contrast, the initial impact between the foot and the ground in FFS and some MFS landings is more compliant and involves the exchange of less momentum and, thus, does not generate a conspicuous impact peak with a high rate and magnitude (4,8,20,21,30,41). This difference presumably accounts for why unshod or minimally shod runners tend to FFS or MFS (21) without the benefit of an elastic heel, which attenuates the larger impact peak forces during RFS landings more effectively than the human heel pad (10). Impact peak forces are hypothesized to contribute to some kinds of injury because they generate a shock wave that travels up the body, generating potentially high stresses and strains in skeletal tissues, which, in turn, generate high levels of elastic hysteresis that can contribute to injury over repeated cycles. Higher rates and magnitudes of impact loading have been shown by some studies to correlate significantly among RFS runners with lower limb stress fractures (25), plantar fasciitis (31), and other injuries such as hip pain, knee pain, lower back pain, medial tibial stress syndrome, and patellofemoral pain syndrome (9,13,31). Other studies, however, have failed to find a correlation between impact peaks and running injuries (28,29). All of these studies, however, examined only habitually shod RFS runners and did not look at FFS runners whose GRF lack a marked impact peak.

A second factor relevant to running injury rates in FFS versus RFS runners is the rate and magnitude of joint moments (or torques), which may cause repetitive stress damage in ligaments, tendons, cartilage, and other nonskeletal connective tissues that stabilize joints (2). During impact, RFS landings generate a lower net moment in the sagittal plane around the ankle than a FFS, but higher net sagittal moments in the knee (1,41). In addition, shoes with thick and wide heels nearly double the pronation-inducing torque in the coronal plane at the ankle (11), and RFS running in shoes increases peak external adductor (varus) rotational moments, external flexion and internal (medial) rotation moments at the knee, and peak external adductor and external (lateral) rotation moments at the hip (17). However, correlations between these moments and running injuries have not been studied.

To sum up, the general hypothesis we test is that, while both FFS and RFS runners incur injuries, FFS runners experience overall lower rates of injury than RFS runners after correcting for covariates such as distance run per week, BMI, sex, and race distance run. We also predict a trade-off among injuries in runners who habitually use FFS and RFS gaits. Runners who RFS are hypothesized to be more likely to incur injuries in the lower extremity caused by repeated, high and rapid impact peaks, as well as injuries caused by repeated, high and rapid moments in the knee and hip. Predicted RFS injuries therefore include injuries of the knee and hip, lower back pain, plantar fasciitis, medial tibial stress syndrome, and stress fractures of bones of lower limb excluding the metatarsals (26,30,31). In contrast, runners who FFS may be more likely to experience higher magnitudes of loading in the forefoot and higher and more rapid sagittal plane moments in the ankle (41). Therefore, predicted FFS injuries include Achilles tendinopathies, injuries of the foot, and stress fractures of the metatarsals.

METHODS

A retrospective cohort study was performed to investigate differences in injury types and rates among 52 athletes who were on the Harvard University Cross Country team between August 2006 and January 2011 (Table 1). All were experienced runners, sufficiently talented to compete at the Division I of the National Collegiate Athletic Association. All subjects were middle- and long-distance runners who competed in races between 800 m and 10 km, and who followed similar training plans developed by the same coach. In the fall cross country season (approximately 3 months), most runners ran four to six races on natural surfaces such as packed dirt and grass: female subjects ran 6- and 8-km races and male subjects 8- and 10-km races. In the winter and spring track season (approximately 6 months), middle-distance runners usually ran eight to twelve 800-m, 1500-m, 1600-m, and 3-km races and long-distance runners usually ran eight to twelve 3-, 5-, and 10-km races on track. The use of medical and training records and the collection of data on running biomechanics for all subjects were approved by the Harvard University Committee on the Use of Human Subjects. Prior written informed consent was obtained from all subjects.

Running training data. Information on each subject's training during the study period was collected from an online running log Web site. Each athlete was required to record daily all running and cross-training information including distance run, times, and comments on performance throughout the 9-month athletic season. The total number of running days, total miles run, total minutes run, average miles per week, and average running pace were computed for each subject while on the team.

Strike type characterization. Foot strike patterns vary during workouts and races depending on several factors such as incline, fatigue, and speed. It is not possible to assess precisely the percentage of different foot strikes each runner uses throughout training, but we can measure the predominant foot strike used for the majority of miles run. To accomplish this, strike type was visually identified using a 500-Hz video camera (FastecInLine 500M; Fastec Imaging, San Diego, CA) from a lateral perspective. Some subjects (n = 31) were recorded while running at four speeds (females: 3.0, 3.5, 4.0, and 4.5 m·s^{-1}; males: 3.5, 4.0, 4.5, and 5.0 m·s^{-1}) on a treadmill with the camera placed 2 m lateral from the recording region 0.25 m above ground level; other subjects (n = 28) were recorded while running on a track at three self-selected speeds (recovery pace, intermediate pace, and 5000-m race pace) with the camera placed 4 m lateral from the recording region, 0.5 m above ground level. Seven subjects ran in both experimental setups to validate the reliability between methods. For these subjects, agreement was 100% in categorizing a runner's habitual strike type in overground and treadmill conditions (intraclass correlation (ICC) = 1.0).

The plantar foot angle at foot strike was determined as the angle between earth horizontal and the plantar surface of the foot. The plantar foot angle was examined to determine the foot strike type using methods reported in Lieberman et al. (21). Strikes in which the heel was the first part of the foot to contact the ground and the plantar angle was positive were categorized as RFS; strikes in which the

TABLE 1. Subject information.

Sex	Foot Strike	n	Duration in Study (yr)	Age (yr)	BMI (kg·m^{-2})	Total Miles Run	Miles Run per Week
Female	FFS	5	2.34 ± 0.93	19.00 ± 0.86	20.18 ± 1.15	3065.26 ± 2409.48	35.29 ± 12.16
	RFS	18	2.18* ± 1.07	19.75* ± 0.58	19.60 ± 1.24	3623.20 ± 2105.26	41.33 ± 10.82
Male	FFS	11	1.86 ± 1.20	19.42 ± 0.85	21.30 ± 1.87	4400.09 ± 3480.37	48.20 ± 15.09
	RFS	18	1.48* ± 0.87	19.33* ± 0.63	20.65 ± 1.27	2996.32 ± 2572.80	43.33 ± 13.16
All	FFS	16	2.01 ± 1.11	19.29 ± 0.85	20.95 ± 1.72	3982.96 ± 3167.30	44.76 ± 15.14
	RFS	36	1.83 ± 1.03	19.54 ± 0.63	20.13 ± 1.35	3309.76 ± 2338.56	42.33 ± 11.92
Female	Combined	23	2.21* ± 1.02	19.59 ± 0.70	19.73* ± 1.22	3501.91 ± 2129.73	40.23 ± 11.03
Male		29	1.62* ± 1.01	19.36 ± 0.71	20.90* ± 1.52	3528.79 ± 2970.76	45.18 ± 13.87

Values are mean ± SD.

* Significantly different between sexes (t-test, $P < 0.05$).

ball of the foot contacts the ground first and the plantar angle was negative were classified as FFS; strikes in which the ball of the foot and heel landed simultaneously (within the 2-ms resolution available from the video) were classified as MFS. A minimum of three strikes was assessed for each runner. For the nine subjects who changed foot strike type with increased speed, the foot strike at which the subject ran the majority of their miles was used to classify that runner (four were classified as FFS runners and five as RFS runners).

Injury data. All athletes on the team are required to report all injuries, which were diagnosed and recorded by the same athletic trainer/physical therapist (G.G.); follow-up consultations were performed by the same team of four physicians at the Harvard University Health Services. Injury diagnosis, physical activity restrictions, treatment plan, and administered treatment were documented approximately 5 d·wk^{-1} during the 9-month athletic season. This system allowed for consistent injury diagnosis and treatment across subjects.

Each injury diagnosis was made by the medical staff after consultations with physicians, if necessary, and after incorporating any medical imaging data that were acquired (e.g., radiographs, magnetic resonance imaging, and computed tomographic scans). Injuries caused by accidents (e.g., falls and collisions) were excluded from this study. The remaining running injuries were grouped into the following categories: tendinopathies (by tendon); plantar fasciitis; stress reactions and stress fractures (by bone, including medial tibial stress syndrome); iliotibial band syndrome; knee pain including patellofemoral pain syndrome, plica syndrome, and bursitis; lower back pain (including sacroiliac joint pain); muscle strains; cartilage damage (by joint); sprains (by joint); and generalized pain (by region).

The severity of each diagnosed injury was quantified in its effect on training using a numerical scoring system based on physical activity restrictions during the entire period that the injury persisted. The following categories of restriction were used: *Full*, athlete continues running without restrictions; *>50%*, athlete runs at a reduced intensity or distance, greater than half of normal training; *<50%*, athlete runs at a reduced intensity or distance, less than half of normal training; *Cross-training*, athlete is not running, but is cross-training; *Off*, athlete is neither running nor cross-training. A Running Injury Severity Score (RISS) was computed by summing the days at each grade of physical restriction multiplied by a coefficient relative to the extent of restriction:

$$\begin{aligned}\text{RISS} \;=\; & \text{full days} + (>50\%\ \text{days} \times 2) + (<50\%\ \text{days} \times 3) + \\ & (\text{cross-training days} \times 4) + (\text{off days} \times 5) \qquad (1)\end{aligned}$$

Although the RISS is a continuous measure of injury severity, we binned all injuries into three major grades: mild (≤10), moderate (11–70), and severe (>70). The following are examples: a mild injury could cause a runner to take at most 2 d completely off or to train through the injury for 10 d; a moderate injury could cause a runner to take up to two complete weeks off or to train through the injury for up to 10 wk; and a severe injury, such as a stress fracture, could cause a runner to take 6 wk off, cross-train for 2 wk, and run at a reduced intensity than normal training for 2 wk. Mild injuries are probably underreported because subjects may have sometimes neglected to report injuries that did not prevent them from training.

Injuries were grouped by type into those predicted to be more common in FFS and RFS runners. On the basis of the general model presented above, predicted FFS injuries were Achilles tendinopathies, foot pain, and stress fractures of metatarsals; predicted RFS injuries were hip pain, knee pain, lower back pain, tibial stress injuries, plantar fasciitis, and stress fractures of lower limb bones excluding the metatarsals. Injuries were also grouped into those likely to be caused by repetitive stress (repetitive injuries) and trauma such as muscle soreness and strains from speed work (traumatic injuries).

To correct for the distance run by each subject, injury rates per 10,000 miles run were quantified for each subject.

Statistical analysis. *t*-Tests were used to compare mean injury rates of four continuous variables (repetitive injury rate, traumatic injury rate, predicted FFS injury rate, and predicted RFS injury rate) between RFS runners and FFS runners (pooled and by sex). These analyses were run separately for mild, moderate, and severe injuries and for combined moderate and severe injuries; for all comparisons, Welch's *t*-tests were used to account for potentially unequal variances. In addition, a generalized linear model (GLM) was used for the four injury groups with the following covariates: foot strike type, sex, BMI, race distance (middle or long distance), average miles per week, duration in study, and the quadratic terms of average miles per week and duration in study. The GLM (24,40) assesses the association between independent variables and a dependent, response variable (in this case, rate of injury). Specifically, the response variable was assumed to have a Poisson distribution, and a log link function was used. This allows the magnitude of the variance of each measurement to be a function of its predicted value and is defined as follows:

$$\text{predicted adjusted number of injuries} \;=\; {}_{e}\beta_{\text{o}} + \sum \beta_i X_I \qquad (2)$$

where β_0 is the intercept term, β_i is the coefficient of the *i*th covariate, and X_i is the *i*th covariate.

Descriptive statistics and statistical tests were weighted by total miles run by each subject during the study period to account for the greater robustness of injury rates from subjects who had run more miles during the study period.

RESULTS

The 52 subjects in the study (males = 29, females = 23; age = 17.75–22.5 yr, BMI = 17.2–24.2 kg·m^{-2}) ran a total of 182,879 miles during the period measured. On the basis of the independent assessment of strike type during overground and treadmill conditions, 16 (31%) were classified

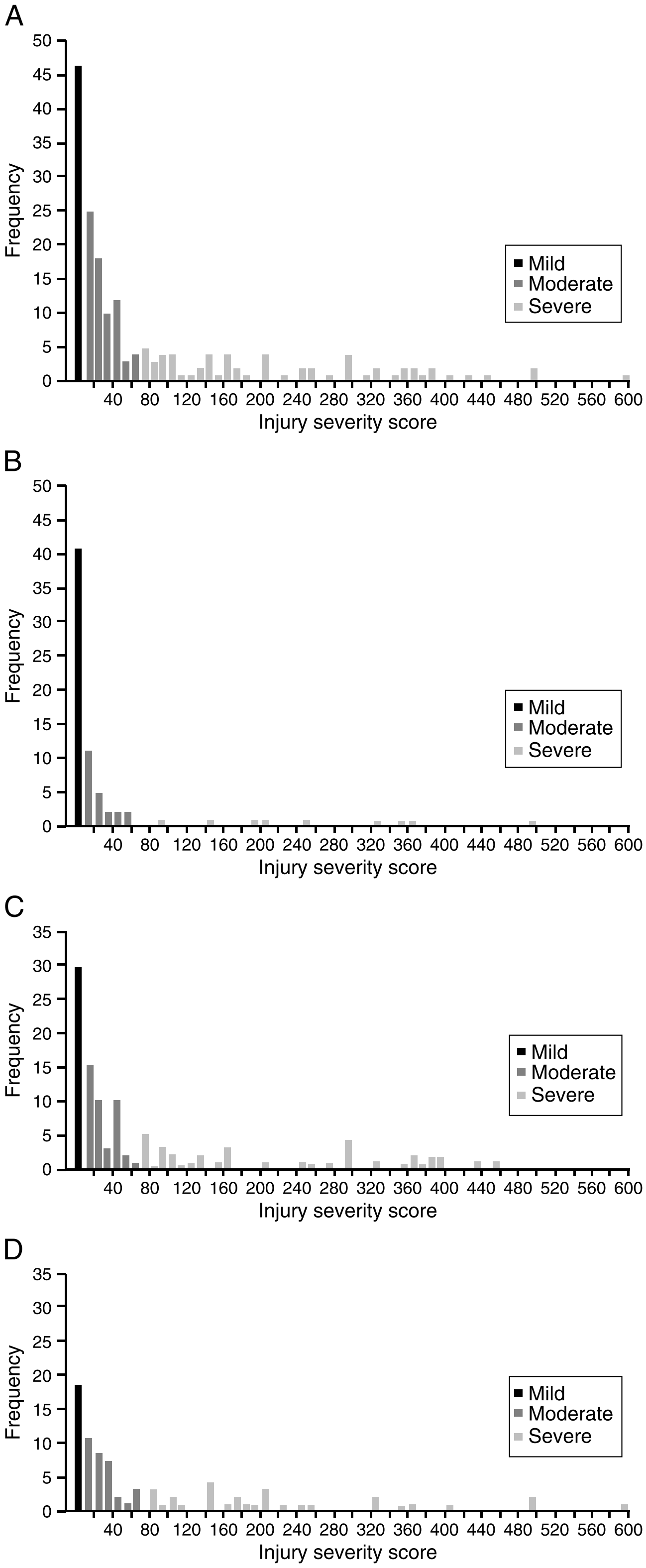

FIGURE 2—Histograms of the frequency of injuries by severity score of repetitive injuries for males and females (A), traumatic injuries for males and females (B), repetitive injuries for females (C), and repetitive injuries for males (D). See text for definition of mild, moderate, and severe injury categories.

as habitual forefoot strikers; 36 (69%) were classified as habitual rearfoot strikers. There were no habitual MFS runners; one subject had a MFS at his slowest recorded speed but ran with a RFS for the other three speeds and was thus classified as a RFS runner. There was no significant difference in foot strike pattern between middle- and long-distance runners (χ^2 test, likelihood ratio: $P = 0.6027$). Although we report injuries per mile, we had more years of data for older subjects who had been on the team longer. This is not a source of bias because there was no significant relationship between years on the team and the number of miles run per week (least squares regression, $R^2 = 0.01$, $P = 0.47$), BMI (least squares regression, $R^2 = 0.0002$, $P = 0.93$), or strike type (Kendall tau result $\chi^2 = 0.35$, $P = 0.56$). Females ran an average of 40 miles·wk^{-1}; males averaged 45 miles·wk^{-1} (Table 1). During this period, a total of 181 repetitive injuries were recorded, of which 46 (25%) were mild, 72 (40%) were moderate, and 63 (35%) were severe (Fig. 2A). There were 67 traumatic injuries, of which 36 (54%) were mild, 22 (33%) were moderate, and 9 (13%) were severe (Fig. 2B). The percent injured (excluding mild injuries) was 74% (females = 79%, males = 68%), but if mild injuries are included, 84% of runners had a repetitive injury (females = 88%, males = 79%). Although overall injury rates were higher in females, the general pattern of injury severity did not differ between the sexes (Figs. 2C and D).

Injury rates by general category (repetitive, traumatic, predicted FFS, and predicted RFS) and severity (mild, moderate, and severe) are summarized by foot strike and sex in Figure 3 and Table 2 (rates of specific injuries are broken down in Table, Rates of individual injuries; Supplemental Digital Content 1, http://links.lww.com/MSS/A153). The most common injuries were muscle strains (21.5% of all injuries), medial tibial stress syndrome (13.8%), knee pain (7.7%), iliotibial band syndrome (7.2%), and Achilles tendinopathies (6.6%). As predicted, repetitive stress injury rates are consistently and significantly higher for RFS runners than FFS runners. For the total sample, injury rates for both mild and moderate (but not severe) repetitive stress injuries are 2.5 times higher in RFS than in FFS runners ($P < 0.05$), and the rate of combined moderate and severe repetitive injuries is 1.7 times more frequent in RFS runners (8.66 injuries per 10,000 miles) than in FFS runners (5.00 injuries per 10,000 miles, $P = 0.04$; Fig. 3A). In contrast, traumatic injury rates (Table 3 and Fig. 3B) do not differ in a significant or consistent pattern between RFS and FFS runners (combined moderate and severe injuries, $P = 0.78$). To test if the results were affected by misdiagnosis of a subject's habitual foot strike type, we redid the analyses without the nine subjects who were recorded using more than one foot strike pattern (see Methods). This smaller sample had four (25%) fewer FFS runners and five (14%) fewer RFS runners, decreasing statistical power but yielding a similar pattern of difference in repetitive stress injury rates between FFS and RFS subjects but with a slightly reduced effect size. Comparing RFS and FFS subjects, the ratio of moderate repetitive stress injuries

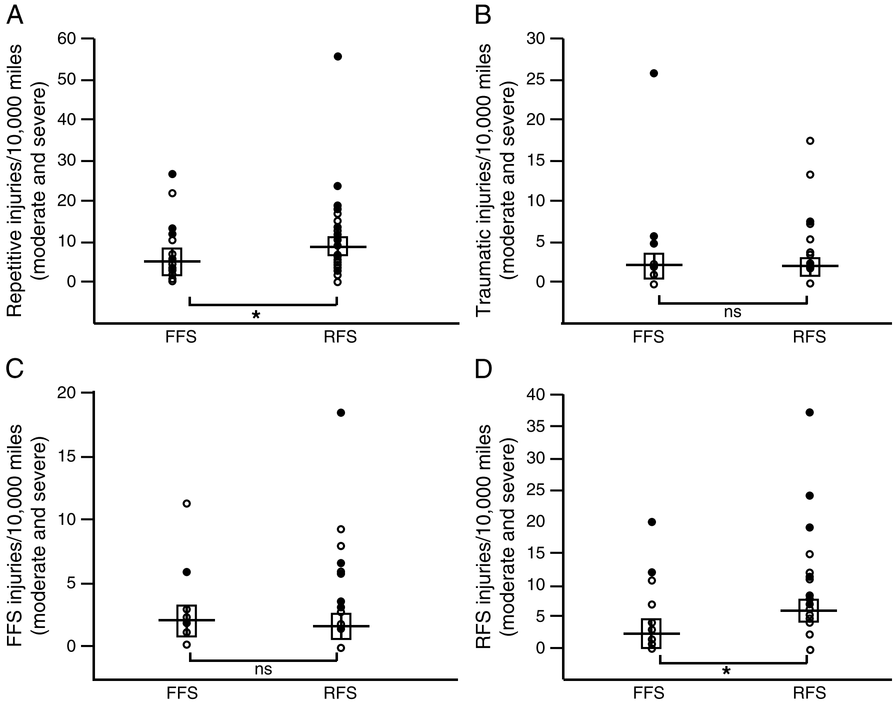

FIGURE 3—Histograms of moderate and severe injuries by strike type: repetitive stress injuries (A), traumatic injuries (B), predicted FFS injuries (C), and predicted RFS injuries (D). *Boxes* indicate mean and SE. Note that the means are significantly different in A and D and that the variation is greater for RFS runners in A and D. *Open circles* indicate females.

decreased from 2.5 to 2.1 and remained significantly different ($P = 0.05$); the ratio of mild injuries decreased from 2.5 to 2.0 ($P = 0.17$) and the ratio of combined moderate and severe injuries decreased from 1.7 to 1.5 ($P = 0.22$).

We also compared the rates of injuries predicted to affect FFS and RFS runners (Table 2 and Figs. 3C and D). Although predicted FFS injury rates are not significantly different between foot strike groups (combined moderate and severe injuries, $P = 0.56$), the rates of predicted RFS injuries are consistently and significantly higher in the RFS runners, with an overall 2.7 times greater frequency of combined moderate and severe injury for RFS runners (5.80 injuries per 10,000 miles) than for FFS runners (2.19 injuries per 10,000 miles), a highly significant difference ($P = 0.0058$). When the nine subjects who were recorded using more than one foot strike pattern were excluded from the analysis, trends in predicted FFS and RFS injuries remained almost the same with no effect on predicted FFS injuries, and the ratio of predicted RFS injuries (combined moderate and severe) between the two groups declined only slightly from 2.7 to 2.5 on the cusp of conventional statistical significance ($P = 0.054$) with the smaller sample size.

TABLE 2. Weighted injury rates (per 10,000 miles) of repetitive, traumatic, predicted FFS, and predicted RFS injuries.

	Female (*n* = 23)			**Male (*n* = 29)**			**All (*n* = 52)**		
	FFS (*n* = 5)	**RFS (*n* = 18)**	***P***	**FFS (*n* = 11)**	**RFS (*n* = 18)**	***P***	**FFS (*n* = 16)**	**RFS (*n* = 36)**	***P***
Repetitive injuries									
Mild	2.06 ± 2.07	3.94 ± 0.78	0.40	1.01 ± 0.65	2.27 ± 0.74	0.20	**1.25 ± 0.67**	**3.19 ± 0.55**	**0.025**
Moderate	**1.37 ± 1.12**	**5.91 ± 1.25**	**0.007**	2.23 ± 0.81	3.78 ± 1.07	0.25	**2.03 ± 0.66**	**4.96 ± 0.84**	**0.006**
Severe	6.18 ± 3.23	3.94 ± 1.04	0.51	2.02 ± 0.79	3.40 ± 0.71	0.19	2.97 ± 1.01	3.70 ± 0.64	0.54
Moderate and severe	7.83 ± 3.41	9.81 ± 1.62	0.60	4.25 ± 1.45	7.18 ± 1.17	0.12	**5.00 ± 1.43**	**8.66 ± 1.02**	**0.037**
Traumatic injuries									
Mild	1.37 ± 2.32	2.27 ± 1.01	0.72	0.61 ± 0.33	3.02 ± 1.34	0.08	0.78 ± 0.56	2.61 ± 0.81	0.06
Moderate	2.75 ± 0.87	1.21 ± 0.82	0.20	0.81 ± 0.28	1.13 ± 0.85	0.72	1.25 ± 0.35	1.18 ± 0.58	0.91
Severe	0.69 ± 0.47	0.30 ± 0.17	0.44	0.20 ± 0.19	0.94 ± 0.39	0.09	0.31 ± 0.18	0.59 ± 0.21	0.32
Moderate and severe	3.43 ± 1.11	1.52 ± 0.81	0.16	1.01 ± 0.29	2.08 ± 0.86	0.24	1.56 ± 0.42	1.77 ± 0.58	0.78
FFS injures									
Mild	0.69 ± 0.47	0.61 ± 0.25	0.88	0.40 ± 0.26	0.19 ± 0.14	0.47	0.47 ± 0.22	0.42 ± 0.15	0.86
Moderate	0.69 ± 0.47	0.45 ± 0.29	0.67	1.01 ± 0.50	0.94 ± 0.45	0.92	0.94 ± 0.39	0.67 ± 0.26	0.57
Severe	2.06 ± 1.58	1.06 ± 0.56	0.55	0.61 ± 0.32	0.38 ± 0.23	0.56	0.94 ± 0.44	0.76 ± 0.32	0.74
Moderate and severe	2.75 ± 1.34	1.52 ± 0.59	0.40	1.62 ± 0.76	1.32 ± 0.58	0.76	1.88 ± 0.65	1.43 ± 0.41	0.56
RFS injuries									
Mild	**0 ± 0**	**2.27 ± 0.62**	**0.0002**	0.61 ± 0.51	1.51 ± 0.61	0.26	**0.47 ± 0.39**	**1.93 ± 0.44**	**0.012**
Moderate	**0.69 ± 1.16**	**4.55 ± 1.07**	**0.015**	0.81 ± 0.47	1.89 ± 0.67	0.19	**0.78 ± 0.43**	**3.36 ± 0.68**	**0.001**
Severe	2.75 ± 2.97	2.27 ± 0.83	0.88	**1.01 ± 0.46**	**2.65 ± 0.66**	**0.042**	1.41 ± 0.75	2.44 ± 0.53	0.26
Moderate and severe	3.43 ± 3.87	6.82 ± 1.35	0.41	**1.82 ± 0.73**	**4.53 ± 0.86**	**0.016**	**2.19 ± 1.00**	**5.80 ± 0.84**	**0.006**

Values are mean ± SEM.
Bold numbers are significant at $P < 0.05$.

TABLE 3. Generalized linear models for repetitive, traumatic, predicted FFS, and predicted RFS injuries.

Parameter	Estimate	SE	Wald 95% Confidence Limits		P
Repetitive injuries					
Intercept	5.3321	1.2681	2.8467	7.8175	<**0.0001**
Foot strike: FFS	−0.5762	0.1344	−0.8396	−0.3128	<**0.0001**
Sex: female	0.3979	0.1446	0.1144	0.6814	**0.0059**
Race distance run	0.7426	0.1546	0.4396	1.0457	<**0.0001**
BMI	0.0691	0.0491	−0.0271	0.1654	0.1593
Average miles per week	−0.2070	0.0341	−0.2739	−0.1402	<**0.0001**
(Average miles per week)^2	0.0019	0.0004	0.0011	0.0026	<**0.0001**
Duration in study	0.1542	0.2680	−0.3712	0.6795	0.5652
(Duration in study)^2	−0.0572	0.0598	−0.1745	0.0600	0.3388
Traumatic injuries					
Intercept	−0.3478	2.4146	−5.0804	4.3847	0.8855
Foot strike: FFS	0.2164	0.2471	−0.2679	0.7006	0.3812
Sex: female	0.0249	0.2832	−0.5301	0.5799	0.9300
Race distance run	0.2980	0.3071	−0.3040	0.8999	0.3320
BMI	0.0929	0.0984	−0.1000	0.2859	0.3453
Average miles per week	−0.0663	0.0665	−0.1966	0.0639	0.3184
(Average miles per week)^2	0.0003	0.0008	−0.0012	0.0018	0.6883
Duration in study	1.1357	0.6719	−0.1812	2.4527	0.0910
(Duration in study)^2	−0.2627	0.1430	−0.5430	0.0176	0.0662
Predicted FFS injuries					
Intercept	9.6523	2.8068	4.1512	15.1535	**0.0006**
Foot strike: FFS	−0.0852	0.2777	−0.6295	0.4592	0.7591
Sex: female	−0.4731	0.3412	−1.1419	0.1956	0.1656
Race distance run	0.5975	0.3263	−0.0421	1.2371	0.0671
BMI	−0.1632	0.1115	−0.3817	0.0553	0.1432
Average miles per week	−0.1931	0.0722	−0.3345	−0.0516	**0.0075**
(Average miles per week)^2	0.0015	0.0008	−0.0001	0.0030	0.0613
Duration in study	−1.1943	0.5611	−2.2940	−0.0947	**0.0333**
(Duration in study)^2	0.3286	0.1239	0.0857	0.5715	0.0080
Predicted RFS injuries					
Intercept	2.5659	1.6760	−0.7191	5.8509	0.1258
Foot strike: FFS	−1.0166	0.1941	−1.3970	−0.6361	<**0.0001**
Sex: female	0.6545	0.1862	0.2896	1.0194	**0.0004**
Race distance run	0.8307	0.2062	0.4266	1.2348	<**0.0001**
BMI	0.1464	0.0631	0.0227	0.2701	**0.0203**
Average miles per week	−0.2050	0.0475	−0.2982	−0.1118	<**0.0001**
(Average miles per week)^2	0.0019	0.0005	0.0009	0.0029	**0.0002**
Duration in study	0.7688	0.3700	0.0436	1.4941	**0.0377**
(Duration in study)^2	−0.2177	0.0834	−0.3812	−0.0542	**0.0091**

Bold numbers are significant at $P < 0.05$.

A complementary method of analyzing differences in injury rates that controls for covariates is to use a generalized linear model. This analysis (Table 3) shows that strike type, sex, race distance, and weekly mileage were significantly associated with the rate of combined moderate and severe repetitive stress injuries, but none of the covariates were significantly associated with traumatic injury rates. In addition, strike type was significantly associated with predicted RFS ($P < 0.0001$) but not predicted FFS injury rates ($P = 0.7591$). For repetitive injures and predicted RFS injuries, being a RFS runner, being female, and being a distance runner (compared with middle-distance runners) contributed to higher injury rates. For predicted RFS injuries, having a higher BMI also contributed to higher injury rates.

DISCUSSION

Compared with the injury rates documented in some other studies (see Reference 39), the runners studied here had a high rate of injury: approximately 75% of subjects incurred at least one moderate or severe repetitive stress injury per year. Injury rates were only slightly higher in females than in males. This generally high rate of injury probably reflects the intense, competitive nature of the population studied and is typical of most collegiate teams. Compared with most recreational runners, these athletes were running more miles per week, training at faster speeds, and racing more frequently, approximately 12–18 races per year, and they are used to training through discomfort and pain. The high rate of injury might also be partially explained by more thorough injury surveillance as runners had nearly daily access to athletic trainers and were required to report injuries. Even so, the most common repetitive stress injuries were similar to those of other studies: medial tibial stress syndrome, iliotibial band syndrome, patellofemoral pain syndrome, and Achilles tendinopathies.

Both FFS and RFS runners were injured at high rates, but differences between the two groups support the hypothesis that foot strike patterns influence injury rates. In terms of the general category of repetitive stress injuries, the pooled sample of RFS runners was 2.6 times more likely to have mild injuries and 2.4 times more likely to have moderate injuries. When moderate and severe injuries are pooled, RFS runners had an overall injury rate that was nearly twofold higher than what FFS runners had ($P = 0.04$). In contrast, traumatic injury rates were not significantly different between RFS and FFS runners. We also tested for differences in the rates of categories of injuries expected to predominantly affect RFS or FFS runners. As hypothesized, the set of predicted RFS injuries (hip pain, knee pain, lower back pain, tibial stress injuries, plantar fasciitis, and stress fractures of lower limb bones excluding the metatarsals) were between twofold and fourfold more frequent in RFS than in FFS runners, with significantly lower rates of mild and moderate injuries in FFS runners ($P = 0.0121$ and $P = 0.0014$, respectively), and a significantly lower rate of moderate plus severe injuries in FFS runners ($P = 0.0058$). In contrast, the incidence of injuries predicted to be higher in FFS runners (Achilles tendinopathies, foot pain, and metatarsal stress fractures) was not significantly different between the two groups. Future studies with larger sample sizes will be necessary to extend these results to specific injuries, and we caution that because many factors probably contribute to each type of injury, these factors likely differ between injuries. As a result, we do not predict that a single nominal variable such as foot strike type can ever explain a high percentage of the variance for specific injury. Figure 3A illustrates the relatively high variance in injury rates within both groups; the subjects studied included some FFS runners ($n = 5$, 31%) with modest to high rates of repetitive stress injury (>10 injuries/10,000 miles) and many RFS runners ($n = 7$, 19%) with injury rates below this arbitrary threshold.

In short, most runners from the population we studied are likely to get a repetitive stress injury in a given year, but subjects who are habitual RFS runners have an approximately twofold higher overall injury rate than what habitual FFS runners have. This difference is comparatively large in relation to previously measured effects of other factors thought to influence injury rates such as age, prior injury, BMI, foot type, lumbopelvic strength, arch type, flexibility, Q angle, and neuromuscular control (3,6,15,22,37). The biggest question these results raise is what about FFS running that makes it less injurious than RFS running in the population studied here? As noted here, of the several differences between FFS and RFS biomechanics, the most important from the perspective of injury is the nature of the impact peak measured in the vertical GRF just after contact between the foot and the ground. All runners experience an initial impact of the foot with the ground, but numerous studies of vertical GRF show that the exchange of momentum between the body and the ground in RFS (heel–toe) and FFS (toe–heel–toe) runners is qualitatively and quantitatively different (4,8,21,27,41). RFS runners usually generate a marked, short spike in the vertical GRF immediately after the foot's initial contact with the ground, but such an impact peak is lacking or barely measurable in FFS and some MFS landings (Fig. 1). Put in practical terms, the rates and magnitudes of vertical GRF during the initial part of stance are lower in FFS runners (barefoot or shod) than in shod RFS runners (21). High and rapid impact peaks measured in terms of vertical GRF apply high and rapid forces to the lower extremity, especially the skeletal tissues. In turn, high and rapid rates of loading are potentially injurious in skeletal tissues, especially the bone, because they increase hysteresis, which leads to structural damage that can accumulate over repeated events (2).

This study did not measure GRF, and thus, it cannot directly test the hypothesis that variations in impact peak loading underlie the differences in injury rates measured here between runners with FFS and RFS strike types. However, these injury differences are relevant to several recent studies that have found that the rate and magnitude of impact peaks are significant predictors of numerous repetitive stress injuries that are experienced by many runners including plantar fasciitis (30), tibial stress syndrome (25,31), and patellofemoral pain syndrome (9). We note that not all studies have found a significant correlation between impact peak loading and injury (28,29). However, because these previous studies compared the rates and magnitudes of impact peaks between samples of just RFS runners, they did not assess the effect of running styles that do not generate a clear, substantial impact peak in the first place. Further research is necessary, but we predict that variations in the rate and magnitude of impact loading explain a significant percentage of the variance in injury rate over long periods both within and between groups of runners who use different types of strike types. Testing this hypothesis is a challenge because the rate and magnitude of impact peak loading varies with speed, terrain, fatigue, and other factors, and it is not possible to quantify accurately or precisely the range of variation that any given runner experiences over the many months or years during which a repetitive stress injury accrues.

Another set of biomechanical factors that differ between RFS and FFS runners and which merit further study in terms of their effect on injuries are joint moments. It is not known if higher joint moments cause injuries, but the few studies that compared joint moments in FFS and RFS runners have generally found that net moment magnitudes are higher in the knee for RFS runners and higher in the ankle for FFS runners (1,11,41). In addition, Kerrigan et al. (17) found lower extremity moments to be higher in habitually shod runners during barefoot running; because runners tend to land more toward the ball of the foot when unshod (12,21), these results support the hypothesis that FFS runners have lower joint moments in the knee and hip. More detailed studies are necessary to comprehensively compare differences in joint moments between RFS and FFS runners and their effect, if any, on patterns and rates of repetitive injuries.

This study, like most injury studies, has limitations and we caution against extrapolating the above results to assuming that all runners are necessarily less likely to be injured if they FFS. For one, the population of subjects studied here, collegiate runners, are not representative of many amateur runners; instead, they are highly competitive and motivated, frequently train at high intensity in terms of distance and speed, and are perhaps more likely to ignore injuries in their early stages—factors that may help account for the high rate of injury. These differences, however, may be useful for studying the causes of injury because the training intensity of the subjects studied likely amplifies injury rates. If RFS runners on a college cross-country team who run approximately 40 miles$\cdot$wk^{-1} at speeds of approximately 3.0 to 4.5 m$\cdot$s^{-1} for women and 3.5 to 5.0 m$\cdot$s^{-1} for men are roughly twice as likely to get a moderate or severe injury than FFS runners are, then it is possible that runners who train less intensely have lower rates of injury but with similar differences in relative injury rates between FFS and RFS runners. This speculative hypothesis merits testing in other populations.

Another limitation to consider is that the subjects studied here vary little in other factors that have been implicated in injury rates such as BMI, previous injury history, age, and overall athletic skill (see Jones et al. [15], Taunton et al. [37], and van Gent et al. [38]). None of the subjects measured here had BMI >25 kg$\cdot$m^{-2}, all had previous injuries, all were younger than 22 yr, and none were novice runners. However, many of these factors would lead to even higher injury rates, and there is no reason to predict that they would do so more for FFS than RFS runners. In addition, we did not measure several other covariates of interest such as shoe type, arch type, and Q angle. We could not quantify shoe type because all the runners in this study used a range of shoes including both trainers and racing flats. However, we noted that many of the FFS runners preferred to run solely in racing flats, which tend to have more flexible soles and lower heel counters than standard running shoes. In hindsight, it would have been useful to assess arch type. Future research is needed to examine the extent to which variations in arch type interact with strike type, shoe type, and body mass to contribute to injury (7,16). A final limitation of the study is that it is retrospective and not randomized. We do not know how and why subjects in this study became either RFS or FFS runners and whether other factors related to injury predisposed them to adopt different running forms. Such explanations seem unlikely but should be explored.

Regardless of these limitations, there is a strong need for further research to replicate and test these findings in other populations, especially with prospective, randomized control studies. We nonetheless propose that the results presented here provide clues on how to help lower the high, persistent incidence of running injuries. Although there has been a tendency to favor technological solutions such as shoes and orthotics to prevent injuries, these prescriptions have little demonstrable efficacy. Decades of improvements to the damping capabilities of running shoe soles have had no apparent effect on injury rates (38,39), and one study even found that more cushioned shoes are actually more likely to cause injury (22), perhaps by encouraging runners to land with a stiffer lower extremity, heightening the impact peak generated by a RFS. In addition, prescriptions for controlling foot motion based on arch anatomy have been shown to have no significant effect on lowering injury rates (18,32,33). Efforts to lower injury rates by correcting for limb abnormalities with orthotics have yielded mixed results with only small effects (23,34,43).

The results presented here suggest that a biomechanically proximate way to lower injury rates is to make runners more aware of the importance of running form, including ways to lessen impact forces. There is no question that there are plenty of shod heel strikers who avoid injury, and we need to find out if these runners generate lower impact forces than those with higher injury rates or are running differently in some other way. However, most FFS runners, shod and unshod, avoid marked impact peaks in terms of vertical GRF, and they generally incur lower moments in the knee and perhaps in other joints. A FFS style of running is also hypothesized to be more natural from an evolutionary perspective because barefoot and minimally shod runners tend to use FFS gaits, most likely because RFS landings are painful without a cushioned elevated heel (21). Because hominins have been running barefoot for millions of years (5), often on very hard and rough substrates, it is reasonable to conclude that FFS styles of running used to be more common. No one knows when shoes were invented, but all athletic footwear until very recently were either sandals or moccasins and thus minimal by today's standards. Although modern running shoes make RFS running comfortable, the human body may be less well adapted to repeated RFS landings than to FFS landings.

The hypothesis that FFS running is more natural and less injurious than RFS running requires further testing with a controlled prospective study. In the meantime, what are the implications of this study for runners who are injured or who want to prevent injury? One point to consider is that many runners who RFS in shoes do not get injured or get injured rarely even when they train at high intensity. We predict that these runners have better form than those who do get injured: they probably land with less overstride and more compliant limbs that generate less severe impact loading and generate less extreme joint moments. They may also have fewer anatomical abnormalities that predispose them to injury than other RFS runners who do get injured. These predictions are supported by several recent studies (9,25,26,30,31), and they emphasize the hypothesis that running style is probably a more important determinant of injury than footwear (with the caveat that footwear probably influences one's running style).

Another point to consider is that this study did not test for the effect of transitioning from RFS to FFS running, and it is unclear and unknown if runners who switch from RFS to FFS strikes will have lower injury rates. FFS running requires stronger calf muscles because eccentric or isometric contractions of the triceps surae are necessary to control ankle dorsiflexion at the beginning of stance, and shod FFS runners also generate higher joint moments in the ankle (41). Runners who transition to FFS running may be more likely to suffer from Achilles tendinopathies and calf muscle strains. FFS running also requires stronger foot muscles, so although impact forces generated by FFS landings are low, runners who transition are perhaps more likely to experience forefoot pain or stress fractures. They may also experience plantar fasciitis if their foot muscles are weak. However, these injuries are treatable, and they may be preventable if runners transition, slowly, gradually, and with good overall form.

In conclusion, there is much research to do, and the results presented here need to be replicated and more fully explored. Regardless, the last few years have seen an exciting surge of research on the biomechanics of running injuries, partly inspired by interest in barefoot running. All runners are at risk of injury, and there are no magic bullets to prevent injuries, but the results of this study support those of other recent analyses indicating that runners and researchers alike may profit from paying more attention to how people run than what is on their feet.

Daniel E. Lieberman has received funding for this research from the American School of Prehistoric Research (Peabody Museum), the Hintze Charitable Trust, Harvard University, and a gift from VibramUSA.

None of these funding sources had any role in the research design and its analysis and publication. For the remaining authors, no conflicts of interest were declared.

The authors thank the subjects as well as Brian Addison, Eric Castillo, Kristi Lewton, Neil Roach, Carolyn Eng, Madhusudhan Venkadesan, Deydre Teyhen, and Irene Davis for their help and discussions and two anonymous referees for their comments.

The authors declare that the results of the present study do not constitute endorsement by the American College of Sports Medicine.

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