Effects of Footwear and Strike Type on Running Economy

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ABSTRACT

PERL, D. P., A. I. DAOUD, and D. E. LIEBERMAN. Effects of Footwear and Strike Type on Running Economy. *Med. Sci. Sports Exerc.*, Vol. 44, No. 7, pp. 1335–1343, 2012. **Purpose**: This study tests if running economy differs in minimal shoes versus standard running shoes with cushioned elevated heels and arch supports and in forefoot versus rearfoot strike gaits. **Methods**: We measured the cost of transport (mL $O_2 \cdot kg^{-1} \cdot m^{-1}$) in subjects who habitually run in minimal shoes or barefoot while they were running at 3.0 $m \cdot s^{-1}$ on a treadmill during forefoot and rearfoot striking while wearing minimal and standard shoes, controlling for shoe mass and stride frequency. Force and kinematic data were collected when subjects were shod and barefoot to quantify differences in knee flexion, arch strain, plantar flexor force production, and Achilles tendon–triceps surae strain. **Results**: After controlling for stride frequency and shoe mass, runners were 2.41% more economical in the minimal-shoe condition when forefoot striking and 3.32% more economical in the minimal-shoe condition when rearfoot striking ($P < 0.05$). In contrast, forefoot and rearfoot striking did not differ significantly in cost for either minimal- or standard-shoe running. Arch strain was not measured in the shod condition but was significantly greater during forefoot than rearfoot striking when barefoot. Plantar flexor force output was significantly higher in forefoot than in rearfoot striking and in barefoot than in shod running. Achilles tendon–triceps surae strain and knee flexion were also lower in barefoot than in standard-shoe running. **Conclusions**: Minimally shod runners are modestly but significantly more economical than traditionally shod runners regardless of strike type, after controlling for shoe mass and stride frequency. The likely cause of this difference is more elastic energy storage and release in the lower extremity during minimal-shoe running. **Key Words:** RUNNING ECONOMY, BAREFOOT RUNNING, MINIMAL-SHOE RUNNING, FOREFOOT STRIKE, REARFOOT STRIKE

Hominins evolved to run long distances more than 2 million years ago (6), but the last few decades have seen two major related changes in human running biomechanics. The first is shoes. Footwear such as sandals or moccasins were invented less than 50,000 yr ago (35), but the modern running shoe with a cushioned elevated heel, arch supports, and a stiffened midsole (hereafter called a standard shoe) was created only in the 1970s. The second likely change has been running form, especially foot strike. More than 75% of today's shod runners typically rearfoot strike (RFS), in which the heel first contacts the ground (18,22), but barefoot or minimally shod runners more often forefoot strike (FFS), with the ball of the foot landing before the heel, or they sometimes midfoot strike (MFS), with the heel and ball of the foot landing simultaneously (12,23). Barefoot and minimally shod runners especially tend to FFS on hard or rough surfaces because FFS landings, unlike RFS landings, generate no impact peak, which is painful without a cushioned heel that slows the rate of impact loading about sevenfold (9,21,23,31). Elevated heels also encourage a runner to RFS, even when the foot is slightly plantar flexed, facilitating a longer stride and eliminating controlled dorsiflexion by the plantar flexors during landing.

If humans evolved to run barefoot, most often with an FFS gait, it follows that natural selection did not adapt the human body to RFS in shoes. One question of interest is whether shoes and strike types affect running economy. To date, several studies have compared running economy in barefoot and shod conditions but with different experimental treatments that did not control for all relevant variables. The first study was conducted by Burkett et al. (8), who measured running economy in 21 habitually shod runners (all orthotics users) at 3.35 $m \cdot s^{-1}$ without controlling for shoe

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type, shoe weight, or strike type. Runners were about 1%–2% less costly when barefoot than shod (with or without orthotics), approximately the difference expected from the extra shoe mass (15). A similar result was obtained by Divert et al. (14), who measured running economy in 12 habitually shod male runners at 3.61 $m \cdot s^{-1}$ barefoot, in socks (50, 150, and 350 g), and in shoes (150 and 350 g). Because runners were 3% more costly in the 350-g shoes and socks than when barefoot, the cost difference was interpreted to be a mass effect. Divert et al. (14), however, noted that 75% of the subjects had no impact peak when barefoot or in socks, suggesting a switch from an RFS gait in shoes to an FFS gait in socks or barefoot. Squadrone and Gallozzi (32) analyzed eight experienced barefoot runners at 3.32 $m \cdot s^{-1}$ barefoot, wearing 148-g minimal shoes (Vibram FiveFingers REI, Kent, WA), and in 341-g shoes. As with Divert et al. (14), shod runners were 1.3%–2.8% more costly when shod, but shoe mass was not controlled, and runners switched from an RFS gait in shoes to an MFS or FFS gait when barefoot or minimally shod. Recently, Hanson et al. (16) compared running economy in 10 habitually shod runners at 70% of $\dot{V}O_{2max}$ in barefoot and shod conditions on a treadmill and overground. Although the barefoot condition was 3.8% more economical, shoe mass and strike type were uncontrolled.

Several factors likely complicate the interpretation of these results. Shoe mass was controlled only by Divert et al. (14), but a typical shoe increases the lower extremity's moment of inertia by adding 300 g to the foot, thus augmenting leg swing cost, which may comprise 20% of total running cost (24,26). At a given speed, the cost of transport (COT ($mL\ O_2 \cdot kg^{-1} \cdot m^{-1}$)) during running increases approximately 1% for every 100 g of added shoe mass (15), potentially explaining the 1%–3% lower costs previously measured in barefoot versus shod conditions.

Another factor to consider is strike type because RFS and FFS gaits have slightly different mass–spring mechanics. Tendons, ligaments, and muscles of the lower extremity store elastic energy during the first half of stance and then recoil during the second half of stance, helping push the body's center of mass upward and forward (4). These structures, which are derived in humans relative to great apes (6), may be used more effectively in barefoot or FFS running through several mechanisms. The first is more elastic energy storage in the Achilles tendon, which recovers approximately 35% of the mechanical energy that the body generates with each step (2,21). Although the initial ground reaction force (GRF) is lower in an FFS than in an RFS, it creates a larger external dorsiflexion moment around the ankle that is countered by an internal plantar flexor moment (13,37). Although higher external dorsiflexion moments in FFS gaits cause higher triceps surae contractile costs, more controlled dorsiflexion during an FFS could permit more elastic energy storage and return because the heel descends substantially under controlled dorsiflexion, stretching the Achilles tendon while the triceps surae contracts eccentrically or isometrically (19). Further, an elevated heel limits ankle dorsiflexion, which may lessen Achilles tendon strain in shod versus barefoot running. It is reasonable to assume that in an RFS gait, the Achilles tendon does not stretch at impact and stretches primarily from dorsiflexion after foot flat as the tibia passes over the foot. Therefore, we predict that the Achilles tendon is likely to store and return more elastic energy in FFS versus RFS running and even more during FFS running in minimal shoes or when barefoot versus in standard shoes. However, a related factor with opposite effects on economy is the force the triceps surae must produce to counter higher sagittal plane moments in FFS versus RFS gaits (Fig. 1). Consequently, the length of the tuber calcaneus, which creates the Achilles tendon's moment arm, has a strong inverse effect on economy because shorter moment arms allow for greater storage and release of elastic strain energy (28,30).

Another biomechanical difference between FFS and RFS running is knee flexion. RFS runners typically land with the foot in front of the knee, which is more extended and less compliant at strike but then flexes more during stance; in contrast, FFS runners land with an initially more flexed knee and have more knee flexion during impact (23,27) but flex the knee less thereafter (5). Because the gastrocnemius originates on the distal femur, knee flexion slackens the Achilles tendon–triceps surae complex (ATTSC) during the first half of stance but differently in RFS and FFS gaits. Because knee flexion lessens ATTSC elongation during the first half of

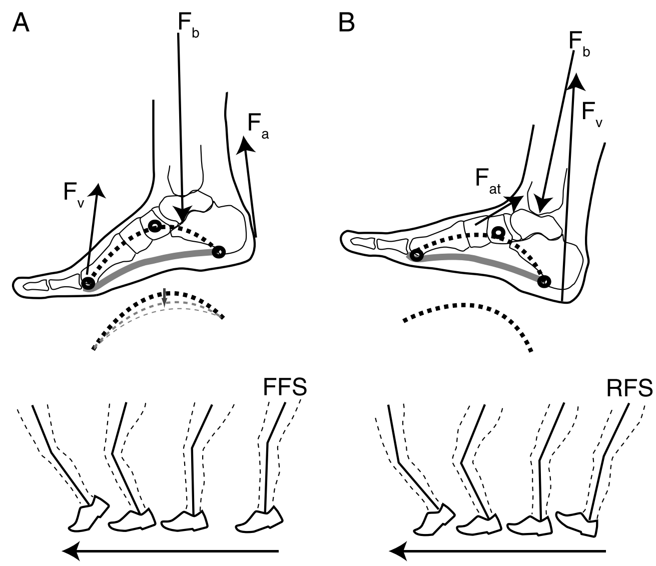

FIGURE 1—Model of different forces (*top*) acting on the longitudinal arch at the moment of impact and thus before foot flat in an FFS (A) and RFS (B). Major kinematic differences in a lateral view are illustrated at the *bottom*, and *circles* indicate locations of landmarks used to measure arch strain. F_v is the vertical GRF, F_{at} is the tibialis anterior force, F_a is the Achilles tendon force, and F_b is the body force. In the FFS, F_v is smaller in magnitude, and the Achilles tendon exerts a plantar flexing force to control dorsiflexion; in the RFS, F_v is greater in magnitude, there is no F_a, and the tibialis anterior must produce a dorsiflexing force, F_{at}, to counter plantarflexion. Because the FFS is loaded in three-point bending before foot flat, the longitudinal arch is predicted to stretch more during this period of stance (*dashed lines*).

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stance and is controlled by the quadriceps, one predicts a positive correlation between COT and total knee flexion during stance.

Energy storage in the arch is another potential source of differences in running economy between the FFS and RFS gaits and between runners who are barefoot, in minimal shoes, or in standard shoes (Fig. 1). The longitudinal and transverse arches of the foot include many elastic structures that recover an estimated 17% of the mechanical energy generated per step (21), making barefoot and minimally shod running likely to store more elastic energy because external arch supports in standard shoes lessen vertical arch compression during stance, limiting how much the arch can stretch and recoil. Another contrast is that FFS runners initially load the arch in three-point bending (Fig. 1A) from the instant the ball of the foot contacts the ground, with a GRF applied upward anterior to the ankle at the metatarsal heads, an upward balancing force applied posterior to the ankle by the Achilles tendon, and a downward force applied by the body's mass through the ankle. In contrast, an RFS runner experiences little or no arch compression at impact (Fig. 1B) because the arch is subject to a GRF below or slightly posterior to the ankle where it is opposed by the downward force of the body's mass and the force from the tibialis anterior applied near the arch's apex at the medial cuneiform. These forces likely stiffen the arch until foot flat, preventing elastic storage of any energy that impact generates. One therefore predicts the arch will store and recover more energy in FFS than RFS running and more so in barefoot or minimally shod runners. A related factor is foot strength. Individuals who wear stiff-soled shoes with arch supports possibly have weaker intrinsic foot muscles than individuals who are habitually barefoot or minimally shod (7). Because foot muscles affect elastic energy storage in the arch, running economy between barefoot, minimally shod, and standardly shod conditions may differ in runners who habitually run in standard shoes versus barefoot or in minimal shoes.

A final factor to consider when comparing cost among different conditions is stride frequency. Experimental studies indicate that the optimal COT in shod runners occurs at stride frequencies of 170–185 steps per minute regardless of incline, leg length, and body mass (10). The explanation for this phenomenon is not well understood, but many joggers in standard shoes adopt a slower preferred cadence compared with barefoot or minimally shod runners who tend to have shorter strides and higher stride frequencies (8,14,32) more common among experienced shod runners. Why some runners prefer lower stride frequencies is unknown, but differences in stride frequency could be a confounder that explains some of the variation in cost previously measured between barefoot/minimally shod and standardly shod conditions. Because there is no *a priori* reason to predict that optimal stride frequency should vary with footwear, this study controlled for stride frequency.

In short, we predicted that footwear usage and strike type have independent effects on running economy after controlling for stride frequency, previous footwear history, and shoe mass. First, we hypothesized that habitual barefoot/minimally shod runners will have a lower COT when minimally shod than in standard shoes, independent of strike type and after controlling for shoe mass and stride frequency, because of more elastic energy storage in the lower extremity. Second, we hypothesized that FFS runners are more economical than RFS runners independent of footwear because of more elastic energy storage in the Achilles tendon and possibly the foot. However, these gains may be offset by higher contractile costs for the triceps surae and the intrinsic foot muscles in an FFS than in an RFS. Finally, we predicted that within a given condition, COT correlates negatively with how much the arch of the foot and the ATTSC stretch and positively with knee flexion.

METHODS

Subjects. Running biomechanics and economy were measured in 15 subjects (13 men, 2 women), all experienced barefoot or minimally shod runners with no major injuries in the past 6 months and with no lower extremity abnormalities. Mean ± SD subject height was 1.75 ± 0.06 (SD); mean body mass was 73.3 ± 10.6 (SD); mean BMI was 23.8 ± 2.6 (SD); mean was 41.3 ± 9.8 (SD); mean weekly mileage was 33.4 ± 16.5 (SD). Subjects had been running barefoot or in minimal footwear for an average of 2.1 years ± 1.1 (SD) (range, 0.6–4.0). These subjects preferred to FFS, but most of them used to run in standard shoes, and all of them were comfortable running with an RFS gait. Subjects who were not comfortable with an RFS were excluded from the study. The collection of data on all subjects was approved by the Harvard University Committee on the Use of Human Subjects, and prior written informed consent was obtained from all subjects.

Treatment. Each subject ran in shoes defined as standard (having a cushioned elevated heel, arch supports, and a stiff sole) and minimal (lacking these features) using both FFS and RFS gaits. Standard shoes used were Asics GEL-Cumulus 10™, a neutral shoe; Vibram FiveFingers™ shoes were used for the minimally shod condition instead of barefoot running to prevent injury on the treadmill; these shoes have previously been shown to have no significant effect on barefoot running kinematics or economy (23,32). All footwear and socks were weighed before each trial to the nearest 0.1 g, and ankle weight belts filled with the appropriate mass of metal washers were strapped around each ankle during minimally shod running. All trials for each subject were completed on the same day, and the order of the running conditions was randomized across subjects. Different treadmills, however, were used for measuring running cost and biomechanics because the instrumented treadmill used for measuring GRF (see below) is not as comfortable for long-term running.

To measure running cost, subjects ran on a treadmill (Vision Fitness T9250; Cottage Grove, WI) at 3.0 $m \cdot s^{-1}$ for approximately 2 min to determine preferred stride frequency

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and to habituate them to the treadmill. Subjects were then connected by a two-valve mouthpiece to a gas analyzer (see below) connected to a flexible lightweight tube with a nasal clip to ensure solely oral breathing. After 2 min of habituation, subjects then performed four trials in a random order: FFS in minimal shoes and ankle weights, FFS in standard shoes, RFS in minimal shoes and ankle weights, and RFS in standard shoes. Each trial lasted a minimum of 5 min, with at least 1 min of running after $\dot{V}O_2$ levels reached a steady state. A metronome was used to keep the runner at his/her preferred stride frequency. Subjects were given 5-min breaks between trials.

Respirometry. Expired gas was collected using a Sable flow generator and controller (500H FlowKit; Sable Systems International, Las Vegas, NV) with an airflow rate of 150 L·min^{-1}. A subsample of expired air was then pushed at 300 mL·min^{-1} into an open-ended syringe where it was then pulled at 100 mL·min^{-1} by a subsampler (SS-4; Sable Systems International) through a Drierite column to scrub water vapor. Subsampled air was then pushed at 100 mL·min^{-1} through a paramagnetic oxygen analyzer (PA-10 Oxygen Analyzer; Sable Systems International), which measured the fractional amount of oxygen at 100 Hz. Room air oxygen levels were measured before and after each condition, and windows were kept closed.

To correct for any drift in oxygen measurement, $\dot{V}O_2$ at steady state was computed as follows:

$$\left(\left(\mathrm{FiO}_{2i} + \left(\left(\mathrm{FiO}_{2f} - \mathrm{FiO}_{2i}\right)T_{\mathrm{ss}}/\left(T_f - T_i\right)\right)\right) - \mathrm{FeO}_{2\mathrm{ss}}\right)\mathrm{FR}$$

where FiO_{2i} is the initial fractional amount of oxygen in the incurrent air stream measured before each trial at equilibrium without the subject connected, FiO_{2f} is the final fractional amount of oxygen present in the incurrent air stream measured after each trial without the subject connected, T_{ss} is the time into each trial when the subject's oxygen consumption reached steady state, T_f is the time when the final incurrent oxygen fraction was measured, T_i is the time when the initial incurrent oxygen fraction was measured, $\mathrm{FeO}_{2\mathrm{ss}}$ is the mean fractional amount of oxygen in the excurrent air stream measured for each subject at steady state for at least 1 min at the end of each trial, and FR is the mean gas flow rate in the mask when steady-state $\dot{V}O_2$ was measured. COT was then calculated as milliliters of oxygen per kilogram per meter.

Kinematics. Kinematic data were collected with an eight-camera Oqus kinematics system (Qualysis, Gothenburg, Sweden) at 500 Hz for 30-s intervals with subjects running in the four conditions at 3.0 m·s^{-1} with the same stride frequency on a custom-built dual-belt force-instrumented treadmill recorded at 5000 Hz (Bertec Corporation, Columbus, OH). Note that subjects ran barefoot only during kinematic testing. Infrared reflective markers were taped onto the right leg at the following landmarks in the barefoot condition: 1) the medial side of the first metatarsal head, 2) the navicular tuberosity, 3) the medial calcaneus process, 4) the location of Achilles tendon insertion on the calcaneus, 5) the lateral malleolus, 6) the medial malleolus, 7) the lateral femoral epicondyle, 8) the medial femoral epicondyle, 9) the greater trochanter, and 10) the proximal fibula head. Because of the running shoe, markers 1–3 were not used for the standard-shoe trials; in addition, during the shod trials, marker 4 was placed on the back of the running shoe approximately posterior to the insertion of the Achilles tendon. Ten-second standing trials were also made to record static marker locations in all conditions.

Kinematic and force data were analyzed using Visual3D (C-Motion Inc., Germantown, MD) to measure arch strain and ATTSC strain. Arch strain was quantified in two ways. First, arch strain was measured using navicular height (NH), the minimum distance from the navicular tuberosity relative to the line formed by the first metatarsal head and the medial process of the calcaneus. Because these three landmarks form a plane, NH is independent of rearfoot inversion or eversion. Arch strain was also quantified by fitting a parabola to markers 1–3 (with the navicular head as the vertex) and then measuring the average curvature at 100 points evenly spaced along the curve. Achilles tendon strain was approximated using the entire ATTSC from marker 4 to the midpoint of markers 7 and 8. The arch and ATTSC strains were calculated as differences from the standing value divided by standing value; change in strain was then quantified as the difference between initial minimum strain and maximum strain. Knee angle was measured using the line segments from markers 5 to 10 and from markers 7 to 9. Kinematic and force data were collected for the barefoot condition first followed by the standard-shoe condition because when the order was reversed, sweat on the foot made it harder to affix markers 1–3.

The impulse produced by the triceps surae during the stance phase was calculated in Visual3D from the integral of plantar flexor force, which was calculated as the dorsiflexion torque (GRF times its moment arm to the center of the ankle joint) divided by the Achilles tendon moment arm. Following Scholz et al. (30), the ATTSC moment arm was measured from the insertion of the Achilles tendon to the calculated midline point between the lateral and medial malleoli. The insertion of the Achilles tendon was determined by palpation as the most inferior point on the tendon superior to the point where one could feel bone through the skin. The moment arm of the Achilles tendon was calculated using markers 4–6 in Visual3D. Leg length was measured from the greater trochanter to the lateral base of the calcaneus.

Statistical analyses were conducted using JMP (SAS Institute, Cary, NC). Because all subjects were compared against themselves, matched-pairs *t*-tests were used to test for significance at the $P < 0.05$ level. Because we tested a small number of *a priori* hypotheses based on a model of expected differences between two different treatments (strike type and footwear condition), each test of significance is treated as independent. An additional reason to use matched-pairs *t*-tests is that we wanted to test for the effect of shoe type on each runner's COT given a particular type of foot strike, not the effect of shoe type across both conditions.

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TABLE 1. Differences in running economy between conditions by subject.

Subject	COT (mL O_2·kg^{-1}·m^{-1})				Running Economy Percent Differences				
	Minimal Shoes		Standard Shoes		FFS vs RFS		Minimal vs Standard Shoes		Minimal FFS vs Standard RFS
	FFS	RFS	FFS	RFS	MS	Shod	FFS	RFS	
1	0.2253	0.2078	0.2094	0.2146	8.07	−2.44	7.32	−3.18	4.89%
2	0.2078	0.2003	0.2150	0.2050	3.66	4.73	−3.41	−2.35	1.31%
3	0.2056	0.2100	0.2106	0.2097	−2.09	0.45	−2.40	0.14	−1.95%
4	0.2356	0.2350	0.2347	0.2547	0.25	−8.18	0.39	−8.04	−7.79%
5	0.2296	0.2303	0.2268	0.2224	−0.31	1.96	1.21	3.48	3.17%
6	0.1981	0.1980	0.2042	0.2051	0.03	−0.46	−3.04	−3.53	−3.50%
7	0.2077	0.2134	0.2147	0.2222	−2.70	−3.43	−3.32	−4.05	−6.75%
8	0.2051	0.1996	0.2049	0.2043	2.69	0.32	0.07	−2.30	0.38%
9	0.1898	0.1918	0.2017	0.2113	−1.05	−4.65	−6.06	−9.66	−10.71%
10	0.2185	0.2169	0.2212	0.2223	0.76	−0.51	−1.23	−2.50	−1.74%
11	0.1864	0.1849	0.1924	0.1914	0.83	0.54	−3.16	−3.45	−2.62%
12	0.2332	0.2272	0.2543	0.2442	2.60	4.04	−8.64	−7.21	−4.61%
13	0.2364	0.2342	0.2419	0.2356	0.94	2.62	−2.29	−0.61	0.34%
14	0.1933	0.1939	0.2027	0.2049	−0.29	−1.12	−4.71	−5.53	−5.82%
15	0.1771	0.1914	0.1899	0.1934	−7.76	−1.82	−6.95	−1.01	−8.77%
Mean ± SD	0.2100 ± 0.0184	0.2090 ± 0.0166	0.2150 ± 0.0181	0.2161 ± 0.0179	0.37 ± 3.44 (0.6791)	−0.53 ± 3.35 (0.5498)	−2.41 ± 3.82 (0.0280)*	−3.32 ± 3.35 (0.0018)*	−2.94 ± 4.51 (0.00241)*

Boxes marked with an asterisk denote statistically significant values ($P < 0.05$). Columns 6–10 were calculated as (condition 1 − condition 2) / ((condition 1 +condition 2)/2); P values are in parentheses.
MS, minimally shod.

Because shoes could have different biomechanical effects on COT in FFS versus RFS gaits, we provide significance levels determined by matched-pairs *t*-tests as well as by repeated-measures ANOVA (when relevant).

RESULTS

Table 1 indicates no consistent or significant pattern of difference between running economy in FFS versus RFS gaits when runners were in minimal or standard shoes but that footwear condition had a predictable effect on economy within strike types. When forefoot striking at the same stride frequency and with the same foot mass, subjects were 2.41% more economical in the minimally shod condition (P = 0.028), and when rearfoot striking, they were 3.32% more economical in the minimally shod condition (P = 0.0018, matched pairs; P = 0.003, repeated-measures ANOVA). Almost all the subjects were more economical when minimally shod, but within-subject differences in cost ranged from being 9.66% more economical to 7.32% more costly. Note that all subjects preferred a relatively high stride frequency: 186.8 ± 12.6 steps per minute.

Arch strain could be measured only in the barefoot condition but consistently differed between FFS and RFS gaits (Fig. 2A, Table 2). FFS runners typically hyperextended the toes just before a strike, which may have caused the arch to heighten slightly before landing, and the arch then flattened from initial contact until midstance. In contrast, in an RFS, the arch first became slightly higher just after impact and then began to flatten from foot flat until midstance. In both FFS and RFS gaits, arch height at the end of stance exceeded its resting height, reflecting the arch's effective recoil mechanism. The arch underwent 44.11% more vertical strain (P < 0.0001) and 78.62% more overall curvature strain (P < 0.0001) in an FFS compared with an RFS (see Table, Supplemental Digital Content 1, http://links.lww.com/MSS/A154, Arch strain differences).

It was not possible to measure Achilles tendon strain directly, so we used a proxy measurement: ATTSC length. ATTSC strain differed considerably in pattern between RFS and FFS gaits and in degree between standard-shoe and barefoot conditions (Fig. 2B; see Table, Supplemental Digital Content 2, http://links.lww.com/MSS/A155, ATTSC strain differences). During a barefoot RFS, the ATTSC initially shortened as the foot plantar flexed; it then began to elongate between 10% and 20% of stance, reaching peak strain just after midstance. This pattern tended to be exaggerated in standard shoes with more initial shortening and then more elongation. In contrast, during an FFS, the ATTSC lengthened from initial contact until midstance as the foot underwent controlled dorsiflexion and then powered dorsiflexion.

There were also significant differences in plantar flexor force production over all of stance (Fig. 2C, Table 2). In the barefoot condition, the mean impulse generated by the plantar flexors was 49.99 ± 7.64 body weight (BW) per second during an FFS but 39.44 ± 7.32 BW per second during an RFS, a 24.0% difference (P < 0.0001, matched pairs). When

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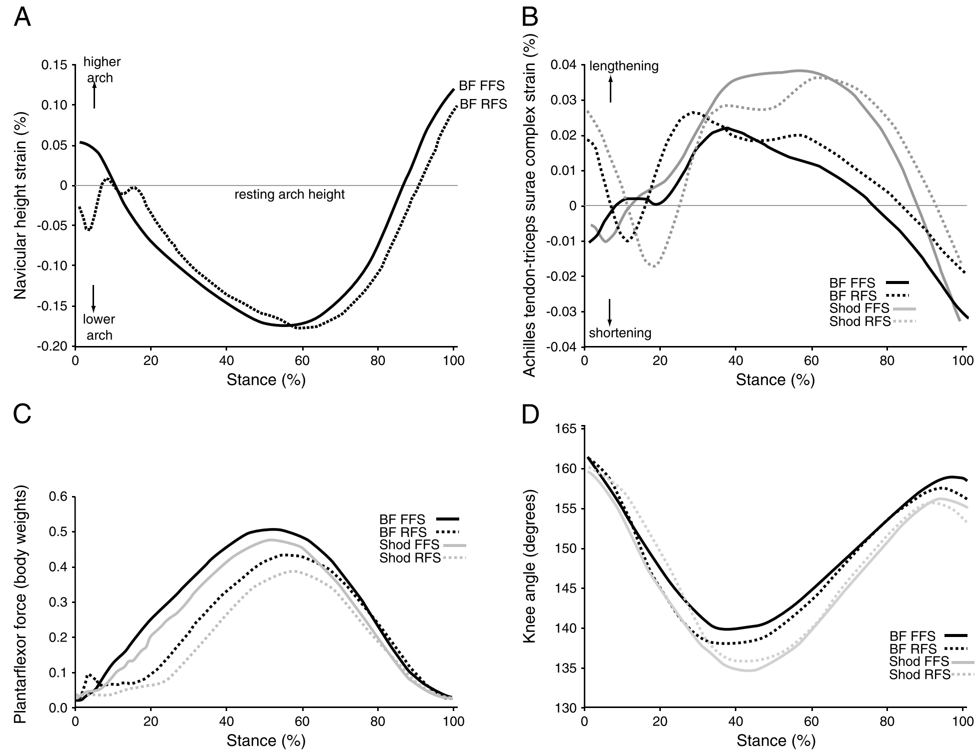

FIGURE 2—Kinetic and kinematic differences between conditions (average of all subjects). A, vertical deformation of the longitudinal arch measured by NH, (B) ATTSC strain, (C) plantar flexor force output, (D) knee angle.

wearing standard shoes, a similar pattern emerged as an FFS generated a mean impulse of 45.12 ± 6.27 BW per second and an RFS generated a mean impulse of 35.01 ± 4.82 BW per second, which was 25.2% smaller (P < 0.0001). FFS and RFS gaits generated mean impulses larger by 8.45% (P = 0.0003, matched-pairs t-test) and 7.24% (P = 0.0519), respectively, when barefoot compared with wearing standard shoes (see Table, Supplemental Digital Content 3, http://links.lww.com/MSS/A153, Plantar flexor force differences).

Knee flexion between contact and midstance (Fig. 2C, Table 2) during barefoot running was significantly less than that during standard-shoe running by 8.83%, for both FFS (P = 0.0030) and RFS (P = 0.0486) gaits. However, the subjects here used the same high stride frequency for every trial, so they had relatively short strides with flexed knees at landing in both RFS and FFS gaits, and total knee flexion over stance did not differ significantly between strike types within the same footwear condition (see Table, Supplemental Digital Content 4, http://links.lww.com/MSS/A157, Knee excursion differences).

DISCUSSION

As predicted, running in minimal shoes is slightly less costly (on average, 2.41%–3.32%) than running in standard shoes after accounting for the effects of shoe mass, strike type, habitual footwear, and stride frequency. If one considers that a typical standard shoe weighs about 350 g, about 200 g more than most minimal shoes, and that every 100 g adds about 1% extra cost (15), then the net savings to minimal-shoe running is between 4.4% and 6.8%. However, when footwear type is held constant, there is no significant difference in cost between FFS and RFS gaits. Overall, minimally shod running with an FFS is about 0.74% less costly than running in a standard shoe with an RFS (P = 0.0241). These results therefore extend those of previous studies (8,14,16,32) that found running barefoot or in minimal shoes to be less costly than running in standard shoes but that were not able to control for possibly confounding or interacting factors. Of these studies, only Squadrone and Gallozzi (32) used habitually barefoot or minimally shod runners, only Divert et al. (14) controlled for shoe mass, and none controlled for strike type or cadence.

Why running barefoot or in minimal shoes is less costly than running in standard shoes cannot be definitively answered by this study, but the aforementioned results suggest several main factors summarized in Table 2. First, minimal shoes may permit more elastic energy storage and recoil in the longitudinal arch. In an FFS, the arch of the foot behaves much more like an elastic spring, stretching from the instant of foot strike until midstance and then recoiling during the second half of stance; in an RFS, the forces that bend the arch cannot do so until foot flat. This study lacks data on arch strain in the standard-shoe condition (such data will require cineradiography), but it is reasonable to hypothesize

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TABLE 2. Running economy and kinematic variables.

	FFS vs RFS				Minimal vs Standard Shoes					
	Minimal Shoes		Standard Shoes		FFS		RFS		MS FFS vs Shod RFS	
	Percent Difference	Effect on COT	Percent Difference	Effect on COT	Percent Difference	Effect on COT	Percent Difference	Effect on COT	Percent Difference	Effect on COT
COT (mL $O_2 \cdot kg^{-1} \cdot m^{-1}$)	0.37 ± 3.44 (0.6791)	No significant difference	−0.53 ± 3.35 (0.5498)	No significant difference	−2.41 ± 3.82 (0.028)*	Lower for MS	−3.32 ± 3.35 (0.0018)*	Lower COT for MS	−0.74 ± 1.13 (0.0241)*	Lower for MS FFS
Arch strain − NH strain (BF)	44.11 ± 22.17 (<0.0001)*	Lower for FFS	No data	Predicted lower for FFS	No data	Predicted lower for minimally shod/BF	No data	Predicted lower for MS/BF	No data	Predicted lower for MS/BF FFS
Arch strain − curvature (BF)	78.62 ± 33.84 (<0.0001)*	Lower for FFS	No data	Predicted lower for FFS	No data	Predicted lower for MS/BF	No data	Predicted lower for MS/BF	No data	Predicted lower for MS/BF FFS
ATTSC strain	8.64 ± 23.60 (0.1925)	No significant difference	−8.13 ± 21.32 (0.1941)	No significant difference	−32.33 ± 35.51 (0.0065)*	Higher for MS/BF	−50.83 ± 18.95 (<0.0001)*	Higher for MS/BF	−10.09 ± 7.50 (0.0004)*	Higher for MS/BF FFS
Triceps surae impulse (BW per second)	24.03 ± 11.66 (<0.0001)*	Higher for FFS	25.18 ± 6.39 (<0.0001)*	Higher for FFS	8.45 ± 6.02 (0.0003)*	Higher for MS/BF	7.24 ± 12.09 (0.0519)	Higher for MS/BF	8.35 ± 2.23 (<0.0001)	Higher for MS/BF FFS
Knee excursion (degrees)	−1.59 ± 15.20 (0.6916)	No significant difference	−2.18 ± 19.59 (0.7068)	No significant difference	−8.82 ± 8.05 (0.0030)*	Lower for MS/BF	−8.84 ± 13.82 (0.0486)*	Lower for MS/BF	1.32 ± 15.29 (0.7610)	No significant difference

Boxes marked with an asterisk denote statistically significant differences between conditions based on ANOVA ($P < 0.05$).
BF, barefoot.

that features present in most running shoes such as arch supports and a comparatively high modulus of elasticity of the midsole limit the springlike action of the foot (25). In addition, the elastic properties of the shoe sole degrade with use, requiring runners to replace their shoes after 500–800 km to lower the risk of injuries such as plantar fasciitis (34). A possible explanation for this injury is that many habitually shod runners have weak intrinsic muscles in the arch of the foot so that when the shoe sole functions less effectively as a spring, these muscles and the plantar fascia have to perform too much work. It would be useful to devise a means of estimating how much the benefits of increased elastic storage by the arch in the barefoot condition are countered by higher muscle costs necessary to stabilize the arch.

A second reason runners who are barefoot or minimally shod tend to be more economical may be that they undergo significantly less knee excursion, about 8.83%, than runners in standard shoes in both the FFS and RFS conditions. Why runners in standard shoes have more overall knee flexion is not tested by this study, but more flexion is unlikely to provide much advantage in terms of elastic energy storage during the first half of stance because knee flexion slackens the Achilles tendon. In addition, eccentric contractions of the quadriceps that control knee flexion must increase the metabolic cost of more knee flexion. To test this hypothesis more fully, future studies should measure how much negative work the quadriceps must perform under different conditions and strike types in relation to running economy.

The methods used in this study limit our ability to evaluate the final variable hypothesized to make minimally shod or barefoot running less costly: Achilles tendon strain. As noted above, we were not able to measure Achilles tendon strain directly but, instead, measured changes in the overall length of the ATTSC, a measurement that is confounded by the extent to which the major plantar flexors contract eccentrically or isometrically during the first half of stance. Hof et al. (19) found that the triceps surae contracts isometrically, but their data came from three shod runners who used an MFS or RFS, and the hypothesis needs to be evaluated *in vivo* in habitually barefoot and FFS runners. With this caveat in mind, the evidence presented above tentatively suggests that conflicting factors cancel out the energetic advantages and disadvantages of variations in ATTSC strain. On the one hand, minimally shod and barefoot runners probably gain an advantage from more controlled ankle dorsiflexion and from less knee flexion (see above), especially if they FFS. These kinematic differences will tend to increase elastic energy storage in the Achilles tendon, which is estimated to contribute considerably to running economy (2,21). On the other hand, more controlled ankle dorsiflexion in the barefoot and minimally shod FFS conditions will incur increased muscle costs, as evinced by the mean impulse of the plantar flexors. This impulse, which is a product of both muscular force output of the plantar flexors and the time of foot–ground contact, will counter the benefit of more elastic energy storage.

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Depending on the magnitude of the force produced by the triceps surae and the extent to which the plantar flexors contract isometrically or eccentrically, the benefit of more elastic energy storage will be reduced or eliminated by higher muscle contraction costs. More data are needed to test this hypothesis.

Although we did find that running in minimal shoes is slightly less costly than running in standard shoes, even after accounting for the effects of added shoe mass, many experimental limitations hamper simple interpretations of the results. Most importantly, we were not able to measure strain directly in either the longitudinal arch or the Achilles tendon but, instead, had to use proxy measurements from kinematic data. We also had no means of assessing arch strain in the standard-shoe condition. How much the height or curvature of the arch changes and how much the Achilles tendon lengthens probably correlate with actual elastic strain in these structures, but *in vivo* measurements are necessary to test the reliability of these proxy measures. Another limitation is that we restricted the subject population to experienced barefoot/minimal-shoe runners. This criterion allowed us to avoid biases caused by weak feet unaccustomed to barefoot or minimal-shoe running, but our subjects were all typical barefoot/minimal-shoe runners who preferred an FFS gait and a high stride frequency (84–106 strides per minute). As such, their knee angles were less extended at heel strike than many shod runners (23). In addition, it is possible that stride frequencies of approximately 180 steps per minute are more economical than lower frequencies typically used by many recreational joggers in standard shoes (10). If so, then we might have measured even more substantial differences in economy had we not controlled for the effects of stride frequency.

In short, although runners in minimal shoes have a lower COT than runners in standard shoes and FFS running is not more economical than RFS running, more research is necessary to determine the causes of differences in economy between runners in different footwear conditions. One point to note is that mean differences in economy between minimal- and standard-shoe running were 2.41%–3.32%, but there was much variation (Table 1). For example, one subject was 7.32% more economical when using standard shoes with an FFS gait but was 3.18% more economical when running in minimal shoes with an RFS gait. In addition, many subjects were measured with 5% or better economy when in minimal shoes with either FFS or RFS gaits, with one subject being 8.64% more economical in an FFS and another subject being 9.66% more economical in an RFS. What biomechanical factors influence this variation requires more study with much larger sample sizes. Regardless of their causes, these substantial differences in economy could have major effects on performance. It is estimated that a 1% decrease in running economy can permit a runner to increase his or her speed per unit cost by approximately 0.049 $m \cdot s^{-1}$ (16). If so, a 3% increase in running economy could permit a runner to increase maximum aerobic speed by 0.147 $m \cdot s^{-1}$. During a marathon, this difference could save a runner approximately 9.5 min.

Finally, these results shed light on the evolution of human running. If humans evolved to run long distances, then one predicts that natural selection would have acted over millions of years to improve performance in the barefoot condition, which is probably very similar to wearing minimal shoes. Given differences between runners in minimal versus standard shoes, the higher economy of minimally shod runners makes sense, as does the evidence that their running economy is improved by several novel structures in the human lower extremity, including the longitudinal arch of the foot and a long Achilles tendon, which evolved after humans diverged from the chimpanzee lineage (6). We do not know when the Achilles tendon became elongated during human evolution, but the fossil record suggests that partial arches evolved at least 3–4 million years ago. Fossils attributed to the genus *Australopithecus* have many features that indicate a partial arch including torsion of the metatarsals, dorsally oriented facets of the metatarsophalangeal joints, marked insertions of the cubonavicular (spring) ligament on several tarsals, and a robust tuber calcaneus (1,33,36). Australopith foot bones, however, have a plantar process on the navicular and a partially divergent hallux (11,17,20). These primitive features suggest that australopiths had a partial arch that would have been capable of stiffening the foot via a windlass mechanism for efficient toe-off during walking but lacked the springlike capabilities present in modern humans. In addition, *Australopithecus* fossils have longer, more curved toes that would have hampered their ability to control extreme bending forces at the metatarsophalangeal joint during running but not walking (29). Comparison of 1.5-million-year-old footprints from northern Kenya, presumably made by *Homo erectus*, with 3.6-million-year-old footprints from Laetoli, Tanzania, which were made by *Australopithecus afarensis*, indicate that a modern foot capable of effective and efficient barefoot running probably did not evolve until the genus *Homo* (3).

Given that the human lineage evolved many adaptations in the lower extremity to walk and run barefoot, one should not be surprised that humans run more economically either barefoot or in minimal shoes than in standard shoes. During the last few decades, shoe manufacturers have made running shoes more comfortable by using stiff soles and adding arch supports, but it is possible that these features interfere to some extent with the natural function of the foot. Most elite runners use lightweight minimal footwear with flexible soles and minimal arch support when they race, and average runners may also reduce their COT by going either barefoot or in shoes that allow the foot to function more as it evolved to do.

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