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Original article

Strike type variation among Tarahumara Indians in minimal sandals versus conventional running shoes

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Abstract

Purpose: This study examined variation in foot strike types, lower extremity kinematics, and arch height and stiffness among Tarahumara Indians from the Sierra Tarahumara, Mexico.

Methods: High speed video was used to study the kinematics of 23 individuals, 13 who habitually wear traditional minimal running sandals (huaraches), and 10 who habitually wear modern, conventional running shoes with elevated, cushioned heels and arch support. Measurements of foot shape and arch stiffness were taken on these individuals plus an additional sample of 12 individuals.

Results: Minimally shod Tarahumara exhibit much variation with 40% primarily using midfoot strikes, 30% primarily using forefoot strikes, and 30% primarily using rearfoot strikes. In contrast, 75% of the conventionally shod Tarahumara primarily used rearfoot strikes, and 25% primarily used midfoot strikes. Individuals who used forefoot or midfoot strikes landed with significantly more plantarflexed ankles, flexed knees, and flexed hips than runners who used rearfoot strikes. Foot measurements indicate that conventionally shod Tarahumara also have significantly less stiff arches than those wearing minimal shoes.

Conclusion: These data reinforce earlier studies that there is variation among foot strike patterns among minimally shod runners, but also support the hypothesis that foot stiffness and important aspects of running form, including foot strike, differ between runners who grow up using minimal versus modern, conventional footwear.

Keywords: Barefoot; Foot strike; Minimal shoes; Running; Tarahumara

1. Introduction

Recent studies of barefoot running have sparked interest in several aspects of running form, especially foot strike. Previous studies have shown that 75%–90% of shod runners tend to rearfoot strike (RFS), landing first on the heel.[1–3] In contrast, several studies have reported that habitually barefoot runners are more likely to land with either a forefoot strike (FFS), in which the lateral metatarsal heads first make contact with the ground, or with a midfoot strike (MFS), in which the heel and ball of the foot simultaneously contact the ground.[4–6] Other studies have found that habitually shod runners asked to run barefoot often switch from an RFS to an FFS when running on a hard surface such as asphalt.[7] One likely cause of these kinematic variations is the relationship between different foot strike types and vertical ground reaction forces (GRF_v). RFSs generate an impact peak, a rapid spike of the GRF_v that occurs within the first 20–50 ms of stance, caused by the nearly instantaneous exchange of momentum between the ground and the effective mass (M_{eff}) of the lower extremity that decelerates completely at the moment of impact.[8] In contrast, FFSs and some MFSs do not cause any measurable impact peak from more lower extremity compliance and less M_{eff}.[6] Accordingly, it is commonly hypothesized that barefoot

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runners are less likely to RFS when running long distances on hard, rough surfaces because repeated high, rapid impact peaks can be painful without cushioning from a shoe's heel.

Evidence that barefoot runners do not RFS as much as conventionally shod runners has received much attention because it suggests that running long distances on hard surfaces with an RFS may be uncommon from an evolutionary perspective even though cushioned shoe heels can make these impacts comfortable. Although some studies have questioned a relationship between repetitive stress injuries and repeated, rapid, and high impact rates,[9,10] others have found that the rate and magnitude of loading of impact peaks is associated with a range of injuries such as patello-femoral pain syndrome, medial tibial stress syndrome, Achilles tendonitis and plantar fasciitis.[11−16] In addition, there is limited evidence that habitually shod runners who FFS are less likely to incur repetitive stress injuries than those who RFS.[17,18]

Much attention has been paid to studies comparing strike types among habitually shod and barefoot runners, but there are reasons to question their relevance to most runners today trying to decide what footwear to use and what kind of running form to adopt. First, all runners (including those who are barefoot) exhibit variation in strike types depending on factors such as incline, speed, the characteristics of the substrate (e.g., hardness, roughness, and slipperiness), calf and foot muscle strength, and fatigue.[6] Future studies should focus more on these and other sources of variation among different populations. Second, strike type is only one non-independent aspect of running form that affects how repetitive forces are generated. Several studies have proposed that habitually barefoot runners tend to run with a high step frequency, little to no overstride (how far the ankle lands in front of the knee), and with a relatively vertical trunk.[4−6,19] These aspects of form, which are not independent, may be relevant to injury prevention. Finally, the majority of runners today grow up wearing shoes, and they rarely run or walk barefoot for long distances. Most who choose not to use standard cushioned, elevated-heel shoes wear minimal footwear that lack cushioned heels and arch supports. Minimal shoes are often marketed oxymoronically as "barefoot shoes", and actual barefoot running is sometimes conflated spuriously with running in minimal shoes. Despite much variation among minimal shoes in terms of heel elevation, midsole thickness, and sole stiffness, these and other shoe components presumably affect proprioception from the plantar surface of the foot as well as how the foot lands and then functions during stance. The effects of minimal footwear on running form and injury are poorly understood, but studies of western runners who have transitioned to minimal shoes suggest that they are more likely to RFS than actual barefoot runners,[20,21] with the possible effect of increasing the likelihood of certain injuries.[22,23]

This study aims to add to our understanding of the effects of footwear on variation in running form by examining a population of runners who traditionally wear minimal footwear: the Tarahumara Native Americans from the Sierra Madre Occidental of northwestern Mexico (also known as the Sierra Tarahumara). The Tarahumara (self-identified as the Rarámuri) are one of several Native American groups that are famous for their tradition of running long distances in very rough terrain. Oral history and ethnographic accounts report that the Tarahumara used to run down prey such as deer and antelopes through endurance running.[24−26] This style of hunting, known as persistence hunting, takes advantage of two unique human abilities: to cool by sweating, and to run long distances at speeds that make quadrupeds gallop. Since quadrupeds cool by panting but cannot simultaneously pant and gallop, persistence hunting through endurance running can drive animals into a state of hyperthermia over long distances in hot, arid conditions.[27−30] The Tarahumara do not train in a conventional sense by running on a regular basis, but instead engage in long distance running several times a year by participating in the *rarajipari*, an ancient ball game in which teams run long distances, often 75 km or more, while kicking and then chasing a small wooden ball. Tarahumara women compete in a slightly different long distance race known as the *ariwete*, which uses a hoop rather than a ball, and typically involves distances of 40 km or less. The antiquity of the *rarajipari* and *ariwete* are unknown, but the *rarajipari* is recorded by the earliest accounts of the Tarahumara, and probably dates back for many thousands of years. Recently, the Tarahumara have also started to compete in ultramarathons. Although the Tarahumara rarely if ever practice persistence hunting today, some older individuals report having done so when they were young, and long distance running remains an important part of their culture through *rarajiparis*, *ariwetes*, and ultramarathons. These races have become well known because of the best-seller *Born to Run*,[31] but it is worth emphasizing that the Tarahumara are just one of many Native American groups that excelled at long distance running.[32]

A second reason to study variation in running kinematics among the Tarahumara is that they traditionally run in minimal footwear. The Tarahumara inhabit an extremely mountainous region that is characterized by steep canyons and very rocky terrain. It is challenging to run barefoot under such conditions, and it is hardly surprising that Tarahumara traditionally run in sandals, known as *huaraches*, that consist only of a piece of rawhide affixed firmly to the sole of the foot by a leather thong that goes between the first and second toes as well as behind the ankle (Fig. 1). According to one early account: they "are often stark naked except for a pair of *guarraches*, or rawhide sandals, these protecting the feet from the flint-like broken rocks of this part of the country, and without which even their tough hides would soon be disabled".[33] The Tarahumara now mostly fabricate *huarache* soles from car tires, but contemporary *huaraches* differ little from sandals recovered from archaeological sites,[34,35] indicating that the basic design has persisted for many thousands of years. Similar sandals that are suitable for running are common forms of footwear among many Native American groups, as are moccasins, which were also used for running.[32,36] Running sandals have recently become more common among western runners.

A final reason to study the Tarahumara is that many aspects of their lifestyle are rapidly changing. Although some Tarahumara still wear *huaraches* and other traditional clothes, as

Fig. 1. *Huaraches* worn by one of the minimally shod participants (during warmup phase of the experiment).

well as grow corn and beans as they used to in isolated farms, many are becoming westernized to varying extents. One dimension of this change is the increasingly common use of imported running shoes that have thick, cushioned, elevated heels, stiffened midsoles, built-in arch supports, and toe springs. Even so, some of the Tarahumara who now wear modern running shoes still participate in traditional running events such as the *rarajipari* and the ultramarathons. As a result, the Tarahumara represent a group in transition in terms of their footwear and running habits.

This study therefore collected data on variation in foot strikes as well as other aspects of running kinematics among Tarahumara who wear *huaraches* as well as those who wear modern, conventional shoes. There are anecdotal reports that the Tarahumara predominantly FFS,[31,37] but to date there have been no studies of their running kinematics. Three hypotheses are tested. The first is that Tarahumara who primarily wear and run in *huaraches* are more likely to FFS or MFS than those who wear and run in western shoes. Second, it is hypothesized that foot strike among minimally shod Tarahumara is uncorrelated with speed, age, and body mass, but covaries with other kinematic variables purportedly associated with barefoot running, notably a high cadence, minimal overstride, and a relatively vertical trunk. Finally, it is hypothesized that Tarahumara who wear *huaraches* have higher and stiffer arches than those who wear modern, supportive shoes. The basis for this hypothesis is that several features of modern running shoes, especially stiff midsoles and arch supports, likely decrease how much work the intrinsic muscles of the foot do, and thus lead to weaker arches that are therefore less stiff and more likely to be low.[38−42]

2. Materials and methods

2.1. Sample

A sample of 35 Tarahumara (Table 1) were studied in the Sierra Tarahumara from the region around the Barranca de Urique and in the highlands between the Barrancas de Urique and Batopilas. Subjects were recruited by word of mouth with the help of a resident who is well known to many Tarahumara and with a local Tarahumara teacher who speaks Rarámuri (the native language of the Tarahumara). Unfortunately, it was difficult to recruit a large sample of individuals because most traditional Tarahumara live in isolated farms, far from roads and towns. In addition, the Tarahumara tend to be reserved and wary of outsiders, and many potential subjects, especially women, declined requests to be videoed while running.

Of the 35 individuals studied, a combination kinematic and anthropometric data were collected from 23 individuals in December 2012. This sample includes 13 males (32.6 ± 12.9 years, mean ± SD) who wear only *huaraches* (hereafter referred to as minimally shod Tarahumara), and 10 individuals (7 males, 3 females, 26.0 ± 11.9 years, mean ± SD) who wear western shoes (hereafter referred to as conventionally shod Tarahumara). Most of the conventionally shod individuals came from the town of Urique. Anthropometric data were collected in December 2013 from an additional sample of 12 individuals (10 who were minimally shod and 2 who were

Table 1
Anthropometric and foot stiff differences between minimally and conventionally shod Tarahumara (mean ± SD).

	Subjects measured in 2012 (n = 20)			Subjects measured in total[a] (n = 32)		
	MS	CS	p	MS	CS	p
n	12	8		22	10	
Kinematic data						
Age (year)	33.4 ± 33.4	25.8 ± 12.5	0.21	34.6 ± 14.5	25.4 ± 12.1	0.09
Footwear history	3.83 ± 0.39	1.63 ± 0.74	**< 0.001**	3.90 ± 0.29	1.60 ± 0.29	**< 0.001**
Height (m)	1.65 ± 0.07	1.63 ± 0.06	0.35	1.65 ± 0.06	1.62 ± 0.07	0.12
Leg length (m)	0.88 ± 0.04	0.85 ± 0.04	0.07	0.86 ± 0.04	0.84 ± 0.05	0.10
Body mass (kg)	65.2 ± 9.4	59.9 ± 6.9	0.19	64.0 ± 8.23	59.2 ± 7.25	0.11
Anthropometric data						
Navicular height (mm)	–	–	–	44.4 ± 4.51	41.5 ± 8.87	0.23
Navicular height/TFL	–	–	–	2.34 ± 0.55	2.28 ± 0.46	0.75
Arch height index standing	–	–	–	0.33 ± 0.03	0.31 ± 0.04	0.19
Arch stiffness index	–	–	–	1607.2 ± 744.1	823.6 ± 223.7	**0.003**

Note: Data in boldface indicate $p < 0.05$.
Abbreviations: MS = minimally shod; CS = conventionally shod; TFL = truncated foot length.
[a] Apart from these measured in 2012, additional 12 subjects were measured in 2013.

conventionally shod). It was not possible to collect kinematic data from these individuals.

None of the individuals measured had current lower extremity injuries, but kinematic data from three individuals (all conventionally shod) were not analyzed for different reasons: one male ran in flip-flops; a second (1 female) was visibly distressed by the experiment, and ran in an awkward and evidently unnatural style; a third (1 female) was recorded with incorrect camera position. Accordingly, Table 2 presents data from 12 minimally shod and eight conventionally shod individuals. All individuals gave their informed consent in Spanish or Raramuri according to protocols approved by Harvard University.

2.2. Anthropometrics and background information

Basic background and anthropometric information was collected from all participants including age, sex, height, body mass, and leg length (measured from the greater trochanter to the base of the heel). Participants were asked to describe how far they travel every day, what kinds of physical activities they do on a regular basis, in what races they participate, and in what kind of footwear. Individuals were binned into four categories in terms of footwear usage, each assigned a rank-ordered numerical value: 1) almost always shod in conventional shoes (less than 10% outdoor activity spent in minimal shoes or barefoot); 2) usually shod in conventional shoes (wear shoes most of the time, but do athletic activities either in minimal shoes or barefoot); 3) mixed (sometimes walk, run or do physical activity in conventional shoes and sometimes in minimal shoes or barefoot); 4) mostly minimally or shod barefoot (more than 80% of walking, running and physical activity done either in minimal shoes or barefoot). They were also asked to describe any lower extremity injuries. All questions were asked in either Rarámuri or Spanish, and then translated into English.

Arch height and stiffness were assessed using an arch height index measurement system[43] that measures total foot length, the length of the foot from the back of the heel to the first metatarsophalangeal joint (TFL), and the height of the dorsum of the foot at 50% of foot length (DH). Participants were measured both sitting and standing with 13 mm thick boards placed under the heel and the phalanges and metatarsal heads to enable the arch to move. Navicular height was measured by having individuals stand on a hard flat surface (a concrete floor or a wooden board), placing a small ink mark on the navicular tuberosity, and then measuring the vertical distance between the ground and the mark using a rigid steel ruler accurate to 1 mm. Following Zifchock and colleagues,[43] the arch height index (AHI) was calculated as DH/TFL both standing and seated; the arch stiffness index (ASI) was calculated as (body mass $\times$ 0.4)/($AHI_{seated} - AHI_{standing}$).

Table 2
Kinematic differences between minimally and conventionally shod Tarahumara (mean ± SD).

Variable	Minimally shod (n = 12)	Conventionally shod (n = 8)	p
Preferred step frequency (steps/min)	171.2 ± 6.5	167.4 ± 8.2	0.26
Actual step frequency (steps/min)	174.7 ± 7.4	175.4 ± 8.5	0.86
Speed (m/s)	3.62 ± 0.24	3.52 ± 0.38	0.47
Foot strike			
Strike type index	2.04 ± 0.71	2.69 ± 0.59	**0.045**[a]
Angle of incidence (°)	−1.42 ± 4.46	−6.27 ± 5.28	**0.04**
Strike mode	MFS	RFS	**0.04**[a]
Ankle (°)	115.3 ± 10.6	114.7 ± 5.9	0.89
Knee (°)	156.4 ± 3.5	155.5 ± 5.1	0.68
Hip (°)	61.8 ± 4.0	59.8 ± 4.3	0.29
Trunk (°)	78.5 ± 5.2	79.5 ± 5.8	0.69
Overstride (°)	93.9 ± 1.8	97.4 ± 2.7	**0.003**
Midstance			
Ankle (°)	91.4 ± 5.8	91.2 ± 6.9	0.93
Knee (°)	128.3 ± 6.5	127.8 ± 6.1	0.87
Hip (°)	72.5 ± 3.7	72.3 ± 4.0	0.91
Trunk (°)	76.0 ± 4.7	77.0 ± 4.4	0.62

Note: Data in boldface indicate $p < 0.05$.
Abbreviations: MFS = midfoot strike; RFS = rearfoot strike.
[a] Calculated using non-parametric test (see text for details).

2.3. Experimental trials

Participants were asked to wear whatever footwear they normally use, and to wear shorts or skirts that could be rolled up to reveal the knee. Reflective tape markers were placed on the following locations on one side of the body: greater trochanter, the center of the knee (in between the lateral femoral epicondyle and the lateral tibial plateau), the lateral malleolus, the lateral surface of the 5th metatarsal head, and the lateral aspect of the tuber calcaneus. Participants were then photographed with a scale in lateral and frontal position with a numeric identification. All participants were then instructed to run around an open field for approximately 5 min at a pace they would choose when running a long distance. After the participant settled into a comfortable gait, step frequency was measured using an adjustable metronome (Matrix, New Market, VA, USA) fitted with an earpiece. Preferred step frequency was considered to be the frequency attained once the cadence stayed constant for at least 1 min. Repeated measurements from the same subjects indicate that step frequency measurements are accurate to approximately 4 steps/min.

Once each subject had warmed up, his or her running kinematics were then immediately recorded in lateral view on a trackway, approximately 15 m in length set up an a flat, grass-free and rock-free area, typical of the surfaces on which the Tarahumara normally walk and run in terms of surface hardness. A high-speed video camera (Casio EX-ZR100; Casio USA, Dover, NJ, USA) was positioned at 0.7 m height approximately 4 m lateral to the 10 m point on the track, providing an additional 3−5 m of track beyond the field of the camera for subjects to run before decelerating. For each trial, individuals were asked to run down the trackway while looking forward and without decelerating until they had passed a marker positioned approximately 3 m beyond the camera's field of view. Participants were asked to run at different speeds they might use when running an ultramarathon or *rarajipari* while using a lightweight metronome either held in the subject's hand or clipped onto his/her clothes to control for step frequency. Although a range of step frequencies were measured (as part of a separate analysis, not reported here) only trials in which the subjects measured step frequencies were within 5% of their preferred step frequency were used for analysis. In order to avoid having subjects alter their gait by stuttering their steps or overstriding as they passed the camera's field of view, there was no landing target or region. If the marked foot did not land in front of the camera, the subject was asked to repeat the trial (without explaining why), until a minimum of three trials were recorded. All sequences were recorded at 240 frames/s.

In order to avoid influencing how participants ran, no questions were asked about running form before or after the trials, and none were informed of the objectives of the experiment other than being told that we were measuring their feet and videoing them as they ran.

2.4. Kinematic analysis

All video sequences were converted to stacks of TIFF files and analyzed using ImageJ, version 1.46r (http://imagej.nih.gov/ij). Scale was determined for each subject using the distance between the markers on the lateral malleolus and knee. Running speed for each trial was quantified by measuring the horizontal translation of the greater trochanter between two homologous points during a stride cycle (e.g., toe-off to toe-off or foot strike to foot strike) relative to time (calculated from the number of frames divided by frame rate). Step frequency was calculated between the measured foot strike and the previous foot strike multiplied by the time sampled per frame.

Foot strike was measured using only sequences in which the markered foot landed in front of the camera permitting a clear, non-parallaxed view of the lateral margin of the foot. Strike type was quantified using the angle of incidence (AOI), by measuring the orientation of the calcaneus and 5th metatarsal head markers relative to horizontal at the first frame of contact minus the same angle measured at foot flat.[6,44] AOIs greater than 1.0° were classified as FFS, AOIs between −1.0 and 1.0° were classified as MFS, and AOIs less than −1.0° were classified as RFS. Because AOI measurements can be affected by which frame is selected to represent the moment of contact, the reliability of assessing strike type by AOI was tested by classifying strike type independently through visual inspection of the video sequence. A strike was classified as an RFS if the vertical translation of the calcaneus marker stopped at the first frame of ground contact while the 5th metatarsal head marker continued to move antero-inferiorly; as an FFS if the vertical translation of the 5th metatarsal head marker stopped at the first frame of ground contact while the calcaneus marker continued to move inferiorly; and as an MFS if vertical translation of the calcaneus and 5th metatarsal head markers ceased simultaneously. The correlation between foot strike type determined by the two methods was 0.94 ($p < 0.0001$). Since the mean AOI only partially captures variation in strike types, a rank-order strike index was computed by assigning FFS, MFS, and RFS strikes scores of 1, 2, and 3, respectively, and then averaging.

As noted above, several other kinematic variables were measured at foot strike and at midstance. Trunk angle was measured as the angle between the greater trochanter and the center of the neck relative to horizontal. Step frequency for each trial was quantified by measuring the time between two foot strike events (calculated from the number of frames divided by frame rate). Overstride (here defined as how far the ankle landed anterior to the knee) was measured as the angle of the lower leg (from the knee to the lateral malleolus) relative to earth horizontal at foot strike (an angle of 0° or less indicates no overstride, and higher angles indicate more overstride). An angular measurement of overstride was used instead of a linear measurement because there is less error in measuring the angle of the lower leg than in measuring the projected distance between the knee and ankle. Finally, to assess general lower extremity kinematics, hip angle was measured as the segment from the knee to the greater trochanter relative to horizontal; knee angle was measured as the angle between the lines from the knee to the greater trochanter and the knee to the lateral malleolus; and ankle angle was measured as the angle between the lines from the knee and to the lateral malleolus and from the lateral malleolus to the lateral metatarsal head. All angles were measured by visual inspection using ImageJ. Since the data were collected under field conditions it is not possible to quantify accuracy, but reliability was assessed in two ways. First repeatability was quantified by taking the same set of measurements from one individual on five separate occasions. The average standard deviation was 0.32° with a range of 0.18°−0.49°. In addition, a test−retest sensitivity analysis conducted by taking all measurements twice from the same trial, yielding a correlation coefficient of 0.927.

2.5. Statistical analyses

Kinematic measurements were averaged for each individual and compared among individuals and between minimally and conventionally shod groups primarily using *t* tests with footwear history (conventional or minimally shod) as the nominal, dependent variable. In addition, kinematic measurements were compared between individuals classified by strike type using ANOVA with modal strike type as the nominal, dependent variable. Mean individual values for strike type and other kinematic variables were also regressed against speed and step frequency. Strike type index and strike mode were compared between groups using a non-parametric Wilcoxon test. Effects were considered significant for $p < 0.05$. All analyses were done using JMP 5.0 (SAS Institute, Cary, NC, USA).

3. Results

The two groups of Tarahumara, summarized in Table 1, did not differ significantly in age, height, leg length, or body mass, although as might be expected, the mean age of the conventionally shod Tarahumara subjects was nearly 8 years below the minimally shod subjects ($p = 0.21$, t test). Footwear history, however, was very significantly different ($p < 0.001$, Wilcoxon test). This reflected the selection criteria used to define the two groups, with minimally shod Tarahumara wearing *huaraches* almost exclusively, and the less traditional, conventionally shod individuals wearing them occasionally or rarely. Very few of the participants reported running barefoot as adults, although some of the minimally shod Tarahumara said they would sometimes take off one or both *huaraches* for kicking the ball during the *rarajipari*, and children often run barefoot.

Although there is much variation, there were significant differences between the groups in terms of strike types, as summarized in Table 2. Among the minimally shod Tarahumara, 40% had a modal MFS strike type, 30% had a modal FFS strike type, and 30% had a modal RFS strike type. Among the conventionally shod Tarahumara, 75% had an RFS modal strike type, and 25% had an MFS modal strike type. As Fig. 2A illustrates, this difference was reflected in mean strike type, which averaged 2.04 for the minimally shod Tarahumara and 2.69 for the conventionally shod Tarahumara reflecting the predominance of MFS landings among the former and RFS landings among the latter ($p = 0.045$, Wilcoxon test). AOIs (Table 2) also indicate that the ankle was significantly more dorsiflexed in the conventionally shod versus minimally shod groups ($p = 0.04$, t test). Speeds used ranged between 2.3 m/s and 4.8 m/s, but as Fig. 2B shows, there was no significant correlation between speed and AOI for subject averages ($r = 0.04$; $p = 0.83$) or for all trials ($r = 0.02$; $p = 0.85$), nor did it correlate significantly with other anthropometric variables. Strike type, however, did correlate significantly with step frequency ($r = 0.47$; $p = 0.03$, ANOVA), with individuals who used higher step frequencies being more likely to FFS or MFS.

Given the high degree of variation within the minimally shod group, which included individuals who used RFS, MFS, and FFS landings, there were not many significant kinematic differences between the groups. Although the conventionally shod Tarahumara had a tendency to have lower preferred step frequencies, neither preferred step frequency nor the step frequency used during the trials differed significantly. Speed also did not differ between the groups. Although ankle, knee, hip, and trunk angles at foot strike and midstance were not significantly different between the conventionally and minimally shod Tarahumara, the degree of overstride as measured by the angle of the tibia at foot strike was significantly lower in minimally shod Tarahumara ($p = 0.003$, t test). In other words, the minimally shod Tarahumara were more likely to land with their ankles below the knee and with a more vertical lower leg. Fig. 3 shows that when kinematic differences between individuals are plotted by mean strike type (as determined from the AOI), the rearfoot strikers had significantly more dorsiflexed ankles ($p = 0.012$, ANOVA), more extended knees ($p = 0.007$, ANOVA), and less flexed hips ($p = 0.006$, ANOVA) at foot strike, but did not differ in terms of trunk angle at foot strike ($p = 0.610$, ANOVA), nor in any of these kinematic variables at midstance (results not shown). FFS and MFS did not differ significantly in any kinematic variables measured.

Finally, variations in arch height and stiffness, summarized in Table 1, indicate that there were no significant differences between groups for absolute arch height (as measured by navicular height), relative arch height (navicular height standardized by truncated foot length) or the arch height index (measured during standing). However, arch stiffness was almost twice as great ($p = 0.003$, t test) among the minimally shod Tarahumara who wear *huaraches* than among conventionally shod individuals. Two of the participants, both conventionally shod, had bilateral *pes planus*.

4. Discussion

Experiments such as those reported here necessarily sample only a portion of the variation that actually exists. With that caveat in mind, minimally shod Tarahumara runners appear to be best characterized as midfoot strikers who also employ forefoot and rearfoot strikes. These data therefore partially support but also modify earlier anecdotal reports that Tarahumara runners who use *huaraches* primarily FFS. The variation within the minimally shod sample, however, is

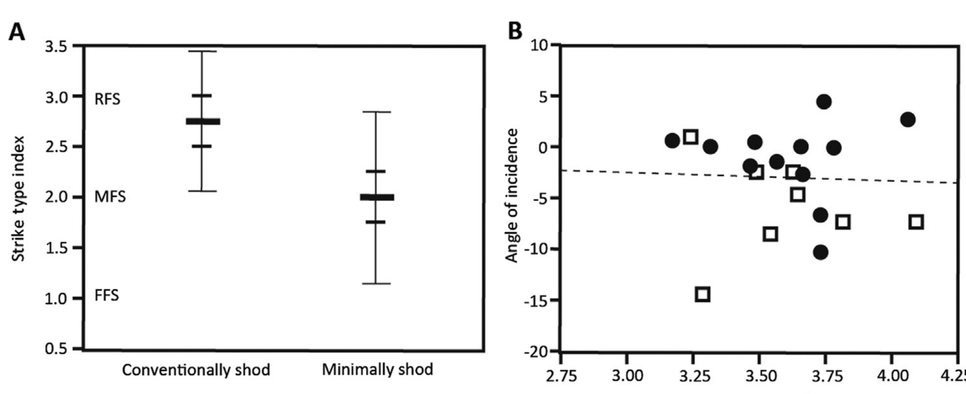

Fig. 2. Foot strike differences between minimally and conventionally shod Tarahumara. (A) strike type index as determined by angle of incidence. Box and whiskers indicate mean, ±1 and ±2SD. (B) relationship between speed and angle of incidence. Closed circles, minimally shod subjects; open squares, conventionally shod subjects.

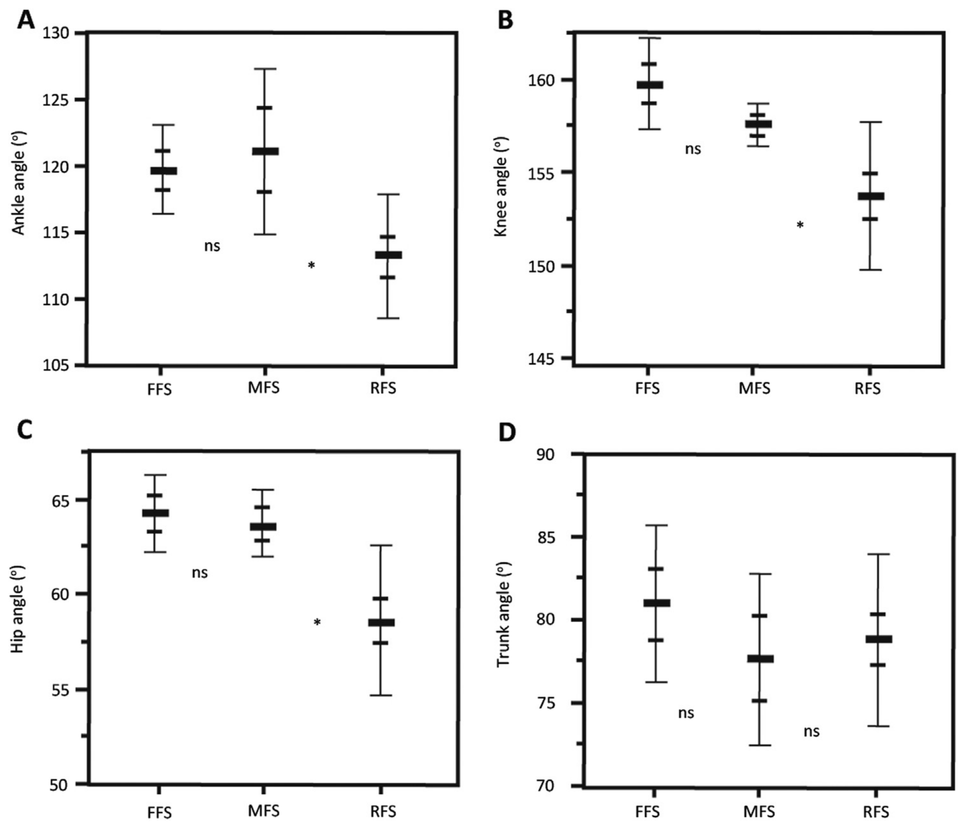

Fig. 3. Kinematic differences at foot strike between minimally and conventionally shod Tarahumara divided by foot strike type. Box and whiskers indicate mean, ±1 and ±2SD. * significant between FFS and RFS. Abbreviations: FFS = forefoot strike; MFS = forefoot strike; RFS = rearfoot strike; ns = not significant.

substantial, making any simple characterization of their strike type problematic. In contrast, Tarahumara who have adopted western running shoes with cushioned, elevated heels, stiff soles, partial arch supports, toe springs and other features common in most athletic shoes are almost entirely rearfoot strikers, much like habitually shod runners who have been measured in countries such as the USA.[2,3] The contrast between minimally shod and conventionally shod Tarahumara therefore supports the general observation that experienced runners who are habitually barefoot or minimally shod tend to land with a flatter foot and RFS less often than runners who habitually use modern running shoes that cushion and elevate the heel.[4−6,45,46]

There is much more to running form than strike type. Although there were no statistically significant differences in step frequency as well as the angles of the ankle, knee, hip, and trunk between the minimally and conventionally shod individuals, minimally shod Tarahumara had significantly less overstride (as measured by the orientation of the tibia at landing), which means that they typically land with their ankle nearly below the knee. In addition, when subjects were grouped by strike type, individuals who used FFS and MFS landings (all but one of which was minimally shod) had significantly more plantarflexed ankles, flexed knees, and flexed hips at the moment of foot strike than individuals who use RFS landings. These kinematic differences were no longer evident by midstance. These data corroborate previous reports that barefoot and minimally shod runners tend to differ from habitually shod runners in a number of aspects of running form.[19] The data also highlight the general kinematic similarity between forefoot and midfoot striking, both of which differ from rearfoot striking in a number of respects, perhaps the most important being less overstride in which the ankle lands nearly below the knee at the moment of strike, providing more limb compliance at the ankle and knee.

Previous studies have found that shod runners are more likely to FFS at higher speeds,[47] and one study found an increased use of FFS at higher speeds among the Daasenech, a habitually barefoot population from northern Kenya that does not run very much, and which lives in a very sandy habitat.[48] In contrast, this study found no effect of speed on strike type. One explanation for this result could be that the range of speeds employed was not great (2.3−4.8 m/s), with most runners choosing approximately 3.3−3.9 m/s. In addition, many of the runners already used FFS and MFS landings. It was not possible to test for the effect of sex on strike type, but there was no effect of age, body mass, preferred step frequency on strike type variation. Future research is therefore needed to understand when and why runners who are minimally shod or barefoot adopt different strike types. In this regard, additional variables to consider are how strong the runner is, especially in terms of the triceps surae and the foot muscles, the effects of distance and fatigue, and the influence of variations in the hardness, roughness, or slipperiness of the substrate. Since minimal shoes such as *huaraches* presumably allow less proprioception than being barefoot but considerably more than standard running shoes (a hypothesis that merits careful testing), it is reasonable to hypothesize that substrate characteristics have less of an effect on strike type choice among minimally shod than barefoot runners, but that other factors related to the skill of running long distances such as overstride, cadence, and posture remain just as important, perhaps even more so when running very long distances.

Although the focus of this study was on strike type, the results presented here also provide evidence for an effect of footwear on arch morphology and function. Most importantly, the minimally shod Tarahumara had significantly stiffer arches as measured by differences in the arch stiffness index. The index measure only static stiffness during sitting and standing rather than during walking or running, but nonetheless suggests that the Tarahumara who wear *huaraches* had stronger intrinsic muscles that lead to a stiffer longitudinal arch. Further data are necessary to measure actual foot strength, but this result accords with other studies which have found that habitually barefoot or minimally shod individuals have less variation in arch shape with a lower likelihood of *pes planus*,[41] and that individuals who wear minimal shoes develop more longitudinal arch strength as well as stiffer arches.[40]

Many limitations caution against over interpreting the results of this study. Most obviously, sample sizes were necessarily small given the challenges of recruiting Tarahumara to participate. Many individuals simply did not want to be measured and videoed. Another non-trivial deficiency is that this study looked only at individuals running on a trackway under conditions that controlled for just a few variables (e.g., incline and step frequency) that were comparatively unchallenging relative to the demanding and extremely varied conditions under which Tarahumara usually run. The canyons of the Sierra Tarahumara are among the most rugged landscapes in the world because they are characterized by extreme, steep changes in elevation, lots of rocks, and very few flat areas. The trackways on which participants were recorded facilitated comparisons of runners, but they were easy and relatively comfortable running surfaces for the Tarahumara. In addition, the Tarahumara rarely go for short runs and they do not train, but instead are celebrated for their abilities and proclivities to run very long distances. Thus in order to characterize how they really run (i.e., their full range of variation), it would be necessary to record individuals after many kilometers of running on conditions vastly different and more challenging than those used here. Although it is possible that runners in *huaraches* are more likely to FFS when running long distances on rocky terrain to minimize impact loading, it is also possible that the increased eccentric contractions of the plantarflexor muscles required during forefoot striking is too tiring over very long distances, favoring the adoption of midfoot strikes. In all likelihood, Tarahumara runners probably use all kinds of strike types over the course of a 50−100km race. Future studies are currently planned to quantify this variation.

Finally, it is worth considering the relevance of these results for the majority of runners who grow up wearing shoes, rarely if ever run ultramarathons, and are habituated to conventional running shoes with cushioned, elevated heels, stiff midsoles, orthotics, and toe-springs. Evidence that traditional Tarahumara who wear *huaraches* mostly avoid RFS landings on flat surfaces at moderate speeds is hardly justification for someone to switch to minimal shoes and stop heel striking. It is possible that people who grow up wearing conventional shoes have weaker feet, and unless they are used to forefoot or midfoot striking, they likely have weaker calf muscles less able to handle the additional eccentric loading these styles of running demand. That said, there is some utility to studying how the Tarahumara run, and how using minimal versus conventional shoes affects their running as well as their feet because a large percentage of conventionally shod people develop repetitive stress injuries and foot problems.[49] As the results presented here show, Tarahumara who run in conventional shoes tend to RFS like people all over the world who wear similar shoes, and they apparently have more compliant arches than those who wear *huaraches*. This study did not collect data on injuries, but several studies have shown how and why runners who generate higher and faster rates of impact loading are more likely to develop a suite of repetitive stress injuries.[9,10,17] In this regard, evidence that Tarahumara who wear *huaraches* are less likely to RFS makes sense because it enables them to avoid painful and potentially damaging impacts rather than use cushioned heels to merely slow the rate of impact loading. To be sure, habitually shod runners who wish to adopt minimal shoes or change their kinematics, should do so cautiously, gradually, and properly (e.g., without overstriding), allowing the body to adapt appropriately. However, there may be some wisdom in using traditional kinds of footwear and learning traditional ways of running.

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