Foot Structure and Function in Habitually Barefoot and Shod Adolescents in Kenya

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Abstract

Habitually barefoot (HB) children from the Kalenjin tribe of Kenya are known for their high physical activity levels. To date, there has been no comprehensive assessment of foot structure and function in these highly active and HB children/adolescents and link with overuse injuries. Purpose: The aim of this research is to assess foot structure, foot function, injury and physical activity levels in Kenyan children and adolescents who are HB compared with those who were habitually shod (HS). Methods: Foot structure, function, injury prevalence, and physical activity levels were studied using two studies with equal numbers of HS and HB. HS and HB children and adolescents were matched for age, sex, and body mass. Foot arch characteristics, foot strength, and lower-limb injury prevalence were investigated in Study 1 ($n = 76$). Heel bone stiffness, Achilles tendon moment arm length and physical activity levels in Study 2 ($n = 62$). Foot muscle strength was measured using a strength device TKK 3360 and heel bone stiffness by bone ultrasonometry. The moment arm length of the Achilles tendon was estimated from photographs and physical activity was assessed using questionnaires and accelerometers. Results: Foot shortening strength was greater in HB (4.8 ± 1.9 kg vs 3.5 ± 1.8 kg, $P < 0.01$). Navicular drop was greater in HB (0.53 ± 0.32 cm vs 0.39 ± 0.19 cm, $P < 0.05$). Calcaneus stiffness index was greater (right 113.5 ± 17.1 vs 100.5 ± 116.8, $P < 0.01$ left 109.8 ± 15.7 vs 101.7 ± 18.7, $P < 0.05$) and Achilles tendon moment arm shorter in HB (right, 3.4 ± 0.4 vs 3.6 ± 0.4 cm, $P < 0.05$; left, 3.4 ± 0.5 vs 3.7 ± 0.4 cm, $P < 0.01$). Lower-limb injury prevalence was 8% in HB and 61% in HS. HB subjects spent more time engaged in moderate to vigorous physical activity (60 ± 26 $\text{min}\cdot\text{d}^{-1}$ vs 31 ± 13 $\text{min}\cdot\text{d}^{-1}$; $P < 0.001$). Conclusions: Significant differences observed in foot parameters, injury prevalence and general foot health between HB and HS suggest that footwear conditions may impact on foot structure and function and general foot health. HB children and adolescents spent more time engaged in moderate to vigorous physical activity and less time sedentary than HS children and adolescents.

Introduction

Humans have engaged in barefoot locomotion or have worn minimal footwear for most of human evolutionary history (3). It is not surprising therefore that barefoot locomotion has attracted significant scientific interest in recent years (9,10) and a flurry of minimalist running shoe companies eager to capitalize on the concept. A highly cited paper describing the generally favorably foot strike patterns and collision forces in habitually barefoot (HB) versus shod runners led initially to increased numbers of barefoot runners and/or the use of minimalist footwear (18,24). However, more recently the interest in barefoot locomotion has faded as a result of the unresolved controversy about the possible benefits as well as associated risks of barefoot locomotion (12,26,31,36). The short-term effects of barefoot versus shod walking and running have clearly revealed a higher risk of certain running associated injuries (12,36). There are only a few studies that have investigated the long-term effects of HB locomotion (see 12,36 for review) however, the quality of these studies are poor. The only systematic review of long-term effects of HB locomotion concluded there was little evidence of lower injury rates or foot pathologies (17). This systematic

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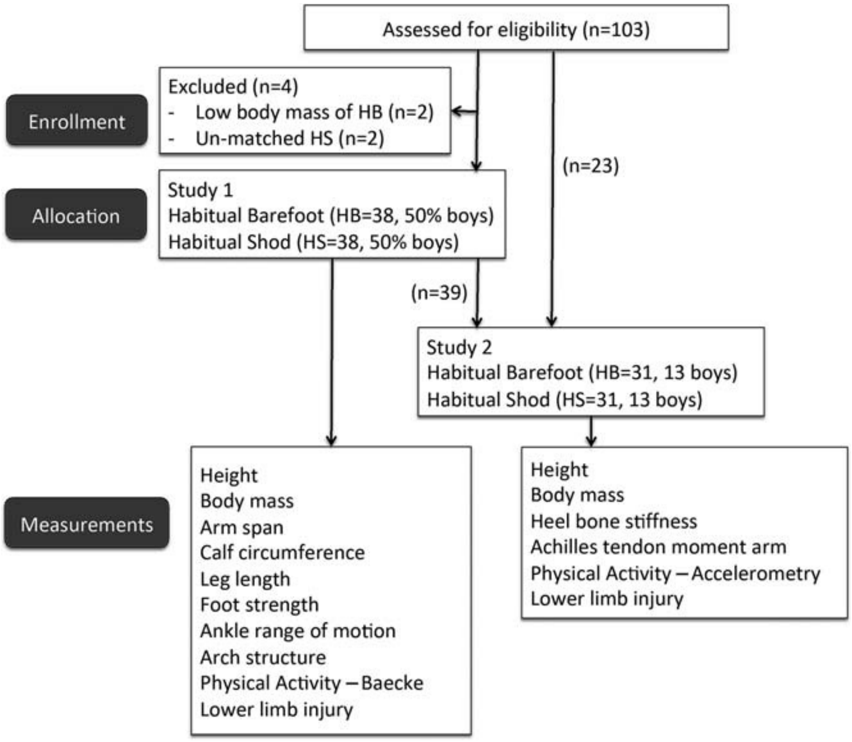

Figure 1: The experimental design flowchart.

review also advocated the need for well-designed prospective randomized controlled studies, to identify the long-term effects of barefoot locomotion. An alternative approach to study the long-term effects of HB lifestyles on structure and function of the lower limb would be to study populations where HB and/or the use of minimalist footwear remain the norm for one population. For example, invaluable information was obtained in a study comparing the strike type variation among Tarahumara Indians wearing minimal sandals versus those wearing conventional running shoes (23). This study discussed the significant variation in foot strike patterns among minimally shod runners and the importance of foot stiffness in determining running form (23) and impact on physical activity levels.

HB children from the Kalenjin tribe of Kenya are known for their high physical activity levels (11,22,28,29,30). Some studies report that HB children from this region run up to 20 km a day to get to and from school (24,30) and furthermore, engage in considerable physically active leisure time activities and household chores. This high habitual physical activity in these children/adolescents is typically conducted barefoot and this factor has been proposed as one of the explanations for the phenomenal success of Kenyan and Ethiopian runners (30,39). To date, no investigation has performed a comprehensive assessment of foot structure and function in highly active and HB children/adolescents in rural Kenya and assessed the link with overuse injuries. The aim of this research is to assess foot structure, foot function, injury and physical activity levels in Kenyan children and adolescents who are HB compared with those who were HS.

Methods

Experimental Design

The experimental design is illustrated in Figure 1. Briefly, subjects were divided into two groups: HB (study 1, *n* = 40 (20 girls, 20 boys); study 2, *n* = 31 (18 girls, 13 boys) school-aged children/adolescents) and habitually shod (HS) groups (study 1, *n* = 38 (19 girls, 19 boys); study 2, *n* = 31 (18 girls, 13 boys) school-aged children/adolescents). Two subjects initially recruited in the HB group were excluded from study 1 because of their low body mass (26.5 and 27 kg) as no matched controls could be found therefore reducing the HB and HS groups to 38 subjects in study 1. The study groups were age-, sex- and body mass-matched and participated in study 1 and study 2, respectively. The overlap of subjects in study 1 and study 2 were 24 subjects in HB (63%) and 15 subjects in HS (40%). Both children and parent(s) gave verbal informed consent to participate in both studies, which were approved by the Institutional Research Ethics Committee, Moi University, Eldoret, Kenya. This was achieved and witnessed by the principal investigators with the help of the children's teachers to provide information and answer questions. Written informed consent was not collected from parents due to illiteracy. Agreement by verbal consent was documented next to each child's name. This process was in line with the approval received from the local ethics committee. The subject characteristics are given in Table 1.

In study 1, height, body mass, arm span, calf circumference, leg length, foot strength, active ankle range of motion and foot structure characteristics were measured and a modified Baecke questionnaire (1) was used to assess levels of physical activity. In study 2, heel bone stiffness and Achilles tendon moment arm

Table 1.
Subject characteristics in study 1 ($n = 76$) and study 2 ($n = 62$), mean ± SD and ranges are presented.

	Subjects (n)	Mean Age ± SD (Range) (yr)	Mean Height ± SD (Range) (cm)	Mean Weight ± SD (Range) (kg)	Mean BMI ± SD (Range)(kg·m^2)
Study 1					
HB	38 (19 b; 19 g)	15.1 ± 1.4 (12−18)	162.3 ± 9.0* (142−177)	44.9 ± 7.4 (27−61)	17.0 ± 2.0** (13.1−21.4)
HS	38 (19 b; 19 g)	15.1 ± 1.4 (12−18)	157.9 ± 9.6 (140−180)	45.3 ± 6.9 (27−61)	18.2 ± 2.1 (13.7−24.9)
Study 2					
HB	31 (13 b; 18 g)	15.5 ± 1.2 (13−18)	157.1 ± 19 (144−172)	46.4 ± 6.4 (30.5−59)	18.0 ± 2.0* (13.9−22.5)
HS	31 (13 b; 18 g)	15.4 ± 1.2 (13−18)	156.1 ± 8 (141.5−170)	46.6 ± 5.3 (39−59)	19.1 ± 1.6 (16−23.1)

HB, habitually barefoot group; HS, habitually shod group; BMI, body mass index; b, boys; g, girls.
*$P < 0.05$.
**$P < 0.01$.

were measured and uniaxial accelerometer was used to objectively measure physical activity levels and patterns. All experiments were conducted in school classrooms. Arm span was measured by positioning the subject's heels together with the back against a flat black board and the arms stretched sideways with the palms facing the investigator. The tips of the middle fingers were marked and the distance between marks was measured. Right calf circumference was measured at the level of the largest circumference of the calf with the subject standing erect and with body mass evenly distributed on both feet and legs shoulder width apart. Right leg length was measured standing from the sharpest lateral projection of greater trochanter to the ground. All linear measurements were taken to the nearest 1 cm with a tape measure. Body mass was measured to the nearest 0.1 kg on a portable scale (Salter 144SVBKDR; Salter Houseware Ltd. UK) while subjects were barefoot and wearing the school uniform (shorts or skirt and blouse with vest). Modifications in Baecke questionnaire included the addition of questions about shoe wearing habits, daily activities specific to the Nandi region such as cattle herding, transport method/distance to school and daily running distance. The presence of lower-limb injuries and foot deformities was not self-reported but a thorough clinical assessment was carried out by an experienced orthopedic surgeon (P.O.).

Given the use of a questionnaire to measure physical activity in study 1, a second study (study 2) was conducted to measure physical activity levels and patterns objectively using the ActiTrainer uniaxial accelerometer (ActiGraph LLC, Pensacola, FL) for six consecutive days during school term time. The accelerometer was worn with a Velcro belt around the waist according to the recommendations of the manufacturer. Each child was instructed to wear the device at all times except when sleeping and bathing. The recording epoch was set at 60 s. Ojiambo et al. (28) have shown that group differences in moderate to vigorous physical activity (MVPA) can be demonstrated with 60 s epoch although some differences — MVPA in very short bouts — would be lost. The monitoring of physical activity levels was considered valid for inclusion in the analysis if a minimum of 12 h of recordings took place per day for at least 3 d (including at least one weekend day). Ojiambo et al. (27) have demonstrated that minimum acceptable reliability can be obtained in 3 d. It should be noted, however, that most of our subjects had considerably more than three valid days of measurement: five had 3 days, one had 5 days, and 53 had 6 or more days. Accelerometer data were analyzed using algorithms developed in R statistical package (27). Sedentary time and physical activity levels were assessed using cut-points for sedentary and MVPA developed by Puyau et al. (33). These cutpoints have been validated in children and adolescent age 6 to 16 years as follows: sedentary time less than 800 counts per minute (CPM) and MVPA greater than 3200 CPM (27).

Foot Strength

For all subjects in study 1, the right foot toe muscle strength (*i.e.*, hallux, digits second to fourth, digits first to fourth) and foot shortening strength were measured using a commercially available foot strength device (TKK 3360; Takei Scientific Instruments Co. Ltd., Japan) (Fig. 2) while subjects were seated on a chair with the hip and knee joints at 90 degrees. The subject's foot was placed on the foot strength device in a manner that allowed the distal part of the toes to be supported on a metal rod that was attached to a strain gauge. Each subject was given as many familiarisation trials required to perform the test correctly. Verbal instructions were given to maintain the foot on the device so that the most posterior part of the heel was in contact with the heel cup of the device. Subjects were instructed not to lift their heel while flexing their toes. An investigator manually assisted by keeping the heel on the surface while maintaining contact with the heel cup and raising the toes or hallux while the subject plantar flexed the great toe or digits second to fourth, respectively. To measure isometric strength, the subject was required to passively invert and revert their foot so that a neutral position with respect to the subtalar joint would be attained. The subject was asked to perform an active toe dorsiflexion and maintain the upright position of the toes, while the instructor placed the foot with the first metatarsal head on the metal rod and fixed the heel against the heel cap. The subject was asked to bring the base of the first metatarsal head towards the heel in a posterior direction while keeping it on the surface and flexing the arch without flexing the toes; the investigator also demonstrated this movement. Subjects were asked to perform several familiarisation trials before the three performance

Figure 2: Measurement of hallux flexor strength using the foot strength device.

trials and the best result was recorded; a single investigator took all measurements.

Ankle Range of Motion

Active ankle dorsiflexion and plantar-flexion was assessed in study 1 using a goniometer (Orthopaedic Equipment Co, Bourbon, IN). Subjects were required to position themselves in a supine position with feet and ankles extended over the edge of a table. The goniometer fulcrum was placed over the lateral aspect of the lateral malleolus with the ankle in 90 degrees. Plantar-flexion and dorsiflexion were performed to maximum reach. Three trials were performed in each direction and the mean taken as the final result. The mean was calculated to minimize the intraobserver and interobserver errors. Total range of ankle motion was calculated as the sum of both movements.

Medial Arch Structure

Medial arch structure in study 1 was defined as navicular bone height and foot dorsum height (at 50% of total foot length) in two conditions: seated and standing. Subjects were seated on a chair placed on a low table to confirm an even surface under the foot and allowing the foot arch to drop naturally. Knee and hip joints were held at 90 degrees flexion with foot firmly planted on the horizontal surface. Total right foot length, length from heel (the most posterior portion of the calcaneus) to the center of the first metatarsal phalangeal joint (truncated foot length), and from heel to tuberosity of fifth metatarsal were measured in cm using a rigid ruler or segmometer (Rosscraft, Canada). Navicular height was first measured seated from the underlying surface of the foot to the most proximate part of the bone using a rigid ruler or segmometer. This procedure was repeated with the subject in a standing position with body mass equally distributed on both feet. Navicular drop was calculated by subtracting standing height from seated height. Similarly, the foot dorsum height was measured in the seated position followed by a standing position using a segmometer. Navicular height and foot dorsum height were divided by total foot length and truncated foot length (measured only seated) for normalizing medial longitudinal arch height to foot length (44). A single investigator took all of these measurements.

Heel Bone Stiffness Index

Heel bone stiffness in study 2 was measured using bone ultrasonometry (Lunar Achilles InSight™, Madison, WI). This technique uses ultrasound waves to quantify the density of the calcaneal tuberosity, and thus measures both bone mineral density and bone volume fraction (16). In comparison to more conventional dual-energy x-ray absorptiometry (DXA), the quantitative ultrasound is a radiation-free method to evaluate bone stiffness in a calcaneus, consist of 90% trabecular bone and bone microarchitecture is similar to that of the lumbar spine and femoral neck. The DXA method is size-dependent, two-dimensional, and does not distinguish between trabecular and cortical bone (15). Quantitative ultrasound measures bone stiffness in stiffness index as the units. Measurements of bone stiffness were performed with the subject seated. The leg was positioned with the foot, calf and thigh aligned with the center of the calf support and foot positioner. The calf was gently resting on the calf support. Propanol alcohol was applied to both sides of the heel to condition the skin and ensure proper ultrasound coupling between membranes and the heel. The subject was asked not to move during the measurement. The speed of the sound waves ($m{\cdot}s^{-1}$) and their frequency-dependent attenuation ($dB{\cdot}mHz^{-1}$) are combined to calculate a stiffness index. The process was repeated until three results from three trials were within 2% and then averaged.

Achilles Tendon Moment Arm

The Achilles tendon moment arm was measured as illustrated in Figure 3. Briefly, the subject was seated with the knee and ankle at 90 degrees. The measured foot was placed on a reference block with first the lateral followed by the medial side of the foot aligned with the tape measure on the reference block. The vertical position of the tibia was corrected with a spirit level. The lateral and medial malleoli were marked on the most prominent aspect with white corrector paint. Left and right foot were photographed (Olympus Digital Camera, c-750 ultrazoom, Camedia, PA) from the lateral and medial side. The Achilles tendon moment arm was determined on the image as the mean of the lateral and medial horizontal distance from the most prominent tip of the tibia and fibular malleoli to the posterior aspect of the Achilles tendon (34,38). The distances determined on the photos using Didge Image Digitizing Software for Windows (courtesy of A. J. Cullum, Omaha, NE). The normalization to truncated foot length was performed by dividing moment arm by truncated foot length, multiplying by 100 and determining a percentage of truncated foot length (13). Achilles tendon moment arm was further scaled to body height. According to Scholz et al. (38), the interobserver and intraobserver reliabilities

Figure 3: Determination of the Achilles tendon moment arm — medial view of the right foot. The medial malleoli are marked on the most prominent aspect with white corrector paint. The Achilles tendon moment arm was determined on the image as the mean of the lateral and medial horizontal distance from the most prominent tip of the tibia and fibular malleoli to the posterior aspect of the Achilles tendon.

of this method is high ($R^2 > 0.95$, $P < 0.001$) when comparisons of two measurements were made by the same person several months apart; the improvised for field study digital photographic measurement method used was also reported to be a valid and reliable clinical and research tool for quantifying foot structure (4).

Statistical Analysis

Comparison between HB and HS subjects in foot structure characteristics were conducted using a two-tailed Student's *t*-test with statistical significance set to $P < 0.05$. Analysis of covariance (ANCOVA) was used to detect whether any of the group differences in anthropometric parameters can be explained by differences in physical activity. A linear model containing only a dichotomous group variable as a predictor is equivalent to a simple *t*-test. To this model, we added physical activity score as a continuous predictor, resulting in an ANCOVA model. The ANCOVA comparison was performed using statistical software package R.

Results

Subject Ages and Anthropometric Measures

Both groups were sex-, age- and body mass-matched but HB children/adolescents were taller and had approximately 5% lower body mass index (BMI) (Table 1). In terms of other anthropometric measurements only arm span and leg length were significantly different (Table 2); approximately 3% longer in HB compared to HS.

Foot Characteristics

Foot dorsum height characteristics are shown in Table 3. As such navicular bone and foot dorsum height were higher (both seated and standing) in HB compared to HS both in terms of absolute and relative height. These differences remained significant between groups when results were controlled for physical activity (total score of Baecke questionnaire) both for dorsum height seated and standing ($P < 0.001$) and navicular height seated and standing ($P < 0.001$). Navicular drop was greater in HB compared to HS. The initial region effect as assessed using an analysis of variance (ANOVA) was significant $F(1, 74) = 5.8$, $P = 0.02$, but after controlling for physical activity the strength of the relationship was no longer significant $F(1, 73) = 2.1$, $P = 0.16$. Ankle dorsiflexion was 2 degrees greater in HB when compared to the HS (13.7 ± 3.6 degrees vs 11.7 ± 3.7 degrees, $P = 0.01$); ankle plantar flexion tended to be greater in HB compared to HS but not significantly ($P = 0.09$). Overall, total ankle ROM was more than 6 degrees greater in HB than HS (58.3 ± 10.2 degrees vs 51.9 ± 13.5 degrees, $P = 0.01$).

Heel Bone Stiffness Index and Achilles Tendon Moment Arm

Calcaneus stiffness index was greater in HB than HS subjects (right 113.5 ± 17.1 vs 100.5 ± 16.8, $P = 0.01$; left 109.8 ± 15.7 vs 101.7 ± 18.7, $P = 0.05$). Achilles tendon moment arm was significantly shorter in HB than HS both in absolute and relative terms (right, $P = 0.01$; left, $P = 0.05$). Heel bone stiffness index and Achilles tendon moment arm results are presented in Table 2. Normalization of Achilles tendon moment arm to truncated foot length was performed by dividing moment arm by truncated foot length, multiplying by 100 and presented as a percentage of truncated foot length (right, 19.7 ± 2.2% in HB vs 21.5 ± 2.5% in HS, $P = 0.01$; left, 19.3 ± 2.1% in HB vs 21.1 ± 2.0% in HS, $P < 0.001$). Similar results were observed when the moment arm was divided by body height (left foot adjusted, $R^2 = 0.14$, $P = 0.002$; right foot adjusted, $R^2 = 0.15$, $P < 0.001$). Heel bone stiffness index and Achilles tendon moment arm length were

Table 2.

Table of subject's arm span, calf circumference, and leg length in study 1 and heel bone stiffness index and Achilles tendon moment arm length in study 2, mean ± SD and ranges are presented.

Study 1				Study 2			
				Heel bone stiffness index		Moment arm (cm)	
	Arm span (cm) range	Calf circum. (cm) range	Leg length (cm) range	Left range	Right range	Left range	Right range
HB	169.2 ± 9.8*	31.8 ± 2.3	91.3 ± 7.1*	109.8 ± 15.7*	113.5 ± 17.1**	3.4 ± 0.5**	3.4 ± 0.4*
	144−187	27−39	78−104	78.3−133.7	84.3−161.7	2.6−4.2	2.6−4.5
HS	164 ± 10.7	31 ± 2.9	88.2 ± 7	101.7 ± 18.7	100.5 ± 16.8	3.7 ± 0.4	3.6 ± 0.4
	144−187	23−36	75−104	73.3−159	75−147.5	2.6−4.4	2.9−4.2

Moment arm, Achilles tendon moment arm length.

*$P < 0.05$.

**$P < 0.01$.

Table 3.

Navicular bone and foot dorsum (at 50% of the total foot length) height characteristics, toe flexion and foot shortening muscle strength and physical activity assessment with modified Baecke questionnaire in HB group and HS group in study 1, mean ± SD and range are presented.

	HB (n = 38)	HS (n = 38)
Navicular process height		
Seated (cm)	5.0 ± 0.6* [4.0–6.5]	4.1 ± 0.7 [2.6–5.1]
Standing (cm)	4.4 ± 0.6* [3.4–6.0]	3.7 ± 0.7 [1.9–5.3]
Seated/foot length (cm)	0.21 ± 0.03* [0.16–0.26]	0.17 ± 0.03 [0.11–0.24]
Standing/foot length (cm)	0.19 ± 0.03* [0.14–0.25]	0.16 ± 0.04 [0.08–0.23]
Seated/HBLm (cm)	0.30 ± 0.04* [0.230.39]	0.20 ± 0.10 [0.14–0.33]
Standing/HBLm (cm)	0.27 ± 0.04* [0.20–0.34]	0.22 ± 0.10 [0.11–0.31]
Navicular bone drop (cm)	0.53 ± 0.32** [0.1–1.6]	0.39 ± 0.19 [0.1–1.0]
Foot dorsum height		
Seated (cm)	6.7 ± 0.7* [5.6–8.1]	6.2 ± 0.5 [4.3–7.2]
Standing (cm)	6.5 ± 0.6* [5.3–7.6]	6.1 ± 0.5 [5–7]
Seated/foot length (cm)	0.28 ± 0.03* [0.24–0.35]	0.26 ± 0.03 [0.18–0.33]
Standing/foot length (cm)	0.27 ± 0.03* [0.23–0.34]	0.26 ± 0.02 [0.21–0.32]
Seated/HBLm (cm)	0.40 ± 0.04* [0.34–0.49]	0.36 ± 0.03 [0.24–0.45]
Standing/HBLm (cm)	0.39 ± 0.04* [0.32–0.47]	0.35 ± 0.03 [0.28–0.44]
Toe flexion and foot shortening muscle strength		
Hallux (kg)	4.9 ± 2.3 [1.5–14.3]	4.8 ± 2.1 [2.1–10.7]
Digits second to fourth flexion (kg)	3.3 ± 1.5 [0.7–8.1]	2.8 ± 1.4 [0.8–6.8]
Digits first to fourth flexion (kg)	9.1 ± 2.5** [4.3–14.8]	7.9 ± 2.6 [3.2–14.8]
Short foot exercise (kg)	4.8 ± 1.9* [1.7–10.2]	3.5 ± 1.8 [0.6–8.7]
Physical activity assessment with modified Baecke questionnaire		
Work score	2.7 ± 0.5* [1.9–3.8]	2.5 ± 0.3 [1.9–3.1]
Leisure score	3.4 ± 0.9*** [1.8–5.3]	2.4 ± 0.5 [1.5–2.8]
Sport score	3.3 ± 0.6** [2–4]	2.9 ± 0.6 [1.75–4.25]
Total	9.4 ± 0.2*** [6.8–11.5]	7.8 ± 0.9 [6.1–9.5]

HBLm, medial truncated foot length from heel to the base of the first metatarsal.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

controlled for amount of MVPA and differences persisted between groups.

Foot Muscle Strength

There were no significant differences between HB and HS in hallux flexor strength and strength when second to fourth flexor digits were compared but when first to fourth flexor digits were compared, HB were stronger than HS (9.1 ± 2.5 kg vs 7.9 ± 2.6 kg; $P < 0.05$). The HB were also stronger in short foot exercise compared with HS (4.8 ± 1.9 kg vs 3.5 ± 1.8 kg; $P < 0.01$) (Table 3). Differences persisted between groups when the strength of short foot exercise was controlled for physical activity (total score of Baecke questionnaire). The initial regional effect as assessed by ANOVA was $F(1, 74) = 8.82$, $P = 0.01$, after controlling for physical activity the relationship $F(1, 73) = 3.74$, $P = 0.06$ is no longer significant.

Lower-Limb and Low-Back Injuries

Lower-limb injury prevalence in the year was 8% in HB and 61% in HS = 17.9; $P = 0.01$ (Table 5). The breakdown of the specific conditions is listed for the HB and HS in Table 5.

Physical Activity Levels

Physical activity as assessed in study 1 using the modified Baecke questionnaire demonstrated that 89% in HB and 26% in HS were involved in cattle herding “sometimes” or “often” (Table 3). The average walking distance was

1 to 5 $\text{km}\cdot\text{d}^{-1}$ for 25 HB subjects (66%) and 37 HS subjects (97%). The average running distance was 1 to 5 km for 24 HB subjects (63%) and 23 HS subjects (61%). Thirty HB subjects (79%) and one HS subject had never watched TV or played computer games.

Physical activity data for study 2 were successfully obtained from 30 HB subjects (13 boys; 17 girls) and 28 HS subjects (12 boys; 16 girls) (Table 4). The HB subjects accumulated an average of 730 ± 244 CPM as compared with 304 ± 65 CPM in HS ($P < 0.001$) over an average recording period of 12 $\text{h}\cdot\text{d}^{-1}$ (7.7 ± 1.9 d in HB and 6.3 ± 0.8 d in HS). The daily mean time spent in sedentary activity was 266 ± 64 min in HB and 610 ± 164 in HS or 56% and 72% of total recording time, respectively. Total time spent in light physical activities was 154 ± 52 min in HB and 207 ± 69 in HS min (32% and 24% of total recording time, respectively), in moderate activity was 35 ± 16 min in HB (7%) and 23 ± 9 min in HS (3%), and vigorous activity was 24 ± 14 min in HB (5%) and 7 ± 5 min in HS (0.8%). MVPA was greater in HB (60 ± 26 $\text{min}\cdot\text{d}^{-1}$ vs 31 ± 26 $\text{min}\cdot\text{d}^{-1}$, $P \leq 0.001$). No relationship was found between sex and levels of physical activity, but all physical activity levels were dependent on regional distribution (sedentary, $R^2 = 0.95$, $P < 0.001$; light, $R^2 = 0.63$, $P = 0.02$; moderate, $R^2 = 0.65$, $P < 0.001$; vigorous, $R^2 = 0.65$, $P < 0.001$; MVPA, $R^2 = 0.57$, $P < 0.001$).

Discussion

The main results of study 1 revealed differences between HB and HS groups in many measures of foot structure. Numerous methods have been used to assess medial longitudinal arch height and deformation in static (8,19,23,25,41,43,44,46) and dynamic conditions (2). The HB subjects had higher medial longitudinal arches and more flexible feet than HS subjects (Table 3). Arch height can be classified according to arch ratio as high (arch ratio of at least 0.356) and low (arch ratio at most 0.275) (46); arch ratio being defined as the height to the dorsum of the foot at 50% of the foot length divided by truncated foot length. Using these criteria, HB subjects in study 1 would be classified as having high arches with arch ratios of 0.40 ± 0.04 (seated) and 0.39 ± 0.04 (standing) as opposed to normal to high arches in HS with arch ratios of 0.36 ± 0.03 (seated) and 0.35 ± 0.03 (standing) (Table 3). However, from an evolutionary perspective, it makes sense to consider habitually unshod feet to be normal, suggesting that normative arch ratios may be biased by modern shoes. Zifchock et al. (46) found a significantly higher arch height index (which was significantly but weakly related to arch stiffness) in the dominant versus the nondominant foot, possibly due to greater neuromuscular activity in the dominant foot. Similarly, greater neuromuscular activity when HB may result in better-conditioned muscles, tendons, and ligaments of the lower limb and therefore stronger feet (Table 3). Subjects in both studies were body mass-matched to prevent a variable load influencing the measures of foot structure and function (Table 1). For example, Villarroya et al. (42) studied 245 children/adolescents aged 9 to 16.5 years and reported lower arches in obese and overweight compared to normal weight subjects. In study 1, HB had longer arm span and leg length than HS but this can be explained by taller mean body height in HB (Table 2). The subjects in the HS group were chosen with matching sex, age, and body mass and not with matching body height, which explains the difference in BMI between groups (Table 1).

The main hypothesis tested in both studies was that high levels of physical activity combined with a HB lifestyle would lead to stronger intrinsic foot muscles and other

Table 4.

Physical activity characteristics in HB group and control group HS group in study 2.

	HB (n = 31) Mean ± SD [Range]	HS (n = 31) Mean ± SD [Range]		
CPM	730 ± 244* [232-1399]	304 ± 65 [219-500]		
Sedentary time (min)	266 ± 64* [175-394]	610 ± 164 [57-781]		
Light activities (min)	154 ± 52* [59-240]	207 ± 69 [11-331]		
Moderate activities (min)	35 ± 16* [10-75]	23 ± 9 [3-42]		
Vigorous activities (min)	24 ± 14* [6-49]	7 ± 5 [0.9-16]		
MVPA (min)	60 ± 26* [16-113]	31 ± 26 [4-56]		
	Boys (n = 13)	Girls (n = 18)	Boys (n = 13)	Girls (n = 18)
CPM	829 ± 249	653 ± 217	328 ± 73	287 ± 54
Sedentary time (min)	274 ± 53	260 ± 72	595 ± 211	621 ± 123
Light activities (min)	159 ± 62	150 ± 46	206 ± 88	209 ± 55
Moderate activities (min)	36 ± 19	35 ± 15	26 ± 9	22 ± 9
Vigorous activities (min)	33 ± 13	18 ± 10	10 ± 5	4 ± 3
MVPA (min)	68 ± 28	53 ± 23	36 ± 13	26 ± 12

Mean ± SD and range are presented. Mean ± SD are presented separately for boys and girls.

CPM, counts per minute; MVPA, moderate to vigorous physical activity.

*$P < 0.001$.

supporting structures of the foot such as ligaments and tendons. Intrinsic foot muscles may influence the change in the medial longitudinal arch depending on the extent of movement and load exerted. As such, significantly greater toe flexor strength in digits first to fourth and in foot shortening exercise, where, according to Jung et al. (19), the abductor hallucis is most active, were found in HB subjects (Table 3). Wong (45) also found that the abductor hallucis dynamically elevated the medial longitudinal arch. Additionally, abductor hallucis muscle has the greatest cross-sectional area of intrinsic muscles, which is an indicator of greater force production capability (21). It is possible that the greater toe flexor strength in HB (Table 3) would help counter the increased mobility in these subjects when pronation control is required and therefore placing less strain on the soft tissue structures such as ligaments and tendons and lead to less prevalence in lower-limb overuse injuries. Anatomical data (45) support the hypothesis that the abductor hallucis may act to decelerate arch flattering after heel strike and to raise the arch before toe-off and work synergistically with the posterior tibial muscle. Habitually barefoot lifestyles may allow the abductor hallucis to reduce loads otherwise borne by the tibialis posterior and potentially avoid the development of tibialis posterior dysfunction. In contrast to the study 1, D'Août et al. (5) found that HS individuals had more variable longitudinal arch heights based on assessments of navicular height and navicular drop during stance. However, these subjects were all adults (in range, 20.3-73.7) unlike those investigated in the present studies (Table 1). Rao and Joseph (35) on the other hand found higher prevalence of flat feet in shod children (between the ages of 4 and 13 years) compared with barefoot children in India. These authors stated that the type of footwear their subjects were wearing influenced the development of the longitudinal arch of the foot. These authors suggested that subjects who wore slippers or sandals were repeatedly activating intrinsic muscles of the foot to keep the slippers on the feet. Some of the HB children/adolescents in both studies would at times wear rubber slippers and findings in general support the hypothesis that not wearing shoes or wearing minimal footwear may strengthen intrinsic foot muscles. In study 1, two of 38 HB subjects had never worn shoes and the mean age of starting wearing shoes was 8 ± 4 years in HB and 1.8 ± 1 years in HS. The frequency of wearing shoes was $2 \pm 1\ \mathrm{d \cdot wk^{-1}}$ in HB, while subjects wore shoes daily in HS. Subjects typically wore traditional school shoes (made out of leather) in HS and rubber slippers in HB. A longitudinal study by Potthast et al. (32) reported the greatest growth of the anatomical cross sectional areas of the muscles: flexor hallucis longus, abductor minimi, quadratus plantae, and abductor hallucis over a 5-month period of wearing minimal footwear. These authors concluded that training in minimal footwear induces mechanical stimuli leading to positive functional adaptations. Miller et al. (25) found that training in minimal shoes significantly increased the size of other foot muscles but not the abductor hallucis. On the other hand, Echarri and Forriol (6) found that footwear had very little influence on the morphology of the foot. These authors studied 1851 Congolese children including HB children aged 3 to 12 years and urban shod children and found age to be the main predictive factor for flat feet (6). It would appear from the present studies that stronger foot muscles can better maintain the medial longitudinal arch and this premise is also supported by Fiolkowski et al. (8). These authors tested the relationship between the medial longitudinal arch and foot intrinsic muscles by ablation of the posterior tibial nerve. A greater navicular drop and less EMG activity were found after administering the anaesthetic leading the authors to conclude that the intrinsic muscles supported the medial longitudinal arch. Furthermore, eliciting fatigue of the intrinsic foot muscles increases navicular drop and induces greater pronation during static stance (14). Like in the present series, these authors (8,14) did not measure extrinsic foot muscle activity, which is a limitation. The significantly greater level of physical activity in HB group (Table 3 and 4) and consequently stronger muscles could not account for all the observed foot characteristics. The greater abductor hallucis strength, greater navicular drop and navicular bone and foot dorsum height in seated and standing persistently remained significant when physical activity was controlled. These differences may be attributed to a barefoot lifestyle, where stronger foot muscles provide more effective pronation control on heel strike and supination in the propulsion phase and greater flexibility by lowering foot arches to generate a larger support surface as well as achieving better balance in static standing.

An additional hypothesis being tested in study 1 was that a rural HB lifestyle will activate the foot muscles, thus enhancing the medial longitudinal arch and inhibiting the development and/or prevalence of overuse injuries of the lower limb and lower back (14). In study 1, standardized questions regarding lower-limb injuries were asked and foot deformities were assessed by orthopedic surgeon, and the results revealed that during the previous year, HS subjects had experienced more pain syndrome of the lower-limb structures and higher prevalence of foot deformities compared to HB (Table 5). In addition, ankle range of motion was measured in study 1 to evaluate the impact of gastrocnemius muscle tightness as greater ankle dorsiflexion has been reported to associate as one of the intrinsic risk factors for developing an Achilles tendon injury (20). In study 1, ankle dorsiflexion was greater in HB compared with HS (see data on Foot characteristics in the Results section). The range for normal motion measured with knee extended is 11.5 degrees to 15.0 degrees according to Kaufman et al. (20) and the results of study 1 were within this range for both groups of subjects. While restricted ankle dorsiflexion is a recognized risk factor that can predispose individuals to lower-limb overuse injuries (20), a 2-degree difference in dorsiflexion reported between study groups in study 1 is unlikely to have a meaningful influence on injury development as the range of motion for both groups was within normal range (see data on Foot characteristics in the Results section). The calf circumferences were also the same between groups (Table 2).

Levels of physical activity were assessed by a Baecke questionnaire in study 1 and objectively measured with accelerometers in study 2. The higher work score in HB subjects reflects the rural lifestyles of the HB children/adolescents where activities such as cattle herding are more frequent (Table 3). The leisure score was higher in HB due to remarkably low levels of TV watching (Table 3). The differences in the

Table 5.
Lower-limb and lower-back injury prevalence in HB and HS.

Injuries/pain over the past year	HB	HS
Lower-limb/back injury prevalence	8%	61%
Injured first metatarsal phalangeal joint	1	—
Thigh muscle pain during running	—	1
Knee pain	1	2
Pain in the great toe region	—	1
Ankle sprain	—	6
Hip pain	—	2
Shin splits	—	2
Plantar fasciitis	—	1
Achilles tendinitis	—	1
General foot pain	—	5
Lower back pain	—	3
Foot deformities		
Hallux valgus		4
Bunions	1	1

sport score were smaller but remained significant between groups (Table 3). The average walking and/or running distance between home and school was approximately 1.5 km·d^{-1} for the majority of subjects in both groups, and this finding is in agreement with the findings of Onywera et al. (30). There were significant correlations between the total score derived from the Baecke questionnaire and MVPA ($r = 0.33$; $P < 0.05$) and average CPM ($r = 0.45$; $P < 0.01$) when analyzing the overlapping 39 subjects in both studies 1 and 2 (Table 4). According to the accelerometer data in study 2, HB and HS subjects spent 56% and 72% of their recorded time in sedentary activities, respectively. Time engaged in light and moderate activity was 39% of recorded time in HB and 27% in HS while vigorous activity comprised 5% in HB and 0.8% in HS (Table 4). These results are in contrast to the findings by Larsen et al. (22) who did not find any differences in physical activity levels, when assessed by questionnaire, between village and town boys at the age of 16 ± 0.7 years in Kenya. The results of both studies revealed a significantly higher level of sedentary activity in HS compared with HB children/adolescents living in the Nandi Escarpment due primarily to differences in lifestyle (Tables 3 and 4).

Physical activity differences also may influence bone structure. In study 2, the heel bone stiffness and Achilles tendon moment arm length were measured as physical activity is thought to act on the skeleton through gravitational forces and through muscle pull producing strain within the skeleton and inducing bone accrual, thus potentially leading to lower prevalence of bone fracture. In study 2, the heel bone stiffness index was greater in HB compared with HS (Table 2). Habitually barefoot lifestyle, in additional to physical activity, may influence bone stiffness when the attenuation effect of shoe sole is eliminated and the higher magnitudes of impact elicit more bone growth during stance.

In study 2, shorter Achilles moment arm length was found in HB (Table 2). Recent studies have found that increasing average relative toe length increases digital flexor impulses and mechanical work (37) and shorter tuber calcanei can improve running economy due to lower rates of metabolic energy consumption (34,38). A shorter Achilles tendon moment arm reflects a shorter heel and increases the amount of elastic energy stored in the Achilles tendon during running (23). The improvised center of rotation method used in study 2 to determine the Achilles moment arm length has several limitations. This method assumes the ankle to be one-axional joint and the plantar-flexion dorsalflexion movement in tibiotalar joint occurs in a sagittal plane (7). However, the misalignment of the axis to the sagittal scanning plane might be up to 10 degrees, and the horizontal line to determine the moment arm length is at a more plantar-flexed angle (7). On the basis of the present data, we were unable to explain or attribute the differences in the length of Achilles tendon moment arm to shoe usage. However, indirect evidence from a study conducted by Trinkaus (40) would support this idea because they argue that wearing soft-soled shoes in contrast to hard-soled shoes increases the robusticity of hallux bones relative to the smaller toes due to increased bending forces on the toe bones during toe-off (40). The meaningfulness of the 2-mm difference in moment arm length is considerable as Scholz et al. (38) showed that 10% differences in moment arm of the Achilles tendon alone could account for a 4.2-mL·kg^{-1}·min^{-1} difference in oxygen uptake.

Lower BMI was found in HB subjects in both studies 1 and 2 (Table 1). In study 1, greater arm span and longer lower limbs were found in HB compared to HS while calf circumference did not differ between groups (Table 2). Irrespective of the precise explanation, these favourable characteristics identified in the HB children/adolescents in studies 1 and 2 could positively predispose these children/adolescents to exceptional physical performance given their high levels of physical activity and energy expenditure, very low BMI, strong intrinsic foot muscles and bone structure, and a shorter Achilles tendon moment arm. It is not surprising therefore, that the maximum aerobic capacity of pupils from this school are amongst the highest ever reported in a recent study (11); the South Nandi region of Kenya is known to produce some of the world's greatest endurance runners.

The study of HB children/adolescent from the Kalenjin tribe of Kenya known for their high physical activity levels (11,22,28–30) has provided some unique insights into an ancestral way of life that will inevitably be lost over the next decades. Given this dwindling window of opportunity, the effects of this unique lifestyle both in terms of high physical activity that is typically being performed barefoot or with minimalist footwear have helped identify some of the long-term effects of this type of locomotion on the structure and function of the lower limb. Despite the novelty, this approach cannot replace well-designed prospective randomized controlled studies of high quality, high external validity, blinding and more resistant to selection bias. Despite all attempts to mitigate against such limitations, the present study was reliant on self-reported or teacher/parent identification of HB or HS status. In addition, for practical reasons related to the location, terrain, and general isolation of the study population, we were required to stagger the fairly state-of-the-art measurements and conduct two related studies rather than one study the consequence of which has been to complicate the interpretation of the data. In addition to these important limitations, recent opinion also has advocated examining the strike types (*i.e.*, rearfoot, midfoot, forefoot) and other sources of variation in locomotion and running form such as step frequency and stride length amongst HB and shod runners as this information would be highly relevant to injury occurrence (23). Future studies in such populations should also control for physical activity levels to determine the effects of physical activity versus being HB on foot parameters, injury prevalence and general foot health.

In conclusion, the significant differences observed in foot parameters, injury prevalence, and general foot health between HB and HS suggest that footwear conditions can significantly impact on foot structure and function and general foot health. However, the effect on physical activity remains unclear.

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