

1 **Title:** Foot structure and function in habitually barefoot and shod adolescents in Kenya

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27 **Corresponding Author:** Professor Yannis P Pitsiladis
28 **Short title:** Foot structure and function in barefoot youth

29

30 Abstract

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2 31 Habitually barefoot children from the Kalenjin tribe of Kenya are known for their high
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4 32 physical activity levels. To date there has been no comprehensive assessment of foot structure
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7 33 and function in these highly active and habitually barefoot children/adolescents and link with
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9 34 overuse injuries. **Purpose:** The present studies tested the hypothesis that children/adolescents
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11 35 with a barefoot lifestyle have better foot health and significantly higher foot shortening
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13 36 strength and navicular drop than shod counterparts. **Methods:** Foot structure and function was
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15 37 studied in 99 habitually barefoot (HB) adolescents and age-, sex- and body mass-matched
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17 38 habitually shod (HS) controls in Kenya. Foot arch characteristics, foot strength and lower
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19 39 limb injury prevalence were investigated in Study 1 (n=38 HB) and heel bone stiffness,
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21 40 Achilles tendon moment arm length and physical activity levels in Study 2 (n=31 HB). Foot
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23 41 muscle strength was measured using a strength device and heel bone stiffness by bone
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25 42 ultrasonometry. The moment arm length of the Achilles tendon was estimated from
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27 43 photographs and physical activity was assessed using questionnaires and accelerometry.
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29 44 **Results:** Foot shortening strength was greater in HB (4.8 ± 1.9 kg vs 3.5 ± 1.8 kg, $p<0.01$).
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31 45 Navicular drop was greater in HB (0.53 ± 0.32 cm vs 0.39 ± 0.19 cm, $p<0.05$). Calcaneus
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33 46 stiffness index was greater (right 113.5 ± 17.1 vs 100.5 ± 116.8 , $p<0.01$ left 109.8 ± 15.7 vs
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35 47 101.7 ± 18.7 , $p<0.05$) and Achilles tendon moment arm shorter in HB (right 3.4 ± 0.4 vs 3.6 ± 0.4
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37 48 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
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39 49 and 61% in HS. HB subjects were more physically active as reflected by a greater moderate to
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41 50 vigorous physical activity (60 ± 26 min/day vs 31 ± 13 min/day; $p<0.001$). **Conclusion:** The
42
43 51 significant differences observed in foot parameters, injury prevalence and general foot health
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45 52 between HB and HS suggest that footwear conditions can significantly impact on foot
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47 53 structure and function and general foot health. However, the effect on physical activity
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49 54 remains unclear.
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55 **Key words:** Barefoot children/adolescents, physical activity, foot health, injury prevalence,

56 South Nandi

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57 **Introduction**

58 Humans have engaged in barefoot locomotion or wore minimal footwear for most of human
59 evolutionary history (3). It is unsurprising therefore that barefoot locomotion has attracted
60 significant scientific interest in recent years (9, 10) and a flurry of minimalist running shoe
61 companies eager to capitalize. A highly cited paper describing the generally favorably foot
62 strike patterns and collision forces in habitually barefoot (HB) versus shod runners led to
63 increased numbers of barefoot runners and/or the use of minimalist footwear (24). This
64 interest in barefoot locomotion has somewhat faded in recent years given the unresolved
65 controversy about the possible benefits as well as associated risks of barefoot locomotion (12,
66 26, 31, 36). While the short-term effects of barefoot versus shod walking and running have
67 clearly revealed a higher risk of certain running associated injuries (12, 36), there are only a
68 few and mostly poorly controlled studies investigating the long-term effects of HB
69 locomotion (see 17 for review). The only systematic review of long-term effects of HB
70 locomotion concluded that from the current available and mostly speculative data in the
71 literature there was little evidence for clinically relevant outcomes such as injury rates or foot
72 pathologies (17). This systematic review also advocated that study designs that assessed HB
73 populations and compared HB and habitual shod subjects within a population could not
74 replace well-designed prospective randomized controlled studies, albeit did allow the
75 identification of some long-term effects of barefoot locomotion. An alternative approach that
76 may shed light on the long-term effects of HB lifestyles on structure and function of the lower
77 limb is to study populations where HB and/or the use of minimalist footwear remain the
78 norm. For example, invaluable information was obtained in a study comparing the strike type
79 variation among Tarahumara Indians in minimal sandals versus conventional running shoes
80 (23). This study reinforced the idea of significant variation in foot strike patterns among
81 minimally shod runners but also the importance of foot stiffness in determining running form

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82 (17). These insights would be very difficult to be gleaned even in well-designed prospective
83 randomized controlled studies.

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85 Habitually barefoot children from the Kalenjin tribe of Kenya are known for their high
86 physical activity levels (11, 22, 28, 29, 30). Some studies report that habitually barefoot
87 children from this region run up to 20 km a day to get to and from school (24, 30) and
88 furthermore, engage in considerable physically active leisure time activities and household
89 chores. This high habitual physical activity in these children/adolescents is typically
90 conducted barefoot and this factor has been proposed as one of the explanations for the
91 phenomenal success of Kenyan and Ethiopian runners (30,39). To date, no investigation has
92 performed a comprehensive assessment of foot structure and function in highly active and
93 habitually barefoot children/adolescents in rural Kenya and assessed the link with overuse
94 injuries. Therefore, the purpose of the present research was to assess foot structure and
95 function of Kenyan children and adolescents who are habitually barefoot and highly
96 physically active with those who are shod.

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98 **Methods**

99 **Experimental design.** The experimental design is illustrated in Figure 1. Briefly, subjects
100 were divided into two groups: habitually barefoot (HB) (Study 1 n=40 (20 girls, 20 boys);
101 Study 2 n=31 (18 girls, 13 boys) school-aged children/adolescents) and habitually shod (HS)
102 groups (Study 1 n=38 (19 girls, 19 boys); Study 2 n=31 (18 girls, 13 boys) school-aged
103 children/adolescents). Two subjects initially recruited in the HB group were excluded from
104 Study 1 due to their low body mass (26.5 kg and 27 kg) as no matched controls could be
105 found therefore reducing the HB and HS groups to 38 subjects in Study 1. The study groups
106 were age-, sex- and body mass-matched and participated in Study 1 and Study 2, respectively.

107 The overlap of subjects in Study 1 and Study 2 were 24 subjects in HB (63%) and 15 subjects
108 in HS (40%). Both children and parent(s) gave verbal informed consent to participate in both
109 studies, which were approved by the Institutional Research Ethics Committee, Moi
110 University, Eldoret, Kenya. This was achieved and witnessed by the principal investigators
111 with the help of the children's teachers to provide information and answer questions. Written
112 informed consent was not collected from parents due to illiteracy. Agreement by verbal
113 consent was documented next to each child's name. This process was in line with the
114 approval received from the local ethics committee. The subject characteristics are given in
115 Table 1.

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117 In Study 1, height, body mass, arm span, calf circumference, leg length, foot strength, active
118 ankle range of motion and foot structure characteristics were measured and a modified Baecke
119 questionnaire (1) was used to assess levels of physical activity. In Study 2, heel bone stiffness
120 and Achilles tendon moment arm were measured and uni-axial accelerometer was used to
121 objectively measure physical activity levels and patterns. All experiments were conducted in
122 school classrooms. Arm span was measured by positioning the subject's heels together with
123 the back against a flat black board and the arms stretched sideways with the palms facing the
124 investigator. The tips of the middle fingers were marked and the distance between marks was
125 measured. Right calf circumference was measured at the level of the largest circumference of
126 the calf with the subject standing erect and with body mass evenly distributed on both feet and
127 legs shoulder width apart. Right leg length was measured standing from the sharpest lateral
128 projection of greater trochanter to the ground. All linear measurements were taken to the
129 nearest 1 cm with a tape measure. Body mass was measured to the nearest 0.1 kg on a
130 portable scale (Salter 144SVBKDR, Salter Houseware Ltd. UK) while subjects were barefoot
131 and wearing the school uniform (shorts or skirt and blouse with vest). Modifications in

132 Baecke questionnaire included the addition of questions about shoe wearing habits, daily
133 activities specific to the Nandi region such as cattle herding, transport method/distance to
134 school and daily running distance. The presence of lower limb injuries and foot deformities
135 were not self-reported but a thorough clinical assessment was carried out by an experienced
136 orthopaedic surgeon (PO).

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138 Given the use of a questionnaire to measure physical activity in Study 1, a second study
139 (Study 2) was conducted to measure physical activity levels and patterns objectively using the
140 ActiTrainer uni-axial accelerometer (ActiGraph LLC, Pensacola, FL, USA) for 6 consecutive
141 days during school term time. The accelerometer was worn with a Velcro belt around the
142 waist according to the recommendations of the manufacturer. Each child was instructed to
143 wear the device at all times except when sleeping and bathing. The recording epoch was set at
144 60 s. Ojiambo et al (28) have shown that group differences in moderate to vigorous physical
145 activity (MVPA) can be demonstrated with 60 s epoch although some differences – MVPA in
146 very short bouts – would be lost. The monitoring of physical activity levels was considered
147 valid for inclusion in the analysis if a minimum of 12 h of recordings took place per day for at
148 least 3 days (including at least one weekend day). Ojiambo et al (27) have demonstrated that
149 minimum acceptable reliability can be obtained in 3 days. It should be noted, however, that
150 most of our subjects had considerably more than 3 valid days of measurement: 5 had 3 days, 1
151 had 5 days, and 53 had 6 or more days. Accelerometer data were analyzed using algorithms
152 developed in R (27). Sedentary time and physical activity levels were assessed using cut-
153 points for sedentary and MVPA developed by Puyau et al (33). These cut-points have been
154 validated in children and adolescent age 6 to 16 years as follows: sedentary time < 800 counts
155 per minute (CPM) and MVPA > 3200 CPM (27).

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157 **Foot strength.** For all subjects in Study 1, the right foot toe muscle strength (i.e., hallux,
158 digits 2nd-4th, digits 1st-4th) and foot shortening strength were measured using a commercially
159 available foot strength device (TKK 3360, Takei Scientific Instruments Co. Ltd., Japan)
160 (Figure 2) while subjects were seated on a chair with the hip and knee joints at 90 degrees.
161 The subject's foot was placed on the foot strength device in a manner that allowed the distal
162 part of the toes to be supported on a metal rod that was attached to a strain gauge. Each
163 subject was given as many familiarisation trials required to perform the test correctly. Verbal
164 instructions were given to maintain the foot on the device so that the most posterior part of the
165 heel was in contact with the heel cup of the device. Subjects were instructed not to lift their
166 heel while flexing their toes. An investigator manually assisted by keeping the heel on the
167 surface while maintaining contact with the heel cup and raising the toes or hallux while the
168 subject plantar flexed the great toe or digits 2nd-4th, respectively. In order to measure isometric
169 strength, the subject was required to passively invert and revert their foot so that a neutral
170 position with respect to the subtalar joint would be attained. The subject was asked to perform
171 an active toe dorsiflexion and maintain the upright position of the toes, while the instructor
172 placed the foot with the 1st metatarsal head on the metal rod and fixed the heel against the heel
173 cap. The subject was asked to bring the base of the 1st metatarsal head towards the heel in a
174 posterior direction while keeping it on the surface and flexing the arch without flexing the
175 toes; the investigator also demonstrated this movement. Subjects were asked to perform
176 several familiarisation trials prior to the three performance trials and the best result was
177 recorded; a single investigator took all measurements.

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179 **Ankle range of motion.** Active ankle dorsi- and plantar-flexion was assessed in Study 1
180 using a goniometer (Orthopaedic Equipment Co, Bourbon, Indiana, USA). Subjects were
181 required to position themselves in a supine position with feet and ankles extended over the

182 edge of a table. The goniometer fulcrum was placed over the lateral aspect of the lateral
183 malleolus with the ankle in 90 degrees. Plantar-flexion and dorsi-flexion were performed to
184 maximum reach. Three trials were performed in each direction and the mean taken as the final
185 result. The mean was calculated to minimize the intra- and inter-observer error. Total range of
186 ankle motion was calculated as the sum of both movements.

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188 **Medial arch structure.** Medial arch structure in Study 1 was defined as navicular bone
189 height and foot dorsum height (at 50% of total foot length) in two conditions: seated and
190 standing. Subjects were seated on a chair placed on a low table to confirm an even surface
191 under the foot and allowing the foot arch to drop naturally. Knee and hip joints were held at
192 90 degrees flexion with foot firmly planted on the horizontal surface. Total right foot length,
193 length from heel (the most posterior portion of the calcaneus) to the center of the 1st
194 metatarsal phalangeal joint (truncated foot length) and from heel to tuberosity of 5th
195 metatarsal were measured in cm using a rigid ruler or segmometer (Rosscraft, Canada).
196 Navicular height was first measured seated from the underlying surface of the foot to the most
197 proximate part of the bone using a rigid ruler or segmometer. This procedure was repeated
198 with the subject in a standing position with body mass equally distributed on both feet.
199 Navicular drop was calculated by subtracting standing height from seated height. Similarly,
200 the foot dorsum height was measured in the seated position following by a standing position
201 using a segmometer. Navicular height and foot dorsum height were divided by total foot
202 length and truncated foot length (measured only seated) for normalizing medial longitudinal
203 arch height to foot length (44). A single investigator took all of these measurements.

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205 **Heel bone stiffness index.** Heel bone stiffness in Study 2 was measured using bone
206 ultrasonometry (Lunar Achilles InSight™, Madison, USA). This technique uses ultrasound

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207 waves to quantify the density of the calcaneal tuberosity, and thus measures both bone
208 mineral density and bone volume fraction (16). In comparison to more conventional dual-
209 energy x-ray absorptiometry (DXA), the quantitative ultrasound is a radiation-free method to
210 evaluate bone stiffness in a calcaneus, consist of 90% trabecular bone and bone
211 microarchitecture is similar to that of the lumbar spine and femoral neck. DXA method is size
212 dependent, two-dimensional and does not distinguish between trabecular and cortical bone
213 (15). Quantitative ultrasound measures bone stiffness in stiffness index as the units.
214 Measurements of bone stiffness were performed with the subject seated. The leg was
215 positioned with the foot, calf and thigh aligned with the center of the calf support and foot
216 positioner. The calf was gently resting on the calf support. Propanol alcohol was applied to
217 both sides of the heel to condition the skin and ensure proper ultrasound coupling between
218 membranes and the heel. The subject was asked not to move during the measurement. The
219 speed of the sound waves (m/sec) and their frequency-dependent attenuation (dB/mHz) are
220 combined to calculate a stiffness index. The process was repeated until three results from
221 three trials were within 2% and then averaged.

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223 **Achilles tendon moment arm.** The Achilles tendon moment arm was measured as illustrated
224 in Figure 3. Briefly, the subject was seated with the knee and ankle at 90 degrees. The
225 measured foot was placed on a reference block with firstly the lateral followed by medial side
226 of the foot aligned with the tape measure on the reference block. The vertical position of the
227 tibia was corrected with a spirit level. The lateral and medial malleoli were marked on the
228 most prominent aspect with white corrector paint. Left and right foot were photographed
229 (Olympus Digital Camera, c-750 ultrazoom, Camedia, Pennsylvania, USA) from the lateral
230 and medial side. The Achilles tendon moment arm was determined on the image as the mean
231 of the lateral and medial horizontal distance from the most prominent tip of the tibia and

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232 fibular malleoli to the posterior aspect of the Achilles tendon (34,38). The distances
233 determined on the photos using Didge Image Digitizing Software for Windows (courtesy of
234 A. J. Cullum, Omaha, NE, USA). The normalization to truncated foot length was performed
235 by dividing moment arm by truncated foot length, multiplying by 100 and determined as a
236 percentage of truncated foot length (13). Achilles tendon moment arm was further scaled to
237 body height. According to Scholz et al (38), the inter- and intra-observer reliability of this
238 method is high ($r^2>0.95$, $P<0.001$) when comparisons of two measurements were made by the
239 same person several months apart; the improvised for field study digital photographic
240 measurement method used was also reported to be a valid and reliable clinical and research
241 tool for quantifying foot structure (4).

242
243 **Statistical analysis.** Comparison between HB and HS subjects in foot structure characteristics
244 were conducted using a two-tailed Student t-test with statistical significance set to $p<0.05$.
245 Analysis of covariance (ANCOVA) was used to detect whether any of the group differences
246 in anthropometric parameters can be explained by differences in physical activity. A linear
247 model containing only a dichotomous group variable as a predictor is equivalent to a simple t-
248 test. To this model, we added physical activity score as a continuous predictor, resulting in an
249 ANCOVA model. The ANCOVA comparison was performed using statistical software
250 package R.

251 252 **Results**

253 **Subject ages and anthropometric measures.** Both groups were sex-, age- and body mass-
254 matched but HB children/adolescents were taller and had approximately 5% lower body mass
255 index (BMI) (Table 1). In terms of other anthropometric measurements only arm span and leg

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2 256 length were significantly different (Table 2); approximately 3% longer in HB compared to
3 257 HS.

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7 259 **Foot characteristics.** Foot dorsum height characteristics are shown in Table 3. As such
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9 260 navicular bone and foot dorsum height were higher (both seated and standing) in HB
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11 261 compared to HS both in terms of absolute and relative height. These differences remained
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13 262 significant between groups when results were controlled for physical activity (total score of
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15 263 Baecke questionnaire) both for dorsum height seated and standing ($p < 0.001$) and navicular
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17 264 height seated and standing ($p < 0.001$). Navicular drop was greater in HB compared to HS. The
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19 265 initial region effect as assessed using an ANOVA was significant $F(1, 74) = 5.8$, $p = 0.02$, but
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21 266 after controlling for physical activity the strength of the relationship was no longer significant
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23 267 $F(1, 73) = 2.1$, $p = 0.16$. Ankle dorsiflexion was 2° greater in HB when compared to the HS
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25 268 (13.7 ± 3.6 degrees versus 11.7 ± 3.7 degrees, $p = 0.01$); ankle plantar flexion tended to be
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27 269 greater in HB compared to HS but not significantly ($p = 0.09$). Overall, total ankle ROM was
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29 270 more than 6° greater in HB than HS (58.3 ± 10.2 degrees versus 51.9 ± 13.5 degrees, $p = 0.01$).
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38 272 **Heel bone stiffness index and Achilles tendon moment arm.** Calcaneus stiffness index was
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40 273 greater in HB than HS subjects (right 113.5 ± 17.1 versus 100.5 ± 16.8 , $p = 0.01$; left $109.8 \pm$
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42 274 15.7 versus 101.7 ± 18.7 , $p = 0.05$). Achilles tendon moment arm was significantly shorter in
43
44 275 HB than HS both in absolute and relative terms (right, $p = 0.01$; left, $p = 0.05$). Heel bone
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46 276 stiffness index and Achilles tendon moment arm results are presented in Table 2.
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48 277 Normalization of Achilles tendon moment arm to truncated foot length was performed by
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50 278 dividing moment arm by truncated foot length, multiplying by 100 and presented as a
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52 279 percentage of truncated foot length (right $19.7 \pm 2.2\%$ in HB versus $21.5 \pm 2.5\%$ in HS,
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54 280 $p = 0.01$; left $19.3 \pm 2.1\%$ in HB versus $21.1 \pm 2.0\%$ in HS, $p < 0.001$). Similar results were
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281 observed when the moment arm was divided by body height (left foot adjusted $R^2=0.14$,
282 $p=0.002$; right foot adjusted $R^2=0.15$, $p<0.001$). Heel bone stiffness index and Achilles tendon
283 moment arm length were controlled for amount of MVPA and differences persisted between
284 groups.

285
286 **Foot muscle strength.** There were no significant differences between HB and HS in hallux
287 flexor strength and strength when 2nd-4th flexor digits were compared but when 1st-4th flexor
288 digits were compared, HB were stronger than HS (9.1 ± 2.5 kg vs 7.9 ± 2.6 kg; $p<0.05$). The
289 HB were also stronger in short foot exercise compared with HS (4.8 ± 1.9 kg vs 3.5 ± 1.8 kg;
290 $p<0.01$) (Table 3). Differences persisted between groups when the strength of short foot
291 exercise was controlled for physical activity (total score of Baecke questionnaire). The initial
292 regional effect as assessed by ANOVA was $F(1, 74) = 8.82$, $p=0.01$, after controlling for
293 physical activity the relationship $F(1, 73) = 3.74$, $p=0.06$ is no longer significant.

294
295 **Lower limb and low back injuries.** Lower limb injury prevalence in the year was 8% in HB
296 and 61% in HS = 17.9; $p=0.01$ (Table 5). The breakdown of the specific conditions are listed
297 for the HB and HS in Table 5.

298
299 **Physical activity levels.** Physical activity as assessed in Study 1 using the modified Baecke
300 questionnaire demonstrated that 89% in HB and 26% in HS were involved in cattle herding
301 “sometimes” or “often” (Table 3). The average walking distance was 1-5 km per day for 25
302 HB subjects (66%) and 37 HS subjects (97%). The average running distance was 1-5 km for
303 24 HB subjects (63%) and 23 HS subjects (61%). 30 HB subjects (79%) and 1 HS subject had
304 never watched TV or played computer games.

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306 Physical activity data for Study 2 were successfully obtained from 30 HB subjects (13 boys;
307 17 girls) and 28 HS subjects (12 boys; 16 girls) (Table 4). The HB subjects accumulated an
308 average of 730 ± 244 counts per minute (CPM) as compared with 304 ± 65 CPM in HS
309 ($p < 0.001$) over an average recording period of 12 hours per day (7.7 ± 1.9 days in HB and 6.3
310 ± 0.8 days in HS). The daily mean time spent in sedentary activity was 266 ± 64 minutes in
311 HB and 610 ± 164 in HS or 56% and 72% of total recording time, respectively. Total time
312 spent in light physical activities was 154 ± 52 min in HB and 207 ± 69 in HS min (32% and
313 24% of total recording time, respectively), in moderate activity was 35 ± 16 min in HB (7%)
314 and 23 ± 9 min in HS (3%) and vigorous activity was 24 ± 14 min in HB (5%) and 7 ± 5 min
315 in HS (0.8%). MVPA was greater in HB (60 ± 26 min/day versus 31 ± 26 min/day, $p \leq 0.001$).
316 No relationship was found between sex and levels of physical activity, but all physical
317 activity levels were dependent on regional distribution (sedentary: $R^2 = 0.95$, $p < 0.001$; light:
318 $R^2 = 0.63$, $p = 0.02$; moderate: $R^2 = 0.65$, $p < 0.001$; vigorous: $R^2 = 0.65$, $p < 0.001$; MVPA: $R^2 = 0.57$,
319 $p < 0.001$).

321 Discussion

322 The main results of Study 1 revealed differences between HB and HS groups in many
323 measures of foot structure. Numerous methods have been used to assess medial longitudinal
324 arch height and deformation in static (8, 19, 23, 25, 41, 43, 44, 46) and dynamic conditions
325 (2). HB subjects had higher medial longitudinal arches and more flexible feet than HS
326 subjects (Table 3). Arch height can be classified according to arch ratio as high (arch ratio of
327 at least 0.356) and low (arch ratio at most 0.275) (46); arch ratio being defined as the height to
328 the dorsum of the foot at 50% of the foot length divided by truncated foot length. Using these
329 criteria, HB subjects in Study 1 would be classified as having high arches with arch ratios of
330 0.40 ± 0.04 (seated) and 0.39 ± 0.04 (standing) as opposed to normal to high arches in HS

331 with arch ratios of 0.36 ± 0.03 (seated) and 0.35 ± 0.03 (standing) (Table 3). However, from
332 an evolutionary perspective, it makes sense to consider habitually unshod feet to be normal,
333 suggesting that normative arch ratios may be biased by modern shoes. Zifchock et al (46)
334 found a significantly higher arch height index (which was significantly but weakly related to
335 arch stiffness) in the dominant versus the non-dominant foot, possibly due to greater
336 neuromuscular activity in the dominant foot. Similarly, greater neuromuscular activity when
337 HB may result in better conditioned muscles, tendons and ligaments of the lower limb and
338 therefore stronger feet (Table 3). Subjects in both studies were body mass-matched in order to
339 prevent a variable load influencing the measures of foot structure and function (Table 1). For
340 example, Villarroya et al (42) studied 245 children/adolescents aged 9-16.5 years and reported
341 lower arches in obese and overweight compared to normal weight subjects. In Study 1, HB
342 had longer arm span and leg length than HS but this can be explained by taller mean body
343 height in HB (Table 2). The subjects in the HS group were chosen with matching sex, age and
344 body mass and not with matching body height, which explain the difference in BMI between
345 groups (Table 1).

346
347 The main hypothesis tested in both studies was that high levels of physical activity combined
348 with a HB lifestyle would lead to stronger intrinsic foot muscles and other supporting
349 structures of the foot such as ligaments and tendons. Intrinsic foot muscles may influence the
350 change in the medial longitudinal arch depending on the extent of movement and load
351 exerted. As such, significantly greater toe flexor strength in digits 1st-4th and in foot
352 shortening exercise, where, according to Jung et al (19), the abductor hallucis is most active,
353 were found in HB subjects (Table 3). Wong (45) also found that the abductor hallucis
354 dynamically elevated the medial longitudinal arch. Additionally, abductor hallucis muscle has
355 the greatest cross-sectional area of intrinsic muscles, which is an indicator of greater force

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356 production capability (21). It is possible that the greater toe flexor strength in HB (Table 3)
357 would help counter the increased mobility in these subjects when pronation control is required
358 and therefore placing less strain on the soft tissue structures such as ligaments and tendons
359 and lead to less prevalence in lower limb overuse injuries. Anatomical data (45) supports the
360 hypothesis that the abductor hallucis may act to decelerate arch flattening after heel strike and
361 to raise the arch before toe-off and work synergistically with the posterior tibial muscle.
362 Habitually barefoot lifestyles may allow the abductor hallucis to reduce loads otherwise borne
363 by the tibialis posterior and potentially avoid the development of tibialis posterior
364 dysfunction. In contrast to the Study 1, D'Août et al. (5) found that habitually shod
365 individuals had more variable longitudinal arch heights based on assessments of navicular
366 height and navicular drop during stance. However, these subjects were all adults (in range
367 20.3-73.7) unlike those investigated in the present studies (Table 1). Rao and Joseph (35) on
368 the other hand found higher prevalence of flat feet in shod children (between the ages of 4-13
369 yrs) compared to barefoot children in India. These authors stated that the type of footwear
370 their subjects were wearing influenced the development of the longitudinal arch of the foot.
371 These authors suggested that subjects who wore slippers or sandals were repeatedly activating
372 intrinsic muscles of the foot in order to keep the slippers on the feet. Some of the HB
373 children/adolescents in both studies would at times wear rubber slippers and findings in
374 general support the hypothesis that not wearing shoes or wearing minimal footwear may
375 strengthen intrinsic foot muscles. In Study 1, two of 38 HB subjects had never worn shoes and
376 the mean age of starting wearing shoes was 8 ± 4 yrs in HB and 1.8 ± 1 yrs in HS. The
377 frequency of wearing shoes was 2 ± 1 days per week in HB, while subjects wore shoes daily
378 in HS. Subjects typically wore traditional school shoes (made out of leather) in HS and rubber
379 slippers in HB. A longitudinal study by Potthast et al. (32) reported the greatest growth of the
380 anatomical cross sectional areas of the muscles: flexor hallucis longus, abductor minimi,

381 quadratus plantae and abductor hallucis over a 5 month period of wearing minimal footwear.
382 These authors concluded that training in minimal footwear induces mechanical stimuli
383 leading to positive functional adaptations. Miller et al. (25) found that training in minimal
384 shoes significantly increased the size of other foot muscles but not the abductor hallucis. On
385 the other hand, Echarri and Forriol (6) found that footwear had very little influence on the
386 morphology of the foot. These authors studied 1851 Congolese children including habitually
387 barefoot children aged 3 to 12 years and urban shod children and found age to be the main
388 predictive factor for flat feet (6). It would appear from the present studies that stronger foot
389 muscles can better maintain the medial longitudinal arch and this premise is also supported by
390 Fiolkowski et al (8). These authors tested the relationship between the medial longitudinal
391 arch and foot intrinsic muscles by ablation of the posterior tibial nerve. A greater navicular
392 drop and less EMG activity were found after administering the anaesthetic leading the authors
393 to conclude that the intrinsic muscles supported the medial longitudinal arch. Furthermore,
394 eliciting fatigue of the intrinsic foot muscles increases navicular drop and induces greater
395 pronation during static stance (14). Like in the present series, these authors (8,14) did not
396 measure extrinsic foot muscle activity, which is a limitation. The significantly greater level of
397 physical activity in HB group (Table 3 and 4) and consequently stronger muscles could not
398 account for all the observed foot characteristics. The greater abductor hallucis strength,
399 greater navicular drop and navicular bone and foot dorsum height in seated and standing
400 persistently remained significant when physical activity was controlled. These differences
401 may be attributed to a barefoot lifestyle, where stronger foot muscles provide more effective
402 pronation control on heel strike and supination in the propulsion phase and greater flexibility
403 by lowering foot arches to generate a larger support surface as well as achieving better
404 balance in static standing.

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

424
425 Levels of physical activity was assessed by a Baecke questionnaire in Study 1 and objectively
426 measured with accelerometers in Study 2. The higher work score in HB subjects reflects the
427 rural lifestyles of the HB children/adolescents where activities such as cattle herding are more
428 frequent (Table 3). The leisure score was higher in HB due to remarkably low levels of TV-
429 watching (Table 3). The differences in the sport score were smaller but remained significant
430 between groups (Table 3). The average walking and/or running distance between home and

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431 school was approximately 1.5 km per day for the majority of subjects in both groups and this
432 finding is in agreement with the findings of Onywera et al. (30). There were significant
433 correlations between the total score derived from the Baecke questionnaire and MVPA
434 ($r=0.33$; $p<0.05$) and average CPM ($r=0.45$; $p<0.01$) when analysing the overlapping 39
435 subjects in both studies 1 and 2 (Table 4). According to the accelerometer data in Study 2, HB
436 and HS subjects spent 56% and 72% of their recorded time in sedentary activities,
437 respectively. Time engaged in light and moderate activity was 39% of recorded time in HB
438 and 27% in HS while vigorous activity comprised 5% in HB and 0.8% in HS (Table 4). These
439 results are in contrast to the findings by Larsen et al. (22) who did not find any differences in
440 physical activity levels, when assessed by questionnaire, between village and town boys at the
441 age of 16 ± 0.7 years in Kenya. The results of both studies revealed a significantly higher
442 level of sedentary activity in HS compared to HB children/adolescents living in the Nandi
443 Escarpment due primarily to differences in lifestyle (Table 3 and 4).

444
445 Physical activity differences may also influence bone structure. In Study 2, the heel bone
446 stiffness and Achilles tendon moment arm length were measured as physical activity is
447 thought to act on the skeleton through gravitational forces and through muscle pull producing
448 strain within the skeleton and inducing bone accrual, thus potentially leading to lower
449 prevalence of bone fracture. In Study 2, the heel bone stiffness index was greater in HB
450 compared with HS (Table 2). Habitually barefoot lifestyle, in addition to physical activity,
451 may influence bone stiffness when the attenuation effect of shoe sole is eliminated and the
452 higher magnitudes of impact elicit more bone growth during stance.

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454 In Study 2, shorter Achilles moment arm length was found in HB (Table 2). Recent studies
455 have found that increasing average relative toe length increases digital flexor impulses and

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456 mechanical work (37) and shorter tuber calcanei can improve running economy due to lower
457 rates of metabolic energy consumption (34, 38). A shorter Achilles tendon moment arm
458 reflects a shorter heel and increases the amount of elastic energy stored in the Achilles tendon
459 during running (23). The improvised center of rotation method used in Study 2 to determine
460 the Achilles moment arm length has several limitations. This method assumes the ankle to be
461 one-axional joint and the plantar-flexion dorsal-flexion movement in tibio-talar joint occurs in
462 a sagittal plane (7). However, the misalignment of the axis to the sagittal scanning plane
463 might be up to 10° and the horizontal line to determine the moment arm length is at a more
464 plantar-flexed angle (7). On the basis of the present data, we were unable to explain or
465 attribute the differences in the length of Achilles tendon moment arm to shoe usage. However,
466 indirect evidence from a study conducted by Trinkaus (40) would support this idea as they
467 argue that wearing soft-soled shoes in contrast to hard-soled shoes increases the robusticity of
468 hallux bones relative to the smaller toes due to increased bending forces on the toe bones
469 during toe-off (40). The meaningfulness of the 2 mm difference in moment arm length is
470 considerable as Scholz et al (38) showed that 10% differences in moment arm of the Achilles
471 tendon alone could account for a 4.2 ml·kg⁻¹·min⁻¹ difference in oxygen uptake.

472
473 Lower BMI was found in HB subjects in both Studies 1 and 2 (Table 1). In Study 1, greater
474 arm span and longer lower limbs were found in HB compared to HS while calf circumference
475 did not differ between groups (Table 2). Irrespective of the precise explanation, these
476 favourable characteristics identified in the HB children/adolescents in studies 1 and 2 could
477 positively predispose these children/adolescents to exceptional physical performance given
478 their high levels of physical activity and energy expenditure, very low BMI, strong intrinsic
479 foot muscles and bone structure, and a shorter Achilles tendon moment arm. It is not
480 surprising therefore, that the maximum aerobic capacity of pupils from this school are

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2 481 amongst the highest ever reported in a recent study (11); the South Nandi region of Kenya is
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5 482 known to produce some of the world's greatest endurance runners.
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8 484 The study of HB children/adolescent from the Kalenjin tribe of Kenya known for their high
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10 485 physical activity levels (11, 22, 28, 29, 30) has provided some unique insights into an
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12 486 ancestral way of life that will inevitably be lost over the next decades. Given this dwindling
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14 487 window of opportunity, the effects of this unique lifestyle both in terms of high physical
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16 488 activity that is typically being performed barefoot or with minimalist footwear has helped
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18 489 identify some of the long-term effects of this type of locomotion on the structure and function
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20 490 of the lower limb. Despite the novelty, this approach cannot replace well-designed
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22 491 prospective randomized controlled studies of high quality, high external validity, blinding and
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24 492 more resistant to selection bias. Despite all attempts to mitigate against such limitations, the
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26 493 present study was reliant on self-reported or teacher/parent identification of HB or HS status.
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28 494 In addition, for practical reasons related to the location, terrain and general isolation of the
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30 495 study population, we were required to stagger the fairly state-of-the-art measurements and
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32 496 conduct two related studies rather than one study the consequence of which has been to
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34 497 complicate the interpretation of the data. In addition to these important limitations, recent
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36 498 opinion has also advocated examining the strike types (i.e., rearfoot, midfoot, forefoot) and
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38 499 other sources of variation in locomotion and running form such as step frequency and stride
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40 500 length amongst HB and shod runners as this information would be highly relevant to injury
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42 501 occurrence (23). Future studies in such populations should also control for physical activity
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44 502 levels in order to determine the effects of physical activity versus being HB on foot
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46 503 parameters, injury prevalence and general foot health.
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505 In conclusion, the significant differences observed in foot parameters, injury prevalence and
506 general foot health between HB and HS suggest that footwear conditions can significantly
507 impact on foot structure and function and general foot health. However, the effect on physical
508 activity remains unclear.

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7 628 **Figure Captions:**

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9 629 **Figure 1: The experimental design flowchart**

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11 630 **Figure 2: Measurement of hallux flexor strength using the foot strength device.**

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14 632 **Figure 3: Determination of the Achilles tendon moment arm - medial view of the right**
15 **foot. The medial malleoli are marked on the most prominent aspect with white corrector**
16 **paint. The Achilles tendon moment arm was determined on the image as the mean of the**
17 **lateral and medial horizontal distance from the most prominent tip of the tibia and**
18 **fibular malleoli to the posterior aspect of the Achilles tendon.**
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Figure 1

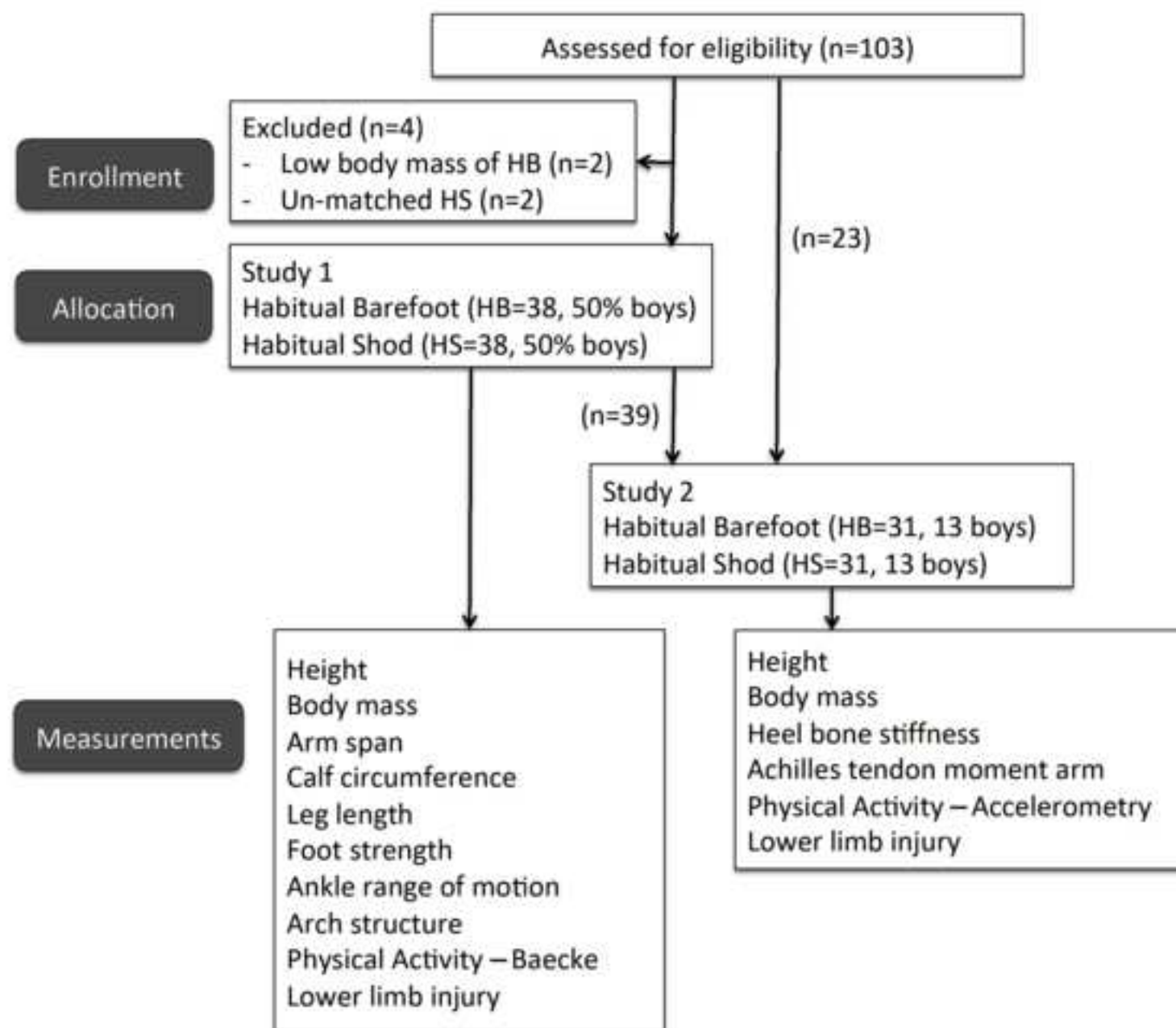


Figure 2



Figure 3



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) (years)	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)

Note: HB – habitually barefoot group; HS – habitually shod group; BMI – body mass index, b – boys; g – girls; *

p<0.05 ** p<0.01

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 \pm SD and ranges are presented.

Study1	Study 2						
	Arm span (cm)	Calf circum. (cm)	Leg length (cm)	Heel bone stiffness index		Moment arm (cm)	
	range	range	range	Left range	Right range	Left range	Right range
HB	169.2 \pm 9.8*	31.8 \pm 2.3	91.3 \pm 7.1*	109.8 \pm 15.7*	113.5 \pm 17.1**	3.4 \pm 0.5**	3.4 \pm 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 \pm 10.7	31 \pm 2.9	88.2 \pm 7	101.7 \pm 18.7	100.5 \pm 16.8	3.7 \pm 0.4	3.6 \pm 0.4
	144 – 187	23 - 36	75 - 104	73.3 - 159	75 – 147.5	2.6 – 4.4	2.9 – 4.2

Note: HB – habitually barefoot group; HS – habitually shod group; Moment arm – Achilles tendon moment arm length;

BMI – body mass index, b – boys; g – girls; * 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 habitually barefoot group and habitually shod group in Study 1. MEAN \pm SD and range are presented.

	HB (n=38)	HS (n=38)
Navicular process height		
Seated (cm)	5.0 \pm 0.6 ** [4.0– 6.5]	4.1 \pm 0.7 [2.6 – 5.1]
Standing (cm)	4.4 \pm 0.6 ** [3.4 – 6.0]	3.7 \pm 0.7 [1.9 – 5.3]
Seated/foot length (cm)	0.21 \pm 0.03 ** [0.16 – 0.26]	0.17 \pm 0.03 [0.11 – 0.24]
Standing/foot length (cm)	0.19 \pm 0.03 ** [0.14 – 0.25]	0.16 \pm 0.04 [0.08 – 0.23]
Seated/HBLm (cm)	0.30 \pm 0.04 ** [0.23 – 0.39]	0.20 \pm 0.10 [0.14 – 0.33]
Standing/HBLm (cm)	0.27 \pm 0.04 ** [0.20 – 0.34]	0.22 \pm 0.10 [0.11 – 0.31]
Navicular bone drop (cm)	0.53 \pm 0.32 * [0.1 – 1.6]	0.39 \pm 0.19 [0.1 – 1.0]
Foot dorsum height		
Seated (cm)	6.7 \pm 0.7 ** [5.6 – 8.1]	6.2 \pm 0.5 [4.3 – 7.2]
Standing (cm)	6.5 \pm 0.6 ** [5.3 – 7.6]	6.1 \pm 0.5 [5 – 7]
Seated/foot length (cm)	0.28 \pm 0.03 ** [0.24 – 0.35]	0.26 \pm 0.03 [0.18 – 0.33]
Standing/foot length (cm)	0.27 \pm 0.03 ** [0.23 – 0.34]	0.26 \pm 0.02 [0.21 – 0.32]
Seated/HBLm (cm)	0.40 \pm 0.04 ** [0.34 – 0.49]	0.36 \pm 0.03 [0.24 – 0.45]
Standing/HBLm (cm)	0.39 \pm 0.04 ** [0.32 – 0.47]	0.35 \pm 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 2 nd - 4 th flexion (kg)	3.3 ± 1.5 [0.7 – 8.1]	2.8 ± 1.4 [0.8 – 6.8]
Digits 1 st – 4 th 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]

Note: HB – habitually barefoot group; HS – habitually shod group; HBLm = medial truncated foot length from heel to the base of the first metatarsal; *p<0.05; **p<0.01.

Table 4: Physical activity characteristics in habitually barefoot group and control group habitually shod group in Study

2. MEAN \pm SD and range are presented. MEAN \pm SD are presented separately for boys and girls.

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

Note: CPM – Counts per minute; MVPA - Moderate to Vigorous Physical activity; HB – habitually barefoot group;

HS – habitually shod group; ***p<0.001

Table 5: Lower limb and lower back injury prevalence in habitually barefoot and habitual shod.

Injuries/pain over the past year	HB	HS
Lower limb/back injury prevalence	8%	61%
Injured 1 st 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		
Bunions		4
Hallux valgus	1	1