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The effects of habitual footwear use: foot shape and function in native barefoot walkers[†]

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The human foot was anatomically modern long before footwear was invented, and is adapted to barefoot walking on natural substrates. Understanding the biomechanics of habitually barefoot walkers can provide novel insights both for anthropologist and for applied scientists, yet the necessary data is virtually non-existent. To start assessing morphological and functional effects of the habitual use of footwear, we have studied a population of habitually barefoot walkers from India ($n = 70$), and compared them with a habitually shod Indian control group ($n = 137$) and a Western population ($n = 48$). We focused on foot metrics and on the analysis of plantar pressure data, which was performed using a novel, pixel based method (Pataky and Goulermas 2008, *Journal of Biomechanics,* 41, 2136). Habitually shod Indians wore less often, and less constricting shoes than Western people. Yet, we found significant differences with their habitually barefoot peers, both in foot shape and in pressure distribution. Barefoot walkers had wider feet and more equally distributed peak pressures, i.e. the entire load carrying surface was contributing more uniformly than in habitually shod subjects, where regions of very high or very low peak pressures were more apparent. Western subjects differed strongly from both Indian populations (and most from barefoot Indians), by having relatively short and, especially, slender feet, with more focal and higher peak pressures at the heel, metatarsals and hallux. The evolutionary history of humans shows that barefoot walking is the biologically natural situation. The use of footwear remains necessary, especially on unnatural substrates, in athletics, and in some pathologies, but current data suggests that footwear that fails to respect natural foot shape and function will ultimately alter the morphology and the biomechanical behaviour of the foot.

Keywords: barefoot; plantar pressure; foot morphology; footwear; biomechanics; physical anthropology

1. Introduction

From a biomechanical point of view, the foot is one of the least understood structures of the human body. It is very complex and highly redundant, with 26 skeletal elements and numerous ligaments, tendons, intrinsic and extrinsic muscles, and is, therefore, a challenging study subject. Nevertheless, pioneering experimental work has been carried out since the early 20th century (e.g. Morton 1935, Elftman 1939, see also Rodgers 1995). Recently, the human foot is increasingly being studied as a multi-segmental structure with complex three-dimensional kinematics (e.g. Stacoff *et al*. 1989, Gefen *et al*. 2000, Carson *et al*. 2001, Cheung *et al*. 2005, Nester *et al*. 2007). These and many other studies have led to a dramatic increase in our knowledge, and the *in vivo* function of the foot during walking and running is being more and more appreciated. However, almost all studies to date have used Western, habitually shod subjects.

While such populations are relevant in a clinical and applied context, one aspect should be borne in mind: the habitual use of footwear from early childhood may influence the shape, and probably the function of the foot. Traditional Chinese foot binding (Jackson 1990) is an extreme example showing that the human foot is a highly plastic structure, but even everyday footwear influences the foot. Studies on Chinese (Sim-Fook and Hodgson 1958) and medieval British populations (Mays 2005) found foot deformities resulting from restrictive footwear, but even recently in the USA, Frey *et al*. (1993) reported that 88% of the healthy women surveyed were wearing shoes smaller than their feet, and that 80% of them had some sort of foot deformity. A relevant question therefore is: is the Western foot, used in most studies, not 'natural' any more, and is our current knowledge of foot biomechanics clouded by the effects of footwear – in other words, are we studying 'deformed', but not biologically 'normal' feet?

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This may be considered likely, when confronting two palaeoanthropological findings. The first finding is that the human foot was anatomically modern long ago. The oldest human (genus *Homo*) footprints have been discovered very recently at Ileret in Kenya (Bennett *et al.* 2009). These 1.5 million-year-old prints are the 'oldest evidence of an essentially modern human–like foot anatomy' (Bennett *et al.* 2009), that is, a foot with a well-developed longitudinal arch and an adducted, non-opposeable hallux. The fossil record of Pliocene hominins (among which *Homo ergaster* and early *Homo erectus*, to which the Ileret prints are attributed) is scarce with regard to foot skeletons (see D'Août and Aerts 2008, for an overview). However, foot bones of *Homo antecessor*, dated 0.8 million years old (Lorenzo *et al.* 1999) differ from modern (*Homo sapiens*) foot bones, dating from 120,000 years ago, only in details.

The second palaeoanthropological finding is that footwear is likely to be a relatively *recent* invention. The oldest 'shoe' that has been found, a non-constricting fibrous sandal, is only 8300 years old (Kuttruff *et al.* 1998). Rock paintings from Spain showing footwear are approximately 15,000 years old and it has been suggested that protective footwear might have become habitual about 30,000 years ago (Trinkaus and Shang 2008), even though barefoot prints from that time have also been found in caves (Trinkaus 2005). In any case, constrictive footwear appeared long after hominin feet were anatomically modern, and hominin feet have, therefore, evolved into their modern anatomy as unshod structures for walking and probably endurance running (Carrier 1984, Bramble and Lieberman 2004) on natural substrates. Therefore, insight into the effects of using footwear throughout life is most relevant, not only for physical anthropologists, but for clinical and applied researchers and footwear manufacturers as well.

Surprisingly, it has not been well established if, or to what extent, the habitually shod foot is different from the habitually unshod foot, even though researchers have asked this question as early as a century ago. Hoffmann (1905), using a limited sample size, noticed that habitual, or native, barefoot walkers universally have wider toe regions, a trend he also observed in classical sculptures. He linked such anatomy to the use of non-constricting sandals in Antiquity. Interestingly, Hoffmann (1905) also describes that only a few weeks of shoe-wearing by children already effects foot shape, especially toe placement. It is not surprising that the effect of footwear appears to be greatest during childhood, when the foot is still maturating (i.e. the bones are being ossified and fused, see Whitaker *et al.* 2002).

Wells (1931) compared (mostly unshod) South African natives to Europeans and described several qualitative differences, e.g. a broader shape and a lower 'less perfect' (*sic.*) medial arch in the Africans. In his seminal book, Morton (1935) compared the angle of gait (a measure for out-toeing during walking) in American students and in Central African natives 'who had not been affected by the influences of civilization, such as shoe-wearing (...) a pure product of nature'. He found no differences in angle of gait between these populations, as measured using his 'kinetograph', an early plantar pressure sensor, but does not discuss possible differences between these populations further. Other relatively old studies have focused on the effect of footwear on hallux position (Barnicot and Hardy 1955, Barnett 1962).

More recently, a few papers have addressed (mostly rather descriptively) foot shape or function in habitually unshod populations. Tuttle *et al.* (1990, 1991, 1992, 1998) and Musiba *et al.* (1997) studied barefoot walkers from Peru and Tanzania, respectively, and found the feet of these populations to be similar in plantar features, and compatible to those seen in the 3.7-million-year-old Laetoli footprints (Leakey and Hay 1979). Echarri and Forriol (2003), studying Congolese children, found a larger proportion of flatfeet in an urban (predominantly shod) population than in a rural (predominantly unshod) population. Ashizawa *et al.* (1997) found that habitual barefoot walkers from Java had relatively long and wide feet and, similarly, Sim-Fook and Hodgson (1958) described a relatively spread anterior part in habitually barefoot Chinese (not seen in South Africans, Thompson and Zipfel 2005). Kadambande *et al.* (2006) found that (unshod) Indians have more pliant feet than (shod) British. Rao and Joseph (1992), studying the incidence of flat feet in Indians, found this condition to be most common in children who wore closed-toe shoes, less common in those who wore sandals or slippers, and least in the unshod.

The studies mentioned here typically focused on qualitative descriptions of foot shape and did not address kinematic aspects. Moreover, some did not have suitable control groups. Comparing shod and unshod individuals of the same ethnic background is important, as differences in foot properties between ethnic groups have been described (Humphry 1858, Wells 1931).

Results from native barefoot subjects (ideally, but rarely, associated with a habitually shod control group) should be compared to results from habitually shod subjects walking and running barefoot (compared to the same subjects walking and running shod). Whereas experimental data using the former approach (such as the present study and the ones discussed higher) are very rare mostly due to practical problems (finding suitable subjects, bringing equipment to the field), there are more studies using the latter approach. These studies are typically not rooted in biological anthropology (like the ones mentioned so far), but address clinical and/or applied questions. Such approach is highly valuable as well, since it is not unlikely that walking and running barefoot, or using a 'minimal shoe' for protection (e.g. the Nike 'Free' or the Vibram 'Five Fingers'), may have health and performance advantages (for a review, see Warburton 2001). Robbins and Hanna (1987) and Robbins *et al.* (1988) have suggested that the habitually unshod foot is less prone to injuries than the shod one and it has indeed been found that people from various regions who had never worn shoes had relatively few foot disorders (Africans: Engle and Morton 1931; Chinese: Schulman 1949; Solomon Island inhabitants: James 1939). Zipfel and Berger (2007), studying skeletal collections from habitually shod and unshod populations, found that metatarsal pathologies were more severe in the shod populations and suggested that 'This result may support the hypothesis that pathological variation in the metatarsus was affected by habitual behaviour including the wearing of footwear and exposure to modern substrates'.

Studies addressing barefoot locomotion in unshod Western subjects have yielded several important results to date. De Wit *et al.* (2000) found significant differences in kinetics and kinematics (e.g. flatter foot placement at touchdown) when running barefoot, compared to running shod. Barefoot and minimally shod running was recently found to decrease the heel strike transient in habitually shod individuals as well as habitually unshod runners (Lieberman *et al.* 2009). Interestingly, the use of a minimal shoe has a positive effect on hallucal flexor strength (Potthast *et al.* 2005). With regard to plantar pressure distributions, reference data are available for barefoot walking (Bennett and Duplock 1993, Blanc *et al.* 1999, Bryant *et al.* 2000, Hennig and Rosenbaum 1991, Hennig *et al.* 1994) and jogging (De Cock *et al.* 2005).

As such detailed biomechanical data are completely lacking for *habitual* barefoot walkers, and, therefore, we do not know the biomechanics of a foot that has been unshod throughout life, we set out to start filling this void by analyzing morphological and functional aspects of the foot (i.e. high-resolution dynamic plantar pressures, basic kinematics) in a large sample of habitually barefoot walkers from South India. Data will be compared to those collected in an identical fashion of habitually shod South Indians and of a Western, Caucasian population. The questions we specifically address are: (1) do we find morphological differences of the feet between these populations? (2) Are there differences in functional aspects of foot roll-off during steady walking at preferred velocity? Our data will also provide baseline data for non-habitually barefoot walking and running, as recent developments in this field are very promising but comparative data are scarce.

The results of this analysis will also help answer fundamental as well as applied questions, such as: do we need to study habitual barefoot walkers for an insight into normal human foot function? Does everyday footwear have effects on the biologically normal function of the foot and if so, does this have implications for clinicians and footwear manufacturers?

2. Materials and methods

2.1. *Subjects and study sites*

We measured and analyzed subjects ($n = 255$) from three populations with different ethnical background and footwear habits:

BI – habitually (native) barefoot Indians from the South-Indian city of Bangalore and nearby rural areas. These subjects ($n = 70$) reported never having worn shoes, or only in extremely rare cases (e.g. flip-flops, and then only worn as an adult when visiting the hospital).

SI – habitually shod Indians from Bangalore and nearby rural areas. These subjects ($n = 137$) use footwear on a daily basis. It should be mentioned that these subjects, according to Indian habits, have walked mostly barefoot as child, and all subjects reported walking barefoot in the house. Outdoors and at work, they sometimes used Western-style closed (potentially constricting) footwear, but often open flip-flops or sandals.

W – Western, Caucasian subjects residing in Belgium ($n = 48$).

For the purpose of this paper, we consider the SI group as intermediate between the BI and the Western group, thus with regards to the intensity of footwear use we have a range BI < SI < W. The latter group differs from the former ones also in ethnicity, but it was impossible to find a reasonable sample of South Indian subjects with Western shoe-wearing habits (or habitual barefoot Western subjects). We will address this potential confounding factor in Section 4.

Subjects were asymptomatic adults of both sexes. Prior to the recordings, they were weighed, measured (stature and leg length, i.e. the height of the major femoral trochanter during quiet barefoot standing) and answered a short questionnaire about footwear habits and recent injuries of the locomotor apparatus (which was an exclusion criterion) and date of birth (or, if unknown, age). When age was reported, we added 0.5 years in order not to bias our averages too low (e.g. a subject will report 'age 50' up to the day he or she turns 51). Throughout the recordings, members of the medical staff of the Foot Clinic of the Jain Institute of Vascular Sciences (JIVAS) were available for linguistic and other practical help. Subject details are presented in Table 1.

The recordings of both Indian groups were done at the JIVAS in the Bhagwan Mahaveer Jain Hospital in Bangalore and in two rural outposts, i.e. Mandya and Kolar Gold Fields (KGF). Data collection for subjects of both subject groups was performed in random order. The recordings of the W group were done at the University of Antwerp or at people's homes (Belgium).

2.2. *Setup and protocol*

For practical reasons (i.e. working in rural outposts), the experimental setup was limited to a plantar pressure plate and two PAL video cameras (transportable in a rickshaw by one person). The pressure plate (RSscan Footscan, size $42 \times 56 \times 1$ cm, 2.53 sensors cm^{-1}) operating at 300 Hz had a USB2 interface to a laptop running Footscan 7 Gait software. Camera 1 (Sony, 50 Hz) was positioned at hip-height and filmed a lateral view covering approximately two complete strides. Camera 2 (Sony 3CCD, 50 Hz) showed a lateral view zoomed in to the width of the plate, providing a detailed view of the foot. At the start of recording sessions, both camera views were calibrated by filming reference rulers. Care was taken to position the pressure plate on a hard, level surface, to provide ample walking space before and after the plate, and to position the cameras perpendicular to the sagittal plane. Both indoor and outdoor experiments were performed. All subject walked barefoot during the experiments.

Prior to the experiments, we drew small marks (using a felt marker) on the left foot (shank, heel, lateral malleolus, fifth metatarsal proximal head, fifth metatarsal distal head) and on the right foot (shank, heel, medial malleolus, navicular, first metatarsal distal head, hallucal interphalangeal joint, Figure 1). Other sides were left unmarked because they would remain obscured, as subjects always walked from right to left through the field of view. The height of the navicular marker to the ground during quiet standing on both feet was measured using callipers, as a reliable estimate for longitudinal arch height (Hawes *et al.* 1992, Razeghi and Batt 2002).

The subject's starting position was fine-tuned so that they would land in the middle of the pressure plate while walking normally at preferred velocity. It has

Figure 1. Still image (de-interlaced and cropped) of camera 2, illustrating the markers on the medial side of the foot. The malleolus and shank markers are not visible on this frame.

Table 1. Subject details. ANOVA analyses revealed significant differences ($P < 0.001$ in each case) between populations for all variables, except for BMI.

Population	*n*	Age (years) avg ± SD range	Mass (kg) avg ± SD range	Stature (m) avg ± SD range	Leg length (m) avg ± SD range	BMI avg ± SD range
BI	70	46.3 ± 14.9	56.4 ± 13.0	1.56 ± 0.09	0.84 ± 0.05	23.1 ± 4.9
	(23♂, 47♀)	20.5–90.5	30–92	1.41–1.79	0.73–0.97	14.3–35.9
SI	137	34.3 ± 11.5	61.5 ± 12.1	1.62 ± 0.09	0.89 ± 0.06	23.4 ± 4.1
	(80♂, 57♀)	17.1–71.5	35–110	1.40–1.89	0.73–1.07	15.1–35.2
W	48	33.9 ± 13.1	70.0 ± 13.8	1.74 ± 0.09	0.95 ± 0.06	22.9 ± 3.2
	(22♂, 26♀)	20.3–73.7	52.0–117.9	1.57–1.93	0.83–1.06	18.2–33.4

For the other variables, Bonferroni *post-hoc* tests revealed differences between each pair of populations, except for the age of the SI and W groups.

been shown that such approach successfully negates potential 'targeting' effects on spatiotemporal and kinetic gait data (Wearing *et al.* 2000). Additionally, subjects were instructed to focus on a distant point at eye level while walking, not on the pressure plate. During experiments, the pressure plate was triggered by initial heel contact and both cameras were recording the full session, which continued until we had three successful trials of each foot. Trials were considered unsuccessful if the subjects were walking unsteadily, targeting the plate, or walking abnormally. A total of 6–12 recordings per subject were necessary; a few subjects were completely excluded from analysis.

2.3. *Analysis – video*

A subset of the data from 141 subjects (48 BI, 58 SI, 35 W) was used for kinematic analysis. Video sequences were grabbed to DV-AVI files on a PC, de-interlaced to yield 50 fields s^{-1} and converted to jpeg stacks using VirtualDub by Avery Lee (http://www.virtualdub.org/). The position of the markers was digitized using the footage of camera 2 and Didge software (http://biology.creighton.edu/faculty/cullum/Didge/index.html). The perpendicular distance D from the navicular marker to the line L connecting the heel and first metatarsal distal head throughout stance was calculated in Excel. The difference between D at foot flat and at its smallest value, divided by L, yielded relative (i.e. corrected for foot length) navicular drop ND (see Saltzman *et al.* 1995). Preliminary frontal-plane recordings had shown that movements in this plane are relatively minor during the period of interest and 2D results would provide a good estimate of navicular drop. Obviously, full 3D kinematics are preferable for foot motions, but very impractical to measure in the field. Our values for navicular height (a measure for arch height) and ND are meant for comparison between populations only. The present paper addresses kinematics only briefly and will focus on foot metrics and plantar pressure recordings.

2.4. *Analysis – plantar pressures*

The complete data set consisted of three plantar pressure recordings per foot (left and right) per subject, i.e. a total of 1530 pressure recordings. The dynamic recordings were exported from the Footscan software to ASCII format. Analysis was done in Matlab 7.4 (The Mathworks) using a novel pixel-level method, 'pedobarographic statistical parametric mapping' (pSPM, Pataky and Goulermas 2008, Pataky *et al.* 2008a). This method is fully automated and does not require user intervention. The consecutive analysis steps performed are:

1. Registration (alignment and rescaling) of the image time series in the two spatial dimensions (i.e. x, y), so that homologous structures on pressure images from different recordings optimally overlap (Pataky *et al.* 2008b), mirroring of the right feet and averaging of all six feet per subject (see Section 4).
2. Calculation of peak pressures (PP) and pressure impulses (PI) images; the latter was computed as the pixel-wise pressure-time integral over stance phase.
3. Calculation of average images and corresponding variances per population. Preliminary analyses showed no major effects of sex (male/female) and of foot (left/right) on the morphological variables and therefore, sexes and feet were pooled in our analysis. Additionally, PP and PI images were normalized by the average PP and PI of the entire image, in order to demonstrate how well PP and PI are distributed (or not) over the plantar surface of the foot, irrespective of absolute values.
4. Statistical comparison of the images between populations. The statistical comparison was done using pairwise t-tests, each at a family-wise alpha level of $P = 0.05$, both unadjusted, and adjusted by accounting for the fact that pressures from nearby locations on the foot sole (and therefore the pressure measurements) are correlated, using random field theory (Pataky 2008).

In addition to the analysis of PP and PI, basic descriptors of foot metrics were extracted from the original (non-registered) data, i.e. foot length (the length of the long principal axis of the peak pressure images) and foot width (the length of the short principal axis of the peak pressure images). These data, and derived data (i.e. foot length as a proportion of stature) were statistically analyzed using the General Linear Model in SPSS 16.0 for Windows, after normal distribution of variances was verified (alpha level = 0.05). Pearson correlations were calculated (SPSS 16.0) between age and peak pressures in the metatarsal zone in order to do a *post-hoc* assessment of age as a potential confounding factor in the between-populations analyses; see Section 4.

To obtain a pressure-based estimate of longitudinal arch height, we measured the area of the midfoot region (Figure 4) as a percentage of total foot area for a subset of 27 BI, 35 SI and 35 W subjects. This method is inspired by the 'Arch Index' (Cavanagh

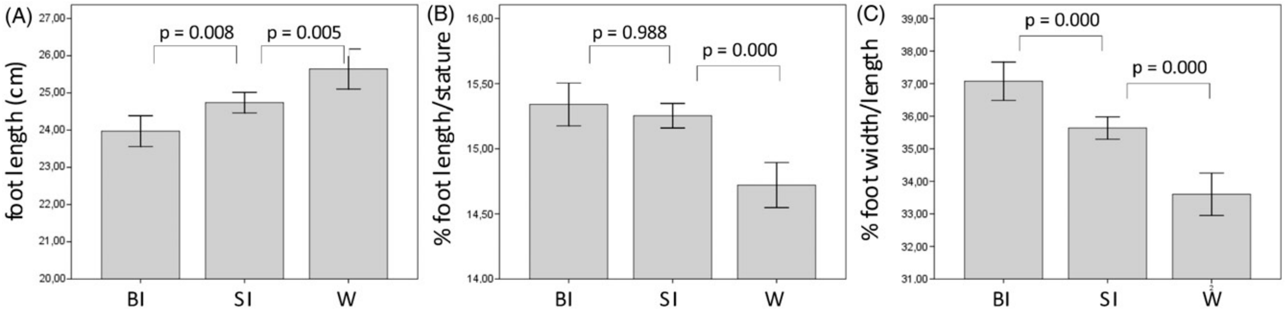

Figure 2. Comparison of foot metrics between the tree populations studied. (A) absolute foot length; (B) foot length as a percentage of stature; (C) width of the foot as a percentage of its length, a measure for overall foot shape. *P*-values of Bonferroni *post-hoc* tests are given.

Figure 3. Examples of feet of BI (habitually barefoot Indian) and SI (habitually shod Indian) subjects. The male BI was a construction worker showing a thicker than most other barefoot walkers and habitually shod Indians. Note the fan-shaped toe placement and overall relative width of the foot in all tree subjects and especially in the habitual barefoot walkers.

and Rodgers 1987) but uses dynamic data and includes the entire (not truncated) foot in the calculations.

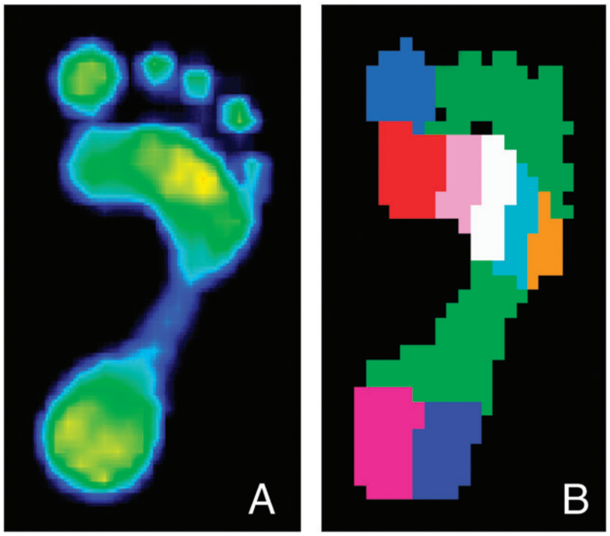

Figure 4. Sample (A) peak pressure image for a habitual barefoot walker and (B) selection of anatomical zones in the Footscan software. The midfoot zone, used for estimating arch height, is shown in bright green.

3. Results

3.1. *Subject and foot metrics*

Average stature, mass, and leg length differed significantly between the three populations, but the BMI, an important factor for scaling plantar pressures (see Section 4) did not.

Size differences between the populations were reflected in average foot lengths (Figure 2A). Expressed as a percentage of stature however, W had significantly ($P = 0.000$) shorter feet (i.e. 14.72%) than both Indian groups. The latter did not differ significantly in this respect, even though the average for SI (15.34%) was slightly lower than for BI (15.25%) (Figure 2B).

Focusing on foot width as a percentage of foot length (a measure for overall foot shape), highly significant differences between all three groups were observed (Figure 2C). BI had the highest value (and thus the ‘stockiest’ feet), W have the lowest value (and thus the most ‘slender’ feet), and SI were in-between. To illustrate this, Figure 3 shows a few typical examples of BI and SI feet. Foot area normalized to stature squared (see Section 4) was 15.5% smaller in the W group than the average for the Indian groups ($P = 0.000$), who did not differ significantly.

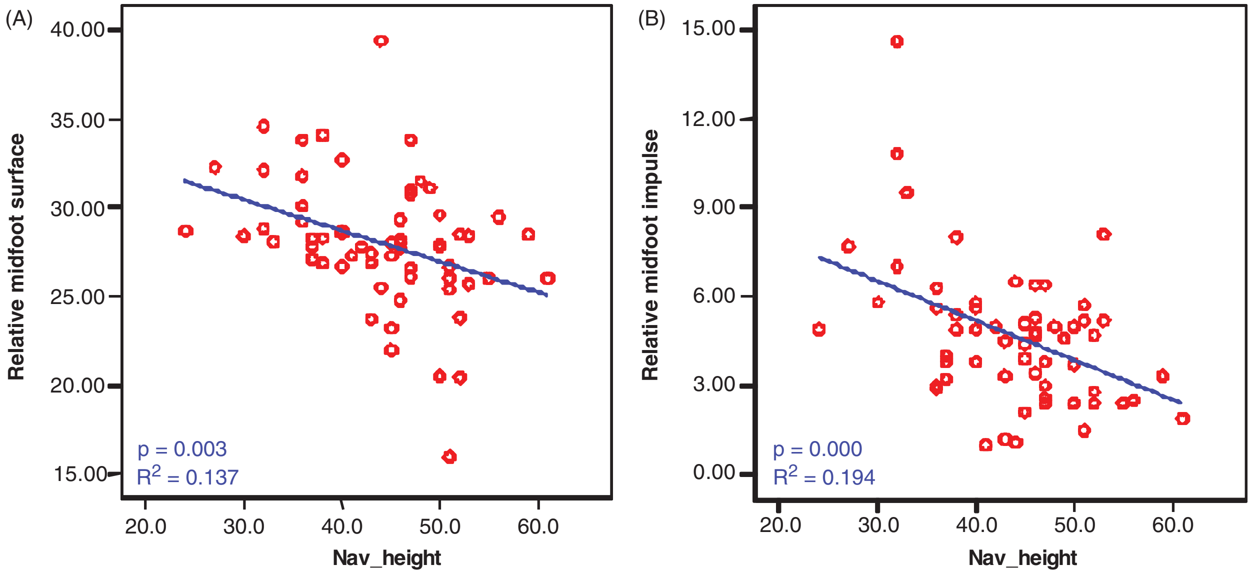

Figure 5. Correlation between navicular height (a measure for height of the longitudinal arch) and relative midfoot surface (A) and relative midfoot impulse (B). Regressions are highly significant, but explain only 14–19% of variance.

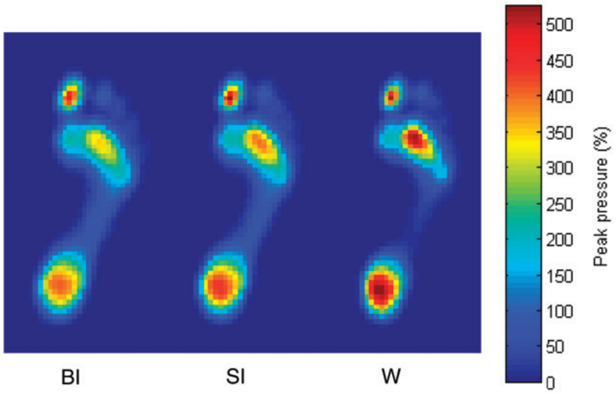

Figure 6. Averaged images of peak pressures for all trials of the BI, SI and W groups. Pressures are expressed as percentages relative to the average of the foot and indicate zones of relatively high or low pressures.

3.2. *Longitudinal arch structure*

A full study of a complex topic such as arch structure and biomechanics requires an elaborate laboratory-based setup and falls beyond the scope of the present paper. Here we present basic data collected 'in the field' in order to estimate potential differences in longitudinal arch between the populations. We assessed (static) navicular height, navicular drop during stance, and the relative surface and impulse of the midfoot region to the total foot surface (Figure 4). Navicular height correlated significantly ($P < 0.005$) but weakly ($R^2 < 0.20$) with both relative midfoot surface and impulse (Figure 5) but the three populations did not differ significantly in navicular height.

Relative midfoot surface was significantly lower ($P = 0.001$) in W subjects than in both Indian groups (who did not differ significantly), but variance is significantly higher in W subjects than in both Indian groups (Levene's test, $P = 0.000$). Briefly, based on relative midfoot measurements, BI and SI seemed to have slightly lower arched feet than W but most subjects did not deviate much from this arch structure, whereas Western feet more clearly ranged from very flat to very high arched.

3.3. *Plantar pressures and pressure impulses*

Figure 6 shows the distribution of peak pressures (scaled to the average of the entire plantar surface) for all subjects of the three groups. The differences in relative midfoot area found using a conventional, zone-based analysis (see above) can be easily discerned in these images: both Indian groups clearly showed a wider, and more loaded midfoot region than the W group. Differences in pressure distribution were most clear in the heel and in the metatarsal region. For both zones, values were lowest in BI, intermediate in SI and highest in W. The results for pressure impulses were very similar to those of peak pressures (Figure 7).

A pixel-by-pixel statistical test (unadjusted for spatial correlation of sensor signals) of BI vs. SI walkers revealed that the differences observed were significant (i.e. having absolute t-values larger than 1.972, $df = 205$) (Figure 8A). The lateral edge of the metatarsal region showed relatively higher (albeit absolutely quite low) values in the BI group, probably due to the added width of the foot (and thus potential for load bearing) in BI subjects. When a novel statistical test was used, which (more conservatively) accounted for spatial correlation of neighbouring signals, results remained significant in the forefoot (Figure 8B). Applying this statistical method to the three groups revealed highly significant differences between SI and W and most clearly, between BI and W. Western subjects displayed higher relative pressures in the heel and under the second to third metatarsal head, but lower relative pressures in the midfoot and the toe region (Figure 9).

4. Discussion

This paper is the first to provide quantitative and dynamic biomechanical data from a large sample of native barefoot walkers. To warrant a large and representative subject sample, data had to be collected in the field (in both urban and rural settings) and therefore the experimental setup was, necessarily, simpler than that of a specialized gait laboratory. Nevertheless, we have been able to collect accurate plantar pressure data and two-dimensional kinematic data for 70 native barefoot walkers (BI) and 137 shod peers (SI), in addition to a Western population (W). The core results of our analyses are that the feet of native barefoot walkers are relatively wider than those of habitually shod walkers, that Western subjects have higher and more variable medial longitudinal arches

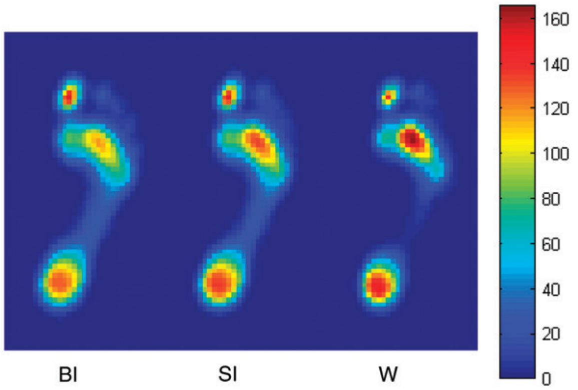

Figure 7. Averaged images of pressure impulses (PI) for all trials of the BI, SI and W groups. PI's are expressed as percentages relative to the average of the foot and indicate zones of relatively high or low PI.

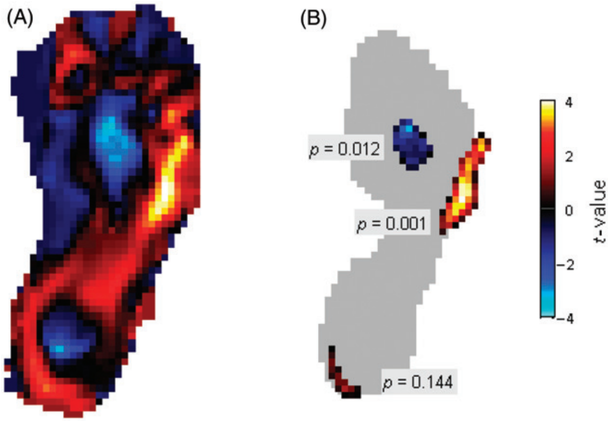

Figure 8. Statistical comparison of peak pressures between BI and SI. (A) *t*-Values per sensor (absolute values greater than 1.972 are significant at the 0.05 level); (B) significantly different zones after adjustment of significance level using random field theory (for details we refer to Pataky 2008). Note that BI have relatively lower peak pressures (blue) where absolute pressures are high and vice-versa, i.e. peak pressures are distributed more evenly than in SI.

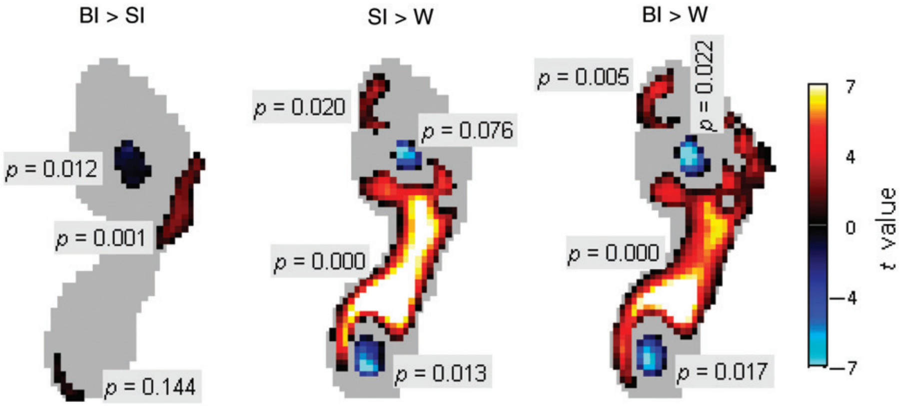

Figure 9. Statistical comparison (with adjusted significance level) of peak pressures between each pair of groups (BI > SI, SI > W, BI > W). Blue: lower peak pressures in the group to the left of the '>'; red: higher peak pressures in the group left to the '>'. Note that, whereas the differences between both Indian groups are relatively subtle, the Western population differs significantly from both Indian populations over almost the entire plantar surface, by having lower relative values in the midfoot and toe region, and higher ones in the heel and under the metatarsal heads (where absolute values are highest).

than Indians and that native barefoot walkers show significantly lower plantar peak pressures than habitually shod subjects.

Our data on overall foot shape is consistent with literature data from other Asian populations. Ashizawa *et al.* (1997) found that, for the same stature and BMI, barefoot populations from Java have longer and relatively wider feet than their shod peers from the Philippines. Results from South African populations however (Thompson and Zipfel 2004) do not support the hypothesis that an unshod life per se results in increased forefoot width. Relative foot length in our W population (14.7%) was quite similar to that of a large sample of habitually shod subjects from Turkey (Atamturk and Duyar 2008), i.e. 14.4%.

With regard to arch structure, Rao and Joseph (1992), studying Indian children, found a higher incidence of flat feet in shod subjects and stated that 'Our findings suggest that shoe-wearing in early childhood is detrimental to the development of a normal longitudinal arch'. In a Central African sample, Echarri and Forriol (2003) also found a greater proportion of flatfeet in shod urban children compared to habitually unshod children. We have not addressed the incidence of flat feet directly, and our measure for arch structure (i.e. relative midfoot area) did not differ between the two Indian populations. However, since variation in our measure for arch height (CI) is much higher in Western than in both Indian groups (where even the shod ones wear less often, and less constricting shoes than Western subjects; see Section 1), it is likely that the incidence of flat feet (as well as high arched feet) is largest in our Western subjects.

Our data show that the shod Western foot differs from the unshod foot (which can be considered the normal condition, from a biological perspective) by being relatively short and narrow (resulting in a smaller area) and by having a slightly higher but more variable medial longitudinal arch.

Differences in footwear habits between BI and SI populations were less dramatic than those between the BI and W population. This is reflected in our morphological and plantar pressure analyses: differences between the Indians groups and Western subjects are major, but differences between the habitually barefoot and shod Indians are more subtle (yet statistically highly significant). As the latter populations differed in average size (body mass, stature), contact times (thus probably, speed) and age, is it possible that these factors explain the observed differences, and not footwear use?

Firstly, with regard to body size, even though populations differed in absolute values, their body mass indexes (BMI) were not statistically different. BMI is defined as mass over stature squared and pressure is defined as force over area. Thus, both variables are a (measure of) force over a length squared and, all things being equal, subjects with similar BMI's should have similar absolute pressures. This theoretical (and convenient) finding results from the fact that human body mass does not scale isometrically (i.e. to stature cubed) but allometrically, to stature squared (e.g. Heymsfield *et al.* 2007). Experimentally, Cavanagh *et al.* (1991) have shown that body mass is a poor predictor of peak plantar pressure.

Secondly, even though subjects were instructed to walk at preferred velocity, might eventual differences in walking speed be a confounding factor? Since BI and SI differed in leg length, theories based on dynamic similarity (Alexander 1977, Hof 1996, see Moretto *et al.* 2006 for its use in plantar pressure recordings) predict that absolute velocities v should differ as well for corresponding dimensionless velocities v_{dl}, as expressed by the cubic root of Froude Number, i.e.

$$v_{\mathrm{dl}} = \sqrt{\frac{v^2}{g \cdot LL}}$$

with g is gravity and LL is leg length.

By using the concept of dynamic similarity and by assuming that the duty factor (stance duration as a fraction of stride duration) is similar for a similar dimensionless speed, it can be estimated that the SI group had a v_{dl} 9% lower than that of the BI group. Literature data have shown that lower walking speeds correlate to lower regional peak pressures (e.g. Rosenbaum *et al.* 1994, Pataky *et al.* 2008b) and therefore, if anything, the differences in peak pressure between BI an SI walkers should become even more pronounced if both groups were walking at dynamically similar velocities.

Thirdly, in order to evaluate whether age differences might contribute to explaining differences between our populations, we have calculated correlations between age and the pressure in the metatarsal head zone, exactly where we found our main differences between populations. This analysis was carried out both for absolute and scaled pressure values, and separately for the three populations (i.e. six analyses). In each of these cases, the correlation was not significant. P values for absolute pressures are 0.469 (BI), 0.537 (SI) and 0.229 (W). P values for scaled pressures are 0.921 (BI), 0.703 (SI) and 0.310 (W). Literature data (Kernozek and LaMott 1995) found similar loading in the heel and central forefoot regions (i.e. the zones where we detected differences between the BI and SI groups) between young and elderly adults. We conclude that age does not contribute to explaining the variation between the populations in the present study.

For the reasons mentioned above, we are confident that the core results of our pressure analyses are robust. It should be mentioned that the BI and SI populations differed in gender distribution (more females in BI, more males in SI; see Table 1). Whereas gender effects on e.g. foot shape (outside the scope of this paper) merit to be explored further, they are not likely to influence the core findings of the present study. Murphy *et al.* (2005) found no significant differences in plantar pressure values between males and females.

Our data show lower peak pressures in habitually barefoot Indian than in shod peers, and the highest peak pressures in Western subjects. Whereas these results are significant (both statistically and biomechanically), the present analyses do not demonstrate exactly *how* (in mechanical terms) the relatively low values for BI are obtained. We will, however, speculate on several possibilities here. Firstly, BI have longer feet than W subjects, and wider feet than both SI and W subjects. As a result, and aided even more by the lower medial arch (see Section 3 and Figure 6), BI (and SI) have a larger relative foot area and thus larger load carrying surface compared to W subjects. Our data are in accordance with Morag and Cavanagh's (1999) experimental data, which show that higher plantar pressure in the heel correlates with a higher foot arch.

Secondly, BI subjects may be able to use more homogeneous pressure impulses (which we did observe), in other words, they distribute pressures more evenly in time, by applying low pressures over a longer period of time instead of high pressures over a short period of time (and very low pressures for the remainder of stance duration). This may very well be part of the explanation, as preliminary observations of the timing of plantar pressure roll-off, as well as foot kinematics, suggest that BI use a flatter initial foot placement. Such an active adaptation has indeed been observed in barefoot (non-habitual) running (De Wit *et al.* 2000) and indirectly, by lower heel-strike transients in barefoot runners (Lieberman *et al.* 2009). Future research should address these issues (i.e. timing aspects of plantar pressure distribution and kinematics) in detail.

Thirdly, BI subjects may be able to better distribute pressure spatially. This can be achieved by, for instance, more 'pliable' feet, which have been observed in barefoot Indians compared to shod British subjects (Kadambande *et al.* 2006). The relatively thick and keratinized skin on the whole plantar foot area in native barefoot walkers (pers. obs.), in itself formed as a response to loading, may also passively distribute pressures (unlike small callused regions, which show higher pressures; Menz *et al.* 2007). Future research should evaluate the mechanics of the plantar soft tissues under dynamic conditions (see Cavanagh 1999) in a range of habitually shod and unshod subjects.

Epidemiological and case studies have suggested that walking barefoot probably may have health benefits (see Section 1). We should stress however, that, while this may be true for healthy individuals, the benefits of footwear in for instance athletics and diabetic care have been very well established. The present biomechanical study has demonstrated that habitual barefoot walking indeed correlates with measurable, significant, and potentially favourable, differences in foot shape and plantar pressure distribution. Combined, these findings strongly suggest that barefoot walking enables the foot to achieve its biologically 'normal' shape and function. Especially during childhood, when the foot is still maturating and achieving most of its final shape and functional properties, walking barefoot should be promoted (see also the review by Staheli 1991). When selecting everyday footwear, we suggest to avoid overly stiff shoes (which might preclude a barefoot-type unroll pattern) and to prefer shoes that are sufficiently roomy, especially in the forefoot region (current designs often constrict the toes). This study does not allow for very specific recommendations as to everyday footwear selection, and more research is needed.

Similarly, we suggest that walking and training barefoot or (if the substrate does not allow) using shoes that allow the foot to function as closely as possible as in the barefoot condition, could lead to performance benefits for athletes. Such performance benefits can be achieved, for instance, by increased muscular performance (as found by Potthast *et al.* 2005 when wearing minimal shoes) or as a result of potentially lower injury rates due to smaller peak pressures.

The present study on habitual barefoot locomotion is novel and has only just started to explore the biomechanics of habitual barefoot walking. Some important aspects have not been dealt with in this initial study, and here we will present some suggestions for future research.

Firstly, our Western population differed from the two populations not only in footwear habits but also ethnicity; therefore, it is not unequivocal to attribute differences to either factor but it is likely that both play a role. Whereas it is probably impossible to find a large population of native barefoot walking Western subjects, it may be more feasible to find a group of subjects of Indian origin, but who have lived in the West (and adopted Western footwear habits) throughout life, e.g. South Indian children adopted by Western families at a very young age or the large Indian population residing in the UK. Such populations would be the perfect control group (notwithstanding potential differences in, e.g. nutrition, with the Indian groups) and would enable the effects of a habitually shod life style to be established most clearly. We have collected data of four adopted Indians (not presented in this paper because of the low sample size) and their foot metrics best resemble those of the SI group.

A second issue relates to the level of detail in the analysis of our kinematic and plantar pressure data. For the present paper, we focused on presenting a broad comparison of selected variables which we deemed important because of theoretical considerations or because of suggestions from the literature (see Section 1). Future analyses should build on the present results and explore additional aspects, such as additional kinematics (especially with regard to foot position at impact, see De Wit *et al.* 2000 and Lieberman *et al.* 2009) and plantar pressure analyses. We have averaged all six trials from subjects (of both sexes) and combined trials from left and right feet. This approach enabled the calculation-intensive pSPM analysis (which, in any case, aligns feet for maximal overlap regardless of absolute size differences) to run with our large number of subjects ($N = 255$) and most likely did not influence our results. Preliminary tests on our data set suggested so, and literature data on slow jogging found high inter-trial reliability and negligible effects of sex and asymmetry on plantar pressure measurements (see De Cock *et al.* 2005). Nevertheless, sex differences in foot shape (even if not the topic of the present paper) have been reported (see e.g. Wunderlich and Cavanagh 2001, O'Connor *et al.* 2006) and are worth exploring in future work. Finally, future work should look into timing aspects of plantar pressure distribution and the path of the center of pressure.

A third way of increasing our knowledge of habitual barefoot locomotion would be to collect additional data of walking and, specifically in order to address issues related to athletic performance, new data of habitual barefoot running. More specifically, high-resolution, full 3D kinematic data of the foot as a multi-segmented structure and accurate kinetic data using force platforms would bring a higher level of detail. Collecting such data in a large sample (in practice, this implies a field setting) would pose a major technical challenge.

5. Conclusion

This paper is the first to study pixel-level plantar pressures in a large population of native barefoot walkers, comparing their data to a control population of the same ethnicity and to Western subjects. To the best of our knowledge, this is the first study to provide detailed biomechanical data of native barefoot walkers. We have shown that the habitual use of footwear influences both the overall shape of the foot and plantar-pressure variables. Habitually barefoot walkers have wider feet, which results (probably along with dynamic adaptations) in lower peak pressures, favourable in injury prevention and therefore most probably in athletic performance. We suggest that frequent barefoot walking, especially in children, can help to preserve natural foot function. When the substrate does not allow for barefoot locomotion, footwear should be worn that protects the foot from injury, but that is unrestrictive, enabling the foot to function as much as possible as in the unshod condition.

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