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Plantar pressures in three types of indigenous footwear, commercial minimal shoes, and conventional Western shoes, compared to barefoot walking

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Keywords

Barefoot; walking; plantar pressure; minimal footwear; biomechanics; anthropology

Abstract

Humans evolved as barefoot walkers, and only started to use footwear recently in evolutionary history. It can be questioned what the effect is of footwear on gait. This effect has previously been studied for a range of conventional and athletic footwear, but this study focuses on indigenous footwear which does not have the features commonly associated with conventional footwear, such as a raised heel, a relatively narrow toe box, arch support, and a firm heel cup. We will assess whether such footwear can be considered functionally 'minimal' and simulate barefoot walking, by analysing spatial and temporal aspects of plantar pressure distribution. We first compare the 2 D spatial distribution of plantar pressure, using 2 D Statistical Parametric Mapping, between four populations walking barefoot and with indigenous or commercial minimal shoes. We compared Indians wearing sandal-like footwear ('Kolhapuri'), Scandinavians wearing boot-type footwear ('Nuvttohat'), Namibian San wearing sandal-like footwear ('N!ang n|osi') and Western Europeans wearing a commercial minimal shoe, and conventional Western footwear. Within each population, indigenous and commercial barefoot footwear data were compared to barefoot walking. No statistically significant differences were found within-population between all footwear conditions and barefoot walking. Second, we question whether there were 1 D temporal differences in centre of pressure movements between three footwear conditions (barefoot, commercial minimal, conventional Western) within one, Western, population. Using 1 D Statistical Parametric Mapping, differences between these three conditions are shown, with barefoot walking keeping a more proximal CoP position than both footwear conditions during most of push-off phase. Based on plantar pressure recordings, we conclude that all indigenous and commercial minimal shoes can functionally be considered 'minimal footwear', but with some differences to barefoot walking.

Introduction

Most people, especially adults, wear some form of footwear on a daily basis. Not surprisingly, a large body of work exists on biomechanical effects of footwear. These studies have focussed predominantly on functional sports shoes, for instance for running (e.g. for injury prevention and performance enhancement; see Nigg, 2010) and on therapeutic footwear and/or orthotics for specific patient groups (e.g. neuropathic diabetic patients; see Bus et al., 2016) where health benefits have been demonstrated. Surprisingly, relatively little work has been done on daily walking, even though it is often suggested that daily footwear might have a large effect on long-term biomechanical health. Specifically high heeled shoes are problematic (Coughlin, 1995; Frey, 2000) and even moderate heels have been suggested to have a negative effect on knee osteoarthritis (Kerrigan et al., 2005). Hallux valgus (bunions), one of the main foot problems especially in women (Easley & Trnka, 2007, for a review, see Nix et al., 2012) has been suggested to be strongly influenced by the adoption of stiff, heeled footwear (Mafart, 2007).

A large variety of footwear is used on a daily basis, ranging from thin-soled ballerina-style footwear, to rigid boots, to high heels; here grouped as 'conventional Western' footwear. Most types of daily shoes make no health benefit claims, and for some it has been clearly demonstrated that they actually impede health (e.g. high heeled shoes; Lee et al., 2001). For most daily shoes it is unclear what their effect on health is, if any.

Interestingly, what we consider 'daily', or 'conventional' footwear is a relatively recent and mostly Western invention. The oldest footwear found is approximately 8300 years old, a sandal made from plant fibre (Kuttruff et al., 1998). Archaeological findings show that also ancient Egyptians (e.g. Sesana, 2005; Veldmeijer, 2012), ancient Romans (Allison, 2006; Cleland et al., 2007; Van Driel-Murray, 2001), and people in the Middle Ages used footwear that could be considered fairly 'minimal' to current standards. Shoes seemed to be non-constricting, there was no rigid heel cup, no arch support, little cushioning and no elevated heel; features with potential biomechanical effects that are omnipresent in conventional Western footwear. For the purpose of this study, and in line with Sinclair et al. (2013), minimal footwear is defined as 'Footwear providing minimal interference with the natural movement of the foot due to its flexibility, low heel to toe drop, weight and stack height, and the absence of motion control and stability devices' (Sinclair et al., 2013). This definition outlines features of the shoe, but also the similarity of the resulting kinematics with barefoot walking.

Our recent adoption of conventional footwear in the last few centuries is in stark contrast with our anatomical, evolutionary development. Indeed, the oldest modern humans, *Homo sapiens*, were dated to approximately 200,000 years ago (McDougall et al., 2005) and hallmark characteristics of the modern human foot may have existed for several millions of years (Bennett et al., 2009). Since humans have been successful for such long periods, it is worth exploring if we need footwear with biomechanical effects and, if so, which effects (of course, footwear can serve other than biomechanical functions, e.g. protection from the cold or from sharp objects). Selection is likely to have acted very strongly on the human foot and on locomotor anatomy in general, and we do not need to interfere with their function for normal daily locomotion, although (minding the naturalistic fallacy; Frankena, 1939) in principle it might be possible to improve on nature. The foot is the only part of the body that is often judged to need biomechanical assistance. For instance, we do not use rigid clothing to help support the weight of the head, or gloves with biomechanical function to carry objects. In the rare cases where we do support parts of the body, e.g. when applying plaster casts to help fracture healing after trauma, muscle atrophy is observed (Appell, 1990). Experimental work to address these issues is impossible for obvious ethical reasons. However, the opposite approach can be used, and indeed it has been shown that athletes training in 'minimal' footwear gain foot muscle strength compared to those using conventional trainers (Goldmann et al., 2013; Miller et al., 2014). Using minimal footwear during daily life has been shown to both increase foot strength (Ridge et al., 2019), balance (Cudejko et al., 2020), and gait performance (Petersen et al., 2020).

Interestingly, even to date, several populations habitually use indigenous footwear that cannot be categorised as conventional Western. Such indigenous footwear has been in use for centuries. Based on their characteristics, the question arises if such footwear might be considered functionally minimal, i.e. lead to gait that resembles barefoot gait. Therefore, in this study we set out to explore some of the biomechanical characteristics of walking in such footwear and we will compare them to a modern, commercially available type of minimal footwear, and to conventional Western footwear. Moreover, every shod condition will be compared within-subject to barefoot walking.

As a first biomechanical approach, we will use plantar pressure recordings to define the variation of the local distribution of pressures under the foot between indigenously or minimally shod walking, and conventionally shod as well as barefoot walking in healthy subjects.

Plantar pressure recordings have been used extensively to assess footwear. Most studies have used pressure-sensitive insoles (e.g. Erdemir et al., 2005; Price et al., 2013; Sacco et al., 2009) and there has been a strong focus on plantar pressure studies in diabetic patients with peripheral neuropathy (e.g. Barn et al., 2015; Frykberg et al., 1998). The vast majority of studies have focussed on running (e.g. De Wit et al., 2000; Semal et al., 2017) or on patient groups.

A previous field study compared walking with indigenous 'Kolhapuri' footwear (worn in South India) to barefoot walking using foot-mounted accelerometery and goniometry (Willems et al.,2017). Based on these data, it was suggested that gait in these to conditions is overall similar, but there are some differences in the timing of plantar/ dorsiflexion during stance which likely influences the unroll pattern. The latter is typically quantified as the motion of the Centre of Pressure, which can be easily calculated from the plantar pressure data. Therefore, this study will explicitly address the timing of foot unroll, in addition to the overall pressure distribution.

Our expectation is that any shoe likely provides some (even if minimal) amount of cushioning or pressure redistribution, and therefore our null hypothesis is that peak pressure distribution in any shod condition is equivalent to the barefoot walking condition. We expect that shod conditions will have more evenly distributed pressures. We also expect the temporal pattern of foot unroll in minimal footwear to be more similar to that of barefoot walking than to that of conventionally Western shod walking.

Materials and methods

Subjects

Four populations were studied. An Indian population (*N* = 34) consisted of adult males and females from in and around the rural village of Athani in the Southern state of Karnataka. A Scandinavian population (*N* = 36) consisted of male and female adults from in and around Inari, Northern Finland, of which a large fraction had a Sami background. A Namibian population (*N* = 33) consisted of adult males and females with a Juj'hoan San heritage at the Nyae-Nyae Concession Area, Otjizondjupa region. A Western population (*N* = 27) consisted of Caucasian male and females, mostly from Belgium. Of the 27 Western subjects 13 were also tested wearing their daily footwear, next to barefoot walking and with minimal footwear. Subjects with current or recent foot or lower limb injuries were excluded. Please see Table 1 and Table 2 for details.

***Table 1**. Indigenously shod group's mean (± standard deviation) biometrics.*

	Finland *n*=36 Barefoot & reindeer boot		India *n*=34 Barefoot & buffalo sandal		Namibia *n*=33 Barefoot and sandal	
	Male (*n*=14)	Female (*n*=22)	Male (*n*=20)	Female (*n*=14)	Male (*n*= 20)	Female (*n*= 13)
Age (years)	52 ± 15.8	46.3 ± 17.6	38.3 ± 10.2	39.6 ± 8.4	39.2 ± 15.7	37.6 ± 11
Mass (kg)	83.9 ± 14.2	65.2 ± 14.1	59.4 ± 11.5	55.4 ± 9.8	44.7 ± 8.3	46.2 ± 9.1
Height (m)	1.74 ± 0.07	1.61 ± 0.09	1.64 ± 0.05	1.49 ± 0.05	1.57 ± 0.09	1.53 ± 0.08
BMI	27.6 ± 4	25.3 ± 5.2	22 ± 3.8	24.8 ± 3.6	18.1 ± 2.4	19.7 ± 3.6

***Table 2**. Western group's mean (± standard deviation) biometrics for both the sub-group that walked barefoot and minimally shod, and the sub-group that walked barefoot, minimally shod and conventionally shod.*

	Belgium barefoot & Vivo *n*=27		Belgium Daily footwear *n*=13	
	Male (*n*=15)	Female (*n*=12)	Male (*n*=6)	Female (*n*=7)
Age(years/mean)	38.9 ± 11	33.5 ± 11.7	36.8 ± 9.7	33.5 ± 7.6
Mass (kg/mean)	84.1 ± 14.2	58.7 ± 6.3	82.5 ± 11.7	58.4 ± 5.9
Height (m/mean)	1.82 ± 0.06	1.69 ± 0.06	1.81 ± 0.06	1.69 ± 0.05
BMI (mean)	25.7 ± 3.6	20.6 ± 1.3	26.4 ± 2.4	20.7 ± 1.4

Materials

The following types of footwear were used.

The first type of indigenous footwear, used by the Indian population, is 'Kolhapuri' footwear, a type of sandal that fits tightly onto the foot through an instep strap, and that has a thin sole made of vegetable tanned buffalo leather, typically with a very thin heel offset created by an extra layer of buffalo leather (Figure 1(A)). The weight of an average single sandal is no more than 100 g (size 37 F). This type of footwear is used in a very hot climate.

The second type of indigenous footwear, used by the Scandinavian population, is 'Nuvttohat' or reindeer boot, as traditionally worn by the Sami people. This boot is made entirely from vegetable tanned reindeer hide and used in an extremely cold climate. Dried grass is used for insulation (and may provide some cushioning) (Figure 1(B)). The average weight of a boot is 220 g for a size 37 F.

A third type of indigenous footwear, used by the Namibian population, is the sandal of the Juj'hoan San (bushmen), N!ang n|osi , used in the southern parts of Africa and made from antelope (giant eland) skin. It is worn to protect the feet from hot sand and thorns. This indigenous sandal features a back-strap, and laces in between the big toe and other toes that keep the foot close to the sole (Figure 1(C)). The weight of an average single sandal is about 150 g for a size 37 F.

The commercial minimal shoe (Vivobarefoot The One), used by the Western population, is a sneaker with a 3 mm puncture-resistant outsole with a wide toe box to allow the toes to move freely (Figure 1(D)). Low mass is an important feature of the four types of footwear (three indigenous and the minimal Western sneaker), together with the absence of arch support and heel support. The commercial minimal shoes weighed 152 g for a size 37 F.

An RSScan Footscan USB (0.5 m version) with Footscan USB 7 Gait software, running on a laptop PC, was used for all pressure recordings. Calibration was regularly performed using the manufacturer's guidelines. Data were recorded at a temporal resolution of 300 fps and a spatial resolution of 7.62 mm along the long axis (walking direction) and 5.08 mm along the short axis (left-right) of the plate. The plate was installed indoors, on a flat and hard surface (see Figure 1(E,F,H)) when recording data of the Indian, the Scandinavian, and the Western subjects. For the recording of the Namibian data, the plate was installed outdoors, on an even terrain in their natural environment (see Figure 1(G)).

Figure 1. *(A) Southern Indian 'Kolhapuri' footwear. (B) Northern Scandinavian 'Nuvttohat'/reindeer boot. (C) Namibian Ju 'hoan San 'N!ang n|osi' sandal. (D) Vivobarefoot, 'The One' trainers. (E) Medio-lateral view of an Indian walking over the pressure mat while barefoot. (F) Medio-lateral view of a Scandinavian participant walking over the pressure mat while indigenously shod. (G) Medio-lateral view of a Namibian participant walking over the pressure mat while barefoot. (H) Anterior view of a Western participant standing on the pressure mat while minimally shod.*

Protocol

All subjects signed informed consent (approved by the University of Antwerp Ethics Committee; ethics number: B300201112278). We collected basic morphometrics (stature, mass, leg length as measured from the trochanter major to the ground, navicular height) as well as mechanical properties of the footwear in the Indian sub-study (for details, see Willems et al. 2017). Subjects were instructed to walk barefoot at preferred speed (assuming dynamically similar gait, see e.g. Alexander & Jayes, 2009) over the pressure plate, with at least three steps before and after the plate, so that the measured step is steady-state. We visually checked for acceleration or deceleration during the measured steps, which would exclude the trial from analysis. The effect of plate targeting was minimised by asking subjects to focus on a distant, eye-level mark. Several trials of normal, comfortable walking were recorded until we had three technically successful recordings for both the left and right foot.

The procedure was repeated for walking with the indigenous footwear for the Namibian, Indian and Scandinavian populations, or with commercial minimal footwear as well as the subject's own conventional footwear for in the Western population (Figure 1(C–E)). A total of 1465 trials were used for this analysis.

Analysis

Preparation of the pressure records

The numerical pressure data (N/cm^2) of every cell over time (s) were exported from the acquisition software to ASCII text files and imported into MatLab (Version 2017a), where all further analysis was performed. In a first step, the pressure images were resampled from the non-square pressure cells into square (5 mm x 5 mm) pixels, and right feet were mirrored, assuming population-level symmetry. From the resampled time series data (see Figure2), we generated footprint plots determining peak pressure for each pixel over the course of the step. We then calculated the average pressure for these 2 D peak pressure matrices and divided every pressure matrix by its respective average, generating relative plantar pressure distribution matrices. This allows for comparisons between the plantar pressure distributions of participants between the populations.

Linear image registration and analysis

Biological data are variable; no two pressure records are identical. To compare pressure records statistically, two approaches can be used. One often-used method requires the selection of landmarks which can then be compared. We choose another method, pedobarographic Statistical Parametric Mapping (Pataky, 2008; Pataky & Goulermas, 2008) that does not require selection of landmarks (which might be difficult between footwear conditions) and performs pixel-level statistics on the entire pressure record. To do this, foot recordings need to be registered so that they show maximal overlap, regardless of the orientation of the foot on the plate, or of the absolute size of the foot. The six records per category (population x condition) were registered within the category (see Pataky, Goulermas, et al., 2008) and averaged. The averaged records were registered between subjects. Consequently, the shod images were registered to the barefoot ones and averaged, allowing for comparisons between conditions.

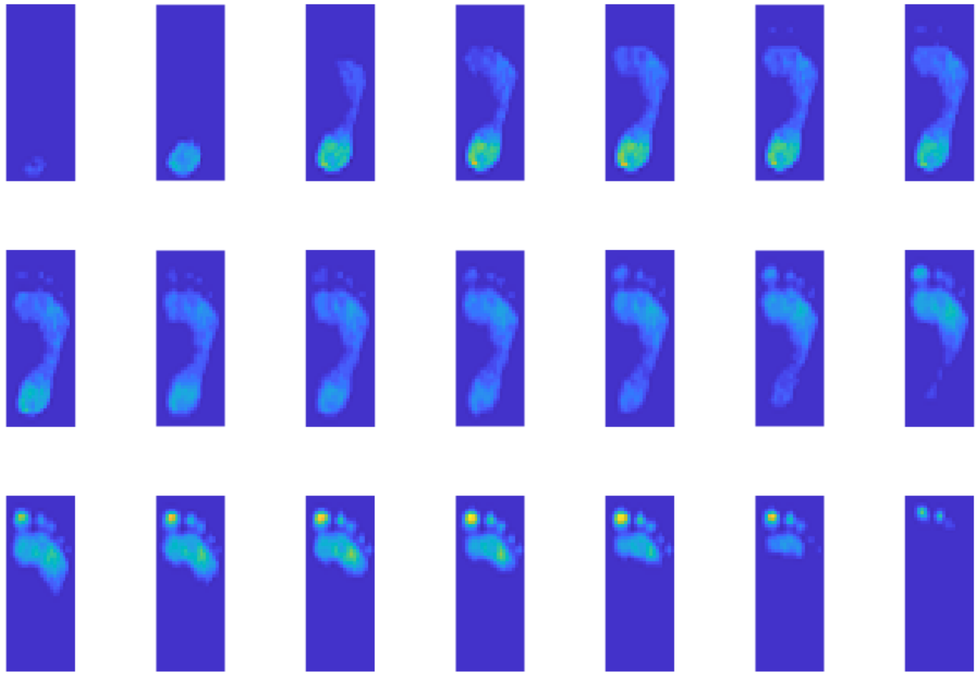

Figure 2. *Example temporal roll-off in a barefoot walking Indian Male. The full trail consists of 206 frames and the plots show the frames corresponding with 5% intervals, in which 0% corresponds to heel strike and 100% corresponds to toe-off (cooler colours represent relatively low pressure, warmer colours represent relatively high pressure).*

We applied this method to the barefoot and indigenously or commercial minimally shod data. This method was also applied to the conventional Western footwear data in the Western data set. However, not enough data was collected for the conventional condition for this analysis method to make conclusive statements. Therefore, we deemed it inappropriate to include in the main body of the paper. These comparisons are available as Appendix 1.

Foot unroll analysis

A subset of 13 Western subjects had plantar pressure distribution measurements taken in barefoot, minimally shod and 'conventionally' shod conditions (where conventionally shod refers to a wide range of footwear that western populations would typically wear during their daily lives). The data was analysed in order to investigate variations of *timing* of the foot unroll in the different conditions, in addition to the relative pressure distribution. Because the Centre of Pressure is calculated on the entire footprint, we deem it to be a robust metric that can be compared between conditions, including the conventional Western shod one (even though the latter's pressures, as such, are highly variable).
The previously prepared resampled time series data of the plantar pressure data is a 3 D matrix (width x height x time) and was used as the starting point for the foot unroll analysis. This data was linearly interpolated about the temporal axis for 101 frames (i.e., 0-100% stance). Each frame was then spatially normalised using the same scaling transformations calculated from the Western 2 D peak pressure matrices (linear image registration and analysis section) for each respective print. The prints were grouped into their respective conditions and mean foot unroll timings were calculated for each group. Foot unroll timings are quantified as the displacement of the CoP from heel to toes along the temporal axis of the registered pressure records. CoP coordinates were calculated, frame by frame, as the weighted average of pressure along the linearly interpolated temporal axis. CoP from each time frame and from each condition were plotted to show the 2 D position of the entire foot unroll for each condition (Figure 7). Proximal/ Distal displacement per frame, and Lateral/Medial displacement were also plotted for the three conditions (Figures 8 and 9, respectively). We then compared the results of three conditions, pairwise, using one dimensional statistical parametric mapping (1 D-SPM) in order to discover significant variations during the stance phase between any two conditions. 1 D-SPM works by detecting field changes in smooth one-dimensional continua (Pataky, 2012).

Results

Peak pressure distribution

In general, peak plantar distribution (or relative pressure recordings) between any minimal condition (indigenous or commercial) and barefoot walking were qualitatively similar, and differences did not reach statistical significance. Indeed, even in the shod condition, the heel, hallux, and metatarsal head region can be easily identified whilst wearing indigenous and minimal shoes. The locations of maximal relative pressure seem to correspond well.

Indian sample

Comparing the full data set for barefoot relative pressure recordings with that for indigenously shod walking shows a good correspondence (Figure 3). The only visual difference between the two relative pressure recordings is that the region of relatively high pressure about the metatarsal head region is smaller in the shod condition. This is largely dueto the additional size of the shoe skewing the perception of the scale. The shod print shows a zone of slight relative pressure distally to the toes due to the presence of a sole that extends beyond the toes. In accordance with the visual correspondence, the pSPM analysis shows no significantly different regions between the two conditions.

Scandinavian sample

Comparing the full data set for barefoot relative pressure recordings with that for indigenously shod walking shows a good correspondence (Figure 4). The visual difference between the two relative pressure recordings is that the region of relatively high pressure about the metatarsal head region is smaller in the shod condition. In accordance withthe visual correspondence the pSPM analysis shows no significantly different regions between the two conditions.

Namibian sample

Comparing the full data set for barefoot relative pressure recordings with that for indigenously shod walking shows some correspondence (Figure 5). The locations of the heel and hallux correspond well between the two trails however the pressure distribution of the metatarsal heads II-III is both proximal and lateral to that in the barefoot condition. In accordance with the visual correspondence the pSPM analysis shows no significantly different regions between the two conditions.

Western sample

Comparing the full data set for barefoot relative pressure recordings with that for commercial minimally shod walking shows a good correspondence (Figure 6). However, the toe region in the shod condition appears to be more condensed than the barefoot condition in the lateral-medial plane. Thisis likely due to the shape of the toe box area of the shoe. In accordance with the visual correspondence the pSPM analysis shows no regions of significance between the two conditions. We did not involve the conventionally Western shod trials in this population-level quantitative analysis, because of the large variation in footwear types, but within-subject comparisons for all subjects are available in Appendix 1. Pressure distribution of conventional Western footwear were very variable and visually different.

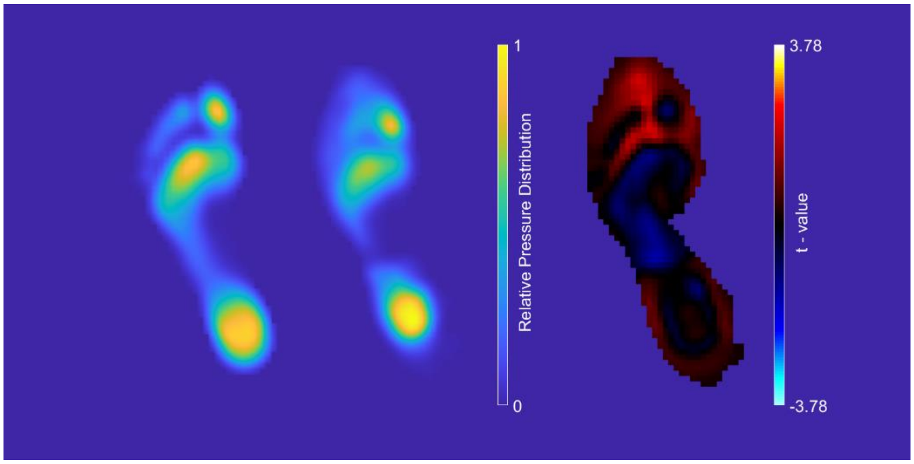

Figure 3. *Comparison of relative pressures for the Indian sample (34 barefoot participants and 34 shod participants with 195 and 198 trials for barefoot and shod participants respectively). From left to right: Average barefoot pressure; Average shod pressure; Raw t values of the statistical inference where cooler colours (blue) correspond to pixels where the barefoot pressure is higher and warmer colours (red-yellow) correspond to pixels where the shod pressure is higher. The colour bar on the furthest right reflects t values with the limits set to t-critical (the minimum value needed to be reached for a statistical significance given alpha set to 0.05). No statistical differences observed.*

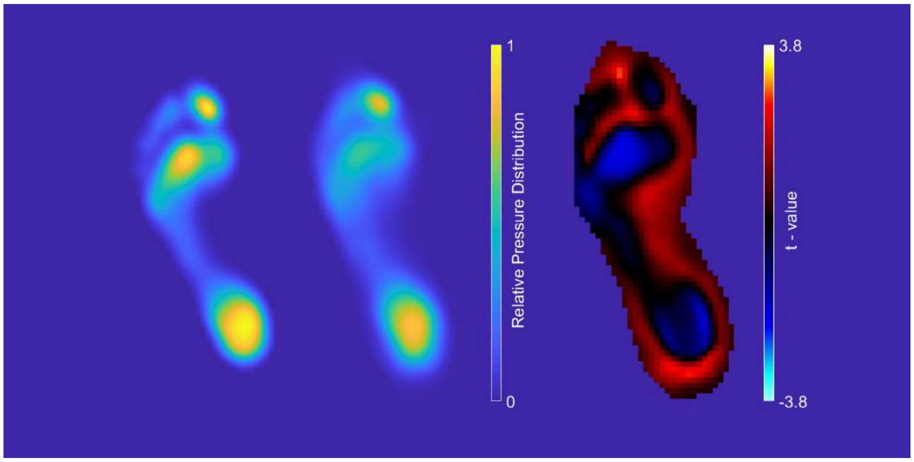

Figure 4. *Comparison of relative pressures across for the Scandinavian sample (36 barefoot and shod participants with 216 trials for both groups). From left to right: Average barefoot pressure; Average shod pressures; Raw t values of the statistical inference where cooler colours (blue) correspond to pixels where the barefoot pressure is higher and warmer colours (red-yellow) correspond to pixels where the shod pressure is higher. The colour bar on the furthest right reflects t values with the limits set to t-critical (the minimum value needed to be reached for a statistical significance given alpha set to 0.05). No statistical differences observed.*

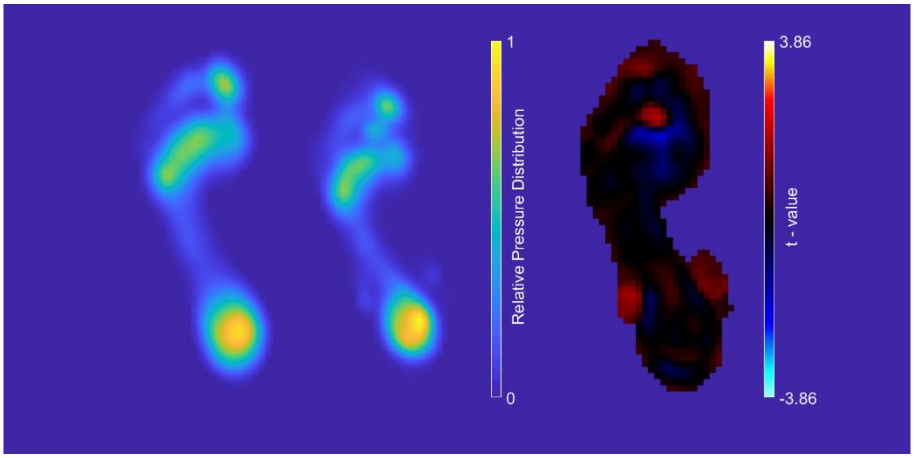

Figure 5. *Comparison of relative pressures for the Namibian sample (33 barefoot participants and 19 shod participants with 199 and 116 trials for barefoot and shod participants respectively). From left to right: Average barefoot pressure; Average shod pressures; Raw t values of the statistical inference where cooler colours (blue) correspond to pixels where the barefoot pressure is higher and warmer colours (red-yellow) correspond to pixels where the shod pressure is higher. The colour bar on the furthest right reflects t values with the limits set to t-critical (the minimum value needed to be reached for a statistical significance given alpha set to 0.05). No statistical differences observed.*

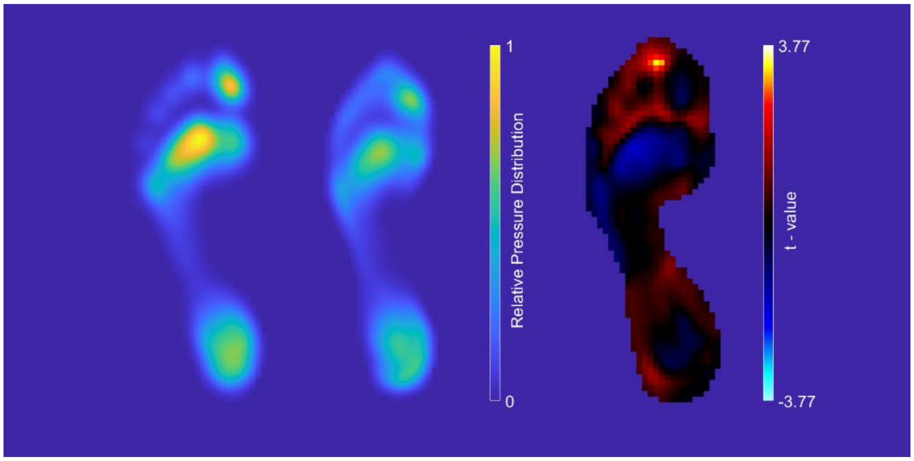

Figure 6. *Comparison of barefoot versus minimal footwear for the Western sample (27 participants with 163 trials and 162 trials for barefoot and minimally shod groups respectively). From left to right: Average barefoot pressure; Average shod pressures; Raw t values of the statistical inference where cooler colours (blue) correspond to pixels where the barefoot pressure is higher and warmer colours (red-yellow) correspond to pixels where the shod pressure is higher. The colour bar on the furthest right reflects t values with the limits set to t-critical (the minimum value needed to be reached for a statistical significance given alpha set to 0.05). No statistical differences observed.*

Roll-off timing

For the Western data, Centre of Pressure (CoP) trajectories were compared between three conditions: barefoot, commercial minimal shoes and conventional Western shoes (Figure 7).

The timing of the foot roll-off, as shown by the Centre of Pressure (CoP) did show significant differences between conventional Western footwear and both minimally shod and barefoot walking, most clearly in the mediolateral direction during mid-stance (Figures 8 and 9). Here we describe foot unroll along the proximal-to-distal and along the medio-lateral axis.

Proximo-distally, all conditions show a similar overall pattern involving an initial fast progression (0–20% of stance), followed by a slower progression during most of stance, and concluded by a fast progression during push-off (90–100%, see Figure 8). Despite their overall similarity, significant differences between the patterns of the three conditions exist.

When the conventionally shod walking condition is compared to the barefoot walking condition, the following significant differences are found. The CoP is more proximal initially (0–20% stance), then more distal (20–60%), thus moving faster early in stance. The clearest difference occurs during push-off (90–100% stance) when the CoP moves more distally.

When minimally shod is compared to barefoot,a similar but less pronounced pattern is observed.

When the two footwear conditions are compared, the only clear difference is from 30% to 50% of stance, where the conventional shoe has a more distal CoP.

On the whole, barefoot and conventionally shod walking show the greatest differences, with minimally shod walking as an intermediate but more similar to barefoot.

Medio-laterally, again all three conditions show a similar overall pattern. After a brief medial displacement (0–10% stance), the CoP moves laterally and keeps doing so until toe-off where a brief medial displacement happens but only when barefoot. Significant differences between the three conditions are only found in mid-stance, where the conventionally shod condition follows a more medial CoP trajectory than the two other conditions (which do not differ between them).

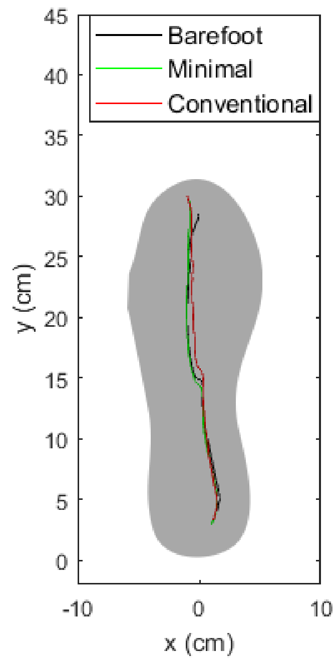

***Figure 7**. Mean CoP trajectories in the x–y plane for the Western sample.*

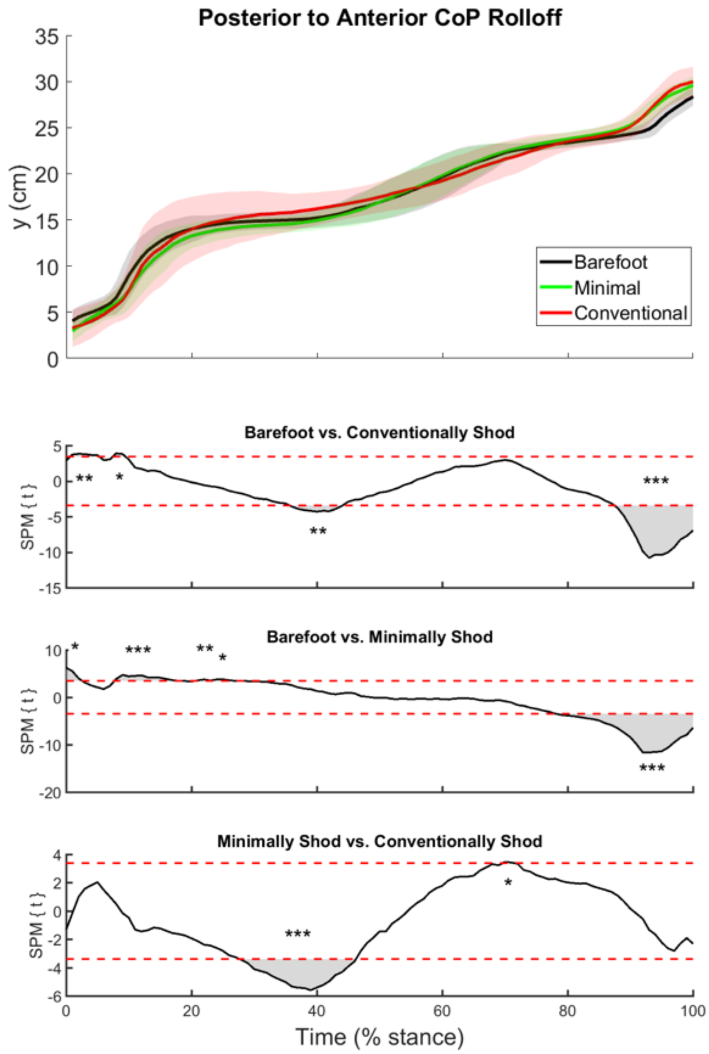

Figure 8. *Top to Bottom: (1) Posterior to anterior Centre of Pressure (CoP) roll-off from 13 Western participants, comparing barefoot, minimally and conventionally shod walking (77, 82, 81, trials respectively). (2–4) 1 D – SPM, 2 sample t-test with Bonferroni correction showing areas of significant differences between the three possible comparisons. Alpha 0.02 as derived from the Bonferroni calculation for all 1 D – SPM plots; t-critical is shown by the red dotted lines in each plot.difference, and additional experiments on a largerpopulation might clarify this.*

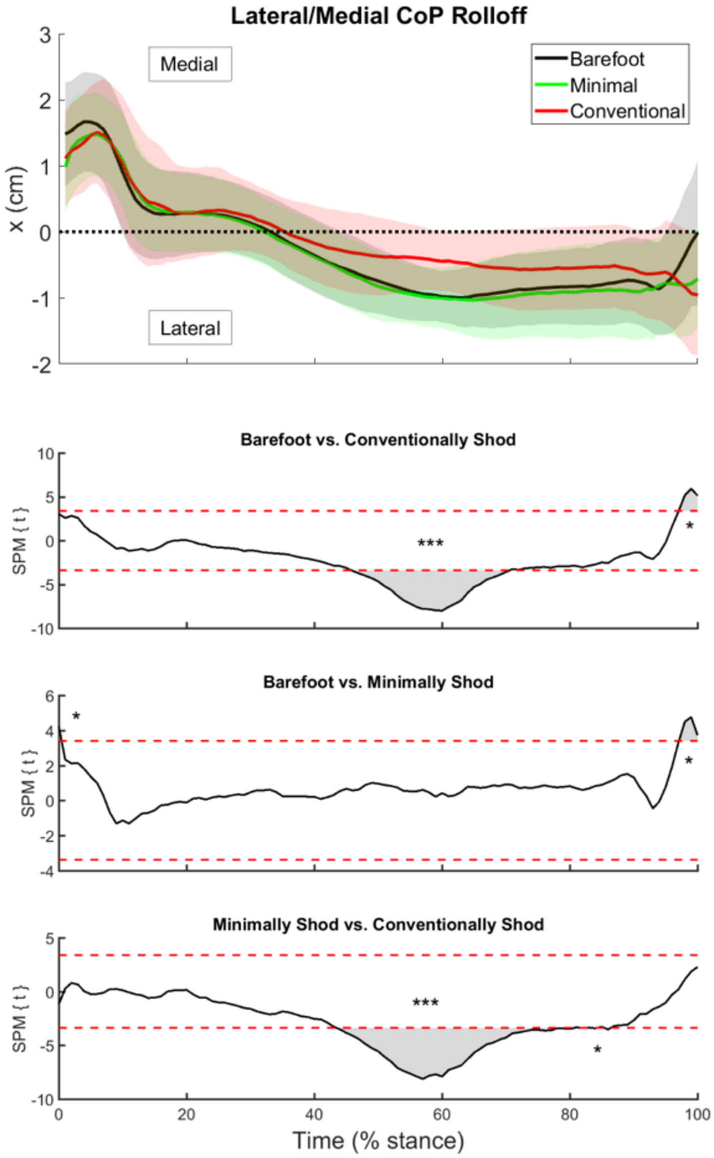

Figure 9. *Top to Bottom: (1) Medial/Lateral Centre of Pressure (CoP) roll-off from 13 Western participants, comparing barefoot, minimally and conventionally shod walking (77, 82, 81, trials respectively). (2–4) 1 D – SPM, 2 sample t-test with Bonferroni correction showing areas of significant differences between the three possible comparisons. Alpha 0.02 as derived from the Bonferroni calculation for all 1 D – SPM plots; t-critical is shown by the red dotted lines in each plot.*

Discussion

In this study, we addressed two main questions. The first question was whether the relative distribution of peak pressures differs between barefoot and shod walking with indigenous or commercial minimal shoes. The second question was whether there were differences in the timing of unroll between three footwear conditions (barefoot, commercial minimal, conventional Western) within one, Western, population.

Shod versus barefoot walking: within-group comparisons of peak pressure distribution

Visual inspection of the relative peak pressure plots reveals close matches between pressure distributions when barefoot, and when using indigenous footwear as well as commercial 'minimal' footwear (Figures 3–6). However, the distributions are not identical and there are visual differences between barefoot and shod relative peak pressure plots. These do not show as significant in the pSPM analyses. It should be noted that variation in the data is large and our sample size is moderate. This might explain the absence of a statistically significant difference, and additional experiments on a larger population might clarify this.

We hypothesised that, since any shoe likely provides some degree of cushioning, peak pressures in any shod condition would be more spatially distributed (and therefore lower on average) than in barefoot walking. This appears to be generally the case in all four populations for the anatomical zones that have the highest relative pressure: the heel, metatarsal (esp.II–III) heads, and the hallux. In contrast, zones that receive low pressures when barefoot, typically show higher pressures when shod. An exception is the midfoot in the Indian sample, which shows a lower peak pressure when shod. This can probably be explained by the presence of a very low heel and stiff outsole in the indigenous shoes, lifting the midfoot off the substrate in many cases. The medial midfoot region is least prone to wear and, therefore, the natural tanned buffalo hide is relatively stiff in that area (Willems et al., 2017).

The combined effect of the general reduction in pressure of high-pressure zones and increased pressure in low-pressure zones is that, as expected, pressures are more equally distributed over a larger area when shod, at least at the level of the shoe-substrate interface.

In the case of the Scandinavian population, it should be mentioned that the indigenous footwear is manufactured to perform best on snow and ice, and that this footwear is traditionally used without a sock, but with a padding of 'kinkaheina' grass. We collected data on a hard surface and thus the pressures experienced when walking on snow would probably be even lower than on our pressure plate, or on ice.

Interestingly, the subtle pattern of more uniform peak pressures, seen in indigenously or minimally shod conditions, bears resemblance to a similar pattern of more uniform peak pressures in habitually barefoot Indians when compared to habitually shod (but barefoot walking in the experiments) peers (D'Août et al., 2009). It could be questioned whether there might be a mechanical explanation for this similarity, i.e. do habitual barefoot walkers have a thicker foot sole functioning in a similar fashion to the very thin leather soles seen in our indigenous footwear, or to the thin rubber sole of commercial minimal shoes? A recent study on foot calluses in barefoot and shod walkers suggests this might be the case (Holowka et al., 2019).

It should be stressed that plantar pressure recordings, while providing crucial information on the interface between the walking humans and their mechanical environment, do not provide a full picture of the complexity of walking, and differences between shod and barefoot walking have been well established by kinematics and kinetics (e.g. a variety of Western footwear, Zhang et al., 2013; flip-flops, Chard et al., 2012, 2013; indigenous footwear, Willems et al., 2017). Walking barefoot, compared to shod walking proved to yield slightly higher impact accelerations, at least on a hard substrate (Willems et al., 2017).

Roll-off timing

Our second hypothesis was that the temporal pattern of foot unroll in minimal footwear would bemore similar to that of barefoot walking, than is the case for conventionally shod walking. Temporal analysis of the Western sample, comparing barefoot with minimally and conventionally shod conditions, suggests that this is partially true. The indigenous or minimal footwear exhibits some temporal patterns similar to the barefoot condition, but also some patterns similar to conventionally shod walking for both proximal/distal and lateral/medial analysis (Figures 8 and 9). In short, indigenous or commercial minimal footwear appears to be a mid-point between walking barefoot and walking conventionally shod. This finding is in keeping with the systematic literature review comparing the current work on barefoot and conventionally shod walking (Franklin et al., 2015).

Methodological challenges

The Indian, Namibian and Scandinavian data for this study were collected in rural settings, by bringing in equipment and setting up a temporal 'gait laboratory'. While this approach has been necessary, and fruitful, to collect the unique data of indigenously shod populations, it does limit technical possibilities. For example, two standard pieces of equipment of a conventional gait lab, force platesand a 3 D motion-capture system, could not be used. A plantar pressure plate is portable and hasbeen successfully used to study walking in field settings before (D'Août et al., 2009; Stolwijk et al., 2013).

The use of plantar pressure plates has been well established and poses few technical issues. While the magnitudes of the recorded pressures might not be as accurate as the forces recorded by a force plate, results from pressure plates provide a good overview of relative pressure distribution and are reliable, even between manufacturers (see Hafer et al., 2013). The main challenge with the use of footwear on a pressure plate is: how do these pressures relate to the pressures experienced by the foot? This question cannot be answered with certainty; this would require simultaneous recording of pressure data using a pressure plate and an insole system. (For overviews of the use of pressure plates and insoles, see e.g. Abdul Razak et al., 2012; Barnett et al., 2001; Giacomozzi et al., 2012; Low & Dixon, 2010.)

Few studies have addressed shod locomotion, running, on a pressure plate but they have focussed on CoP displacement and not on a complete spatial analysis of the pressures themselves (e.g. Dixon & McNally, 2008; Greenhalgh et al., 2014). In the caseof our indigenous footwear and commercial minimal shoes, however, the correspondence between shod and barefoot prints is striking, and even shod prints reveal a good degree of anatomical detail such as a clearly defined hallux. We hypothesise that the pressures as measured by the plate correlate closely to what the foot experiences. It should be noted that all soles (except for the conventional Western shoes) are only a few mm thick, relatively hard but flexible.

The use of pressure sensitive insoles worn inside shoes has one advantage over the use of a plate, in that they measure the interface between the foot and the substrate rather than the ground-shoe interface. Insoles have indeed been used extensively in non-minimal footwear, where plate pressures could potentially be very different from plantar pressures. However, the use of pressure insoles would be a challenge in the barefoot condition as they would require some form of gluing or use of a sock (e.g. Burnfield et al., 2004), potentially affecting results, and mechanical issues such as slipping might occur. The mixed use of insoles in the shod condition but of a plate in the barefoot condition is not preferable if a direct comparison (as in this study), without technical confounding factors, is to be made. For these reasons, we opted to use a pressure plate rather than insoles, but it should be borne in mind that they report on the interface between the substrate and any structure in contact with it, whether it is a bare foot or a shoe.

The use of pixel-based pSPM instead of zone based analyses has been shown to give valid and objective results without prior anatomical assumptions (e.g. Bates et al., 2013; Pataky, Caravaggi et al., 2008; Pataky & Goulermas, 2008). Image registration between different shaped plots (e.g. barefoot versus shod) is not unequivocal, and although non-linear registration (Pataky et al., 2011) is a suitable solution for plots made by comparable morphologies, in the future it would be worth exploring to what extent registration mightimpact the results between barefoot and shod prints.

Based on plantar pressure recordings, we conclude that all three types of indigenous footwear, as well as commercial minimal shoes, can functionally be considered 'minimal footwear'.

When comparing Western conventional footwear with minimal footwear and barefoot walking, there are subtle but significant differences regarding temporal patterns.

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Disclosure statement

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Appendix 1

Barefoot, minimally and conventionally shod walking plantar pressure data was collected from 13 participants. The differences between the barefoot and minimally shod conditions compared to the conventionally shod condition are clear just by simply visual inspection of the 1st print (out of 6 trails or more) per condition for each participant (Figure 10). It can be seen that the barefoot and minimal prints many similar characteristics. They both have a clear toe, ball, midfoot and heel region in all the prints displayed in these conditions. They also have a very comparable shape. The conventional condition on the other hand does not have these clearly defined regions or a similar shape. And where the barefoot and minimal conditions are consistent throughout the participants within their respective conditions, the conventional condition is not. The highly varied nature of the prints displayed proves how variable walking in conventional footwear is.

Pedobarographic Statistical Parametric Mapping was applied to the barefoot vs. conventionally shod conditions in the western subset, and the results can be seen in Figure 11. The barefoot average relative pressure distribution has three distinct pressure points, located at the hallux, heel and most notable, the ball of the foot. The conventionally shod average relative pressure distribution has one notable pressure point at the heel that is lower than the relative pressure experienced at the ball of the foot, meaning that pressure is more evenly distributed in conventional footwear. This does not mean that walking in conventional footwear reduces pressure as the comparison is made between relative pressure distributions and conventional footwear increases the area pressure can be dissipated through during impact. In contrast with the visual correspondence, the pSPM analysis shows no significantly different regions between the two conditions. This is likely due to two factors: firstly, the small sample size and secondly, the level of variation in the conventional condition. These factors combined makes it likely that the variation within the conventional condition hide any statistically significant difference between the two conditions, despite the clear visual differences between the averages of the two conditions. This is just speculation however, further work is required with a larger subset, in order to determine any significant differences between conventionally shod walking and barefoot walking.

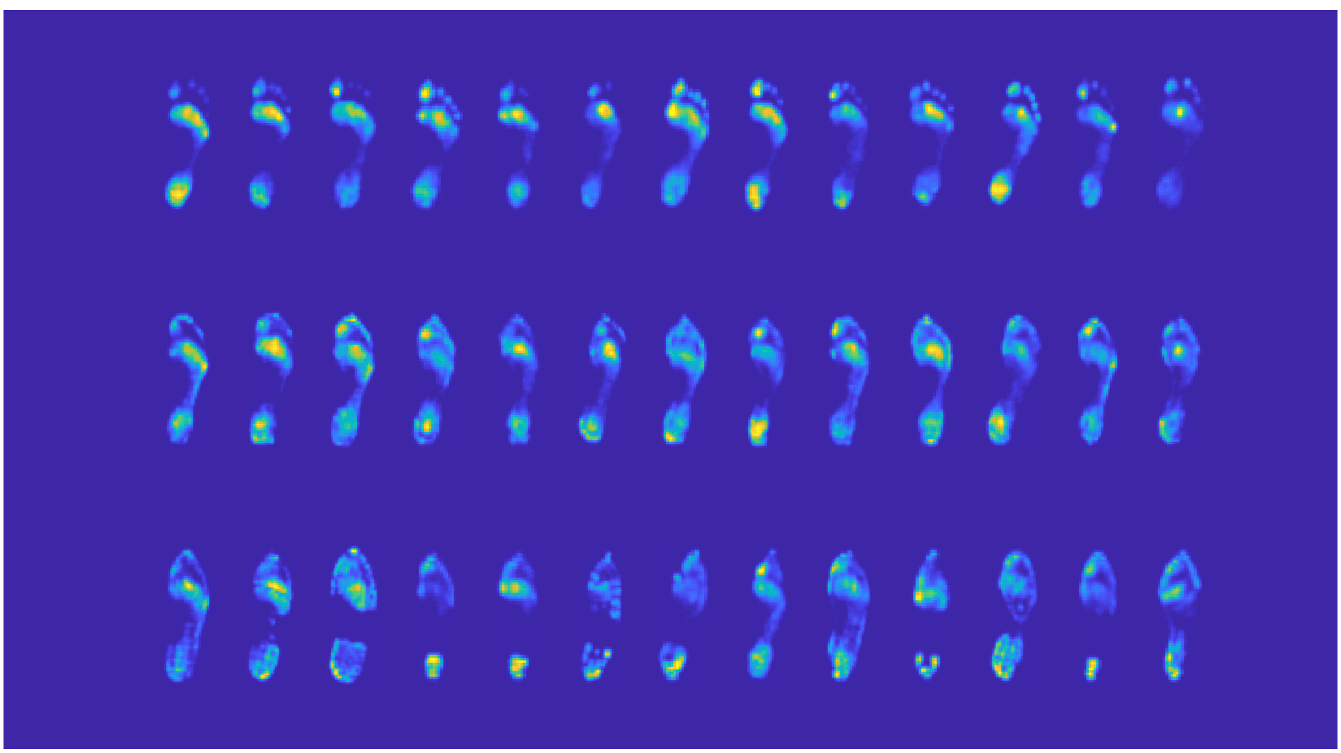

Figure 10. *Normalised max pressure prints from the 13 Western participants that walked barefoot, minimally shod and conventionally shod. Each column is a participant and each row is a condition (top row: barefoot; middle row: minimal; bottom row: conventional).*

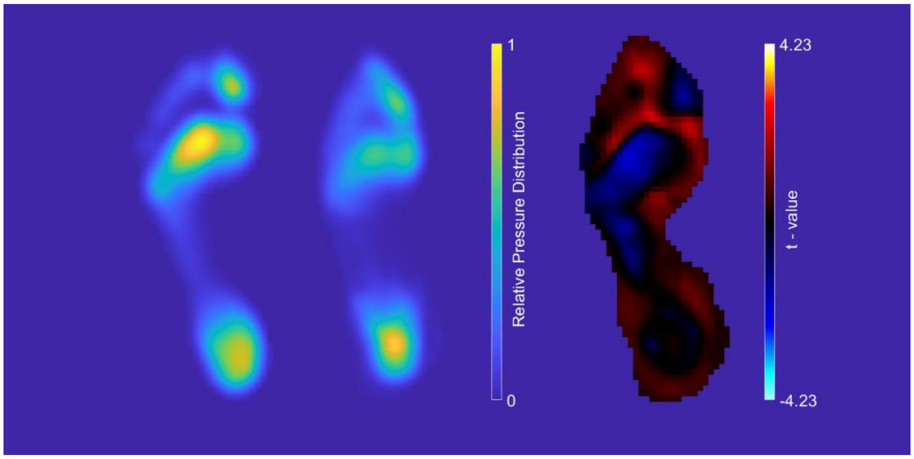

Figure 11. *Comparison of barefoot versus conventional footwear for the Western participants (13 participants with 77 trials and 81 trials for barefoot and conventionally shod groups respectively). From left to right: Average barefoot pressure; Average shod pressures; Raw t values of the statistical inference where cooler colours (blue) correspond to pixels where the barefoot pressure is higher and warmer colours (red-yellow) correspond to pixels where the shod pressure is higher. The colour bar on the furthest right reflects t values with the limits set to t-critical (the minimum value needed to be reached for a statistical significance given alpha set to 0.05). No statistical differences observed.*