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Hallux anatomy: much ado about shoes—an attempt to prove that constrictive V-shaped toe-box shoes deform the hallux

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Abstract

Purpose A question still remains as to whether constrictive toe-box shoes (TBS) cause disability only due to pain on pressure points or if they can cause permanent changes in the hallux anatomy. The aim of this study is to compare the hallux morphology in 3 groups classified according to their use of constrictive or open TBS.

Methods 424 patients were classified into 3 groups: group A used open TBS daily; group B used constrictive TBS daily; group C used both open and constrictive TBS. Hallux's angles, presence of exostoses and shape of the distal phalanx (DP) were analyzed on dorsoplantar weight-bearing radiographs and compared amongst groups.

Results The intermetatarsal (IMA), metatarsophalangeal (MTPA), DASA, PASA, interphalangeal (IPA), obliquity (AP1), asymmetry (AP2) and joint deviation (JDA) angles for group A were 10°, 8°, 5°, 4°, 9°, 3°, 5°, 3°; for group B were 9°, 19°, 5°, 6°, 12°, 2°, 8°, 2°; and for group C were 10°, 10°, 4°, 4°, 12°, 3°, 8°, 1°. Only the differences in the MTPA, IPA and AP2 were statistically significant ($p < 0.05$). The prevalence of exostoses on the tibial side of the DP was 22, 36, and 29% in groups A, B and C, respectively ($p < 0.05$). We found similar distributions of the different DP shapes in the three groups.

Conclusions Our results suggest that the use of constrictive TBS, even if used only occasionally, could change hallux anatomy from a young age increasing MTPA, IPA and AP2. Moreover, we have found that DP exostoses are present as a "normal variation" in patients who wear an open TBS, but their prevalence is higher in those wearing constrictive toe-box shoes. This could be due to a reactive bone formation secondary to the friction caused by the inner border of the shoe.

Level of clinical evidence 3.

Keywords Hallux anatomy · Hallux valgus · Shoes · Triangular toe-box shoes · Exostosis · Hallux distal phalanx · Hallux angles

Introduction

According to SEMCPT (Spanish Foot an Ankle Medicine and Surgery Society) hallux disability constitutes 40–60% of the reasons for consultation of a foot practice. It has an important social and economic repercussion. In the United States, surgery of the first ray accounts for more than 200,000 operations per year. The greatest concern is that hallux valgus deformity comes along with muscular and ligamentous imbalance and can cause secondary deformities of lateral toes [1]. Painful hyperkeratosis secondary to exostoses of hallux distal phalanx (DP) has also gained importance recently in the literature and in scientific meetings, and has been postulated as a possible source of complications after correction of hallux valgus [2, 3].

Traditionally, a certain genetic component has been considered at least partially responsible for the development of

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hallux valgus (HV) [4–6]. However, recent studies indicate that no genetic inheritance exists as such but that shared environmental factors determine the development of a HV [7]. Some authors suggest that the use of constrictive footwear produces pressure on the medial aspect of the hallux and can lead to both reactive bone formations at that level (exostosis of DP), and valgus deviations of the first toe [3, 8–15].

Despite having found differences between groups of people who use regular closed or open footwear, there is still some controversy because some of these studies compared 2 groups that, in addition to using different footwear, were of different ethnicity [16]. Furthermore, while some authors describe variations in the angles of the hallux based on ethnicity, others state that there are none [17, 18]. The studies that determine the normal angles and anatomy of the first toe have classically included people who usually wear closed shoes, but there are not many studies of hallux morphology in people that walk barefoot or use open toe-box shoes [16, 19].

Woman's shoe design is very influenced by tradition and fashion, which do not consider the fact that a triangular tip of the shoe (convergent or V-shaped) can cause changes in the morphology of the forefoot [12]. Several studies have linked development of hallux valgus with narrow toe-box (V-shaped) shoes, that is, a small width of the space in which the fingers are lodged producing the effect of a funnel [20, 21].

The presence of exostoses of DP is not described in depth in classic or current books of anatomy. Although these bony excrescences have been the subject of some studies, their clinical significance is unknown [3]. Some authors sustain DP exostoses are a calcification of the insertion zone of a DP ligament and others that it they are a reactive bone formation secondary to the friction or pressure against the inner border of the shoe [3, 22, 23]. Complaints secondary to these exostoses have been first reported in patients with surgical overcorrection of hallux valgus [2]. Anyhow, there is no consensus among the scientific community regarding its prevalence in asymptomatic people [3].

The aim of this study is to describe the foot's first ray's morphology in terms of angles, presence of exostoses and shape of DP in three groups that use different kinds of toe-box shoes.

Patients/materials and methods

We analyzed 424 feet of patients who came to the foot clinic for any reason that required a foot AP radiograph, other than first ray disability. The patients were divided in three groups. The 60 patients who wore open toe-box shoes were included in group A. This population had a mean age of 30 (SD 15) years and belonged to a rural area of the Democratic Republic of the Congo. The 229 patients who wore constrictive toe-box shoes were included in group B. This population had a mean age of 37 (SD 24) years and belonged to our clinic in Spain. The 135 patients who wore constrictive and open toe-box shoes indistinctively were included in group C. The patients in this last group did not wear the constrictive toe-box shoes on a daily basis and use them only for special occasions (weddings, celebrations, weekends). This population had a mean age of 36 (SD 14) years and belonged to an urban area of the Democratic Republic of the Congo. Considering the mean MTPA differences reported between patients wearing closed and open toe-box shoes in the literature and assuming an alpha of 0.05 and a power 0f 0.85 a sample size of 53 patients per group was estimated.

Given the differences in mean age found in our groups, we also compared the angles in different age groups to analyze if age made a difference in the hallux angles. We divided the sample in three groups (Table 1): patients 19 years old or younger (125 patients [29.5%]: 17 in group A, 92 in group B, 16 in group C), patients between 19 and 37 years old (112 patients [26.2%]: 29 in group A, 18 in group B, 65 in group C) and finally patients aged 37 or older with arthritic changes (187 cases [44.2%]: 14 in group A, 119 in group B, 54 in group C). This division was not arbitrary, it allowed us to divide the smallest group (group A with patients who usually use open toe-box shoes) equally, leaving more or less half of its population in the intermediate age group and the other half divided in the youngest and oldest group. This allowed us to compare the three types of shoe groups by age group to make sure that the differences we observed were not due to the mean age difference between groups.

Our inclusion criteria included patients with a dorsoplantar weight-bearing foot radiograph of one foot and no pain or other symptoms specifically on the first ray of the foot. Exclusion criteria were deforming arthritis, previous foot surgery or neurological disease.

The proximal angles, intermetatarsal angle (IMA), metatarsophalangeal angle (MTPA), distal articular set angle (DASA), and proximal articular set angle (PASA) were measured according to standard guidelines by the same examiner on dorsoplantar weight bearing radiographs

Table 1 Age distribution in the three groups

Age	Group A: Open toe-box shoe	Group B: Constrictive toe-box shoe	Group C: Constrictive and open toe-box	Total
< 19	17	92	16	125
20–37	29	18	65	112
> 37	14	119	54	187
Total	60	229	135	424

centered in the middle of the third metatarsal bone (Fig. 1) [8, 9, 12].

The distal angles, interphalangeal angle (IPA) factorized in asymmetry angle (AP2), obliquity angle (AP1), and joint deviation angle (JDA) were also measured as described in the literature (Fig. 2). Sorto et al. described the AP2 as the angular relationship between a tangent line to articular surface of the base of the DP and a perpendicular to the longitudinal bisection of the DP; the AP1 as the angular relationship between a perpendicular line to the bisection of the proximal phalanx and a tangent line to the distal articular surface of the proximal phalanx; and the JDA as the angle between the tangent lines to the articular surface of the proximal phalangeal head and the distal phalangeal base (Fig. 2) [24].

Metatarsal formula and digital formula—or coronal plane alignment of the metatarsal heads and toes, respectively—were evaluated too as described by Viladot et al. [1, 25].

The shape of the DP of the hallux was also analyzed and classified into three groups according to the diaphyseal length and base width ratio of the DP (Fig. 3a–c):

Longitudinal phalanx (Fig. 3a): DP with a narrow base and a disproportionate long diaphysis regarding the rest of structures. The distal tuberosity was slimmed following the shaft.

Pyramidal phalanx (Fig. 3b): DP with a wide base and a slim shaft that became progressively narrower and finishing in a small distal tuberosity. This morphology did not allow clear discrimination of the base of the shaft and distal tuberosity.

Standard phalanx (Fig. 3c): DP with a clear wide base, followed by a short shaft and finishing in a wider distal ungual tuberosity. This shape is the one described as anatomical in classic texts.

We examined the DP looking for the presence or absence of medial or lateral exostoses and their correlation with the other measurements (Fig. 4).

Statistical analysis was performed using STATA 12.0 for macOS. Kruskal–Wallis test was used to compare the mean angles between two groups and ANOVA when there were more than two groups. Chi-squared test was used to compare proportion. Simple linear regression was used to evaluate the influence of constant variables (angles). The $p < 0.05$ was considered to indicate statistical significance.

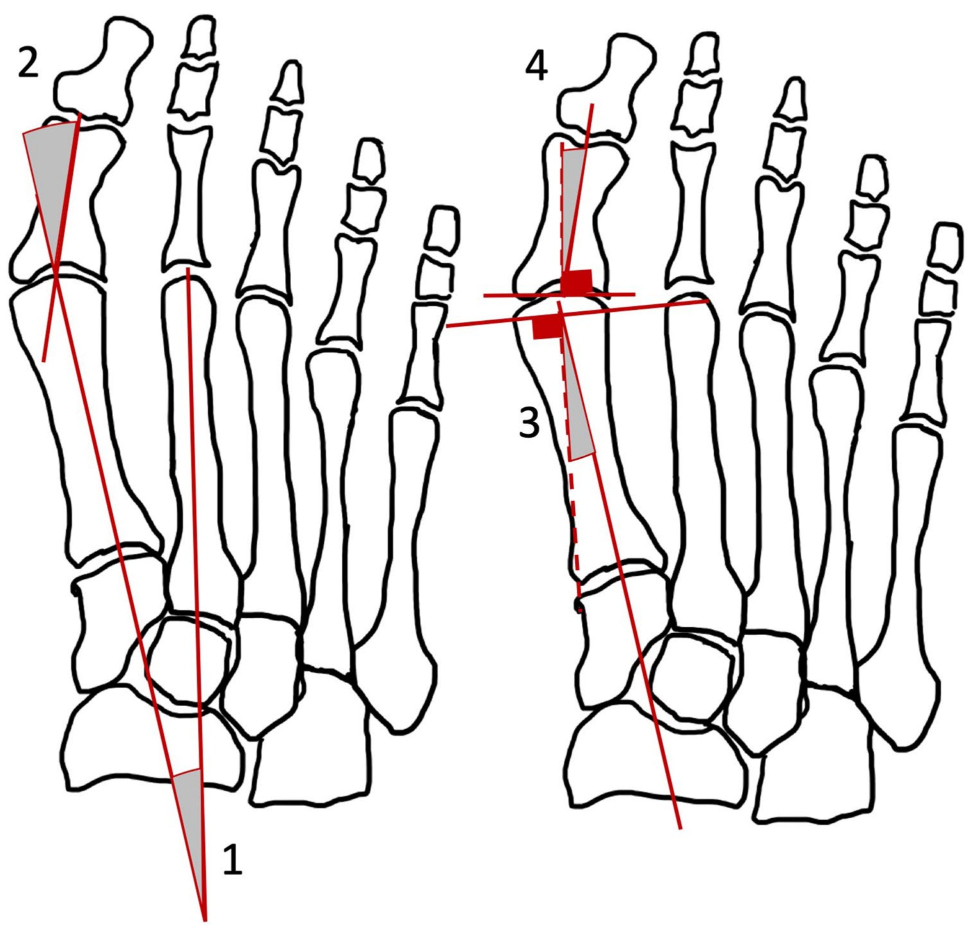

Fig. 1 Proximal angles: (1) intermetatarsal angle (IMA), (2) metatarsophalangeal angle (MTPA), (3) proximal articular set angle (PASA), (4) distal articular set angle (DASA)

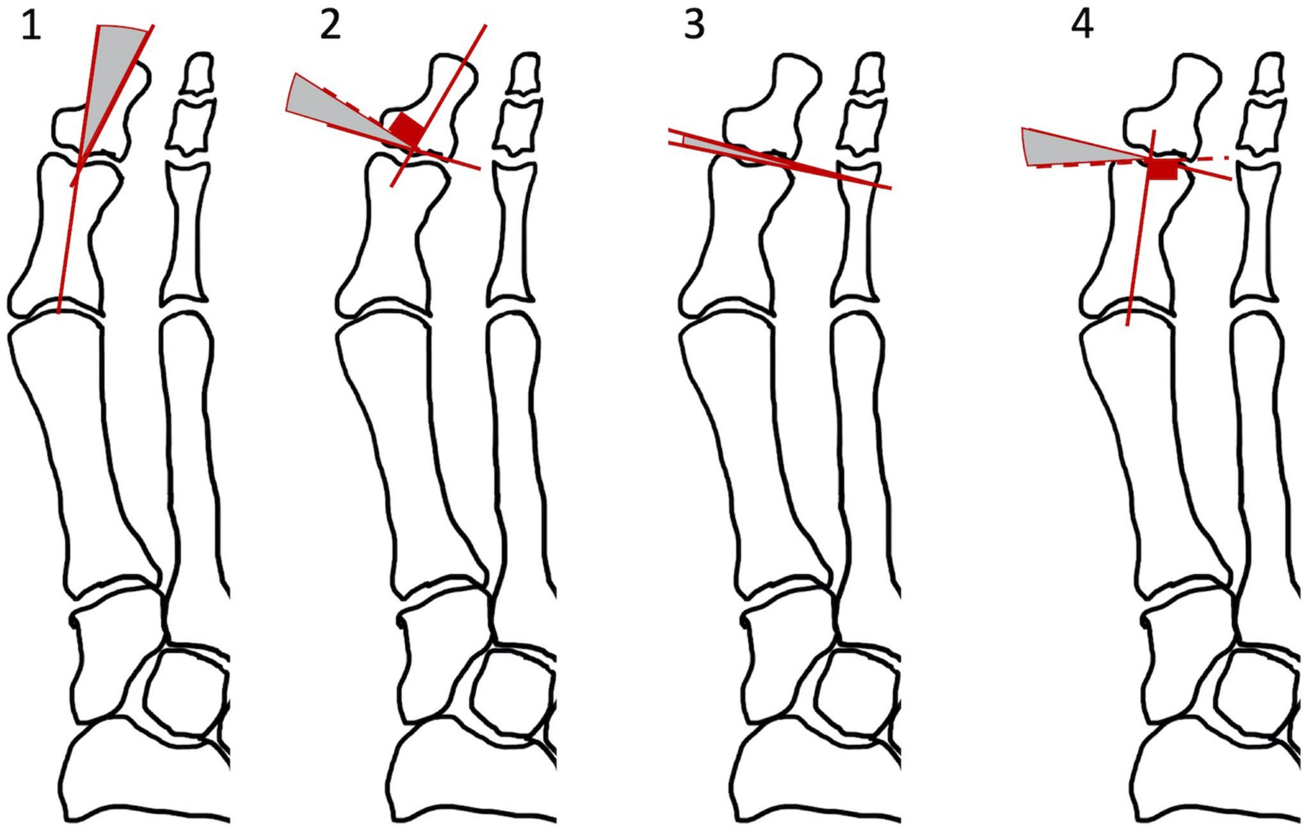

Fig. 2 Distal angles: (1) interphalangeal angle (IPA), (2) asymmetry angle (AP2), (3) joint deviation angle (JDA), (4) obliquity angle (AP1)

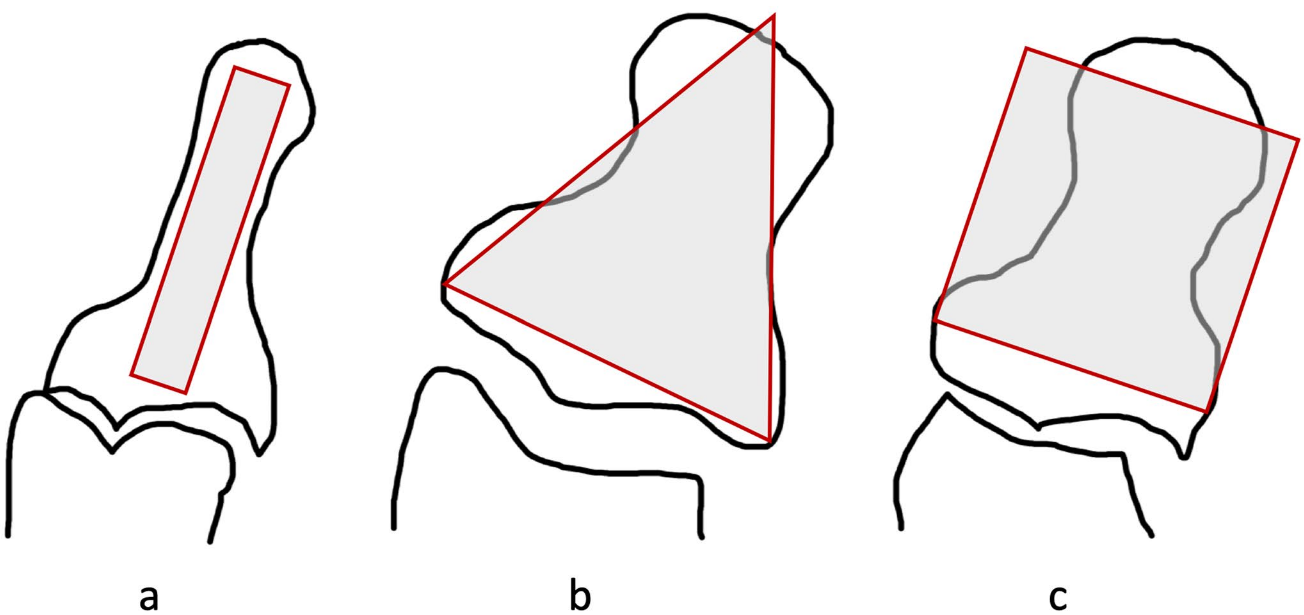

Fig. 3 Shape or the distal phalanx (DP): **a** longitudinal; **b** pyramidal; **c** standard. **a** Longitudinal phalanx: the length of the phalanx is ≥ 1.5 times the width of the base of the phalanx, the diaphyseal width of the phalanx ≤ 0.5 times the width of the base of the phalanx. **b** Pyramidal phalanx: the length of the phalanx ≤ 1.2 times the width of the base of the phalanx, the diaphyseal width of the phalanx ≥ 0.5 times the width of the base of the phalanx. **c** Standard phalanx: the length of the phalanx is ≤ 1.5 and ≥ 1.2 times the width of the base of the phalanx, the diaphyseal width of the phalanx ≥ 0.5 times the width of the base of the phalanx

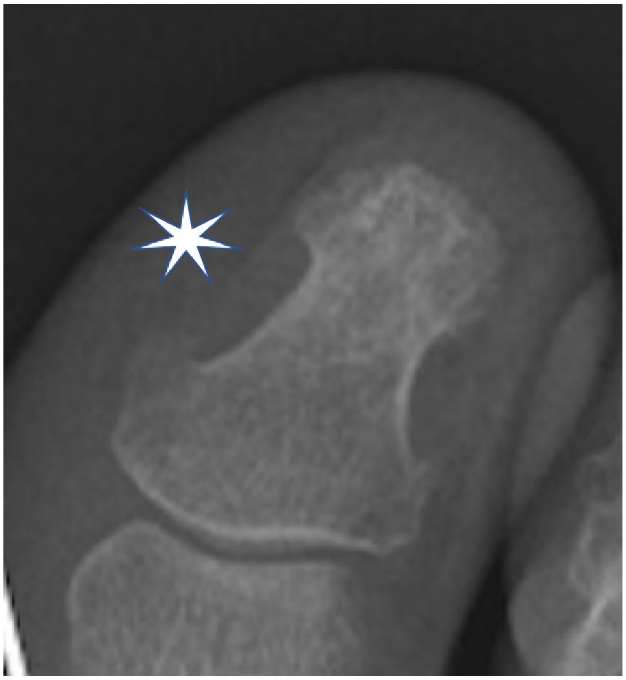

Fig. 4 Exostosis in the distal phalanx (DP)

Table 2 Mean (SD) age and angles for the three groups

Angles	Group A: Open toe-box shoe	Group B: Constrictive toe-box shoe	Group C: Constrictive and open toe-box
N	60	229	135
Age	29.5 (15.4) y.o.[a]	36.8 (23.9) y.o.[a]	36.1 (14.0) y.o.[a]
IMA	10.1° (2.2°)	9.3° (4.2°)	9.7° (2.2°)
MTPA	**7.7° (5.6°)**	**18.6° (11.2°)**	**10.3° (7.5°)**
DASA	4.7° (2.7°)	5.2° (3.3°)	3.9° (2.5°)
PASA	4.0° (2.9°)	5.5° (4.4°)	4.4° (3.9°)
IPA	**9.3° (3.6°)**	**11.7° (5.0°)**	**11.7° (5.5°)**
AP1	2.7° (2.4°)	1.8° (1.6°)	2.5° (3.2°)
AP2	**4.5° (3.3°)**	**8.0° (4.1°)**	**8.2° (4.1°)**
JDA	3.4° (1.7°)	1.9° (1.9°)	1.4° (2.3°)

The differences marked in bold (MTPA, IPA and AP2) were statistically significant ($p < 0.05$)

[a]y.o.: years old

Results

The mean angles of the patients of the three groups have been summarized in Table 2. The patients who used open toe-box shoes (group A) had the lowest, MTPA, IPA, and AP2, 8° (SD 6), 9° (SD 4), 5° (SD 3), respectively. On the contrary, the patients who used constrictive triangular toe-box shoes (group B) had the highest MTPA, IPA and AP2, 19° (SD 11), 12° (SD 5), 8° (SD 4), respectively. Finally, the patients who used open and constrictive toe-box shoes indistinctively (group C) had MTPA, IPA, AP2 in-between the other groups, 10° (SD 2), 12° (SD 6), 8° (SD 4), respectively. These differences were clinically relevant and statistically significant ($p < 0.05$). The other angles IMA, DASA, PASA, AP1, JDA showed no significant differences between groups (Table 2). The post hoc power calculation revealed a power ranging between 0.77 and 1 assuming an alpha of 0.05 for the differences found in the MTPA, IPA and AP2. We have found a negative correlation between the MTPA and IPA that was statistically significant ($p < 0.05$), represented with the formula MTPA = 20.1 − (0.5 × IPA); and a positive correlation between MTPA and IMA that was statistically significant ($p < 0.05$), represented with the formula MTPA = 5.5 + (1.1 × IMA) (Fig. 5). Finally, the changes in the angles according to age group in every shoe type group of are represented in Table 3. We found that 30% of the change in the MTPA is due to changes in age, but only in the constrictive shoe box group (group B). These changes can be represented with the formula MTPA = 9.2 + (0.3 × age) (Fig. 6). Likewise, a negative correlation was found between IPA and age (right), in which the 40% of the change in IPA can be explained by the change in age. These changes can be represented with the formula IPA = 13.1 − (0.4 × age).

The prevalence of exostoses on the tibial side of the DP has been recorded on Table 4. The prevalence of tibial side exostoses was significantly different between the groups, observing percentages of 22, 36, and 29% in groups A, B and C, respectively ($p < 0.05$) (Table 4). The prevalence of tibial side exostoses was higher in the patients who used constrictive TBS (group B), and 68% of the patients who used an open TBS (group A) did not have an exostosis at all.

In our series, we found similar distributions of the different DP shapes amongst the three groups (Table 5).

Discussion

The most important finding of our study is that not only does the MTPA increases with the use of constrictive toe-box shoes, but also de IPA and the AP2. Moreover, there is an increase in the prevalence of tibial exostoses in patients who use constrictive toe-box shoes.

These findings are consistent with the ones describes in the literature. Choi et al. described a mean IMA of 7.59 (±2.17) and MTPA of 7.57 (±4.43) in a Maasai population that walks barefoot or wearing a pair of traditional shoes made from recycled car tires which have an open toe-box. Meanwhile he found significantly a greater mean IMA of 10.86 (±2.19) and a MTPA of 13.99 (±4.88) in a Korean population that uses modern ready-made shoes. Despite having found these differences between groups of people who

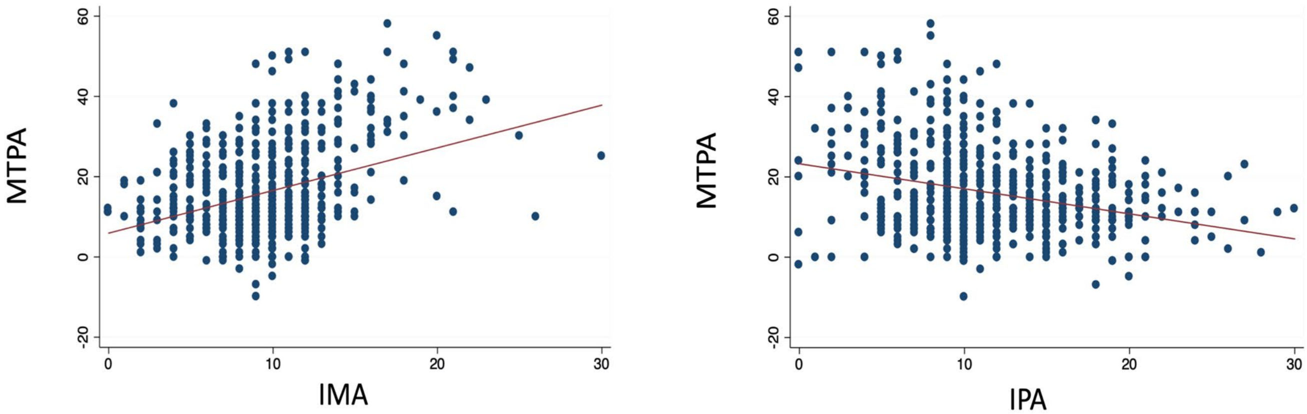

Fig. 5 Positive correlation between MTPA and IMA (left). Negative correlation between MTPA and IPA (right)

Table 3 Mean (SD) age and angles for the three types of shoes and the three groups of age

Angles	Group A: Open toe-box shoe			Group B: Constrictive toe-box shoe			Group C: Constrictive and open toe-box		
Age group	< 20	20–38	> 38	< 20	20–38	> 38	< 20	20–38	> 38
Age (y.o.[a])	17 (2)	24 (6)	54 (10.9)	10 (3.6)	29 (6.3)	58 (10.1)	14 (3.3)	30 (4.6)	50 (8.3)
IMA	9.7° (1.2°)	10.1° (2.3°)	10.0° (2.6°)	8.5° (3.2°)	8.0° (4.4°)	10.1° (4.7°)	9.9° (2.4)	9.8° (1.8°)	9.5° (2.6°)
MTPA	**7.2° (4.1°)**	**6.7° (4.9°)**	**10.4° (7.8°)**	**11.5° (7.2°)**	**20.0° (6.5)**	**23.9° (11.3°)**	**10.5° (7.4)**	**10.3° (6.9°)**	**10.5° (8.3°)**
DASA	5.3° (2.6°)	4.3° (1.9°)	4.5° (4.0°)	4.3° (2.9°)	6.5° (3.4°)	5.8° (3.5°)	4.8° (2.0)	4.2° (2.5°)	3.3° (2.7°)
PASA	3.2° (2.7°)	4.1° (3.0°)	5.0° (2.9°)	4.6° (3.7°)	4.4° (3.0°)	6.4° (4.9°)	2.8° (3.3)	4.8° (3.7°)	4.5° (4.2°)
IPA	**9.4° (3.7°)**	**9.1° (3.6°)**	**10.0° (2.5°)**	**14.0° (4.5°)**	**11.9° (5.8)**	**9.9° (4.5°)**	**12.8° (6.0)**	**11.9° (5.5°)**	**11.1° (5.6°)**
AP1	3.2° (2.3°)	2.7° (2.6°)	2.4° (2.3°)	2.2° (1.7°)	1.5° (1.7°)	1.5° (1.4°)	2.7° (2.4)	2.4° (3.4°)	2.7° (3.3°)
AP2	**4.0° (2.8°)**	**4.9° (3.9°)**	**4.6° (2.9°)**	**9.5° (3.7°)**	**8.6° (4.8°)**	**6.7° (3.9°)**	**9.9° (4.5)**	**8.3° (3.8°)**	**7.7° (4.4°)**
JDA	3.6° (1.2°)	3.1° (1.6°)	3.6° (1.4°)	2.4° (1.5°)	1.5° (1.5°)	1.5° (1.5°)	1.8° (1.8)	1.4° (2.5°)	1.4° (2.0°)

The differences given in bold were statistically significant($p < 0.05$)

[a]y.o.: years old

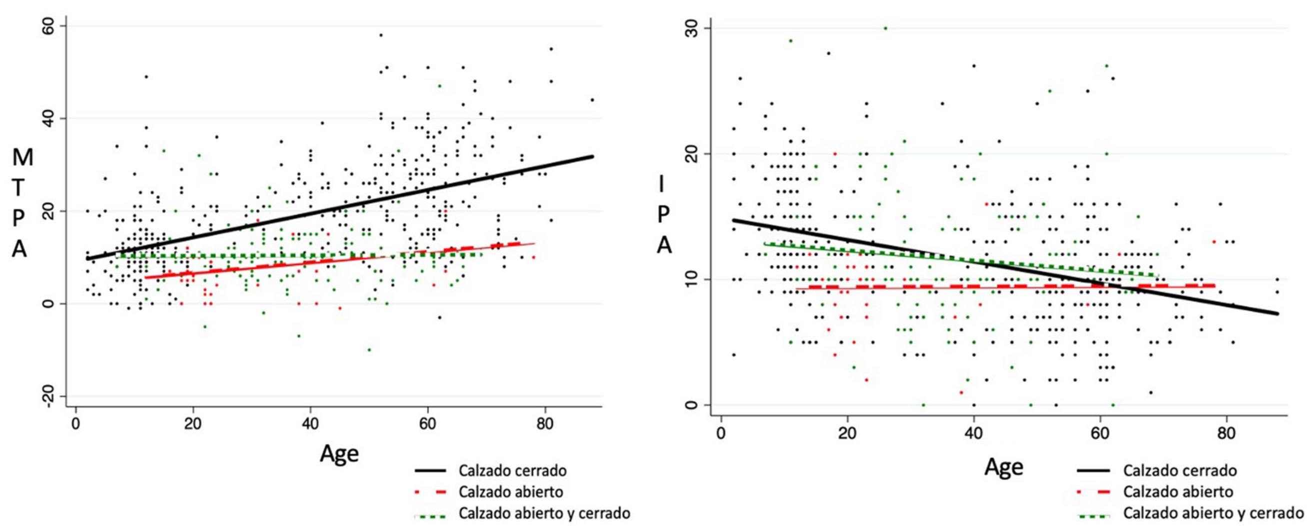

Fig. 6 Positive correlation between MTPA and age (left). This correlation was only statistically significant for group B and follows to the formula MTPA = 9.2 + (0.3 × age). Negative correlation IPA and age (right). This correlation was only statistically significant for group B and follows to the formula IPA = 13.1 − 0.4 × age

Table 4 Percentage (%) of patients with exostoses on DP and their locations in the three groups

Exostosis	Group A: Open toe-box shoe (%)	Group B: Constrictive toe-box shoe (%)	Group C: Constrictive and open toe-box (%)
No	68	50	52
Tibial	22	36	29
Peroneal	0	1	2
Tibial and peroneal	10	13	17

Table 5 Percentage (%) of patients with each shape of DP in the three groups

DP	Group A: Open toe-box shoe (%)	Group B: Constrictive toe-box shoe (%)	Group C: Constrictive and open toe-box (%)
Longitudinal	17	21	30
Pyramidal	10	13	10
Classic	73	66	60

use regular closed footwear or open footwear, there was still some controversy because the differences could be due to genetic or ethnic factors [16]. In addition, some authors had already described variations in the angles of the hallux based on ethnicity, but others support that there are none [17, 18]. Trying to clarify this, Choi et al. expanded his study further by adding a third group of Maasai women that wore ready-made shoes. He found that Maasai women who wore ready-made shoes had a mean IMA and MTPA of 9.29 (± 2.69) and 10.15 (± 5.62) which were in between the ones obtained for the other two groups and therefore stated that although part of the differences in hallux angles could be due to ethnic differences, the type of footwear used also contributes to at least part of the differences observed [19].

Some authors have described an IPA of 8° in barefoot patients and of 12° in shod patients, and state that there is no correlation between age and deformity [24, 26]. We have also found differences in the IPA and AP2 angles between the patients that use constrictive toe-box shoes and open toe-box shoes. These angles have been found to be increased even when the use of constrictive toe-box shoes were only used occasionally. Studies carried out in children have described deviations in hallux development resulting from an inappropriate length or width of the shoe [21, 27, 28].

Several authors have described that 80% of children have a certain inclination of DP that decreases after the age of 14, when the hallux valgus begins to develop as a result of the external influence of footwear [29, 30]. The inverse correlation between MTPA and IPA, which is statistically significant, is in line with other articles stating that a rigid metatarsophalangeal joint can cause deviation of the interphalangeal joint [6, 24]. Moreover, we have found that 30% of the changes in the MTPA are due to changes in age, but this correlation is only observed in the constrictive TBS group which leads us to think that it is not age itself that causes changes in the hallux angles but the years that the patient has been wearing constrictive toe-box shoes.

There is not much literature regarding exostoses on the base of the DP. Keats et al. described exostoses as a “normal variant” of DP morphology and our results showed a high prevalence (51%) of these exostoses on the tibial side in patients in our daily practice [3, 31]. These osseous excrescences have been described by some authors as possible calcifications of a ligament insertion in DP, or as a reactive bone formation secondary to the friction caused by the inner border of the shoe by others [3, 22, 23]. The fact is that, although they are present in patients who wear an open toe-box shoe, their prevalence is higher in those wearing constrictive toe-box shoes. Therefore, we consider that the shoe pressure in that area plays some kind of role in their development, but this study is not accurate enough to determine a certain etiological correlation.

The high prevalence of these exostoses found in all types of foot and DP morphology would imply that they are not specific of any particular foot or phalanx ($p > 0.05$).

Our study is not without limitation, like in previous studies genetic and ethnic factor might influence the outcomes of our study. We have tried to minimize this influence by including a third group of patients from the Democratic Republic of the Congo that wear both constrictive and open toe-box shoes. Moreover, we cannot quantify for how long the patients in group C have worn the constrictive toe-box shoes. Therefore, we cannot prove a direct causative correlation between the use of constricted TBS and the changes in the hallux anatomy, but the results point in that direction. Lastly, we have an irregular distribution of our population in the three groups. This is because it is easier to recruit patients in our hospital than in rural areas of the Democratic Republic of the Congo.

In conclusion, these results suggest that the use of constrictive TBS, even if used only occasionally, could change hallux anatomy from a young age increasing MTPA, IPA and AP2, and increasing the prevalence of exostoses on the tibial side of DP. Moreover, we have found a correlation of the MTPA and IPA with age only in the patients who wear constrictive (V-shaped) TBS. Although we cannot prove a direct causative correlation, the results lead us to think that what truly impacts de MTPA and IPA is the time (years) that the patient has used constrictive TBS rather than the age itself.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interest.

Ethical review committee statement This paper did not require institutional review board approval. All the data has been anonymized and cannot be traced back to the patients and no invasive procedure additional to our regular practice was performed.

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