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The different growth zones of the fetal foot

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Summary. Previous publications revealed no reliable data or models concerning the three-dimensional ontogenesis of the lower extremity. Using the method of plastination-histology in combination with 3D-computer-reconstructions we were able to produce exact, virtual 3D-specimens of 19 healthy fetal feet. The fetuses were aged between 9 to 38 weeks of gestation and age-dependently related to four defined age-groups. We compared these feet with the help of a new geometrical method. Thus, we obtained a kind of "slow-motion-picture" of the undisturbed three-dimensional development of the fetal foot. Our results show that the human fetal foot has a desultory mode of growth and that growth priorities within the foot-skeleton change dependent upon age and region. Though the growth of the fetal foot-skeleton is desultory, it is not disconnected. The result of this peculiar mode of growth is to create the foot arches and thus seems to be functionally-oriented toward the human foot's specific purposes.

Key words: Human fetal foot – Foot-arch formation – Growth mode – Geometry – Three-dimensional computer reconstruction

Introduction

Knowledge of the normal formation of the foot is essential for the understanding of possible disorders and their treatment. Developmental processes of the locomotor system do not happen as successively as one would expect. The formation of the lower extremities starts with bud-like formations of the lower lateral rump-wall in late embryonic stages (Streeter 1945, 1948; Gardner et al. 1957). Shortly after forming plate-like endings these limb-precursors undergo a so-called "inner formation", creating the basis for the different parts of the locomotor system of the developing foot (His 1880; Collins 1995). In the early footplate all anlagen of the future bones are positioned in one plane oriented more or less sagittally. At the end of the embryonic period a "positioning work" within the foot takes place moving it out of the so-called "praying position" (Streeter 1951), so that a "miniature adult" foot results from an outer aspect (Hasselwander and Schwalbe 1903; Whillis 1940; Kaback and Boizow 1987; Uhthoff 1990). Nevertheless the arrangements of the "end-embryonic" foot and its skeletal size-relations have not yet reached an adult situation (Gardner and O'Rahilly 1975).

The fetal period is characterised not only by the growth of the foot's preformed cartilaginous bone-anlagen but also by their definite arrangement. There is no doubt that the post-embryonic positioning of the cartilaginous anlagen is based on slight but tangled movements (Pisani 1998). The few studies dealing with the fetal cartilaginous anlagen are only partially concerned with their size and unaltered position (Gardner et al. 1959; O'Rahilly 1972; McKee and Bagnall 1987). Most authors studying this problem have focussed on descriptions of the alteration of the developing foot's outer appearance (Bardeen and Lewis 1901/1902; Blechschmidt 1961; Christ 1990; Pisani 1998; Tillmann and Töndury 1998). Even excellent attempts at measuring and qualifying single fetal foot-skeleton elements concerning their age-dependent mode of growth have not been able to answer the question of how these interactive proceedings occur (Lippert 1963; Martin 1957).

All previous theories about growth and positioning are either based on incomplete observations of the fetuses' outer appearance or solely on histological sections through the foot. There is no reliable data on growth and position of the skeletal foot-elements as a single undisturbed entity during certain periods of development

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(Hale 1949; Victoria-Diaz and Victoria-Diaz 1984). For this reason any explanation of the development of congenital foot deformities – such as clubfoot – remain theories with the immanent necessity of revision (Böhm 1929; Debrunner 1945; and Herzenberg et al. 1988).

For postnatal life, it has been proved that many parameters of the human lower extremity change desultorily by certain growth-priority zones related to certain age-groups (Maier 1961; Schilling 1985).

The purpose of the following paper is to find an answer to the still immanent question of the three-dimensional and chronological growth of the fetal foot. In our study we want to show the main tendencies during fetal foot development and not to give exact data of geometrical differences between defined points of measurement that can never be provided significantly by a limited number of specimens available to us. In order to get reliable data, we had to develop a new method making spatial analysis as infallible as possible.

Our data is of morphological as well as of clinical importance for the access to similar problems, as for example the understanding, the clinical-radiological analysis and the treatment of the infantile foot and its deformities (Bardy 1951; Victoria-Diaz and Victoria Diaz 1984; Pisani 1998). Until now the aetiology of many skeletal abnormalities could not be determined. Thus treatments of foot deformities are mainly empiric (Correl 1993; Forst 1993; Hippe et al. 1993; Marronna 1993; Tönnis and Buckup 1993). It is the purpose of our study to create a basis for a morphologically correct and standardized treatment.

Material and methods

Plastination-histology. Serial sections of 19 fetal feet were prepared according to the plastination histology method (Fritsch 1988). The feet originated from 15 legally aborted or miscarried fetuses. The specimens showed no signs of any basic disease or macroscopic abnormality. To equalize the different information about their age, the crown-rump-lengths (CRL) were measured. By comparing the CRL with those of the standard-tables of Patten (1968), and O'Rahilly and Müller (1999) the fetuses were found to be of a gestational age of 9 to 38 weeks.

Each fetal foot was dissected about 2 cm proximal to the ankle mortise and then fixed in 4% formaldehyde solution by immersion for at least two months. After draining and degreasing the specimens with acetone at –25 °C for six weeks, they were impregnated with an epoxy resin mixture (Von Hagens et al. 1987). Before polymerisation the specimens were put in a standard position; i. e. their plantar surface parallel to the transverse plane. After polymerisation the blocks were cut either in the frontal, sagittal or horizontal plane. The thicknesses of the sections were 300, 400 or 500 μm. After mounting the sections on microscopic slides they were polished, stained with azure II/methylene and counterstained with basic fuchsine in water (Fritsch 1989). Continuous sequences of the obtained feet-series were documented size-dependent either on a macroscope (Wild®, Heerburg, Switzerland) or a macrophotofacility (F3, Nikon®) and transferred to a computer for the three-dimensional reconstruction of their skeletal components.

Three dimensional computer reconstruction. The photographs of the foot-slices were traced on transparent paper one after the other and the skeletal elements copied exactly. The produced papers were put together so that the contours fit one to the next and the positions of the sheets were marked for orientation at computer-reconstruction. Then they were shot by a black and white video camera and transferred to a computer, where they could be handled. After conversion into "tif" picture data format the 3D-reconstruction program Slicer® (Fortner Research LLC) was able to visualise the skeletal contents of each series. The spatial orientation of the so created virtual foot was chosen in a way that the horizontal plane was congruent with a line through the most distal points of the medial and lateral malleolus. Using this indication we were able to produce comparable horizontal and sagittal projections of the virtual skeletons to do our measurements.

Measurements. It was necessary to divide the virtual fetal foot-skeletons into four regions to avoid dealing with size changes, in their single bones. Thus we defined a foot-subdivision as follows (Fig 1 A, B):

Hind foot: region of talus and calcaneus; Proximal middle foot: region of the scaphoid bone and the corresponding part of the cuboid; Distal middle foot: region of the cuneiform bones and the corresponding part of the cuboid; Forefoot: region of the metatarsal bones.

To recognize age-depent processes the "computer-specimens" were divided into 4 age-groups as follows:

Age-group 1 (AG 1) 9th week p. c. (n = 3)
CRL 34 to 42 mm
Age-group 2 (AG 2) 12th to 15th week p. c. (n = 6)
CRL 73 to 125 mm
Age-group 3 (AG 3) 21st to 27th week p. c. (n = 4)
CRL 196 to 250 mm
Age-group 4 (AG 4) 34th to 38th week p. c. (n = 6)
CRL 330 to 360 mm

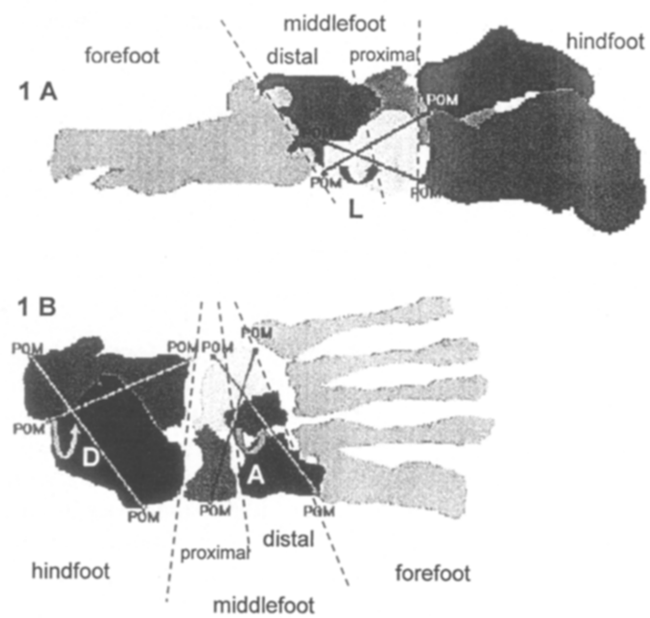

Fig. 1 A, B. Scheme of measurements. A. Sagittal projection, lateral aspect; example of an angle open to the plantar foot border (L). B. Horizontal projection, dorsal aspect; example for angles open to the medial foot border (A; D).

On the horizontal and the sagittal projection, points of measurement (POM) were defined (Tables 1 and 2). The POM had been chosen so that they are reproducible even in reconstructions that are based on only few sections. We connected the POM by lines (Fig. 1 A, B). These lines were placed from the medial to the lateral as well as from the plantar to the dorsal border of the projected virtual feet, respectively.

The lines connecting the POM resulted in several intersectiones by the help of which foot-regions could be characterized either in the horizontal (A–F) or in the sagittal (G–L) projections (Fig. 1 A, B). We measured the angles open to the plantar foot border in the sagittal projection and to the medial foot border in the horizontal projection. For a geometrical description of the growth-mode these resulting angles (angles A to F) were brought into relation two by two, dividing the first by the second one. The so given indices – named after the intersections used for their calculation separated by a slash (e. g. Index D/A, meaning "index out of the division of the angle D by the angle A – defined by their corresponding intersections D and A") – are the basis of our results.

The calculated indices could be compared and provided information on the course of proportions and size relations between distinct foot-regions during fetal life.

Table 1. Points of measurement (POM) on horizontal projections

CROSS (angle)	POM 1	POM 2	POM 3	POM 4
A	Medial cuneiform medio-distal edge	Cuboid latero-proximal edge	Navicular most medial point	Cuboid latero-distal edge
B	Medial cuneiform medio-distal edge	Cuboid latero-proximal edge	Medial cuneiform medio-proximal edge	Cuboid latero-distal edge
C	Medial cuneiform medio-proximal edge	Cuboid latero-proximal edge	Navicular most medial point	Cuboid latero-distal edge
D	Talus most medial point of head	Calcaneus most lateral point of the lateral process of tuber	Talus most posterior point of the posterior process	Calcaneus latero-distal edge
E	Talus most medial point of head	Cuboid latero-proximal edge	Talus most posterior point of the posterior process	Cuboid atero-distal edge
F	Medial cuneiform medio-distal edge	Calcaneus most lateral point of the lateral process of tuber	Navicular most medial point	Calcaneus latero-distal edge

Table 2. Points of measurement (POM) on sagittal projections

CROSS (angle)	POM 1	POM 2	POM 3	POM 4
G	Medial cuneiform dorso-distal edge	Medial cuneiform planto-proximal edge	Medial cuneiform planto-distal edge	Navicular dorso-proximal edge
H	Medial cuneiform dorso-distal edge	Medial cuneiform planto-proximal edge	Medial cuneiform planto-distal edge	Medial cuneiform dorso-proximal edge
I	Talus most dorsal point of head	Calcaneus most plantar point of tuber	Calcaneus plantar edge of cuboid articulation face	Talus most superior point of trochlea
J	Talus most dorsal point of head	Cuboid planto-distal edge	Medial cuneiform planto-distal edge	Calcaneus most posterior point of tuber
K	Medial cuneiform dorso-distal edge	Calcaneus most plantar point of tuber	Navicular dorso-proximal edge	Calcaneus plantar edge of cuboid articulation face
L	Calcaneus dorsal edge of articulation face	Cuboid cuboid plantar edge of metatarsal-V face	Calcaneus plantar edge of cuboid articulation face	Cuboid cuboid dorsal edge of metatarsal-V face
TAA[1]	Talus most dorsal point of head	Talus most superior point of trochlea	Calcaneus most posterior point of tuber	
X	X = TAA/I			

[1] Trigonum-Apical-Angle

Results

Horizontal projections (Fig. 2 A–D)

The definite values of the indices are listed in Tables 3 (horizontal projections) and 4 (sagittal projections). To understand each value, we first explain its relevance theoretically and then by the measured and calculated values.

Index D/A: If the value of this index is high then the hind foot is larger than the whole proximal and distal middle foot together. Our results show that the hind foot is obviously oversized in relation to the whole middle foot between age-group 1 and age-group 2.

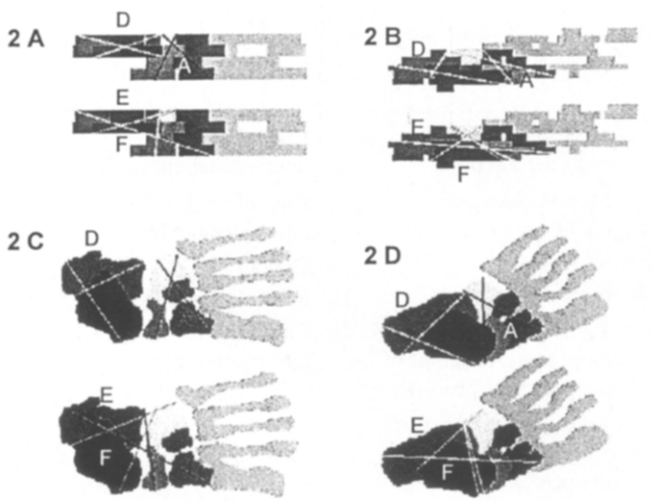

Fig. 2. A–D. Horizontal projections in dorsal views. A. Age-group 1. B. Age-group 2. C. Age-group 3. D. Age-group 4. The angles A, D, E, F out of the according intersections are defined by the POM in Table 1.

Table 3. Values from horizontal projections

Horizontal	AG 1	AG 2	AG 3	AG 4
Index **D/A**	1.64	2.81	2.27	2.34
Index **C/B**	0.96	0.92	0.87	0.77
Index **D/E**	3.76	1.58	2.37	2.02
Index **D/F**	1.59	3.02	2.00	1.89
Index **E/F**	0.55	2.24	0.58	0.94
Angle **E**	34.80°	75.17°	52.25°	59.75°
Angle **F**	77.00°	44.08°	61.88°	64.00°

Table 4. Values from sagittal projections

Sagittal	AG 1	AG 2	AG 3	AG 4
Index **G/H**	1.14	1.12	1.10	1.12
Index **X**	1.58	1.95	1.40	1.51
Index **X/G**	0.017	0.033	0.013	0.012
Index **X/J**	0.027	0.023	0.028	0.022
Index **X/K**	0.027	0.062	0.023	0.030
Index **J/K**	0.97	2.61	0.93	1.36
Index **L/G**	1.00	1.33	0.97	1.04
Angle **I**	63.67°	66.41°	69.50°	71.67°
Trigonum-Apical-Angle (TAA)	97.17°	109.58°	97.50°	106.75°

Index C/B: If the value of this index is high then the proximal middle foot is larger than the distal one. Our virtual skeletons show gradual and slight size-diminution of the proximal to the distal middle foot over time.

Index D/E: If the value of this index is high then the medial hind foot is smaller than the whole middle foot. In relation to the whole middle foot in age-group 2 and 4 the medial hind foot is larger than in age-group 1 and 3.

Index D/F: If the value of this index is high then the lateral hind foot is smaller than the whole middle foot. The lateral hind foot is smallest in age-group 2 in relation to the whole middle foot.

Index E/F: If this value is higher than 1 then the foot is larger medial than lateral. In age-group 2 the medial foot is larger than the lateral one in contrast to each other age-group.

Angle E and Angle F

The maximum of the angle E indicates the maximum of the medial hind foot's extension and the maximum of the angle F shows the maximum of the lateral hind foot size. The maximum values of the angles E and the minimum values of the angles F show a maximal extent of the medial hind foot in age-group 2. An inverse situation is indicated in age-group 1.

Sagittal projections in medial (Fig. 3 A–D) and lateral aspect (Fig. 3 E–H)

Within the interpretation of intersection I a problem emerged, because of its describing the size of the hind foot and the height of the talar trochlea at the same time. That is why the apical angle (TAA) of a TRIGONUM, which was defined by three distinct POM (Tables 2 and 4), was used to calculate an index (index TAA/I called "index X" for simplicity) at each virtual specimen. Index X made if possible to distinguish length and height of the hind foot exactly.

Index G/H: If the value of this index is higher than 1 then the proximal middle foot is larger than the distal one. In each age-group the proximal middle foot is larger than the distal one.

Index X: If the value of this index is high then the hind foot except the talar trochlea height is large. The maximum of this relative extent is reached in age-group 2.

Index X/G: If the value of this index is high then the length of the extent is larger than the whole middle foot. This relative length of the hind foot is largest in age-group 2.

Index X/J: If the value of this index is high then the plantar hind foot is larger than the whole middle foot. In this relation the plantar hind foot is smallest in age-group 2 and 4.

Index X/K: If the value of this index is high then the dorsal hind foot is larger than the whole middle foot. In this relation the dorsal hind foot is largest in age-group 2.

Index J/K: If the value of this index is higher than 1

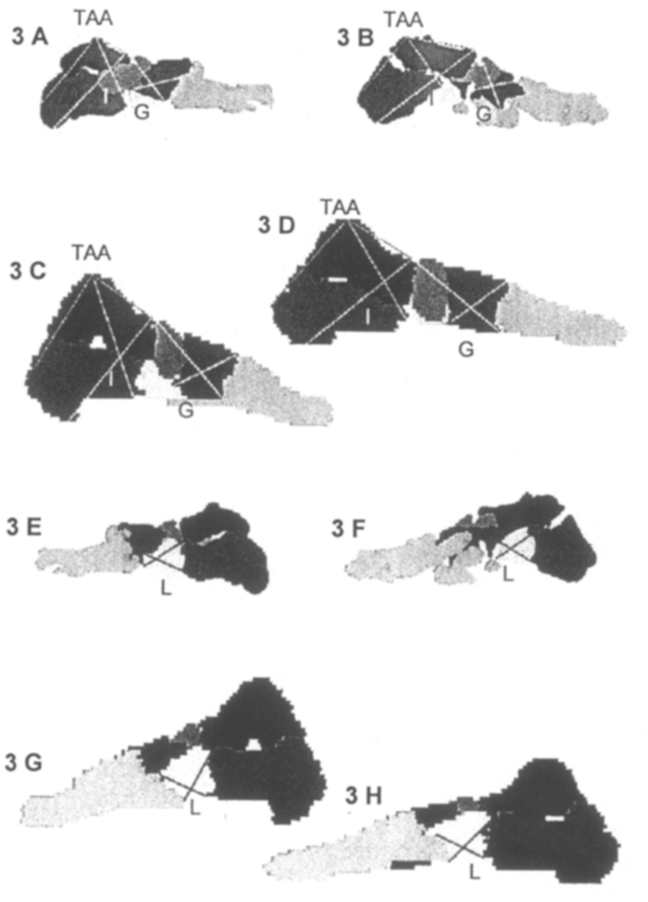

Fig. 3 A–D. Sagittal projections, medial views. A. Age-group 1. B. Age-group 2. C. Age-group 3. D. Age-group 4. The angles J, G resulting from the respective intersections are defined by the POM in Table 2. The construction of TAA is also defined by POM in Table 2.

Fig. 3 E–H: Sagittal projections, lateral views. E. Age-group 1. F. Age-group 2. G. Age-group 3. H. Age-group 4. The angle L from its respective intersection is defined by POM in Table 2.

then the dorsal hind foot is larger than the plantar one. In age-groups 2 and 4 a dorsal disproportionately large size can be stated.

Index L/G: If the value of this index is higher than 1 then the whole lateral middle foot is higher than the medial one. The height relations between the medial and the lateral middle foot are quite balanced with exception of age-group 2.

Hind foot and talar trochlea: The formation of the talar trochlea shows no relationship between its steepness, its height and the size of the hind foot itself.

Discussion

Discussion of the methods. The method of plastination-histology was used to get unaltered, unshrunken slices of each fetal foot. Any other method of preparation; i. e. conventional dissection as well as paraffin-embedding, would not have been suitable for our purposes because of the usual positional- and size-alteration of the so prepared specimen.

Our two-dimensional sections of the human body show the undisturbed skeletal situation on the one hand, on the other hand they have the same immanent limitation as 2D-pictures of sonography, MRI and CT: the restricted presentation of spatial situations and relations. In former publications this problem was often completely neglected and even less reliable data of abortuses, conventionally sectioned specimens, radiological images, wax-models and living beings (Krogman 1941; Bardy 1951; Jelisiejew and Blachno 1975; Jordaan 1982; Miakiewics et al. 1984; Rossavik and Deter 1984; Schilling 1985; McKee and Bagnall 1987; Mandarim De-Lacerda 1990; De-Vasconcellos et al. 1994; Kumar and Kumar 1994; Hata et al. 1996; De-Vasconcellos and Ferreira 1998; Hata et al. 1998) were used for investigation.

In the morphological as well as in the radiological field the above-mentioned problem can best be solved by using computer-supported 3D-reconstructions. The quality of such reconstructed "virtual" specimens is only limited by the resolving power of the method used for the 2D-basis-data (sonography, CT, MRI) – in our case photography-equivalent resolution.

Consequently an objective mode of description of the thus created virtual specimen had to be developed. Certain "views" of our virtual skeletons had to be defined in a way that measurements on specimens of different age-groups became comparable. By the definition of angles due to intersections based on points of measurement (POM) not being restricted to single bones, we had the advantage of comparability independent of the "true" foot size. Additionally, the non-bone-dependent auxiliary-construction of intersections made possible a spatial integration of the position and extent of the interesting regions. Another reason for using angles instead of distances is that on the one hand at any slight inaccuracy angles do not change as rapidly as distances do, and on the other hand the index-calculation following the single angle-values additionally reduced each possible remaining measurement-error. The obviously notched borders of our 3D-computer-models had not been smoothed. Yet no additional information would have been gained and the smoothing algorithms of the program might have even disturbed our measurements.

The subdivision of our specimens in four instead of commonly used 3 prenatal developmental trimesters was intended. Age-group 1 contains a representative number of specimens of the 1st trimester, age-group 2 specimens of the transitional period between the 1st and the 2nd trimester, age-group 3 consists of the specimens of the 2nd trimester and the transitional period between the 2nd and the 3rd, and the age-group 4 of specimens of the 3rd trimester. Our age-group-distribution provided the best representative number of specimens with a minimum of 3 in each group. This premise of "group-homogeneity" was fulfilled best by the fact that each age group's data was coherent.

Discussion of the results. We presume to be the first to show different spatial growth zones in the undisturbed developing human fetal foot by defined foot-regions. These zones are dependent on the alteration of extension and on the adjustment of the spatial position of the bones as well, and show no steady mode of growth. The relationships between definite foot-regions change in the course of the prenatal life desultorily, too. Contrary to many other body-regions the human foot has to pass through several remarkable alterations during the fetal period, because of its restricted and highly specialized functions in postnatal life (Debrunner and Jacob 1998; Pisani 1998).

By the geometrical system we defined, we were able to measure angles with a high accuracy and comparability of specimens of different sizes. The quintessence of the single results shows the following:

Concerning the horizontal projections our virtual models show a fast one-centred growth in the proximal middle foot in the 9th week p.c. In the 12th week p.c. this growth-centre gets subdivided in two parts: one of which shifts to the hind foot and the other to the more distal middle foot. Between the 12th and 15th week p.c. the medial foot shows a size-maximum in relation to the other foot-regions. Despite an intermittent sequence of size-maxima between the both foot borders, the medial foot grows faster than the lateral one.

From these facts we conclude a spatial shift of growth-priority during ontogenesis. It ends in a relative oversize of the medial foot-ray. In the following period (21st to 38th week p.c.) of fetal development this oversize diminishes rapidly.

Concerning the sagittal projections we detected a quite similar situation. A one-centred growth-priority of the proximal middle foot, which later shifts towards the hind foot. Between the 12th and 15th week p.c. the lateral middle foot is higher than the medial one and a maximum of size of the dorsal border of the foot can be stated. Additionally we identified a desultory and disproportionally greater growth of the talar trochlea with no chronological relationship to hind foot-growth itself.

In the sagittal view a desultory shift of growth-priorities must be stated, too. Again the fetal foot shows a period of a relative oversize. The latter is found in the dorsal hind foot and rapidly diminishes in the following period. Especially the developing talar trochlea shows a changing degree of steepness during its fetal formation.

The question is whether these discrepancies in size make sense and why they diminish so suddenly?

When regarding our virtual specimens it is obvious that the more the longitudinal and the transverse arch of the foot are intensifying, the more the disproportionately large sizes are diminishing. The reason of the disproportionately large sizes therefore can be seen in the availability of the material for the foot-arch formation. The mean part of this arch development takes place between the 15th and 21st p.c., but the disproportionately large sizes do not gut "consumed" totally. Their residuals are still to be detected in the adult foot. They may be necessary for the bipedal standing and gait. This special mode of growth has to be seen as adaptive work of the foot-skeleton trying to orient joints and motion-axes as well as possible for the necessities of the healthy foot (Abramson 1927; Debrunner and Jacob 1998).

In addition to primary growth-processes during pre- and postnatal foot-formation an undisturbed interaction between skeletal components and secondary contractile elements (muscles and their reflexes) is essential for regular foot development and function. These underlying mechanisms, which form an adult foot out of a plane embryonic foot-skeleton, happen desultorily but precisely. It is evident, that, whenever these complicated mechanisms get uncoupled, a more or less deformed foot skeleton results (Böhm 1929).

If our assumption, that the postnatal foot growth also happens desultorily, can be proved, every "disturbing" treatment during a regional "time of growth" could seriously alter motion axes, size relations and functions of the infantile foot. This presumption for postnatal foot development is speculative but is indicated by our data. The explanation that the lower extremity develops out of two growth-zones (Victoria-Diaz and Victoria-Diaz 1984) oversimplifies the facts and makes a reliable explanation of deformities almost impossible.

With the help of our data we intend to give new orientation on fetal foot-development for morphological and clinical use. Further studies must clarify how the arrangement within the foot is controlled and continued in postnatal life. By the future help of pediatric experimental subjects and the use of radiological tools and thereby defined, reproducible and easily usable objective measurements we will try to provide new data and thus a new tool for the orthopaedic evaluation and treatment of the infantile foot.

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