Difference in Shape and Dimensions between Adult and Children Feet Based on 40.000 3D Scans

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Abstract

Human foot shape affects the fit of shoe significantly. Some shoes fit better to some types of feet, while other shoes fit better to other types of feet. The paper analyzes human feet from the perspective of shoe fit. We analyzed and compared the width and length of feet as well as the shape of toe area (by classifying feet into Greek, Roman and Egyptian type). We focused to differences between adult and children feet.
In the analysis we included a huge number (more than 40.000) of 3D scans of human feet. The 3D scans were obtained in EU project Dorothy, internal foot scanning campaigns and mostly from feet scanners installed round the world. Currently about 170 scanners are installed in retail shops and are available for feet scanning and for recommendation of shoes to end customers.

Keywords: foot shape, forefoot, foot types, foot scanning, children, adults

1. Introduction

3D body scanning has become an affordable technology. The use of 3D body scanning has the potential to play an important role in the development of customized products [1,2]., i.e. in design and fabrication of products, that are designed for the individual using their precise anthropometric measurements. The 3D body scanners are also widely used in many anthropometric surveys [3].
In parallel to the 3D body scanners also specially dedicated scanners for precise feet measurement have been developed. A valuable overview of research in foot 3D scanning has been made by Telfer [4]. A quantitative description of foot shape is important for a number of different applications relating from the custom and/or ergonomic design of footwear, recommendation of optimal shoe size and/or style, foot orthotics and insoles, and for research into clinical assessment of foot deformities.
Many anthropometric campaigns have been focusing to foot measurement primary with a goal to provide information relevant to shoe designers. A large study of 2867 feet was carried out by Mauch et al [10] who categorized feet into three different types. In a recent study, Mauch et al [11] scanned the feet of almost 3,000 children and identified 5 foot types: flat, robust, slender, short and long. Luo et al [12] used 3D scanning to assess the differences in male and female feet and found that men tend to have longer and wider feet than women, in line with results from previous studies that took manual measurements [13].
Luximon and Goonetilleke [14] have argued that the foot shape can be modeled using just length, width, height and a measure of the curvature of the metatarsal-phalangeal joint in order to negate the use of 3D scanners. This is true only to some extent.
Researchers have used 3D foot scanners to investigate the quality of fit between foot and shoe [5,6,8]. Poorly fitting shoes have been linked to falls, and the development of multiple conditions including knee and low back pain, foot ulcerations and foot deformities such as hallux valgus, hammer toes [7]. Proper shoe size of a person is initially derived from basic foot characteristics such as length and width of feet. However, the shape of forefoot and the shape of toe box of shoes play a very important role in shoe fit. Not much research has been done in the evaluation of forefoot and the shape of toes. Some researchers have shown large correlation between shape of toes and foot problems [15]. A study of 1221 male subjects was conducted to determine normative data with respect to forefoot shape and dimension [16]. Here also the comparison of shapes between two races have been indicated. Hawes et al. compared toes lengths and identified two toes patterns (1st toe longer or 2nd toe longer) [13]. Foot morphology in the course of a working day has also been evaluated in [13]. Sexual dimorphism of feet were evaluated in [14] and similarly for the purpose of shoe design in [15].
The analysis of toe shape from the perspective of shoe fit must necessary consider also the shape of the shoe (especially the toebox). Therefore, besides a foot scanner a crucial component for fit estimation and recommendation system is a shoe inner dimension measurement system [9].

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The objective of this work was to investigate the differences between adult and children feet from the perspective of a shoe fit. We pointed out the differences between adult and children feet. We showed how the length and width of feet changes with age. Additionally, we classified all feet into three basic feet types (Egyptian, Roman, Greek) based on the shape of toes. Such information is crucial for shoe producers making highly comfortable shoes for all generations.
The analysis done in this paper includes a huge number (more than 40.000) of 3D scans of human feet. The 3D scans were obtained in EU project Dorothy, internal foot scanning campaigns and mostly from 170 UCS feet scanners installed round the world.

2. Methods

In this work we evaluated width and length of feet as a function of the age of person. The comparison has been done in two phases. The first phase evaluates the basic foot characteristics such as the length and the width of foot. The second phase focuses more to the forefoot (toe) shape. Here we classify the feet into three well known types (Egyptian, Roman, and Greek).
The analysis considers more than 40.000 right feet of European population from 1-70 years. The scans evaluated in the paper were obtained with 2.5D scanner (2x 2D (top and side) scans) [20]. All the subjects were scanned in a similar posture (with approximately 30% of weight on the foot being measured). For the details regarding the foot scanner and scanning posture see [20].

2.1. Evaluation of foot length and width

The length of foot is the distance between the heel and the longest toe. The width of foot is defined as ball width. To have a reliable definition of length and width we prescribe the following procedure for foot orientation and length and width definition.
The orientation of top view of a foot scan is presented in Fig. 1. Foot scans were oriented according to two points: A and B; where point A is defined at exactly 10% of foot length along X axis, at the middle of utmost points on Y axis; and point B is defined at exactly 66% of foot length along X axis, at the 60% of distance between utmost points on Y axis. Both points are detected on up to 10 mm of foot height on Z axis (by that ankle was excluded from orientation). The orientation procedure is an iterative procedure. It is repeated until a satisfactory orientation is obtained.

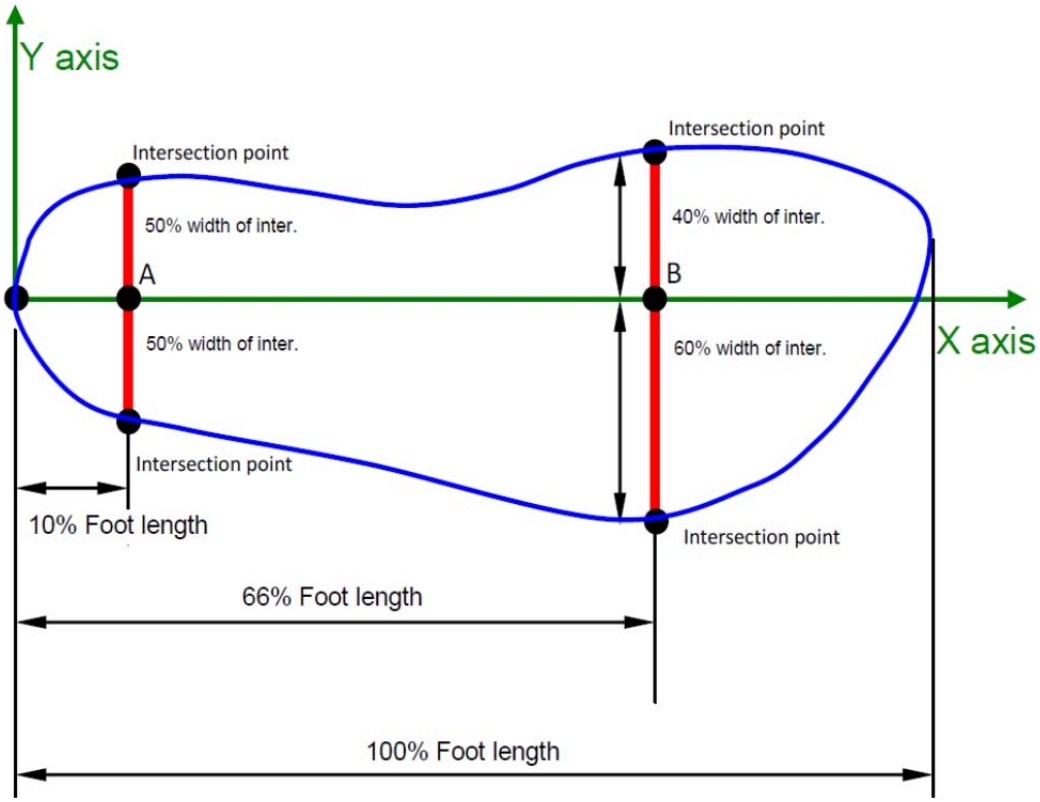

Fig. 1.Example of foot scan orientation.

Foot length and width were extracted for each foot scan as shown in Fig. 2. Foot length is the distance along X axis, measured from the minimum x-point within the heel area, to the maximum x-point within the toes area (the later may be either first or second toe).
Foot width is determined as the distance in y direction between the two points: Inner (medial) contour maximum y-point (ICMP) and outer (lateral) contour minimum y-point (OCMP). ICMP is detected in the range 65% to 80% foot length, whereas OCMP is detected in the range 50% to 80% length. This methodology eliminates questionable local maximums related to flat feet and first toe pointing outwards.

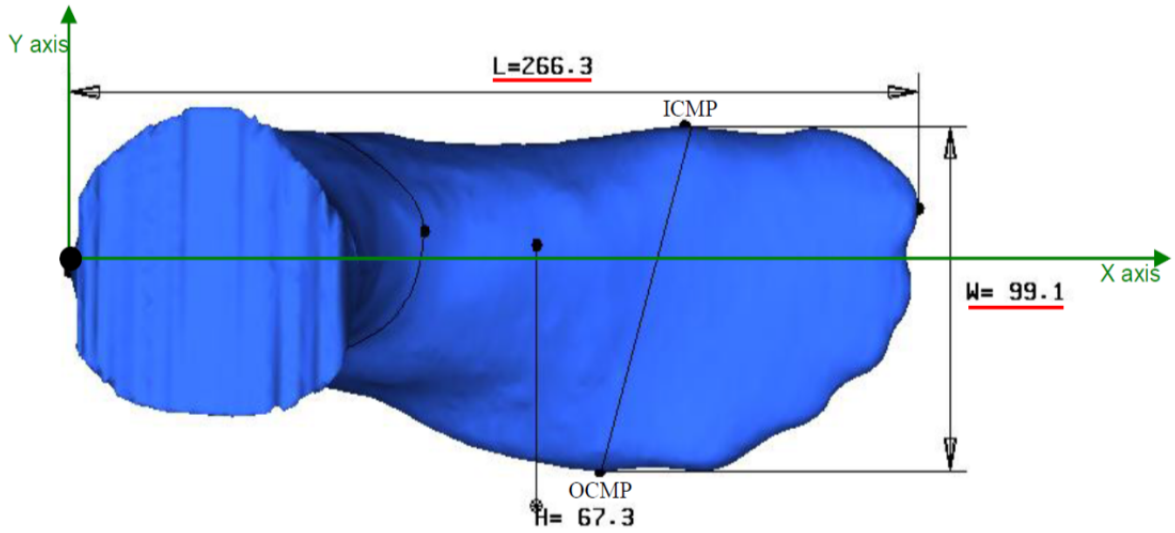

Fig. 2. Foot length and width.

2.2. Evaluation and classification of toe shape

In the first part of analysis we consider length and width of a foot. Here we are only interested in the shape of toes.
There exists a few different classifications of feet. One of the most widely used is the classification into the following three types (see Fig. 3):

- Egyptian (1st toe is the longest)
- Roman (square shape, also named peasant's foot)
- Greek (2nd toe is the longest, also named Morton's toe)

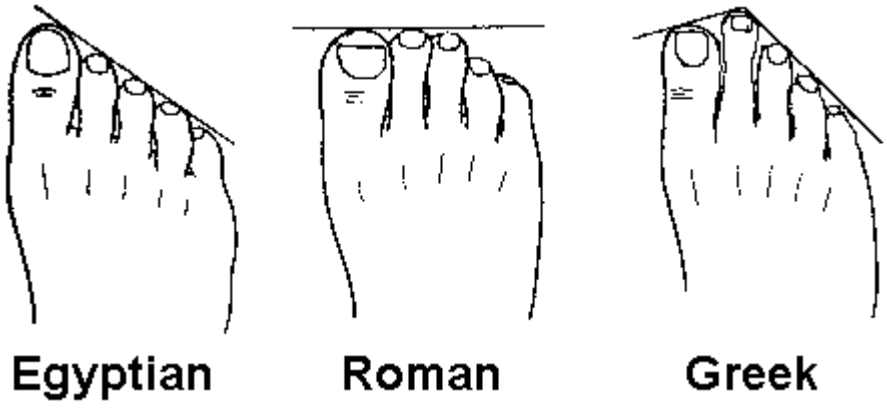

Fig. 3. Feet types.

This type of classification is difficult to find in scientific literature. Greek foot is the type of foot mostly found in many Greek and Roman statues. Da Vinci placed Greek foot on many of his paintings. Statue of liberty also has Greek foot. Morton called it "a prehuman grasping toe."
There is no clear and objective method for classification of feet into this three types. The boundaries between the classes are not very well defined, so a foot can fit into one or another type.
Since there is no strict algorithm for feet classification into the three types, we have defined an algorithm (set of rules) for the feet classification. The classification algorithm is a simple decision tree.

We started by defining a large set of learning instances – i.e. a set of feet and corresponding foot types. Initially, a set of 300 feet has been selected and classified by at least two expert judges. These learning foot/type pairs have been later used in an evaluation function of a classification algorithm.
Following Fig. 3 the classification algorithm is based on two lines that approximate front shape of the toes. Fig. 4 shows an example for each foot type. The two lines used for the classification are marked with dotted lines in blue and magenta color. Depending on the angles and the lengths of the two lines we built a classification algorithm that emulates the classification done by experts on the learning set. The classification algorithm has been verified by comparing results to the learning set.

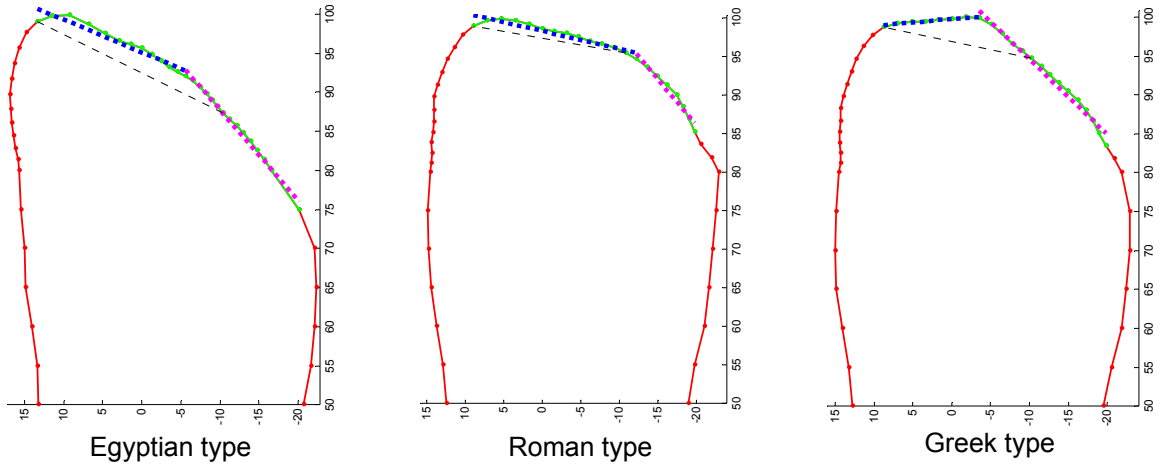

Fig. 4. Examples of feet types.

2.3. Classification algorithm

A foot is classified to one of the three classes by following the next steps:

- All feet are normalized, since we are interested only in shape and not in the length and width. 3D foot scans are normalized to 100mm in length and 38 mm in width (the average foot width/length ratio for all feet is 0.38).
- Two lines that approximate toe shape are generated (see blue and magenta lines in Fig. 4). The lines are created so that the difference between points on the two lines and the foot contour is minimized.
- The foot is Greek type if:
  - angle of blue line < 0.02 & length of blue line >= 6 units
- The foot is Roman type if:
  - it is not Greek foot
  - angle of blue line < 0.25 & length of blue line >= 12 units
  OR
  - angle of blue line < 0.20 & length of blue line >= 10 units
  OR
  - angle of blue line < 0.15 & length of blue line >= 8 units
  OR
  - the angle of all toes is < 0.25
- The foot is Egyptian type if:
  - it is neither Greek nor Roman foot

Here all angles are in radians. Units are distance measure and correspond to 5 degrees steps of polar description of the foot.
Despite the simple form of the algorithm the classification accuracy is acceptable close to the training set.
We have experimented the classification using support vector machine classification, however, the results did not justify the complexity.

3. Results

We have extracted the length and width of feet as explained in the previous section. Additionally we have classified the feet into three feet types. In the analysis we considered right feet of more than 40.000 subjects. There are many children included in the analysis. The age distribution of subjects is shown in Fig. 5. 42 % of the test group are male, 58% are female.

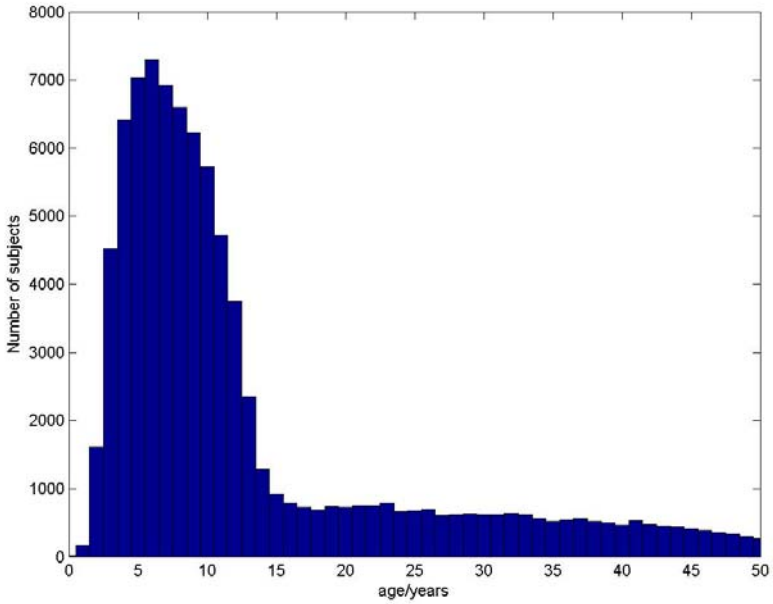

Fig. 5. Age distribution of test population vs age

3.1. Dependence of foot length and width on age

Fig. 6 shows how the length and width of foot changes with age. The lowest graph shows relative width of foot (i.e. the ratio between the width and the length). The three graphs show moving average from the age of 2 years up to 50 years where the window of moving average is ± 0.5 year.

As we can see in Fig. 6 the male and female feet are very similar up to the age of about 12 years. The rate of growth of feet is constant almost to the time when the feet stop growing. Even though we know that feet grow in intervals, this information is lost in averaging used in this work. After the age of 12 the female feet slowly stop growing, while the male feet still grow for another 3 years.

The width of feet increases with age in similar way as the length.

Relative foot width (i.e. width divided by length) shows that the feet of children are wider comparing to adults. At the age of 2 years the relative width is about 0.45. The relative width slowly decreases and stabilizes at the same time when feet stop growing. At this time the relative width is about 0.38.

In the growing period are male feet relatively wider comparing to female feet (but not significantly). Adult females have nearly the same relative width comparing to males.

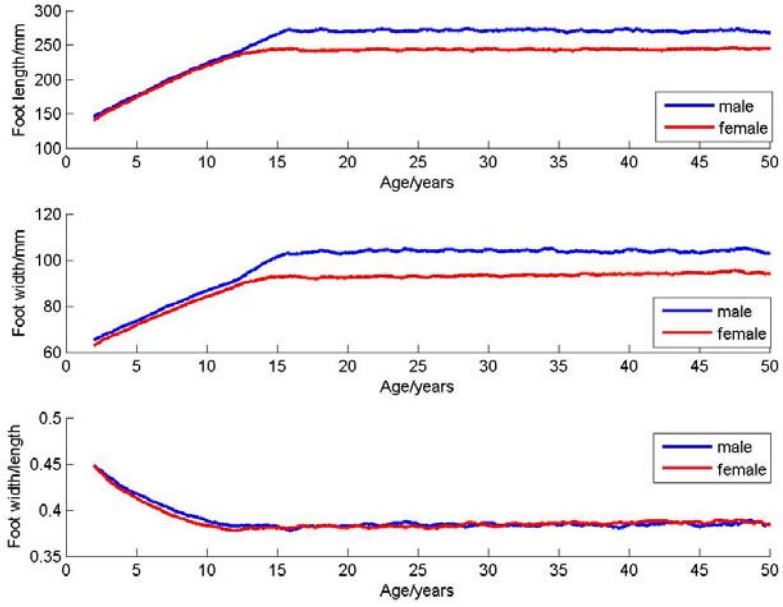

Fig. 6. Length/width feet dependence on age

3.2. Dependence of foot type on age

All feet were classified into three foot types using algorithms described in the previous section. The following table shows the distribution of foot types for the whole test population. Note that the population includes more children than adult subjects. The distribution at a specific age is shown in Fig. 7.

Foot type	Relative part
Egyptian	0.50
Roman	0.38
Greek	0.12

Fig. 7 shows the distribution of feet at a specific age. Egyptian feet are the most represented feet. The Greek feet are the less represented. We can see that there are differences between adult and children feet. It is interesting that there are significant differences between female and male feet. The reason for that might the in inappropriate footwear. However, this is only a hypothesis and is out of scope of this paper.

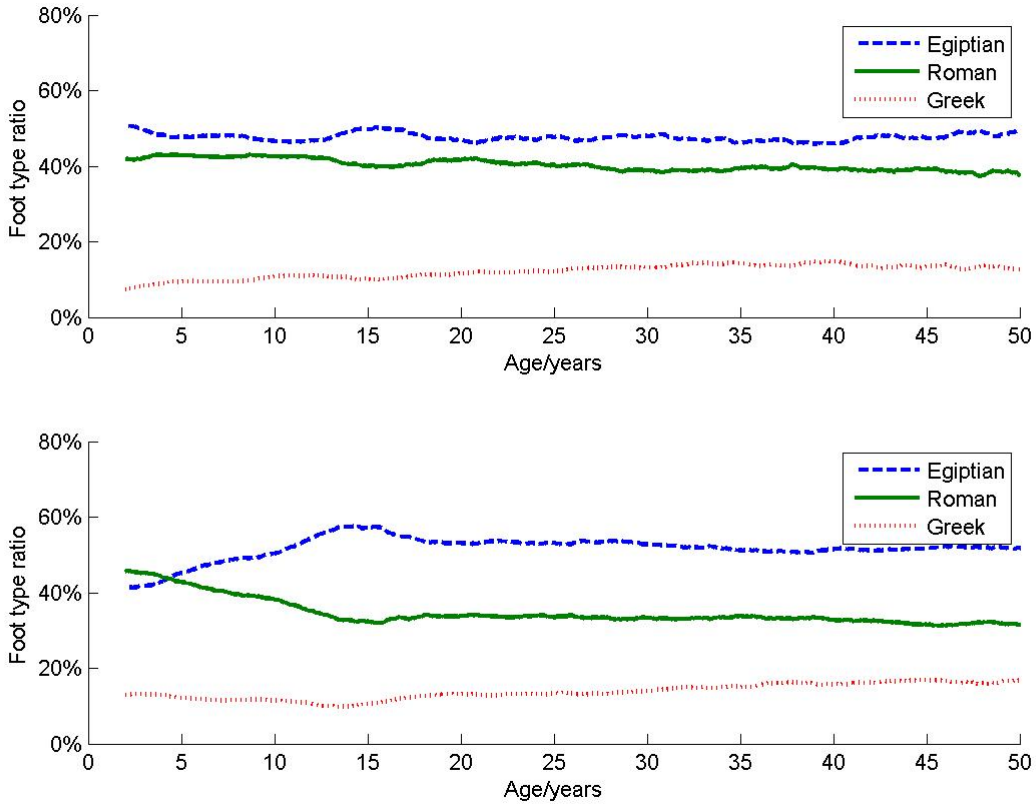

Fig. 7. Foot type dependence on age (male – above, female – below)

4. Conclusion

This paper deals with the evaluation of human feet. The results have shown significant differences between children and adult feet. There are significant differences in basic characteristics (such as length and width). Additionally, there are differences in the shape of toes.
Such information indicates the importance of difference between adult and children shoes.

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