Geometric morphometrics in the analysis of bilateral feet symmetry

Jacqueline Domjanić, PhD
Prof. **Darko Ujević**, PhD
University of Zagreb, Faculty of Textile Technology
Department of Clothing Technology
Zagreb, Croatia
e-mail: jacqueline.domjanic@ttf.hr
Received January 17, 2015

UDK 687:611:572:685.3
Original scientific paper

For design and production of functional and comfortable shoes the knowledge of the morphology of the feet is of vital importance. Development of the technology of 3D-scanning of human body and personal computers has enabled the application of the new methods of data analysis using the empirical and theoretical knowledge in anthropology, statistics as well as the clothing and footwear technology. The aim is to study bilateral symmetry of the complex human foot in selected student population of young girls using geometric morphometrics, which has become the main direction of research in the field of morphometrics in the last thirty years. Due to the application of the proposed methodology, this method compares body forms on the basis of the set points of anatomic characteristics. The paper examines anthropomorphic characteristics of the body and feet to enable graphical representation of composition of the feet for the selected pattern that may have wide application in practice. The results of research indicate that there is a variability of morphologic characteristics of feet and that the need of further study of variations in the shape and size of the feet is justified.
Key words: *human feet, 3D foot scanner, asymmetry, deformation*

1. Introduction

Italian Renaissance artist Leonardo da Vinci described the human foot as "The engineering masterpiece" which was certainly true, because the human foot forms a single functional unit, which consists of 26 bones, connected by firm ligaments and muscles. The interaction of bones, joints, ligaments, tendons and muscles is described through morphology (shape and structure) and mechanics (statistic-dynamic function) of feet [1]. The human body was created as a complex entity, where the three-dimensionality of the body is spatially determined by the main body planes. The central plane divides the body into right and left symmetrical halves, where the left and the right foot represent the reflected image of the body, forming the so-called bilateral symmetry, Fig.1 [2].

During bipedal movement the foot changes its shape. The differences become apparent in the length, shape and angle of toes, width and shape of the heel as well as in the shape of lateral and distal arch of feet. The variations in these characteristics indicate the need of analysis of shape because a single shape can not be sufficiently precise in the description of a human foot and meet the requirements of footwear comfort for a large number of people. In urban civilization, the emphasis is increasingly being put on the health of feet. Therefore, systematic analysis of the variations of feet shapes is necessary, which can be applied to the modification of the last and shoes to fit the feet of different shapes [2-4].

The primary task of socks and shoes is to protect the feet from extreme temperatures, injuries as well as external influences. Unsuitable footwear, however, can contribute to the appearance of deformations. In the mid 19th century, the German doctor

Fig.1 Bilateral symmetry of human feet pair unit

Hermann von Meyer launched a groundbreaking research, which proved the occurrence of deformations of feet as a result of wearing footwear of inappropriate construction. Until then, the shoes were made on the basis of symmetrical lasts, left and right insoles were completely identical, and the shoes came out identical as well. The greatest deformations were caused to the forefeet. In 1965, Debrunner warned that the deformation known as Hallux valgus (bunion) appeared as a result of wearing too short shoes. Footwear laboratory in Krakow obtained the evidence that each shoe hinders the freedom of pedal joints to a certain extent. The stiffer the shoe, the greater the constraint. From all above one can conclude that the knowledge of morphology of feet is of vital importance for design and production of functional footwear [5].

The national research and development project entitled Croatian Anthropometric System (CAS) has been conducted in the Republic of Croatia within anthropometric measurements of 30,866 individuals were performed with the aim to establish a new sizing system in apparel and footwear. The conventional measuring method was used to collect length characteristics of the population and to create a unique database. Data analysis consisted of a description of certain variables with a systematic review of evaluation parameters distribution of body measurements that were listed in tables and published in CAS book series [6, 7]. In a traditional approach of anthropometric data presenting, a separation of size and form variability is immanent. For this reason, the paper presents a new approach of morphological unit analysis by direct graphical form visualization where it is possible to detect small shape changes, which is not possible using traditional methods.

2. Materials and Methods

2.1. 3D foot scanner

The foot scanner Pedus® was used to scan the feet of a sample of 83 young women in an age range from 18 to 36 years. Pedus® (Vitronic and Human Solutions GmbH, Germany) is an optical 3D digitizer with physical dimension of 600 x 600 x 800 mm, with a defined three-dimensional scanning volume of 100 x 190 x 320 mm. It is a contact-free measuring device with an active optical triangulation as the measurement principle according to the way how the position of the measuring point on the surface is defined relative to the measuring sensor. By the triangulation method the laser light illuminates the object, while simultaneously the camera aquire the position of the laser dot on the object. The laser source, the projected laser dot on the foot and the sensor element of the camera form a triangle. The distance between the transmitter, the sensor element of the camera are known as well as the angles that form the transmitter and camera with the object. As a result, the shape and the size of the triangle that together form the laser source, sensor element of the camera and the iluminated object can be determined. These three pieces of information fully determine and store coordinates of the object (x, y, z). Before each cycle of scanning, sensor calibration was performed in order to set the parameters for each of the 3 CCD camera which is

Fig.2 Foot scanner Pedus® [1]

achieved by scanning special calibration tool of known geometry [1, 8-10]. The used 3D foot scanner is located at the Faculty of Textile Technology, University od Zagreb in the Department of Clothing Technology in the Laboratory for taking anthropometric body measurements and garment construction, Fig. 2.

Before the scanning process started, the purpose of the research and procedure was explained to all individuals the details of the purpose of research and the procedures being used. All participants took part in the research voluntarily. For each person we additionally collected the data on body mass and height to calculate the Body mass index, which is being used as a general indicator of obesity, however doesn't take into account the body composition of the person measured. The Body mass index (BMI) is being calculated in such a way that the body mass of the respondent displayed in kilograms is divided by the square of height in meters [11]:

$$BMI = \frac{Body\ \ Mass\ (kg)}{Body\ \ Height\ (m^2)} \tag{1}$$

The World Health Organization uses the Body mass index as a diagnostic method, and the values are categorized as follows: BMI <20 underweight, BMI 20-25 ideal weight, BMI 25-30 overweight and BMI >30 obesity [12]. In recent decades, the number of obese people has increased, and there are studies that explore the impact of body mass on the shape of feet, especially on the structure of the medial arch [5, 13-15].

2.2. Surface model preparation for analysis

Footprints were generated from three--dimensional surface models using the Amira® software by placing a transverse plane at 2 mm from the surface ground. For the geometric morphometrics analysis, the software packages TPS (James Rohlf) and Mathematica® were used. For data acquisition, 85 evenly aranged landmarks and semilandmarks were digitized using the software program TPSDig2. Fig. 3 shows positions of the selected semilandmarks that slide along the curve based on the Sliding Landmark Algorithm [16], in order to estimate the position of specific points of the foot in all forms, whereas Table 1 provide the number and description of the types and positions of digitized landmarks. The literature [17-21] most often cited three main types of landmarks points that were defined in 1991 by Bookstein, based on anatomical and geometrical criteria, but recently the number has expanded to six types of points.

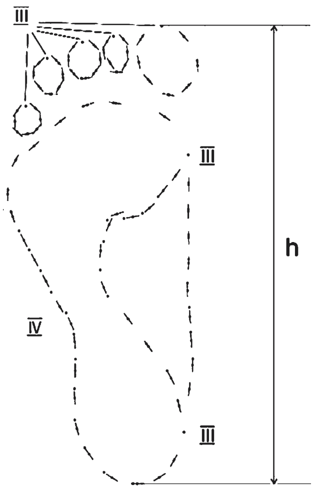

Fig.3 Footprint of one individual extracted from three dimensional surface foot model together with landmarks and semilandmarks for morphometric analysis [1]

Geometric information from data collection are remained on an object after removing differences in size, location and orientation using generalized Procrustes analysis (GPA) whereat shape variables are filtered out from each object in the sample [21].

2.3. Morphometrics

Morphometrics (from the Greek μορφή "morphé" = shape and μετρία "metría" = measurement) is a scientific discipline, which studies the shape variability of morphological entities with the aim of quantitative determination of anatomical differences between individuals or groups. The basic application of morphometrics was recorded in anthropology and biology, and it has been recently applied in medicine, veterinary, forestry and experiences wider use, even in the clothing and footwear technology. In literature, we distinguish between the two basic directions of research: the so-called traditional morphometrics and geometric morphometrics (GM), or, the new GM. While traditional morphometrics uses morphometric variables (length, width, etc.) for the analysis, geometric morphometrics analyzes mathematic shape of morphological structures through geometry of the studied shape. Size, position and orientation of the morphologic entity were excluded from the mathematic shape, thus only geometric information is being obtained, and tiny changes in the studied shape can be detected [16-24].

The use of personal computers has contributed to the development of the new methodology in morphology. Based on the known deformation grids by Albrecht Dürer and D'Archy Thompson, Bookstein in the late eighties developed the TPS (Thin-Plate Spline) method. With the help of the TPS algorithm it is possible to mathematically calculate the energy of deformation, hypothetically speaking, „of an unlimited, infinitely thin metal plate" due to the relative change in the coordinates of homologous anatomical points in some morphological entity. The main feature of the TPS algorithm is the visualization of shape variations [19,20,23].

Tab.1 Types of used landmark points [10]

Landmark type	Number	Description
Type III	5	Tip of the distal toe part
Type III	2	Most prominent medial position of the foot outline
Type IV	35	External toe outline (each toe separate)
Type IV	34	External outline of the forefoot, midfoot and the heel
Type IV	9	Medial foot outline (begining and finishing from most prominent medial position of the foot outline

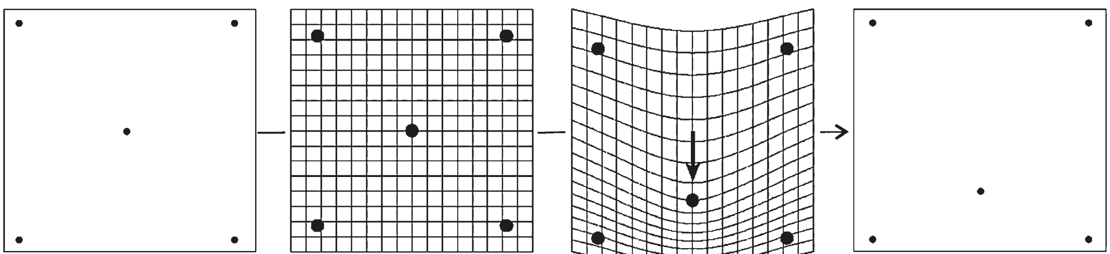

Fig.4 Deformation presented with TPS algorhythm [1]

3. Results and discussion

For the analysis of the overall changes in shape of bilateral symmetry of a female shape the method of geometric morphometrics was used. From the literature [2] it is well-known that the foot arches play a significant role in walking, where the body weight is transferred from the heel to the lateral longitudal arch, and then to the front part of the foot. The mechanical forces created in the bipedal movemant of the human are caused by the body mass, therefore the Body mass index, as well as bilateral symmetry, is included in the analysis to determine the deformation of feet during walking, which also has an impact on the comfort of shoes. In addition to the pedal arch, subcutaneous adipose tissue also takes part in the forming of the footprint shape [2]. After placing the points on the footprints, the method of the Generalized Procrustes analysis is being used, which excludes from the sample variables containing the data about the shape of every foot in the sample. The coordinates of points after scaling, centering and rotation are called Procrustes coordinates and are taken as initial data for further analysis. The calculated values of the Body mass index (BMI) lie in the range from 15,1 to 29,4, and the impact of body mass on the shape of footprints was investigated by using a regression model, where the Procrustes coordinates are taken as a dependent variable, Fig. 5.

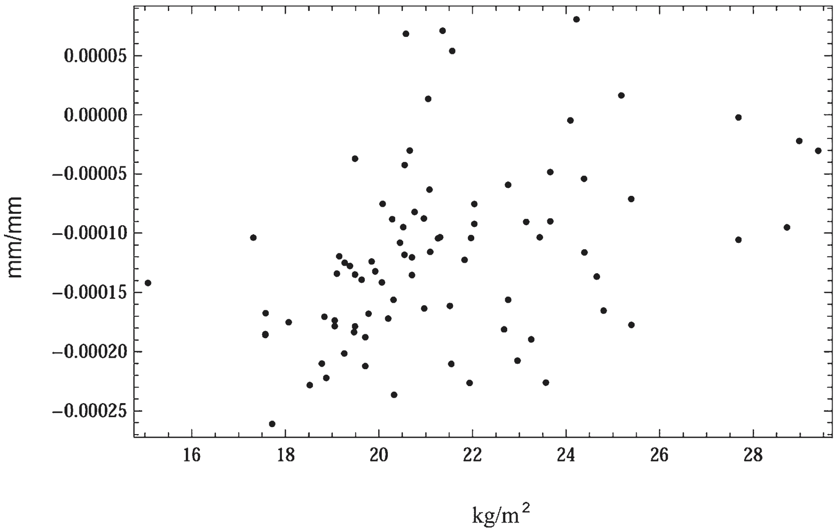

Fig.5 Scaterplot of Procrustes shape coordinates against body mass index [1]

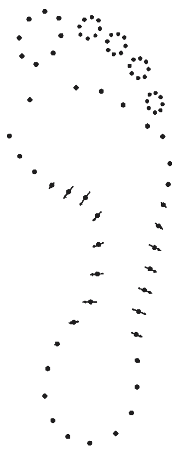

Fig. 6 Regression footprint shape - deformation for BMI

The changes in the shape of footprints with the implication of the Body mass index and the use of multivariant regression show the stretching in the area of the middle part of the foot. The model of change is that the medial and lateral contour move outwards. The value of covariance between the BMI and the shape is given in vectors, that show the displacement of certain points, Fig.6.

The Body mass index has a statistically significant impact on the shape of footprints ($p < 0,001$). Lower values of the Body mass index are associated with a marked medial pedal arch, while higher BMI values are associated with a lower arch. Fig. 7 provides the visualization of the impact of BMI on the length to width ratio for the values of BMI 15, BMI 20, BMI 25, BMI 30 and BMI 35.

a) b) c) d) e)

Fig.7 Visualization of the impact of BMI on footprint shape for: a) 15, b) 20, c) 25, d) 30 and e) 35 BMI [1, 23]

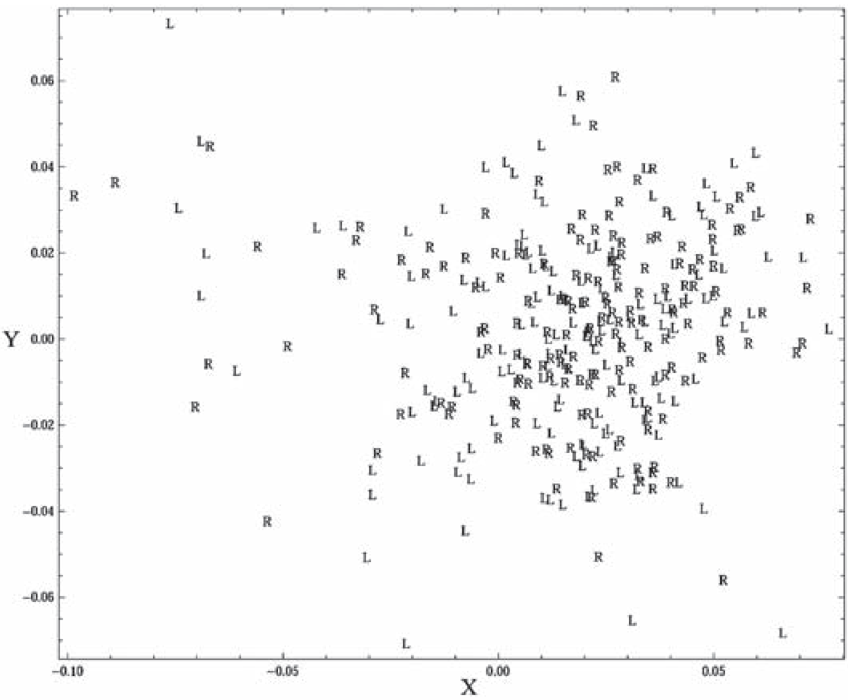

Fig.8 Visualization of the variance of Procrustes shape coordinates for the sample for the left (L) and right (R) feet [1]

a) b) c) d)

Fig.9 Mean footprint shape: a) left foot, b) right foot, c) for a better shape change visualization the signal was 4 times exaggerated for c) left foot and d) right foot [1, 23]

Fig.8 provides a numerical presentation of the Procrustes coordinates of the analyzed specific points (landmarks, semilandmarks) of the left and right feet. Based on the different positions of specific points the energy of deformation and the excluded variables of shape that represent their own vectors of deformation energy matrix were calculated. The Fig.9a and 9b give a graphical presentation of the average left and right feet of the studied sample. In order to test whether there is a statistically significant difference in the obtained shapes, the permutation test was used. The left and right feet differ greatly statistically ($p < 0,001$). The right feet are on average wider in relation to their length and the boundary between the front and the middle part has a larger angle in right feet when compared to the left.

Visible shape changes are quite moderate. In order to improve the visual effects, the variation signal has been amplified by factor 4 (Fig.9c and 9d), using four times the shift component of the coefficient vector of the spline equation [25].

4. Conclusion

The feet of 83 young girls were scanned using 3D foot scanner. Traditional foot measures have been replaced by specific points in specific positions on the transverse plane of the feet and analyzed using the algorithm for quantification of differences in the shape. Variability of results obtained using Procrustes analysis shows the greatest change of shape in the area of longitudinal, medial and lateral pedal arches.

On the average the right feet are wider than the left, and the contours of the medial pedal arches show a higher angle in the right feet. Variability of asymmetry in the sample also changes according to the value of the Body mass index, so the symmetry is greater for young women with body mass index smaller than 21. It can be assumed, that the more the body mass value affects the load on the feet during walking, the more it affects the morphological symmetry of the feet. It is also evident, that the higher values of the Body mass index are associated with wider and lowered feet. This study provides insight into morphological characteristics of human variability and can be seen as a basis for future research. Geometric morphometrics turned out to be the new method in the clothing and footwear technology to test the change of the shape of feet caused by internal and external factors that affect the human body, and can contribute to improve footwear design and manufacture of functional and comfortable footwear with good fit.

The research was conducted within the cooperation with em. O. Univ.-Prof. Dr. Horst Seidler and Prof. Mag. Dr. Priv. Doz. Philipp Mitteröcker from the University of Vienna.

References:

[1] Domjanić J.: 3D Surface Models and Geometric Morphometric Analysis of Female Feet. Doctoral Dissertation. University of Zagreb. Zagreb, 2013.

[2] Keros P., M. Pećina: Funkcijska anatomija lokomotornoga sustava. Medicinska biblioteka. Naklada Ljevak, Zagreb, 2006. ISBN 978-953-178-787-1

[3] Kalebota N.: Regionalne razlike u građi stopala mladih muškaraca u Hrvatskoj, Magistarski rad, Sveučilište u Zagrebu, Zagreb, 2006

[4] Akalović J. Anthropometry in Footwear Design and Last Making. In Theoretical Aspects and Application of Croatian Anthropometric System, Zagreb, 2010, ISBN 978-953-7105-28-0

[5] Mauch M.: Kindliche Fußmorphologie: Ein Typisierungsmodell zur Erfassung der dreidimensionalen Fußform im Kindesalter. AV Akademikerverlag. 2012, ISBN 978-3-639-42138-5

[6] Ujević D. i sur.: Hrvatski antropometrijski sustav : Podloga za nove hrvatske norme za veličinu odjeće i obuće, Publikacije serije HAS, ISBN 953-7105-09-1, 2006

[7] Ujević D. et al.: Theoretical Aspects and Application of Croatian Anthropometric System, Zagreb, Croatia. 2010, ISBN 978-953-7105-28-0

[8] Bogović S.: Konstrukcija odjeće prilagođena tjelesnim deformitetima primjenom topoloških invarijanti, Doktorska disertacija, Sveučilište u Zagrebu, Zagreb, 2012.

[9] Ivšac D.: Usporedba 3D mjernih postupaka u kontroli kvalitete, Diplomski rad, Sveučilište u Zagrebu, Zagreb, 2014.

[10] Weber G.W., F.L. Bookstein: Virtual Anthropology: Mapping the physical world: Digitise, Wien, New York: Springer Verlag. ISBN 978-3-211-48647-4

[11] Indeks tjelesne mase, dostupno na http://hr.wikipedia.org/wiki/Indeks_tjelesne_mase, pristupljeno 11.01.2015.

[12] World Health Organization: Obesity: preventing and managing the global epidemic Report of a WHO Consultation (WHO Technical Report Series 894). 2000.

[13] Sforza C, G. Michielon, N. Fragnito, V.F. Ferrario: Foot asymmetry in healthy adults: elliptic fourier analysis of standardized footprints. J Orthop Res **16** (1998) 6, 758-765

[14] Kraus I. et al.: Sex-related differences in foot shape. Ergonomics **51** (2008) 11, 1693-1703

[15] Kraus I., M. Mauch: Foot Morphology, The Science of Footwear. Taylor & Francis Group, Boca Raton, 2013, ISBN 13:978-1-4398-3569-2

[16] Bookstein F.L.: Landmark methods for forms without landmarks: morphometrics of group differences in outline shape. Med Image Anal 1 (1997) 3, 225-243

[17] Bookstein F.L.: Morphometric tools for landmark data: geometry and biology. Cambridge (UK); New York: Cambridge University Press, 1991

[18] Ivanović A., M. Kalezić: Evoluciona morfologija: teorijske postavke i geometrijska morfometrija. Biološki fakultet, Beograd, 2009., ISBN 978-86-7078-100-9

[19] Mitteroecker P, P. Gunz: Advances in geometric morphometrics. Evolutionary Biology (2009) 36: 235-247

[20] Gunz P., P. Mitteroecker: Semilandmarks: a method for quantifying curves and surfaces. Italian Journal of Mammalogy **24** (2009) 1, 1-7

[21] Zelditch M.L., D.L. Swiderski D.H. Sheets & W.L. Fink: Geometric morphometrics for biologists: a primer. - Elsevier Academic Press, London, 2004, ISBN 0-12-77846-08

[22] Janković I.: Neandertal Lateral Midface: A Morphometric Analysis. Hrvatsko antropološko društvo. Zagreb, 2009., ISBN 978-953-7467-01-2

[23] Domjanić J. et al.: Geometric morphometric footprint analysis of young women, Journal of Foot and Ankle Research 6 (2013) 27, 1-8

[24] Bookstein F.L., J. Domjanić: Analysis of the Human Female Foot in Two Different Measurement Systems: From Geometric Morphometrics to Functional Morphology, Collegium Antropologicum 38 (2014) 3, 855-863

[25] Bookstein F.: A hundred years of morphometrics, Acta Zoologica Academiae Scientarium Hungaricae, 44 (1998) 1-2, 7-59