Coll. Antropol. **30** (2006) 4: 815–821
Original scientific paper

Foot Anthropometry and Morphology Phenomena

Ante Agić[1], Vasilije Nikolić[2] and Budimir Mijović[3]

[1]Faculty of Chemical Engineering and Technology, University of Zagreb, Zagreb, Croatia
[2]Faculty of Medicine, University Josip Juraj Strossmayer, Osijek, Croatia
[3]Faculty of Textile Technology, University of Zagreb, Zagreb, Croatia

ABSTRACT

Foot structure description is important for many reasons. The foot anthropometric morphology phenomena are analyzed together with hidden biomechanical functionality in order to fully characterize foot structure and function. For younger Croatian population the scatter data of the individual foot variables were interpolated by multivariate statistics. Foot structure descriptors are influenced by many factors, as a style of life, race, climate, and things of the great importance in human society. Dominant descriptors are determined by principal component analysis. Some practical recommendation and conclusion for medical, sportswear and footwear practice are highlighted.

Key words: *foot anthropometry, foot shape, foot biomechanics*

Introduction

The human foot is a complex structure, playing an important role in the locomotion processes of the lower extremity. It is a part of the body that acts on external surface, providing support and balance during stance and gait. The foot structure description, beside geometrical anthropometric descriptors needs biomechanical factors such as muscle deformation, tissue stiffness, stress and strain distribution[1]. The full morphological description of the foot for more than 26 anthropometric measures is desired. Foot dynamic anthropometry has a vital role in medical rehabilitation, sport science, and footwear design among others[2]. Distribution of the internal foot structure for given population is an indicator of the foot deformity, aging, and body growth anomaly among other things. The human foot as a complex structure is under dynamic loads, producing elevated plantar pressure and stress evolution within and between its structural components. Several techniques have been developed to study the morphology, architecture and kinematics of the food[3]. Integrated experimental technique is able to measure simultaneously both the kinematics and dynamic structural behaviours of the foot during gait, including development and validation of the 3D finite element model of the foot. The purpose of this study is to investigate the relationship between foot anthropometrical and biomechanical descriptors and derive usefulness regression equations for Croatian population. Scatter data of the individual foot variables are interpolated by multivariate statistics. This is multiple regression analysis, in which various combinations of these variables were regressed against each other with physical explanation.

Foot Anthropometric Descriptors

Anthropometric variables such as foot length, joint girth, bottom width, are stochastic variables in geometrical description of the foot[4]. Probability distribution of these variables is determined by measurement for given population in determined geographic region in specified time interval. In the past decade there has been some remarkable advance achieved in morphometrics and multivariate statistics of the shape object[5]. In the footwear practice, manufacturers assume that most foot dimension follow multivariate n – dimensional normal distribution

$$f(x)=\frac{1}{(2\pi)^{n/2}|\Sigma|^{1/2}}\exp\left[-\frac{1}{2}\{x-\mu\}^T\left[\Sigma^{-1}\right]\{x-\mu\}\right] \quad (1)$$

Here $\{x\}^T=\{x_1,x_2,\ldots x_n\}$ is an n – dimensional vector, $\{\mu\}^T=\{\mu_1,\mu_2,\ldots\mu_n\}$ is a mean vector, and $[\Sigma]$ is $n\times n$-covariance matrix. Traditional shoe size system has

Received for publication August 28, 2006

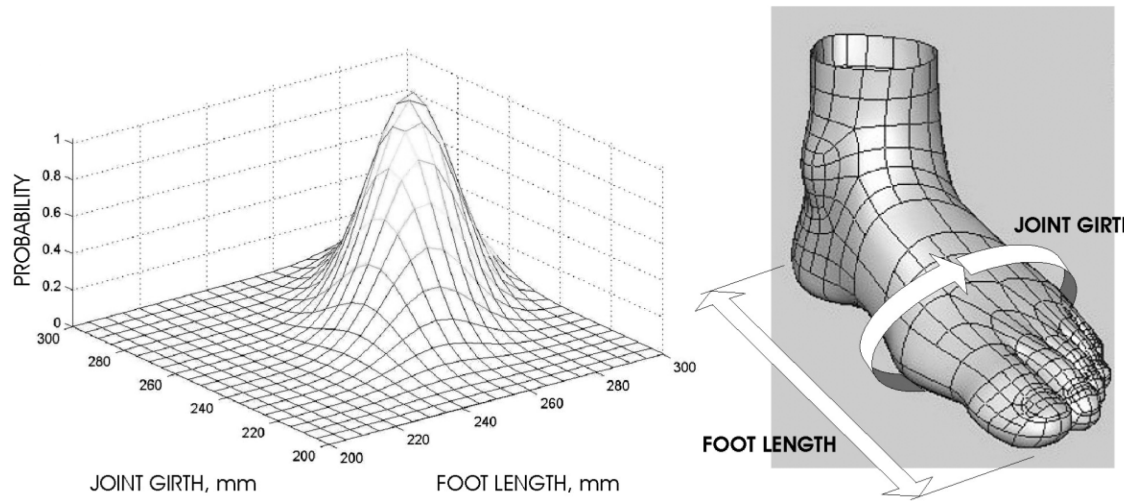

Fig. 1. Bivariate normal distribution of foot length and joint girth.

been constructed using bivariate normal distribution (Figure 1) with adequate classes and intervals for both foot length and joint girth.

In Japanese Industrial Standard[6], shoe size is defined by three parameters; length of foot, joint girth and width of foot. The industrial footwear production can be adopted for given population by constructing their size distribution function according to the stochastic interpolation theory. These few measures are not sufficient for proper foot fit and comfort under shoe; hence a good description of the 3D foot shape is necessary. The anthropometric variables are ordered in a hierarchical manner based on the geometric and statistical relationships among the variables. Length and height variables measure the lengths of the foot segments. In contrast, width, depth and circumference variables measure the cross-sectional sizes of the foot.

Foot Shape Representation

A foot in CAD (Computer Aided Design) is represented as a set of digitized points on the surface that more closely approximate an average shaped foot[7]. The 3D foot surface can be represented using Bezier or B spline, as the closest interpolating surface across digitizing points. According to the shape searching techniques, we classify 3D shape representation into the following categories[5]; global feature-based, manufacturing feature recognition-based, graph-based, histogram-based, product information-based and 3D object recognition-based method. Global feature-based methods use global properties of the 3D model such as moments, invariants and Fourier descriptors. The foot surface A can be approximated using spherical harmonics, the three coordinate functions are decomposed and the surface $A(\phi,\vartheta)=\{x(\phi,\vartheta), y(\phi,\vartheta), z(\phi,\vartheta)\}$ had the following form

$$A(\phi,\vartheta)=\sum_{i=0}^{\infty}\sum_{m=-1}^{i} C_i^m \cdot Y_i^m(\phi,\vartheta) \tag{2}$$

where the coefficients C_i^m are 3D vectors, Y_i^m are spherical harmonic basic functions, and Φ and ϑ are polar angles. The spherical harmonics had been frequently used for visualization and comparison of human body objects in medical practice. Another accurate shape description relies on geometric moments up to the second order. A three-dimensional moment λ_{ijk} can be described by the following integral

$$\lambda_{ijk}=\int\int\int f(x,y,z)x^i z^j y^k dxdydz \tag{3}$$

$$i, j, k = 1,2$$

where f(x,y,z) describes the object. Using this notion the mass m and inertia tensor I_{ij} can be expressed as

$$m=\lambda_{000}=\int\int\int f(x,y,z)dxdydz \tag{4}$$

$$I_{ij}=\begin{bmatrix} \lambda_{020}+\lambda_{002} & -\lambda_{010} & -\lambda_{101} \\ -\lambda_{110} & \lambda_{200}+\lambda_{002} & -\lambda_{011} \\ -\lambda_{101} & -\lambda_{011} & \lambda_{200}+\lambda_{020} \end{bmatrix} \tag{5}$$

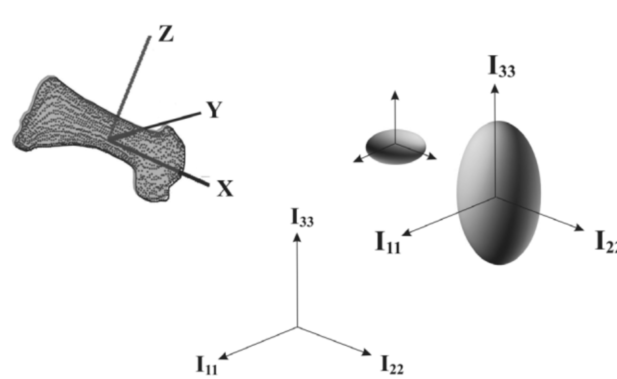

Fig. 2. Bone inertial tensor space.

The principal axes orientation is determined by the eigenvectors of the inertia tensor I_{ij}. The shape of each bone is characterized by eigenvalue of the inertial tensor defined for a coordinate system in bone centroid. Each bone is defined by the confidence ellipse in eigenvalue space. The separation between bone types is evident[8], (Figure 2). The inertial tensor of the group bones can be useful morphological descriptor of the foot functionality.

Some 3D shape can be represented by graph-based techniques, as other shape representation possibilities. Topology is typically represented in the form of a relational data structure such as graphs and trees. The shape can be represented by boundary representation, spectral, Reeb or skeletal graph. One of the shape description methods is medial representation m-rep of the foot. The m-rep parameters are element of the Lie groups, and therefore all statistical calculations must be performed in tangent space.

Principal Component Analysis

The recent development of 3D laser scanner has provided another efficient way for surface registration and analysis. The scattered grid point data are fitted by small second-order polynomial surface patch. At each point we have calculated the principal curvatures, mean curvature, Koenderink shape index[9], which are shape representing parameters. On the basis of parameter values at each point, potential landmark area could be detected. Now the shape descriptor becomes a 3n element vector (n – number points)

$$X_i = \{x_1, y_1, z_1, \ldots x_n, y_n, z_n\}^T \qquad (6)$$

Each shape S_i is represented by a set of n landmarks (i.e. sampling points) X_i.

$$S_i = B \cdot X_i \qquad (7)$$

where B is spline matrix. The mean shape $\overline{X}$ for a group of N shapes can be calculated using

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} X_i \qquad (8)$$

where X_i is the landmark shape descriptor of the i-th shape. Principal component analysis is applied to reduce dimensionality, for example reduction 3D (X, Y, Z) to 2D (*PC*1, *PC*2) as shown by Figure 3. The global covariance matrix Ξ of the data

$$\Xi = \frac{1}{N-1}\sum_{i=1}^{N}(X_i - \overline{X})\cdot(X_i - \overline{X})^T \qquad (9)$$

$$\Xi = \Phi \cdot \Lambda \cdot \Phi^T \qquad (10)$$

where the columns of Φ hold eigenvectors, and the diagonal matrix $\Lambda = diag\ (\lambda_1 \ldots \lambda_i, \lambda_j \ldots)$, $\lambda_i > \lambda_j$ holds eigenvalues of Ξ. The first few eigenvectors $m \le 3n$ (with greatest eigenvalues) can explain most of the variance in the data. This means that the $3n$ dimensional space is approximated by the m dimensional space (Figure 3) Now any shape X in the data can be obtained by writing

$$X = \overline{X} + \Phi \cdot A \qquad (11)$$

Where A is a vector containing the components of X in basic Φ, which are called principal components?

$$A = \Phi^T\ (X - \overline{X}) \qquad (12)$$

The analysis for the foot structure[7] has shown that the first principal component (PC) reflects foot size, while the second PC's define the shape parameter of the foot, and the third PC's define comfort.

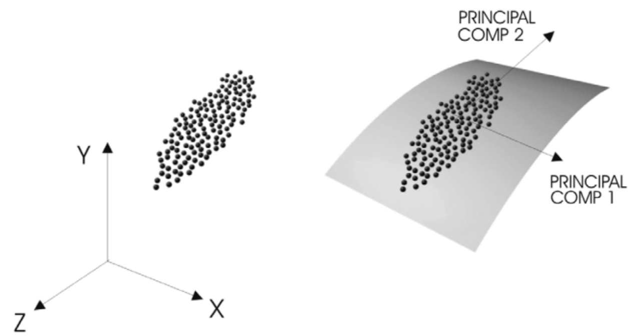

Fig. 3. Principal component analyses.

Comparison and Adjustment of the Foot and Shoes

Some known morphological measures (shape distance metric, segmentation, clustering) applied to fully 3D foot shape can explain many foot deformity phenomena in the best possible way. Proper fit is more than fit length and width; it requires a good understanding of the total 3D shape. The starting point is the geometric similarity between two feet and between foot and last. The basic idea is to compare the lasts which were used to manufacture the shoes and the scanned feet of the clients. The foot geometric similarity can be described by two-step procedures: the pose estimation and object comparison[10]. The appropriate pose estimation, which consists of computing the scaling, translation and rotation of the objects, so that their surfaces lay one on the other. The cost function had minimized the following least-squared distance metrics

$$\min_{R,T} \sum_i \left\| A_i - (R \circ B_i + T_i) \right\|^2 \qquad (13)$$

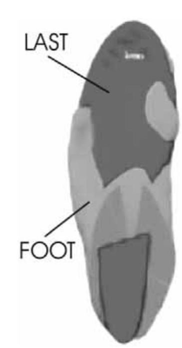

Fig. 4. Comparison between last and foot.

Where A_i and B_i represents points on the objects A and B respectively. The goal is to find a rotation R and translation T matrix, which minimize the least-squared distance metric. By co-locating the centroids of two objects at the origin of the reference coordinate system 3 degrees of freedom for translation can be removed. The closest pose is derived by comparing the ray distances while one shape is virtually rotated with respect to the other[11].

After the pose estimation, we determine for each object how big portion of its volume is outside of the other object (Figure 4). This comparison problem is possible to be resolved by discrete 3D distance field the concept of which is described in[10]. We transform each triangle of the foot surface into the closest triangles on the last by spatial distortion. This comparison method is better replaced by Free Form Deformation (FFD) method because foot is not a simple deformable shape[12]. The FFD technique smoothly transforms a shape of an object by setting control lattice points around the object and then moving these control lattice points.

Material and Methods

A group of 103 normal adult males selected among student population in Croatia has participated in this study. Their stature height and weight were first recorded. All measurements were made under 'no-load' conditions. The age of participants was between 18–21 years. The five dimensions (Figure 5) on the left foot have been measured for each subject (foot length, joint girth, maximum foot width, heel width and circumference).

According to footwear practice, we assume that foot length and joint girth obey bivariate normal distribution

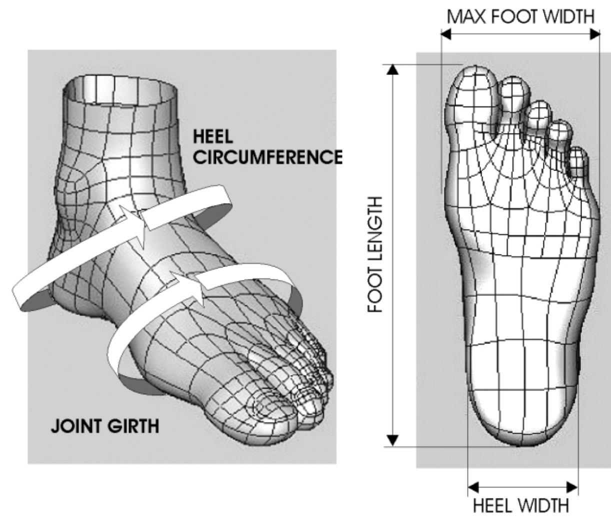

Fig. 5. Measured foot dimensions.

$$f(x) = \frac{1}{2\pi|\Sigma|^{1/2}} \exp\left(-\frac{1}{2} \{x-\mu\}^T \left[\Sigma^{-1}\right] \{x-\mu\} \right) \quad (14)$$

The scatter data (Figure 6) are interpolated by bivariate normal distribution. The calculated average foot length is μ_1=273.29 mm (standard deviation is σ_1= 12.01 mm) and the average joint girth is μ_2=263.18 mm (standard deviation is σ_2=12.52 mm). The correlation coefficient of foot length and joint girth is ρ_{12}=0.665 (Figure 6).

We calculated inter-variable correlation coefficients for the measured data displayed in the Table 1.

In order to study the influence of race on basic footwear dimensions, we compared bivariate normal distribution foot length – joint girth for Croatian population with some other nationality and race. We compared our

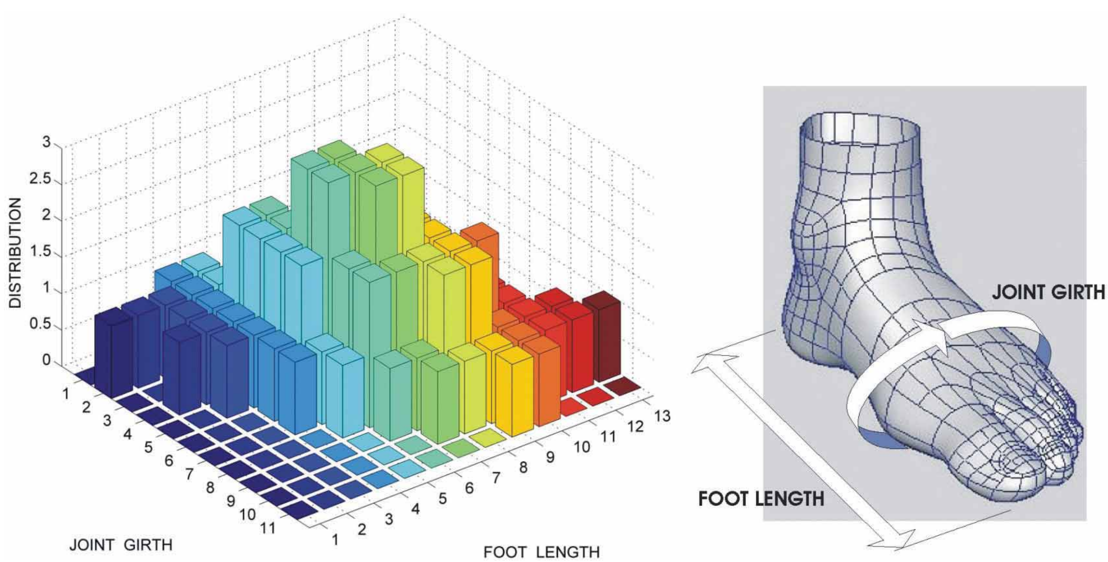

Fig. 6. Calculated normal distribution foot length-joint girth.

TABLE 1
INTER-VARIABLE CORRELATION COEFFICIENTS

	Foot Length	Joint Girth	Foot Width	Heel Circum.	Stature
Foot Length	1	0.665	0.560	0.410	0.930
Joint Girth		1	0.925	0.829	0.78
Foot Width			1	0.865	0.721
Heel Circum.				1	0.609
Stature					1

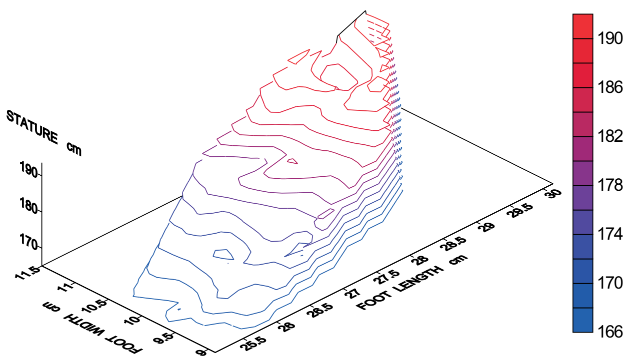

Fig. 7. The stature dependence on foot length and on maximum foot width.

data with literature data[13], for urban population in Russia and four populations in East Asia, i.e. Chinese, Japanese, Korean and Taiwanese[14]. In terms of race, the people in the region of East Asia belong to the Mongolian race and they have significantly different foot shape than the Europeans. Ethnic diversity is a significant factor and affects foot shape, too. It is possible to conclude that the Croatian population has large feet and different correlation coefficient. Therefore, establishing a national anthropometry database for the population is now inevitable. In medical and forensic practice the correlation between foot dimensions, stature height and body weight is recommended as shown on Figure 7.

One important structural characteristic is the height of the medial longitudinal arch above the ground plane during weight bearing activities[15]. The variations of the foot structure influence the shape of a footprint made by that foot. The measurement of the width or the contact area on the imprint is suggested to provide simple and objective means of foot classification. The arch index Θ is defined as the ratio of area of the middle third part area A_2 (Figure 8) of the footprint the entire footprint area ($A_1 + A_2 + A_3$), (excluding the toes) and it can be written as

$$\Theta = \frac{A_2}{A_1 + A_2 + A_3} \qquad (15)$$

The dependence of the body mass index (BMI) on arch index (Figure 8) indicates that the sample population has got normally distributed foot structure. The subjects with a lower arch (higher arch index) appeared to have a greater BMI. We can conclude that both body mass and arch index contribute to increased foot pressures. The objective of classification of the foot according to arch type can be helpful for sporting people in searching proper performance, and useful for people with abnormal foot structure to prevent injury. Some of subjects have been selected to test comfort and fit. The most preferred wearing shoes out of 10 pairs of running shoes are compared. The appropriate shoe size is supplied by last. The main fit indicator was circumference allowance defined as follow

$$\lambda = \frac{(C_{last} - C_{foot})}{C_{foot}} \qquad (16)$$

Where C is circumference? On Figure 9 constructed confidence region between foot circumference and allowance.

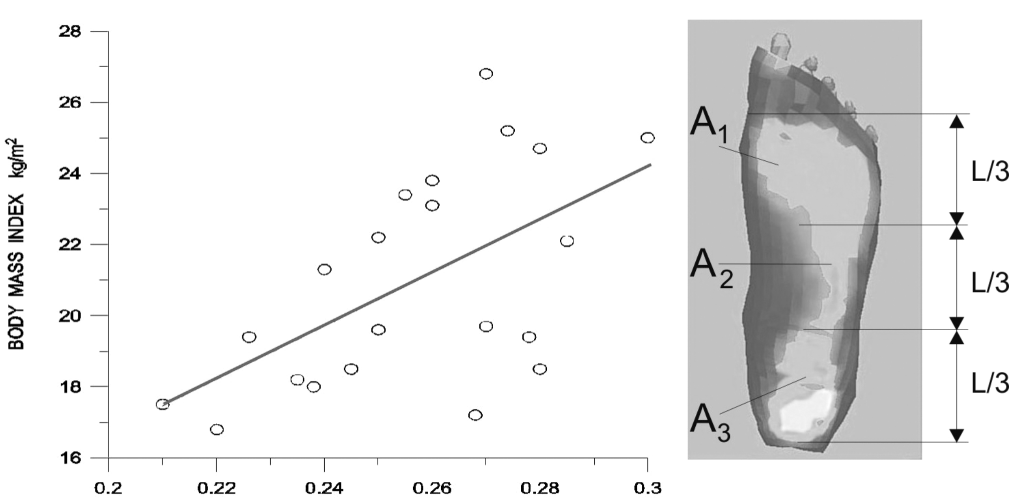

Fig. 8. Dependence of the body mass index on Arch index.

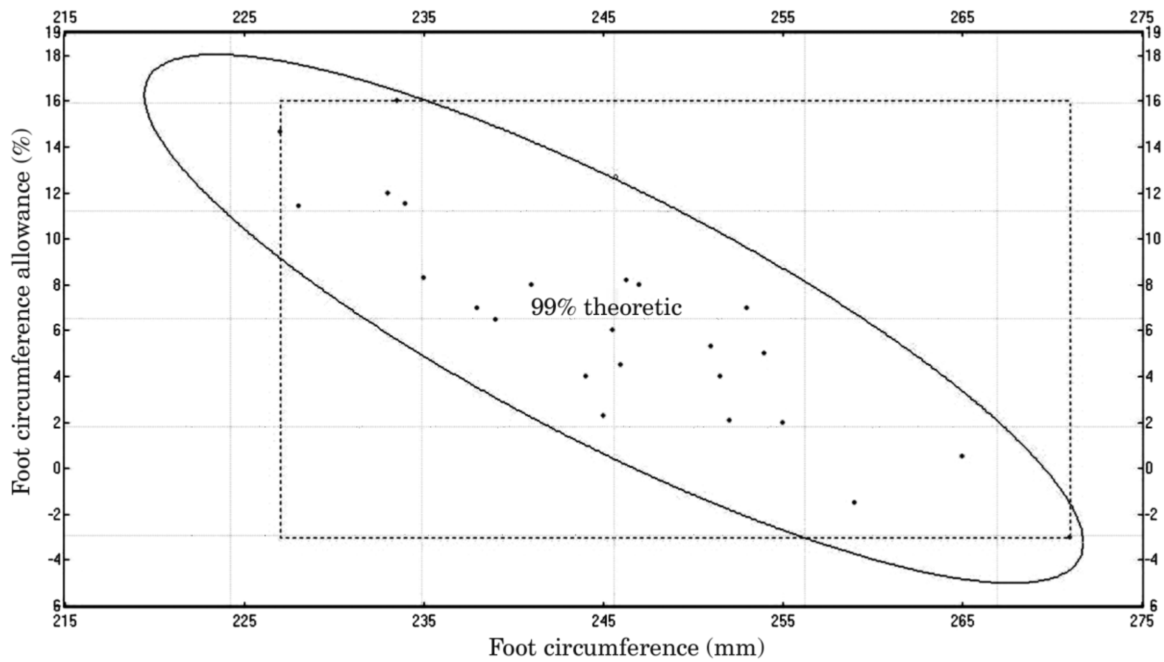

Fig. 9. Confidence regions for foot circumference-allowance.

The calculated average foot circumference is μ_1=245.57 mm (standard deviation is is σ_1=10.69 mm and the average circumference allowance is is μ_2=6.52 % (standard deviation is is σ_2=4.71 %). There is evident negative correlation between comfort and foot circumference s is ρ_{12}=–0.85 (Figure 9).

According to collected data some well-known relationships for foot structure have been confirmed, for example that length dimensions are proportional with foot length. The influence of the candidate's birthplace and the style of life are indicative for some foot dimensions. The mean (virtual) shape is based on homologous modelling[16]. The shape distribution maps visualize the distance relationship between individuals calculated on the basis of the homologous shape model. According to the shape theory, the distance metric could be established by using multidimensional scaling. After that, we can categorize a foot into sizes or types for target population.

Discussion and Conclusion

There are many factors that influence foot structure; therefore 3D foot shape descriptor has been supplemented by biomechanical structural and functional factors. Multivariate analysis between foot dimensions reveal how to precisely improve footwear fit and comfort. The future standardization decisions must be made to choose a few dominant descriptors needed for foot customization. The computational methods needed for comparison and adjustment must be adopted in shoemaking practice.

REFERENCES

1. ABBOUD, R. J., Current Orthopaedics, 16 (3002) 165. — 2. DEISINGER, J., R. BREINING, A.: RLER, Of Virtual Environments 2000. (ERGONAUT, Amsterdam, 2000). — 3. SCOTT, S. H., D. A. WINTER, J. of Biomechanics, 26 (1993) 1091. — 4. KALEBOTA, N., L. SZIROVICA, LJ. TUCAKOVIC, M. DRENOVAC, Coll. Antropol., 27 (2003) 635. — 5. IYER, N., S. JAYANTI, K. LOU, Y. KALYANARAMAN, K. RAMANI, Computer Aided Design, 37 (2005) 509. — 6. CHENG, F. T., D. B. PERNG, Int. J. Industrial Ergonomics, 25 (2002) 171. — 7. LUXIMON, A.: Foot shape evaluation for footwear fitting, Ph.D Thesis. (The Hong Kong University for Science and Technology, Hong Kong, 2001). — 8. STINDEL, E., B. E. HIRSCH, C. COUTURE, Computer Med. Imaging and Graphics, 23 (1999) 75. — 9. LIU, X., W. KIM, B. DRERUP, Real-Time Imaging, 10 (2004) 217. — 10. NOVOTNI, M., M. KLEIN, ECDl WS Generalized Documents, 3 (2001) 73. — 11. HWANG, T. J., K. LEE, H. Y. OH, J. H. JEONG, Computer-Aided Design, 37 (2005) 241. — 12. HIROTA, G., R. MAHESHWARI, M. C. LIN, ACM Solid Modelling 99, 12 (1999) 45. — 13. HOLEBA, E.: Zasady prawidlowej konstrukcji kopyt i obuwia. In Polish. (Wydawnictwa Naukowo-Techniczne, Warszawa, 1976). — 14. LIN, Y. C., M. J. WANG, E. M. WANG, Appl. Ergonomics, 35 (2004) 173. — 15. RAZEGHI, M., M. E. BATT, Gait and Posture, 15 (2002) 282. — 16. MIJOVIĆ, B., D. UJEVIĆ, S. BAKSA, Coll. Antropol., 26 (2002) 189.

A. Agić

Faculty of Chemical Engineering and Technology, University of Zagreb, Marulićev trg 19, 10000 Zagreb, Croatia
e-mail: aagic@marie.fkit.hr

ANTROPOMETRIJSKI I MORFOLOŠKI FENOMENI STOPALA

S A Ž E T A K

Strukturni deskriptori stope su važni iz mnogo razloga. Antropometrijski i morfološki fenomeni analizirani su zajedno s biomehaničkom funkcionalnošću s ciljem potpune karakterizacije funkcije i strukture stopala. Za hrvatsku studentsku populaciju izvršena je statistička obrada prikupljenih podataka. Funkcionalni i strukturni deskriptori stopala ovise o mnogo faktora kao napr. stilu života, klimi i nizu dominantnih faktora ljudske zajednice. Bitni faktori određeni su metodom glavnih komponenti. Neki bitni zaključci za proizvodnju medicinske i sportske obuće su komentirani.