Patterns of variability of the shape of the human hand

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SUMMARY

The differences between the hands of men and women are mainly observed in the difference in the ratio of the lengths of the index and ring fingers (ratio 2d:4d) or in the difference in the proportional ratios of longitudinal and transverse dimensions, identified using classical morphometry methods, which give only indirect ideas about variations in the shape of the hand. The object of this study was digital images of radiographs of the right hands of 50 men and 50 women, on which 20 landmarks were located, the configuration and two-dimensional coordinates of which were studied using geometric morphometry methods.

The predominance of the general variability of the hand's shape was associated with a combined multidirectional transformation in the space of the elements of the II-V rays of the hand relative to the longitudinal axis with simultaneous compression or stretching of the shape relative to the transverse axis. At the same time, men have a stretching of the shape of the hand from the IV-V rays and compression from the II-III rays, while women have reverse changes. The relationship between the shape and size of the hand, regardless of gender, is minimal – 5.82% and 3.93% of hand allometry were detected in men and women, respectively. This study shows that the shape of the hand is markedly different in men and women, which indicates a significant sexual dimorphism affecting this trait. Based on the detected sexual differences, it is possible to distinguish the male and female morphological type of the hands.

Key words: Human hand – Shape variability – Sexual dimorphism – Geometric morphometry

INTRODUCTION

Hands are vital anatomical parts for humans, as they are used to grip manipulate and shape various objects of the environment. Being an important part of the upper limbs and giving the latter functional completeness, human hands have some differences in men and women (Khanpetch et al., 2012). One of the factors determining the size and shape of the hands is gender. Studies show that men have bigger hands than women of the same height (Case and Ross, 2007). A comparative analysis of the size of the hands also demonstrates that the length of the hand is longer in men than in women, while the same ratios were found for the metacarpal bones and phalanges of the fingers (Hsiao et al., 2015). In addition, one of the differences between the hands of men and women is the ratio of the lengths of the index and ring fingers (2d:4d ratio) – in men, the length of the ring finger prevails over the length of the index finger, while in women the opposite ratio is observed (Sanfilippo et al., 2013; de Sanctis et al., 2017; Ernsten et al.,

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2021). To study the variability of the hand associated with gender, the following are used: subjective criteria based on morphological features and objective criteria based on size analysis, including various measurements and indices (Kanchan and Krishan, 2011; Kondo et al., 2017). Despite numerous studies, single works are devoted to the analysis of the shape of the hand of a modern person in the context of sexual differences (Sanfilippo et al., 2013; Karakostis et al., 2018).

Anthropometry (Kanchan and Krishan, 2011; de Sanctis et al., 2017), osteometry (Cihák, 1972), morphometry of photographs (Jakubietz et al., 2005) or digital images of hands (Hsiao et al., 2015; Kim et al., 2018; Ernsten et al., 2021), as well as morphometry according to radiography data are used to assess the shape and size of the hand (Kondo et al., 2017). However, classical anthropometric measurements of the hands have a number of disadvantages due to the different index of soft tissues in men and women, as well as measurement errors (Kanchan and Krishan, 2011).

In addition, most studies of the hand have focused on the morphological features of individual segments or bones of the hand related to size, and the components of the shape change of the latter have been underestimated due to conceptual difficulties in quantifying such an abstract concept as shape. Attempts to describe the shape of the hand based on data obtained using classical morphometric methods are indirect – there is no analysis of the shape as such, and it is impossible to assess spatial morphological changes and the geometry of the object under study as a whole (Klingenberg, 2011).

Given the differences between the hands of men and women observed in previous studies, the question arises whether a more detailed analysis of the variations in the morphology of the hand using methods based on geometric morphometry can provide an understanding of the sexual differences in the shape of the hand from radiography data.

MATERIALS AND METHODS

Sample

The object of the study was digital images of radiographs of the right hands (anteroposterior projection, fingers in the position of bringing) of 100 adults (50 men and 50 women) from the archive of the Department of Radiation diagnostics of the Doctor Chuchkalov Ulyanovsk Regional Clinical Center of Specialized Types of Medical Care. The criteria for inclusion in the study were the absence of integrity disorders, developmental anomalies, deformities and bone and joint pathology of the hands. The average age of men was 46.3±1.1 years, and women - 49.2±0.9 years.

Digitization and locating landmarks

In Adobe Photoshop CS6 13.0.1 (Adobe Systems Incorporated Co., USA), digital images of radiographs were edited so that the middle of the metacarpophalangeal joints of the middle finger on each image coincided. On each digital image of the radiograph of the hand there are 20 landmarks in the Cartesian coordinate system using the on-screen digitizer TPSdig2 (Fig. 1, Table 1) (Rohlf, 2015).

Table 1. Definition of landmarks located on digital images of radiographs of hands.

Landmarks	Description
1	Second carpometacarpal joint
2	Metacarpophalangeal of the index finger
3	Proximal interphalangeal joint of the index finger
4	Distal interphalangeal joint of the index finger
5	Tip of the distal phalanx of the index finger
6	Third carpometacarpal joint
7	Metacarpophalangeal of the middle finger
8	Proximal interphalangeal joint of the middle finger
9	Distal interphalangeal joint of the middle finger
10	Tip of the distal phalanx of the middle finger
11	Fourth carpometacarpal joint
12	Metacarpophalangeal of the ring finger
13	Proximal interphalangeal joint of the ring finger
14	Distal interphalangeal joint of the ring finger
15	Tip of the distal phalanx of the ring finger
16	Fifth carpometacarpal joint
17	Metacarpophalangeal of the ring finger
18	Proximal interphalangeal joint of the little finger
19	Distal interphalangeal joint of the little finger
20	Tip of the distal phalanx of the little finger

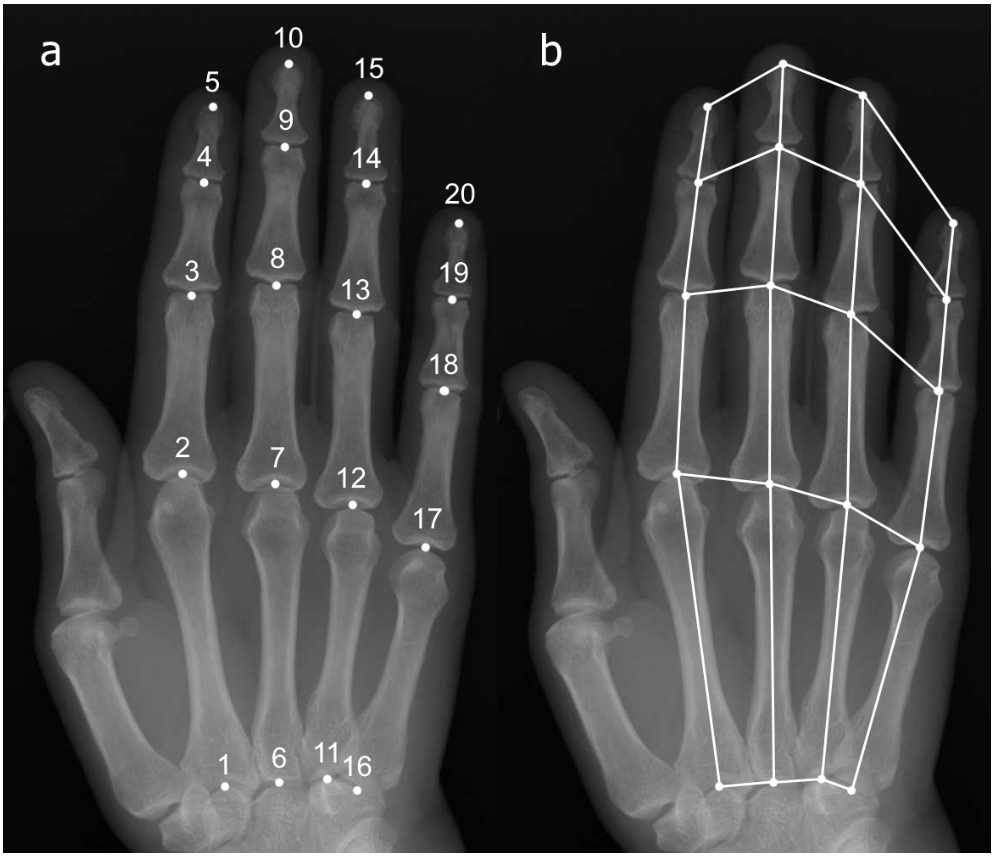

Fig. 1.- Landmark locations (**a**) and wireframe diagram of linked landmarks (**b**).

Geometric morphometrics and statistical analysis

The analysis of hand shapes was carried out using MorphoJ 1.07a (Klingenberg, 2011). In order to eliminate the effects not related to the shape of the hands (position, orientation, scale) and optimal alignment of the configuration of landmarks in the general space of the shape, the configurations of two-dimensional coordinates (n=100) were subjected to generalized Procrustean analysis (GPA). The general variability of the shape of the hands in space relative to each other to assess the similarity or difference in the sample under study was studied using principal component analysis (PCA). The size of the studied hands was expressed in the form of centroid size (CS), as the most common size estimation indicator used in geometric morphometry. To determine the effect of size on the shape (allometry) of the hand, a multidimensional regression was performed, where the CS was used as an independent variable as a size variable, and Procrustean coordinates as a shape variable as a dependent variable (Klingenberg, 2016). In addition, a permutation test was performed using 10 000 iterations to assess the significance of the effect of size on shape. Discriminant function analysis (DFA) was performed to compare the differences between male and female hands. The significance of differences between two groups was assessed using the Mann-Whitney U test for independent variables. The significance level of $p<0.05$ was assumed to be statistically significant.

RESULTS

Among the configurations of hand shapes after GPA, the proportion of total shape variability was determined, taken into account by each main component (PC) from the resulting eigenvalues (total eigenvalues=0.00165468) (Fig. 2). The first main component (PC1) describes 32.4% (eigenvalue=0.00058184) of the total variability of the shape of the hand; the second main component (PC2) describes 20.3% (eigenvalue=0.00029552) of the total variability of the shape of the hand; the remaining 34 PCs were ignored.

The PCA results demonstrate that the main deformations of the hand shape are observed along the PC1 axis regardless of gender, and the differences along the PC2 axis are less pronounced (Fig. 3). PC1 describes the space of forms associated with the morphological type of the hand – the configurations of landmarks distributed in the direction of lower values (PC1-) have a more elongated contour of II-III fingers and a shortened contour of IV-V fingers, while the configurations of landmarks distributed in the direction of higher values (PC1+), on the contrary, have a more elongated contour of IV-V fingers and a shortened contour of II-III fingers. PC2 describes the shape space associated with the transverse and longitudinal proportions of the hand – the configurations of landmarks distributed in the direction of lower values (PC2-) have somewhat narrow and elongated shapes (simultaneous compression of the shape in the transverse and stretching in the longitudinal axis), while the configurations of landmarks distributed in the direction of higher values (PC2+) have shorter and wider shapes (simultaneous stretching of the shape in the transverse and compression in the longitudinal axis).

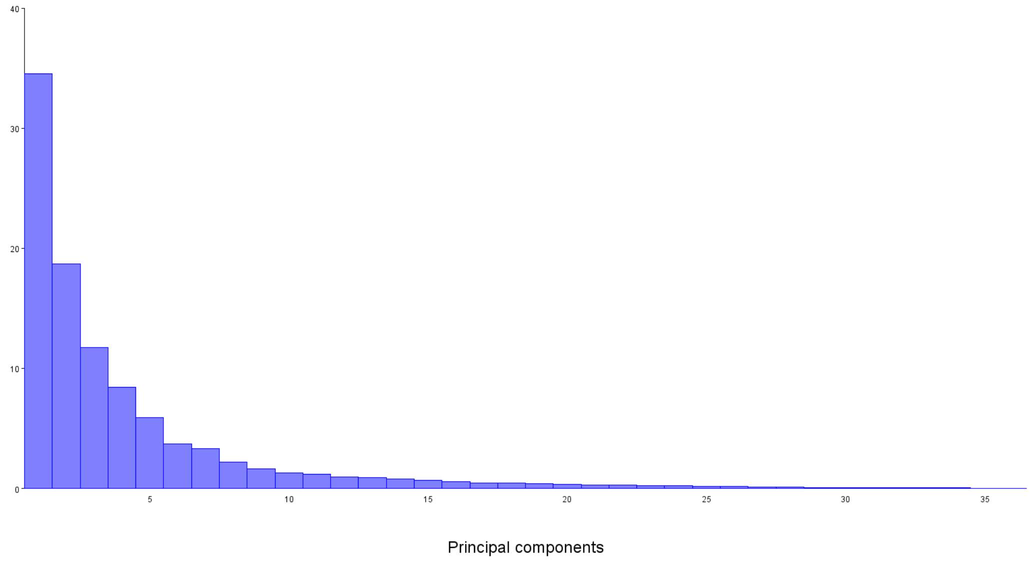

Fig. 2.- Proportion of the total hand shape variance explained by each PC.

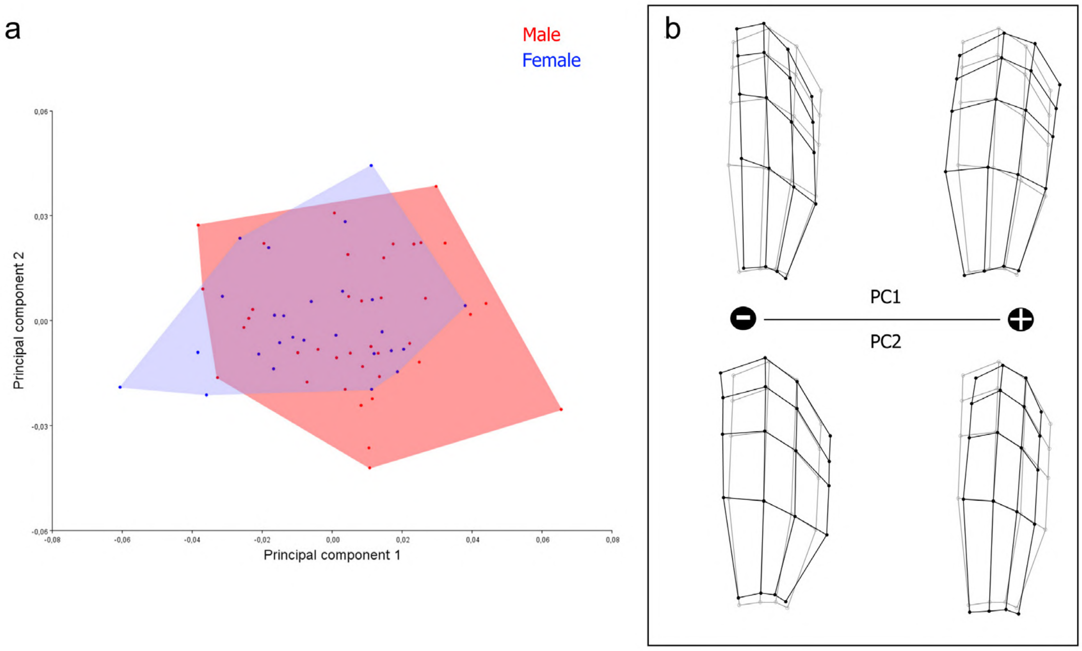

Fig. 3.- Patterns of changes in the configurations of the hand in the morphospace (**a**). Changes in the shape of the hand relative to the average configuration along the axes PC1 and PC2 (magnitude -0.1 and +0.1 for PC1 and PC2, respectively) based on the data of the covariance matrices of procrustean coordinates (**b**).

In men, the shape of the hand is wider relative to the average configuration than in women (Fig. 4). The width of the hand in both men and women is determined by the location of the distal epiphyses of the second and fifth metacarpal bones (landmarks 2 and 17). The smallest differences in shape configurations were found for the segments of the third and fourth rays of the hand (landmarks 6-15).

According to the results of the DFA, statistically significant differences were revealed between the hands of men and the hands of women (the measure of distance is the distance of the Procrustes distance, the distance of Mahalanobis=3.09, T^2=238, p<0.001). The demarcation point is 0.018. Therefore, values of the size of the Procrustes distance exceeding this value indicate male hands, while smaller values are estimated as female (Fig. 5).

The accuracy of the hand shape classification according to the DFA results reaches 86% for men and 80% for women. The cross-validation procedure gives exactly the same results (p <0.0001 with 1000 repetitions) (Table 2).

Table 2. Percentage of hands of men and women correctly and erroneously distributed using the analysis of canonical variations.

Sex	Distribution based on hand shape data	
	Correct distribution, n	**Incorrect distribution, n**
Male	43	7
Female	40	10

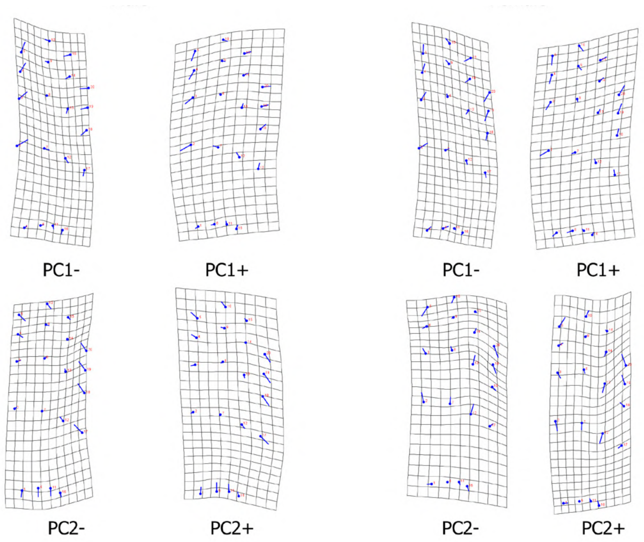

Fig. 4.- The space of hands shapes with corresponding landmarks.

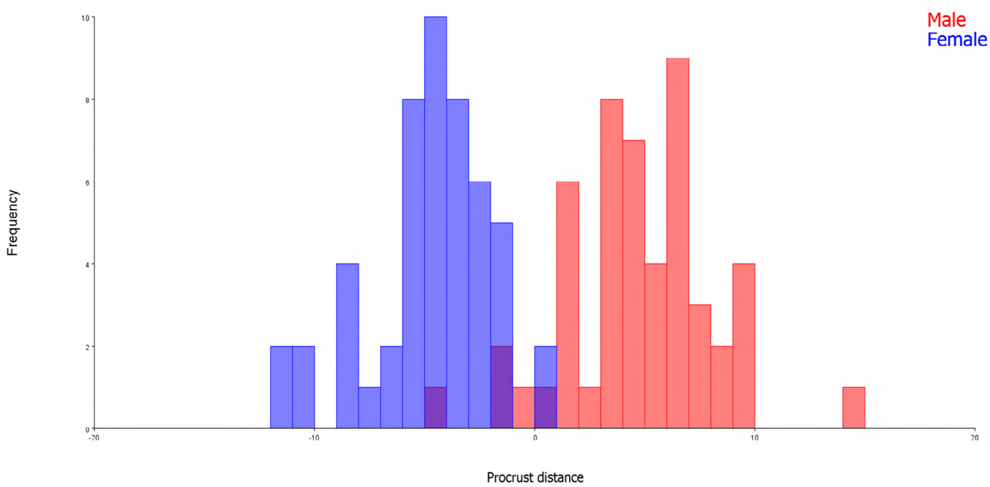

Fig. 5.- Sexual differences between the hands.

When comparing the CS of the hands, statistical sexual differences were revealed (Table 3). Multivariate regression showed 5.82% and 3.93% allometry of the hands in men and women, respectively, with a significant permutation value ($p < 0.0001$) (Fig. 6).

Table 3. Descriptive statistics for CS (in mm) and results for average differences.

Sex	CS		Mann-Whitney U Test		
	Me	IQR	U	Z	p value
Male	53.78	5.99	372	6.05	0.0001
Female	47.57	4.37			

important step in assessing the sexual differences in the shape of the hand in humans. However, the preliminary preparation of digital images of the studied objects before the location of landmarks (alignment of samples), the limited use of the obtained quantitative data in cladistic analysis, the inability to generate new data that are not related to the shape are somewhat narrowing the limits of GMM capabilities.

Nevertheless, the results of this study demonstrate how the spatial orientation of the II-V metacarpal bones and phalanges of the II-V fingers affects the shape of the hand in men and women.

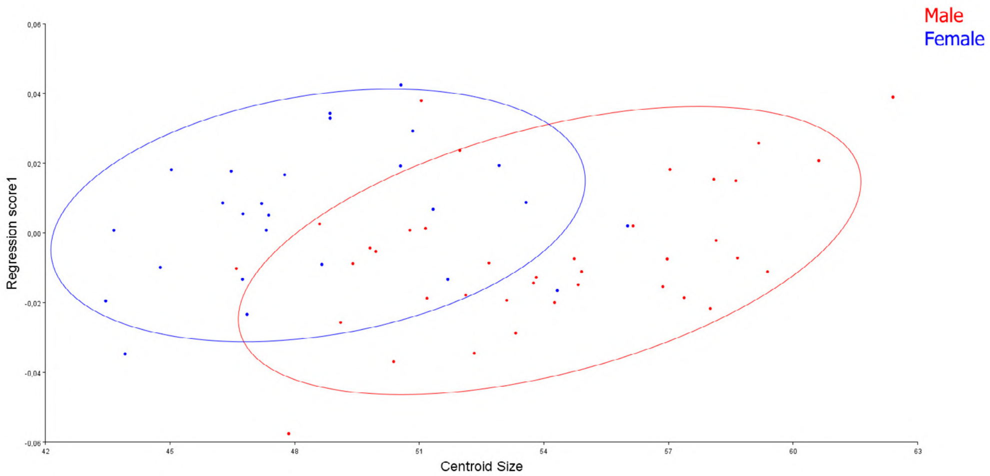

Fig. 6.- Regression of relative deformation estimates by CS. A plot summarizing the relationship between size change and shape.

DISCUSSION

Apparently, this is the first publication in which geometric morphometric methods (GMM) are used to study the sexual differences in the shape of a person's hand according to radiography. In previous studies, it was shown that the differences between the hands of men and women are mainly observed in the difference in the ratio of the lengths of the index and ring fingers (2d:4d ratio), or in the difference in the proportional ratios of longitudinal and transverse dimensions revealed using classical morphometry methods, which give only indirect ideas about variations in the shape of the hand. Thus, the use of GMM is an

Changes in the shape of the hands of men and women consist in its uniform transformation in space relative to the longitudinal (geometry changes are associated with the morphological type of the hand – a combined multidirectional stretching / compression of the shape of elements II and IV-V rays of the hand relative to each other) and transverse (geometry changes are associated with the brachycheiria-dolichocheiria pattern). It is assumed that genetic determination (HOXa and HoxD) against the background of effects caused by different concentrations of steroid hormones in the blood of a pregnant woman leads to sexual dimorphism of fetal finger length (de Sanctis et al., 2017).

The study showed the presence of differences both in the shape of the hands and in their CS, which characterizes men's hands as larger compared to women's. These sex differences may be due to the action of prenatal sex hormones of developing gonads (Blecher and Erickson, 2007). The regression of the apical ectodermal ridge observed at the beginning of the second trimester of pregnancy, located at the distal end of the rudiment of each limb with the formation of hand rays and subsequent interdigital apoptosis under the influence of androgenic stimulation proportional to both the level of androgens in the blood and individual sensitivity to these hormones, causes a different ratio of fingers during their development (Breedlove, 2010).

The results of the study demonstrate a minimal degree of allometry, while in men it is slightly higher than in women. This is consistent with the data that in the process of ontogenesis, despite the fact that the size of the hands varies by several orders of magnitude (from several tenths of a millimeter to several millimeters), their proportionality, including shape, does not change so much – the hands of human embryos are similar to the hands of an adult (Hattori, 1986). The general similarity of the proportions of the fetal and adult hands does not exclude minor changes in the shape and proportions of the hand during ontogenesis, as well as individual differences in these changes (Cihák, 1972). Another form of sexual dimorphism, manifested as previously indicated in the form of uniform transformation, are differences in the relative width of the hand, which may be due to allometry, since the size of the hand correlates with changes in the relative width of the hand – large hands, regardless of gender, are somewhat wider (Jakubietz et al., 2005). The results obtained by us – i.e., that the male hand is somewhat wider than the female hand – are consistent with the results of traditional morphometry (Xiao et al., 2015). The transformation of the hand observed in postnatal ontogenesis in the form of transverse compression (both in men and women) due to more intensive growth of the hand in length than in width, both in men and women, maintains positive dynamics and reaches a maximum during puberty. One of the important aspects of sexual dimorphism of the hand shape is that the differences associated with gender are the result of both uniform shape transformation and the result of proximal-distal displacement of the hand rays relative to the width of the latter – since the fourth and fifth rays are displaced more distally, the hand becomes relatively wider. It is possible that the detected sex differences in the shape of the hand reflect the different effects of genetic and hormonal factors affecting the development of the hand at different stages of embryogenesis.

Thus, GMM can be an assessment of the morphology of the hand by extracting shape variability at various scales and analyzing their relationship. In addition, the results of this study may be useful in the development of algorithms for assessing gender in forensic medicine and in biometric authentication systems. It is likely that with a larger number of participants in the study, it would be possible to study the age-related aspects of hand shape variations in men and women. In addition, it is of interest how changes in the geometry of the configurations of individual parts of the hand (the pastern, the distal part of the hand, which is formed by the fingers) in men and women affect the shape of the hand as a whole.

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