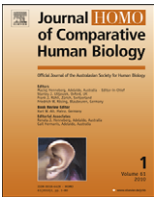
HOMO — Journal of Comparative
Human Biology 61 (2010) 16–32

Contents lists available at ScienceDirect

HOMO — Journal of Comparative Human Biology

journal homepage: www.elsevier.de/jchb



Three-dimensional geometric morphometric analysis of cranio-facial sexual dimorphism in a Central European sample of known sex

L. Bigoni [a], J. Velemínská [a,*], J. Brůžek [a,b,c]

[a] Department of Anthropology and Human Genetics, Faculty of Science, Charles University in Prague, Czech Republic
[b] Laboratoire d'Anthropologie des Populations du Passé et UMR 5809 du CNRS-PACEA, Université Bordeaux I, Talence, France
[c] Department of Social and Cultural Anthropology, Faculty of Humanities, University of West Bohemia, Plzeň, Czech Republic

ARTICLE INFO

Article history:
Received 10 March 2009
Accepted 1 September 2009

ABSTRACT

This article presents an approach for estimating the sexual dimorphism of adult crania using three-dimensional geometric morphometric methods. The study sample consisted of 139 crania of known sex (73 males and 66 females) belonging to persons who lived during the first half of the 20th century in Bohemia. The three-dimensional co-ordinates of 82 ecto-cranial landmarks and 39 semi-landmarks covering the midsagittal curve of the cranial vault were digitised using a MicroScribe G2X contact digitiser. The purposes of the investigation were to define the regions of the cranium where sexual dimorphism is most pronounced and to investigate the effectiveness of this method for determining sex from the shape of the cranium. The results demonstrate that it is better to analyse apportionable parts of the cranium rather than the cranium as a whole. Significant sexual differences (significance was determined using multivariate analysis of variance) were noted in the shape of the midsagittal curve of the vault, upper face, the region of the nose, orbits, and palate. No differences were recorded either in the shape of the cranium as a whole or in the regions of the base and the neurocranium. The greatest accuracy in determining sex was found in the region of the upper face (100% of study subjects correctly classified) and the midsagittal curve of the vault (99% of study subjects correctly classified).

* Corresponding author. Tel.: +420 221951 612; fax: +420 221951619.
E-mail address: velemins@natur.cuni.cz (J. Velemínská).

0018-442X/$ - see front matter © 2010 Elsevier GmbH. All rights reserved.
doi:10.1016/j.jchb.2009.09.004

Introduction

The existence of sexual dimorphism of the skeleton and its evaluation represent a presumption on which scientists base current methods for sex determination of a human skeleton (Rösing et al., 2007). Sexual dimorphism results in part from differing reproductive roles of the sexes and the strong selection pressure to which humans have been exposed throughout evolution. The degree of sexual dimorphism is influenced by environmental factors and thus differs in each population, though, on average, males are always larger, have more robust joints, and have a stronger musculature than females. Although sexual diagnosis is more accurate and reliable when based on the pelvis (Brůžek and Murail, 2006), the often poor state of pelvic preservation necessitates use of the cranium for the assessment.

An objective, quantitative approach to the study of sexual dimorphism is represented by conventional classification techniques of univariate and multivariate statistics. This approach uses measurements (distances, angles, or distance ratios) (Birkby, 1966; Boulinier, 1968; Giles, 1964; Giles and Elliot, 1963; Hanihara, 1959; Henke, 1974). These methods are based on observation of differences in the size of the skeleton, and any proposed discriminant function analyses are population specific. This is accentuated in recent forensic anthropology reports (Barrio et al., 2006; Bidmos, 2006; Bidmos and Dayal, 2004; Franklin et al., 2005; Frutos, 2005; Gualdi-Russo, 2007; Kemkes-Grottenthaler, 2005; Purkait and Chandra, 2004; Rösing et al., 2007; Šlaus et al., 2003). The quantitative approach to sex determination is also considered when studying skeletal samples derived from archaeological sites (Brůžek and Velemínsky, 2006; Özer et al., 2006; Wrobel et al., 2002).

The accuracy of methods based on sexual dimorphism of the cranial measurements will diminish when these methods are used outside the reference population. Using population-specific methods or national standards with respect to the size of the skeletons (İşcan, 1988) is not a solution, as useful collections of skeletons of known age and sex are not available for every population. Body size has changed through generations of the same population as a consequence of secular trend (Jantz, 2001; Jantz and Jantz, 1999; Klepinger, 1999; Meadows and Jantz, 1995). Thus, it may be assumed that methods for determining sex, in which measurements obtained from collections of skeletons of known sex from the first half of the 20th century, are used, cannot guarantee the same reliability of results when they are used in attempt to identify unknown human remains from recent populations. This disadvantage could be eliminated by using re-scaling three-dimensional geometric morphometrics (3D GM). Although visual (qualitative) methods of sex determination are mostly not population specific and are relatively simple and accurate (Williams and Rogers, 2006), their use requires a lot of training and their application is subjective. The problems presented by both of these approaches have been well documented by Bookstein et al. (1985) and Slice (2005, 2007).

Geometric morphometrics represents a new approach in the evaluation of variability, not only in the biomedical disciplines but also in such areas as bioarchaeology, evolution, and ecology. The term geometric morphometrics, which was first used by Corti (1993), includes methods based mainly on 3D co-ordinates of homologous landmarks that describe the studied object. The co-ordinates thus represent complete geometric information related to the studied object (Slice, 2007). When analysing the forms of biological objects, GM enables differentiation of variability due to both size and shape. Quantification of shape and size using statistical GM procedures specifies and renders more accurate results than those that have been obtained to date with other methods, thus increasing their reliability (Bookstein, 1991; Dryden and Mardia, 1998; Richtsmeier et al., 2002; Rohlf, 2003; Slice, 2007).

The most frequent applications of geometric morphometrics in forensic anthropology relate to determination of population affinity or ancestry (Buck and Vidarsdottir, 2004; Ross et al., 1999), assessment of age at death (Braga and Treil, 2007), and determination of sex (Franklin et al., 2006a,b, 2007b, 2007c; Kimmerle et al., 2008; Oettlé et al., 2005; Pretorius et al., 2006; Ross et al., 2006; Steyn et al., 2004). GM methods are not intended to replace methods currently used for sex assessment. Rather, their aim is to quantify shape and characterise shape variability and, in doing so, to evaluate objectively any differences in shape and compare them with other variables while preserving all of the geometric information corresponding to the original object (Slice, 2005).

The current economic globalisation and the associated movement of people require that methods of sexual determination used in forensic anthropology take these facts into consideration as seriously as in the case of age estimation (Schmeling et al., 2001). This means that the methods for determining sex should not be population specific but should, if possible, be both accurate and reliable.

The aim of our study was to analyse the sexual dimorphism of crania from the Central European population and to verify whether sex can be determined using shape characteristics of the cranium. Another task was to locate the regions of the cranium where sexual dimorphism was most pronounced. We believed that comparison of the results of a North American sample (Kimmerle et al., 2008) and a South African population (Franklin et al., 2006a, 2007a) with a Central European population would show whether sexual dimorphism of cranial shapes demonstrates logical homology in various populations.

Material

A series of 139 adult crania of known age and sex from the Central European population, from the so-called Pachner collection housed in the Department of Anthropology and Human Genetics, Faculty of Science, Charles University, Prague, has been used for this study. Among the 139 crania, all without significant pathology, 73 were male of ages ranging from 20 to 96 years (average age 51 years) and 66 were female crania ranging in age from 20 to 91 years (average age 53 years).

The collection originated in the 1930s with the intent of studying the sexual dimorphism of the human skeleton (Borovanský, 1936; Pachner, 1937). According to Pachner (1937), the material came from inhabitants of Bohemia, mainly from lower socioeconomic classes. During the second half of the 20th century this collection was often used for studying and revising methods for sex determination (e.g. Černý and Komenda,1986; Novotný, 1986; Novotný et al., 1993; Strádalová, 1972).

Methods

Data acquisition

To answer *a priori* questions of sexual dimorphism of the cranial shape, we chose 82 ecto-cranial anatomical landmarks (Martin and Saller, 1957) that provided a high level of anatomical detail of 7 regions (the configuration of neurocranium, cranial base, midsagittal curve of vault, upper face, orbital region, nasal region, and palatal region). The chosen landmarks were precisely defined and could be located unambiguously, thus were repeatable. To adequately represent the cranium as a whole, we chose crania on which the landmarks were as widely distributed as possible (Rohlf, 1996; Snow, 2004; Table 1).

Because only a few landmarks were available on the brain vault, it was digitised as the midsagittal curve (from the *nasion* to the *opistion*) on the external neurocranial surface as a series of discrete points—39 semi-landmarks. It should also be noted that no landmarks around alveolar processes were used for analysis, because of frequent intravital loss of the anterior teeth.

All landmarks and the curve in the midsagittal plane were recorded in three dimensions using a MicroScribe G2X contact digitiser (Immersion Corp., San Jose, CA, USA). Each cranium, fixed in plasticine, was digitised in two positions (DeLeon, 2004). The first position with the cranium resting on its base enabled the recording of almost all landmarks chosen in the region of the face and vault. The remaining landmarks, especially on the *basicranium*, were then acquired with the cranium resting on its vault. In both positions, three reference points (*bregma*, *nasion* and *lambda*) were marked on each cranium as the origin and *x*- or *y*-axis directions. These points were used to align all landmarks of each cranium within a common co-ordinate system. The combination of the superior and inferior aspects provided a complete configuration.

Table 1
List of landmarks.

No.	Abbreviation	Landmark	Use of Landmarks in Studied Regions of Skull	Definition
Midline Cranial Points				
1	b	*bregma*	Va	Intresection of the *sut. coronalis* and *sut. sagittalis* in the midsagittal plane
2	ns	*nasion*	NsR, UpF	The middle of the *sut. nasofrontalis* in the midsagittal plane
3	l	*lambda*	Va	Intersection of the *sut. sagittalis* and *sut. coronalis* in the midsagittal plane
4	rhi	*rhinion*	NsR	The lowest point of the *sut. internasalis*
5	ns	*nasospinale*	NsR, UpF	Intersection of the subtence/chord inferior margins of the *apertura piriformis* and the midsagittal plane
6	pr	*prosthion*	Pl	The most prominent point in the midsagittal plane between the upper incisors
7	o	*opisthion*	Ba, Va	The midpoint of the posterior margin of the *foramen magnum* in the midsagittal plane
8	ba	*basion*	Ba, Va	The midpoint of the anterior margin of the *foramen magnum*, opposite the opisthion.
9	ho	*hormion*	Ba	Intersection of the midsagittal plane and the line where the base of *vomer* meets *os sphenoidale*
10	sta	*staphylion*	Pl	The point where subtence/chord of posterior margin of the palate intersects the midsagittal plane
11	sr	*staurion*	Pl	Intersection of the *sut. palatina mediana* and *sut. palatina transversa*
12	inc	*foramen incisivum*	Pl	The point on the posterior margin of the *foramen incisivum*
Bilateral Cranial Points				
13&14	ast	*asterion*	Va	Intersection of the *sut. lambdoidea, sut. parietomastoidea* and *sut. occipitomastoidea*
15&16	ent	*entomion*	Va	The point, where the *sut. squamosa* passes into *sut. parietomastoidea*
17&18	k	*crotaphion*	Va	Intersection of the *sut. sphenosquamosa, sut. sphenoparietalis* and *sut. squamosa*
19&20	sphn	*sphenion*	Va	Intersection of the *sut. coronalis, sut. sphenoparietalis* and *sut. sphenofrontalis*
21&22	eu	*euryon*	Va	The extremity, on either side, of the greatest transverse diameter of the skull
23&24	co	*coronale*	Va	One of the two most widely separated points on the *sut. coronalis* at the poles of the greatest frontal diameter
25&26	ft	*frontotemporale*	UpF, Va	The most anterior point of the *linea temporalis* on the *os frontalis*
27&28	au	*auriculare*	Va	Intersection of the base of zygomatic arch and the midline of the opening of the *meatus acusticus externus*
29&30	zts	*zygotemporale superior*	UpF	The most superior point on the *sut. zygomaticotemporalis*
31&32	x	*landmark x*	Va	Intersection of the *sut. sphenozygomatica, sut. sphenofrontalis* and *sut. frontozygomatica*
33&34	ju	*jugale*	UpF	The point at the union of the *processus frontalis* and *processus temporalis* of the *os zygomaticus*
35&36	zy	*zygion*	UpF	The most lateral point of the zygomatic arch
37&38	apt	*apertion*	NsR, UpF	The most lateral point on the nasal aperture
39&40	fmt	*frontomalare temporale*	UpF	The most posterior/lateral point on the *sut. frontozygomatica*
41&42	fmo	*frontomalare orbitale*	Or, UpF	Intersection of the *sut. frontozygomatica* and the lateral margin of the orbit
43&44	mnf	*maxillonasofrontale*	NsR, UpF	Intersection of the *sut. frontonasalis, sut. frontomaxillaris* and *sut. nasomaxillaris*

Table 1 (*continued*)

No.	Abbreviation	Landmark	Use of Landmarks in Studied Regions of Skull	Definition
45&46	mf	*maxillofrontale*	Or, NsR, UpF	Intersection of the *sut. frontomaxillaris* and the medial margin of the orbit
47&48	ek	*ectoconchion*	Or, UpF	Intersection of the lateral margin of the orbit and the line from the *mf* parallel with the superior margin of the orbit
49&50	spa	*supraconchion*	Or, UpF	Intersection of the superior margin of the orbit and normal to the line *mf–ek*
51&52	sbk	*subconchion*	Or, UpF	Intersection of the inferior margin of the orbit and normal to the line *mf–ek*
53&54	zti	*zygotemporale inferior*	UpF	The most inferior point on the *sut. zygomaticotemporalis*
55&56	zm	*zygomaxillare*	UpF	The most inferior point on the *sut. zygomaticomaxillaris*
57&58	io	*infraorbitale*	Ba, UpF	The most lateral point on the margin of the *foramen infraorbitale*
59&60	ms	*mastoidale*	Ba, Va	The most inferior point on the *processus mastoideus*
61&62	basty	*basostyloidion anterior*	Ba	The most anterior point on the base of the *processus styloideus*
63&64	fol	*foraminolaterale*	Ba	The most lateral point on the margin of the *foramen magnum*
65&66	laco	*occipitocondylion laterale*	Ba	The most lateral point on the margin of the *condylus occipitalis*
67&68	meco	*occipitocondylion mediale*	Ba	The most medial point on the margin of the *condylus occipitalis*
69&70	antco	*occipitocondylion anterior*	Ba	The most anterior point on the margin of the *condylus occipitalis*
71&72	poco	*occipitocondylion posterior*	Ba	The most posterior point on the margin of the *condylus occipitalis*
73&74	cam	*caroticum mediale*	Ba	The most medial point on the margin of the *foramen caroticum externum*
75&76	ovm	*ovale mediale*	Ba	The most medial point on the margin of the *foramen ovale*
77&78	spi	*spinale*	Ba	The most medial point on the margin of the *foramen spinosum*
79&80	poa	*postalverion*	Pl	The most posterior point on the *processus alveolaris* of the *maxilla*
81&82	it	*infratemporale*	Ba, Va	Intersection of the *sut. sphenosquamosa* and *crista infratemporalis* of the sphenoid bone

Use of Landmarks in Studied Regions of Skull:
Or–Orbits; NsR–Nasal Region; Pl–Palate; Ba–Base; UpF–Upper Face; Va–Vault.

Precision of measurement

All landmarks and semi-landmarks of six specimens were digitised six times, with a minimum of 1 day allowed between digitisation to assess the degree of intra-observer error in data acquisition. The six repeated sets of co-ordinates were submitted to generalised Procrustes analysis (GPA) and principal component analysis (PCA) along with the total sample, in accordance with the method used by O'Higgins and Jones (1998), and Franklin et al. (2006a, 2007b).

Shape analysis

Using GPA, raw landmark co-ordinates were re-scaled, translated, and rotated for elimination of nonshape variation in the sample. For each cranium, the centroid size was calculated and used in subsequent statistical analysis (Bookstein, 1991, Dryden and Mardia, 1998). Multivariate analysis of variance (MANOVA) was used to assess the significance of sexual differences in the sample.

Procrustes residuals were analysed using PCA, which explores the relationships between the population means of male and female crania. Because size had effectively been removed from the analysis, the PCA was more sensitive to subtle shape differences, spread over a large number of principal components (PCs) (Franklin et al., 2006a). The PCA scatterplot visually represented the variation among different individuals of the sample. The mean shape of the sample was situated where the PCs crossed. The associated shape variations were visualised and explored using wire-frame models. The thin-plate spline (TPS) provided an exact mapping of the landmarks of one configuration onto another and supplied a maximally smooth interpolation of the interlandmark space (Slice, 2007). TPS was used to show deformation of shape using Cartesian grids to visualise which landmarks were responsible for the differences in shape between PC extremes. Discriminant function analysis was performed to assess the sex classification accuracy of the discriminant functions (Davis, 1986; Franklin et al., 2006b).

Statistical analysis was performed using the following software programs: Morphologika for TPS and PCA (http://www.york.ac.uk/res/fme/resources/software.htm) (O'Higgins and Jones, 2006), PAST for discriminant function analysis (http://folk.uio.no/ohammer/past) (Hammer et al., 2001), and Morpheus et al. for MANOVA (www.morphometrics.org/morpheus.html) (Slice, 1998).

Results

Intra-observer variation of the landmark positions was tested using six repetitions of six specimens (two females and four males) clustered closely together on PCs 1 through 10. The first two PCs are plotted in Fig. 1. This indicates that errors of precision of measurement were small with respect to sample variability and were unlikely to have unduly influenced the results.

Initially, we focused on determining sexual dimorphism of the entire shape of the cranium. The preservation of the crania and thus the number of possible landmarks was a significantly limiting factor that decreased the number of individuals in the sample. We did not find any sexual differences in whole crania in our sample. Nonetheless, the presence of partial shape differences drew our attention to areas of the cranium on which to focus our subsequent steps. When we monitored shape

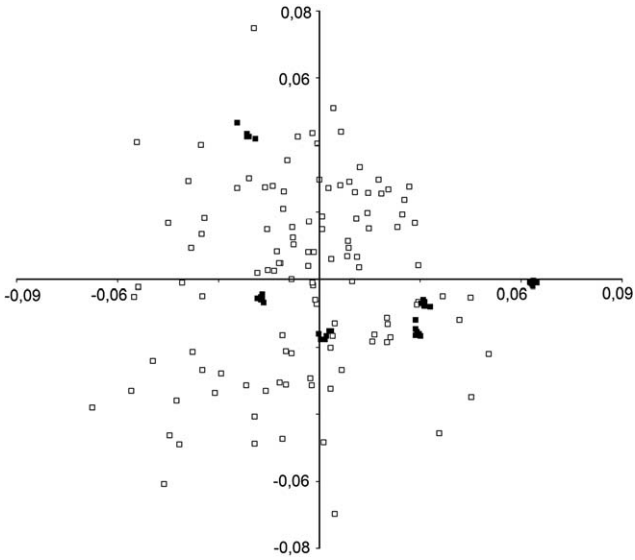


Fig. 1. Precision of measurement: Principal component (PC) 1 (horizontal axis) accounts for 14.9% and PC2 (vertical axis) for 13.4% of the total variance in the sample. In this chart, the six instances of each test specimen (five repeats plus one original) are plotted in black. The other specimens (one set of measurements from each) are plotted as open symbols.

Table 2
Results of MANOVA

Region	Number of Landmarks	MANOVA		% Correctly Classified (n)	
		p	Total	Male	Female
Upper Face	32	0.002[b]	100.000	100.000 (67 of 67)	100.000 (58 of 58)
Nasal Region	9	0.002[b]	77.120	77.400 (48 of 62)	76.800 (43 of 56)
Orbits	10	0.002[b]	74.440	70.800 (51 of 72)	78.700 (48 of 61)
Palate	6	0.006[b]	70.410	71.200 (37 of 52)	69.600 (32 of 46)
Midsagittal Curve	41	0.024[a]	99.260	100.000 (73 of 73)	98.400 (62 of 63)

MANOVA, multivariate analysis of variance.
[a] 5% level of statistical significance.
[b] 1% level of statistical significance.

dimorphism of seven specific regions of the cranium, the size of the sample increased from $n=98$ to $n=136$. Among these regions, the area of the cranium base and the neurocranium configuration did not demonstrate significant sexual dimorphism. We have therefore limited the subsequent presentation of our results to those regions where we noted significant differences between the sexes: the midsagittal curve, the upper face, the orbital region, the nasal region, and the palatal region. All five selected regions demonstrated strong sexual dimorphism.

The results of MANOVA and discriminant function analysis are presented in Table 2.

The midsagittal curve of the neurocranium

For assessing sexual dimorphism on the midsagittal curve of the vault, a total of 41 landmarks (the *nasion*, *opistion*, and 39 semi-landmarks between them, which cover the midsagittal curve) and 136 crania were tested (females, 63; males, 73). MANOVA showed significant differences between sexes in this region ($p=0.02$).

The PCA showed that PC4 represented the part of shape variability that is most responsible for sexual differences (Fig. 2). Fig. 3 shows the shape changes visualised by morphing from the negative (female) to positive (male) extreme of PC4.

Females had a more spherical neurocranium. The *bregma* region was found to be relatively higher in males than in females. Males had a more posteriorly projecting occipital plane; the frontal region was flatter and the *glabella* more prominent. Females had a more rounded forehead, flatter *bregma* region, and a rounded occipital region. In females, a relatively shorter distance between the *nasion* and *opisthion* points was noted.

Discriminant analysis showed 99% accuracy of sex determination (females, 62 of 63; males, 73 of 73) when using landmarks on the midsagittal curve (Table 2, Fig. 4).

The upper face

Significant sexual dimorphism was found (MANOVA *t*-test: $p=0.002$) when using 32 landmarks on the upper face region in a sample of 125 specimens (females, 58; males, 67). The PC most responsible for sexual dimorphism in the shape of the upper face was PC4, which accounted for 7% of the total shape variance of the sample.

As illustrated in Fig. 5, males had a relatively lower and wider face than females. In general, males exhibited relatively flatter and more vertical upper face and relatively wider and higher zygomatic arches in the upper part of the face. In contrast, females in the sample typically had a relatively higher forehead and face. Viewed from above, females had a more convexly shaped face compared with a flatter profile among males.

A more detailed frontal view shows that females had a relatively parallel *ft-ju* line, whereas in males, the *jugale* points were relatively further apart. (See Table 1 for definitions of landmark

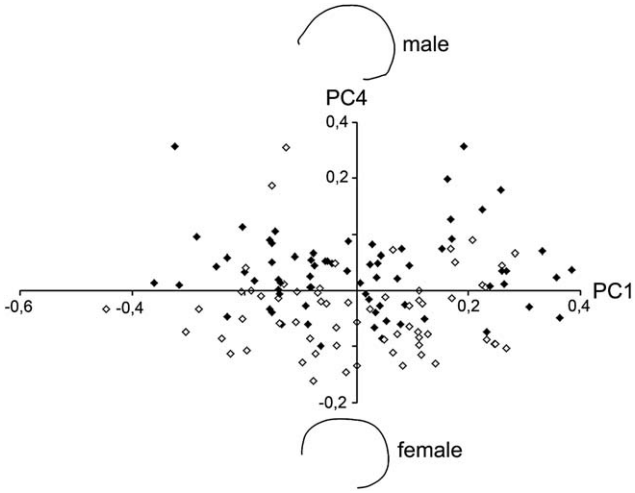


Fig. 2. Principal component analysis of the shape variance on the midsagittal curve of the neurocranium. Principal component (PC) 1 accounted for 32.2% of the total shape variance of the sample versus PC4, which accounted for 7.1%. N=136; 41 landmarks. PC4 separated the two sexes. Lateral views of the midsagittal curve show the variation in cranial shape represented by PC4. Males, solid-black symbols; females, open symbols.

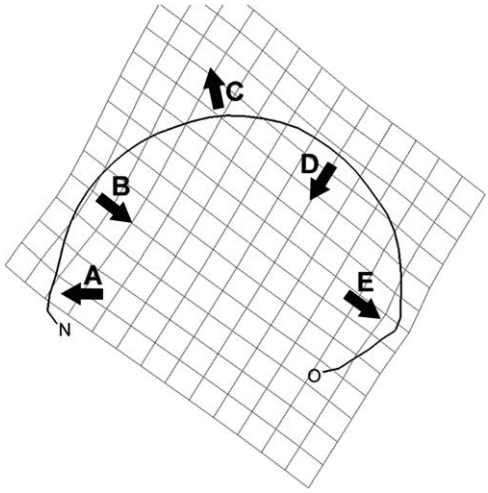


Fig. 3. The thin-plate spline grid shows the variation in shape of the midsagittal curve of the vault represented by PC4 (sexual differences; female→male). Reference shape is represented by "female," target shape by "male." (A) protrusion of the *glabella* region; (B) flattening of the frontal region; (C) vaulting of the *bregma* area; (D) flattening of the *lambda* region; (E) acute angle of the *inion*.

abbreviations.) Compared with females, males had a relatively shorter distance between the *frontotemporale* and the *fmo* and *fmt* points, as well as a shorter height of the nasal region. Overall, males had relatively wider zygomatic arches and more distant *zygion* points, whereas the *zygomaxillare* points were relatively closer and the angle *zm–io–apt* was more obtuse than in females. A detailed view from above shows a more vertical upper face and orbit in males. In females, the *subconchion* jutted more anteriorly and the *supraconchion* shifted posteriorly. Similarly, the *frontotemporale* shifted more posteriorly compared with the *fmt* and *fmo*. The *nasospinale* in males

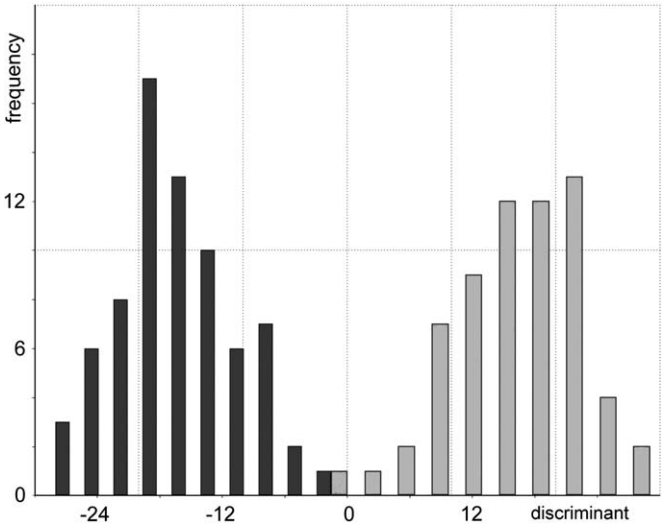


Fig. 4. A graph of the results of discriminant analysis conducted on the midsagittal curve of the vault. Negative values of the discriminant—males, positive—females. One female was classified as a male.

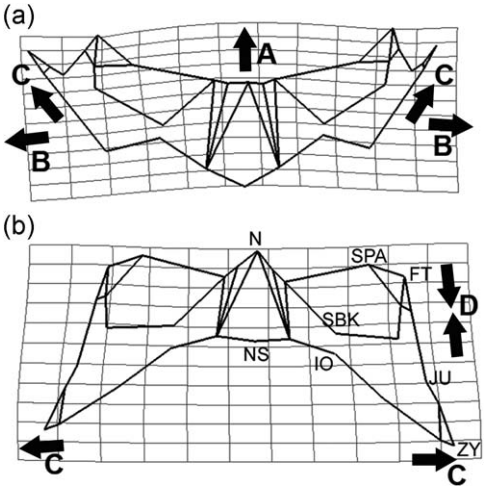


Fig. 5. The thin-plate spline grid shows the variation in the shape of the face represented by PC4 (sexual differences; female→ male). Reference shape is represented by "female," target shape by "male." (a) superior view; (b) frontal view. (A) antero-posterior flattening of the face, shifting of the maxilla posteriorly; (B) relative widening of the face; (C) wider zygomatic arches; (D) relative lowering of the face. See Table 1 for definitions of landmark abbreviations.

jutted relatively more to the front than in females. In this view, females had a more acute facial angle; for example, in the angle *zy–n–zy*, the points *zy–zy* were relatively closer to each other. The lateral view shows that the *frontotemporale* was significantly shifted anteriorly in males, whereas the distance of *frontotemporale* from the *fmo* and *fmt* points was shorter. The angle *zy–ju–fmt* in males was more obtuse than in females, and the *zti–zts* line was more vertical to the base (in females, *zts* projected more forward, and *zti*, more backward than in males). *Nasospinale* and *nasion* in males shifted more anteriorly and *maxillonasofrontale* and *maxillofrontale*, more posteriorly.

The sexing accuracy for the region of the upper face was 100% (females, 58 of 58; males, 67 of 67).

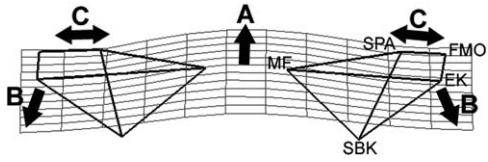


Fig. 6. The thin-plate spline grid shows the variation in shape and space orientation of orbits represented by PC4 (sexual differences; female→male). Reference shape is represented by "female," target shape by "male." (A) posterior shift of the medial landmarks; (B) anterior shift of lateral landmarks; (C) relative widening of the orbit. See Table 1 for definitions of landmark abbreviations.

Orbital region

When analysing landmarks on the orbits (133 crania: 61 females and 72 males; 10 landmarks), MANOVA showed significant differences between sexes (p=0.002). The PCA showed that the PC4 (8.6% variability) was most responsible for the sexual differences of the shape and spatial orientation of the orbits.

Compared with the more rounded orbit in females (Fig. 6), in males the orbit was relatively lower and wider. The *aditus orbitae* (orbit aperture) of males was parallel to the frontal plane; in females it was positioned in a slightly sagittal direction. In females, the orbit medial landmarks (*maxillofrontale*) shifted more anteriorly and the lateral landmarks (*ectoconchion* and *frontomalare orbitale*) more posteriorly when compared with males. The frontal view shows that in females, the line connecting *mf–ek* was almost horizontal with respect to the base, while in males the *maxillofrontale* had a higher location.

The accuracy of sex determination for the region of the orbit was 74% (females, 48 of 61; males, 51 of 72).

The shape of the nasal region

The sexual dimorphism of the nasal region was assessed with the help of 9 landmarks in a sample of 118 crania (56 females, 62 males). The results of MANOVA showed significant differences between sexes (p=0.002). The PC most responsible for the sexual differences of the shape of this region was PC3 (11.2% variability).

In males, the nasal aperture was relatively higher and narrower, with a deeper nasal base (*nasion* and *maxillonasofrontale* deeper but widely spaced apart), and the nasal bones were more prominent. In females, the nasal bones (and also the base of the nose) were flatter, the nasal aperture was relatively wider, and the orbits were relatively farther apart than in males (Fig. 7). The frontal view shows that in males the *maxillonasofrontale* and *maxillofrontale* were relatively higher and closer together than in females. In females, the *rhinion* was located relatively lower. The view from above shows that the *apt–n–apt* angle was more acute in males, whereas in females it was almost 180°.

The sexing accuracy for the region of the upper face was 77% (females, 43 of 56; males, 48 of 62).

The shape of the palate

For the assessment of sexual dimorphism of the palate, a total of 98 crania (females, 46; males, 52) and 6 landmarks were analysed using MANOVA, and significant differences between sexes were found (p=0.006). PCA showed that PC3 most significantly distinguished the two sexes (18.7% variability).

The *prosthion* projected more anteriorly relative to the rest of the cranium in females when compared with males. Females had a relatively lower and wider palate compared with males, who had a deeper and narrower palate (Fig. 8). The view from above shows that in females, thestaphylion and staurion are closer to each other than in males. Using the frontal view, we noted that the *poa–sr–poa* angle was nearly flat.

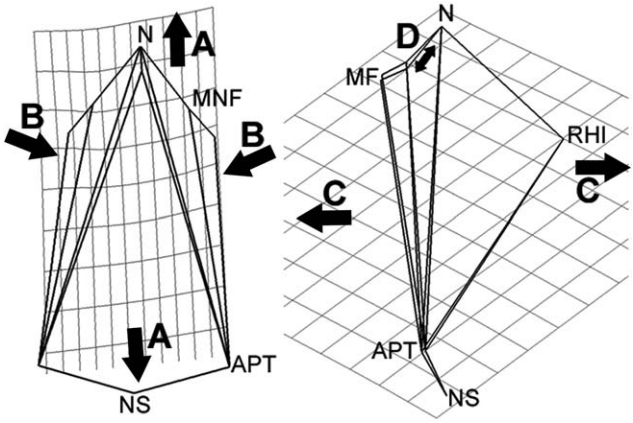


Fig. 7. The thin-plate spline grid shows the variation in shape of the nasal region represented by PC3 (sexual differences; female→male). Reference shape is represented by "female," target shape by "male." (A) relative elongation of the nasal aperture; (B) relative approximation of the orbits and relative narrowing of the nasal aperture; (C) greater prominence of the nasal bones; (D) *nasion* and *maxillofrontale* relatively more widely separated. See Table 1 for definitions of landmark abbreviations.

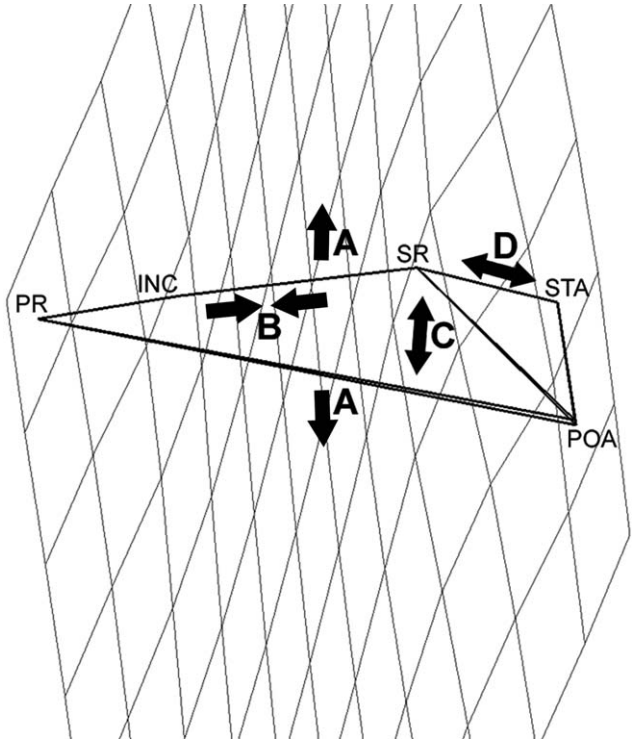


Fig. 8. The thin-plate spline grid shows the variation in the shape of the palate represented by PC3 (sexual differences; female→male). Reference shape is represented by "female," target shape by "male." (A) excavation of the palate region; (B) relative shortening of palate length; (C) excavation of the palate in the area of the *sutura palatina transversa*; (D) elongation of the posterior section of the hard palate. See Table 1 for definitions of landmark abbreviations.

The discriminant analysis showed 70% accuracy for sex determination (females, 32 of 46; males, 37 of 52) of the palate.

Discussion

Current difficulties of traditional sexing techniques

Determination of sex (sexing) is important in forensic sciences and archaeology (Brinkmann, 2007; Cattaneo, 2007; Graham, 2006). In sex determination, classical visual methods generally reach a sexing accuracy of about 90%. A set of morphologic traits of the cranium allow for accurate estimation of sex in 80% of cases, with a risk error of less than 10% (Williams and Rogers, 2006). However, in general, it is not suitable to rely on only one morphologic trait when estimating sex (Sjøvold, 1988). The application of logistic discriminant analysis models, thanks to the cranial trait scoring system, increases the accuracy of correctly classifying crania to 84% or even 88% (Walker, 2008). Even this approach, however, shows population specificity. The greatest problem in evaluating individual morphoscopic traits is the significant degree of subjectivity.

The advantage of traditional morphometric methods lies in their objectivity. Moreover, discriminant functions calculated on the basis of cranial measurements reach a high accuracy (85% to 95% of correctly classified individuals; Franklin et al., 2006a; Giles and Elliot, 1963; Howells, 1964; Steyn and İşcan, 1998). Morphometric methods are burdened by a classification error that ranges between 10% and 15% (Krogman and İşcan, 1986; Mays and Cox, 2000; Meindl et al., 1985), and up to 20% with crania (Masset, 1987;St. Hoyme and İşcan, 1989). The main problem of sexing forensic and archaeological material is the damage such material has incurred. Determination of sex with the help of dimensions from a single anatomic region of the cranium provides a lower, but still relatively high, success rate of classification (e.g. Gapert et al., 2009; Holland, 1986; Monticelli and Graw, 2008; Nagaoka et al., 2008; Wahl and Graw, 2001).

With cranium dimensions, however, size-related sexual dimorphism shows significant inter-population variability (e.g. Kemkes and Göbel, 2006). Both general robustness/gracility and the magnitude of sex-related differences (sexual dimorphism) depend on the particular regional population (Rösing et al., 2007). The application of discriminant functions on populations other than those for which they have been calculated leads to significant errors (e.g. Spradley et al., 2008). Sexual dimorphism of cranium size is also subject to demographic changes affecting population composition and the influence of secular trends. These findings are supported by studies of the North American population (e.g. Jantz, 2001) as well as of the Central European population (Buretić-Tomljanović et al., 2006; Jonke et al., 2007; Susanne et al., 1988). At the same time, the significant movement of residents, in connection with trade and tourism, prevents determination of the population specificity of an identified case with absolute certainty, and thus the application of population-specific methods is limited. Sex determination using the human cranium is generally based on size differences and robustness (Gapert et al., 2009). For these reasons, it is very important to determine whether it is possible to successfully determine sex using the shape of the cranium, after removing the size factor, the main variable in the population specificity of the methods.

Geometric morphometrics and sexual dimorphism of the cranium

GM present a possible solution to this problem (see above). According to Slice (2005), GM represents "the suite of methods for the acquisition, processing, and analysis of shape variables that retain all of the geometric information contained within the data." The main contribution of GM to forensic anthropology lies in eliminating subjectivity from the evaluation of shape and the possibility of an objective proposal of categories for nonmetric standards of sexual dimorphic traits (Franklin et al., 2006a, 2007b; Pretorius et al., 2006). Moreover, GM methods also enable the quantification of regions lacking sufficient incidence of suitable landmarks with the aid of curves serving as contours that can be digitised to form a series of discrete landmarks, so-called semi-landmarks (Perez et al.,

2006). Another advantage of GM is its frequently higher classification accuracy when separating groups of crania according to sex, when compared with the traditional discriminant functional analysis of linear dimensions (Franklin et al., 2006a, 2007b). Authors describe a classification accuracy of 87% in methods using the cranium as a whole, which is more than in the case of traditional morphometric techniques (e.g., in the same population, the classification accuracy of linear dimensions was only 80%; Franklin et al., 2005).

It is well known that sexual dimorphism is expressed more distinctly, the better the living conditions and health status of the given population (Lazenby, 2001). Our series comes from a lower social class of the populace (Pachner, 1937), which has been confirmed by studies that monitored the condition of dentition (Stránská et al., 2005), or the asymmetry and robustness of the skeleton (Fialová, 2004; Kujanová et al., 2008; Žaloudková, 2004). In such collections, it is useful to use 3D GM methods, which enable detection of specific traits of sexual dimorphism, which cannot be distinguished using traditional visual or metric methods. This is also due to the fact that sexual dimorphism is moreover based on fundamental and unique changes of shape with imperceptible differences between populations and is not merely an issue of size (Kimmerle et al., 2008).

Geometric morphometrics and sexing

Our results show that geometric morphometrics are a suitable instrument for evaluating the sexual differences of crania. In the series studied, we attained 100% classification accuracy for both sexes in the case of the upper face, and 98% accuracy in females and 100% accuracy in males in the case of the midsagittal curve of the neurocranium. Such results fully meet the requirements of forensic practice for high accuracy and reliability in sex determination (Scheuer, 2002).

The success of sexual diagnosis depends not only on the method selected but also on the anatomic regions of the skeleton and the degree of sexual dimorphism of the given population. Three-dimensional methods of studying cranium variability have shown the importance of the shape component of the facial skeleton for describing the variability within and between various population samples (Bruner and Manzi, 2004; Hennessy and Stringer, 2002), as well as the cranium as a whole (Badawi-Fayad and Cabanis, 2007; Franklin et al., 2007b). Sexual differences in the cranium are evidently associated with the physical constitution and energy requirements (Rosas and Bastir, 2002); this applies especially to the area of muscle attachments. Examples include, for example, facial prognathism, the relative bizygomatic width, the degree of glabella development, the profile of the forehead, the development of the mastoid processes, and the shape of the occipital region (Franklin et al., 2006a; Hennessy et al., 2002).

According to Franklin et al. (2006a), relative bizygomatic width best determines the sex, followed by the shape and profile of the forehead and the face. Our results show that the best sex-discriminating region of the cranium is the shape of the upper face (females, 100%; males, 100%). We recorded the most significant sexual differences in the relative width and robustness of the zygomatic arches. In male crania, the upper face was both relatively lower, wider, flatter, and vertically oriented. Female crania had a more convexly shaped face when viewed from above.

Although the shape of the orbits is not a commonly used method for sex determination (Pretorius et al., 2006), we recorded significant sexual differences in the shape, mutual position, and spatial orientation of the orbits. Apart from the commonly described more oval orbit in females and the more angular (relatively longer and lower) orbit in males (Krogman and İşcan, 1986; Pretorius et al., 2006), we discovered differences in orbit orientation. The orbits of males were more or less parallel to the frontal plane, whereas those of females were oriented more in the sagittal direction. Such findings are possible only when using GM methods. Pretorius et al. (2006) were surprised by the percentage of correctly classified individuals, where 80.0% of females and 73.3% of males were classified correctly on the basis of orbit shape, these values being higher than those in the case of the shape of the mandibular arms in the same sample of South African crania. Our values (females, 78.7%; males, 70.8%) are somewhat lower, probably because of the generally lower sexual dimorphism of this Central European series. Nonetheless, it is clear that the area of the orbit identifies females better. The relatively high percentage of correctly classified individuals

demonstrates the appropriateness of using GM methods in forensic anthropology. Such claims are also supported, for example, by the fact that neither the distance and height of the orbit in this series (Hudcová, 2006) nor the distance of the orbits in the recent adult Czech population as calculated using radiographs (Šmahel et al., 1998) shows sexual dimorphism.

We conducted the analysis of the nasal region on the basis of uncovered nonsignificant sexual differences in the width of the nasal aperture, the length of nasal bones, and the height of the nasospinale-prosthion in this series of crania (Hudcová, 2006) and the length of the nasal bones on radiographs of the adult Czech population (Šmahel et al., 1998). This uncommonly used region is often limited by insufficient preservation. In the case of male crania, however, the nasal region surprisingly discriminated sex better than the orbital region did (females, 76.8%; males, 77.4%). Our results confirm, similarly to those of Franklin et al. (2006a), the more prominent nasal bones along with deeper nasion depression in males. Our study, moreover, describes a relatively longer and wider nasal aperture in male crania.

Significant sexual dimorphism was also noted in the area of the palate. Our results are consistent with the findings of Šmahel et al. (1998), whose studies were conducted using radiographs and 3D models of the palate of the adult Czech population, as well as with findings of the study of Franklin et al. (2006a) on the South African population. Females had a more prominent proclination of the upper alveolar process with respect to the level of the palate—or, in other words, males had a relatively shorter, deeper, and narrower palate.

Although significant sexual differences are described in the region of the cranium base using size and robustness (Gapert et al., 2009; Holland, 1986) as well as shape with the aid of GM (Bruner and Ripani, 2008; Franklin et al., 2006a), our study did not demonstrate any significant sexual dimorphism of the shape of the cranium base. In contrast to Franklin et al. (2006a), for example, we did not record any significant sexual dimorphism in the region of the neurocranium configuration either. The shape of the midsagittal curve represents an exception. The landmarks on the midsagittal curve of the vault, defining its shape, enabled us to achieve a surprisingly high classification accuracy of sexing (females, 98.4%; males, 100%), although another study using the same material (Hudcová, 2006) did not show significant sex-related differences in the linear dimensions of the forehead region and inion. In our sample, we observed a more spheric neurocranium in females, as females had a more vertical and dome-shaped forehead, a less prominent glabella and inion region, and a relatively lower cranium in the region of the bregma. Franklin et al. (2006a) reached similar conclusions with a series of South African crania, just as Šmahel et al. (1998) did with a Czech population.

Conclusion

Our results show that a higher success rate in classifying the shape of crania according to sex may be attained by analysing individual regions of the cranium, rather than by including models that characterize the cranium as a whole, with all its landmarks, in the analysis. The success rate of sex differentiation is also higher than when using routine discriminant function analysis of linear dimensions. These findings are in line with the requisites of practice and the state of preservation of the available material. GM is a suitable tool for determining sex, and such research deserves increased attention. Determining whether sexual dimorphism of cranium shape shows logical homology in various populations will be made possible by comparing the results of classification among groups of crania from various geographically or chronologically distant populations.

Acknowledgments

The authors thank the reviewers for their recommendations. This project was supported by a grant from the Grant Agency of the Czech Republic (GAČR, project 206/07/0699), by research grant MSM 0021620843 from the Ministry of Education, Youth and Sports of the Czech Republic, and by

Centralized development project C16 3a from the Ministry of Education, Youth and Sports of the Czech Republic. We thank Katharine O'Moore-Klopf, ELS, for providing editorial assistance.

References

Badawi-Fayad, J., Cabanis, E.A., 2007. Three-dimensional procrustes analysis of modern human craniofacial form. Anat. Rec. 290, 268–276.
Barrio, P.A., Trancho, G.J., Sanchez, J.A., 2006. Metacarpal sexual determination in a Spanish population. J. Forensic Sci. 51, 990–995.
Bidmos, M., Dayal, M., 2004. Further evidence to show population specificity of discriminant function equations for sex determination using the talus of South African blacks. J. Forensic Sci. 49, 1165–1170.
Bidmos, M., 2006. Metrical and non-metrical assessment of population affinity from the calcaneus. Forensic Sci. Int. 159, 6–13.
Birkby, W.H., 1966. An evaluation of race and sex identification from cranial measurements. Am. J. Phys. Anthropol. 24, 21–27.
Bookstein, F.L., 1991. In: Morphometric Tools for Landmark Data: Geometry and Biology. Cambridge University Press, Cambridge.
Bookstein, F.L., Chernoff, B., Elder, R.L., Humphries, J.M.J., Smith, G.R., Strauss, R.E., 1985. Morphometrics in evolutionary biology. Spec. Publ. Acad. Nat. Sci. Phila. 15, 1–277.
Borovanský, L., 1936. Pohlavní rozdíly na lebce člověka [Sexual differences in human skull]. Česká akademie věd a umění, Praha.
Boulinier, G., 1968. La détermination du sexe des crânes humains à l'aide des fonctions discriminantes. Bull. Mem. Soc. Anthropol. Paris 3, 301–316.
Braga, J., Treil, J., 2007. Estimation of pediatric skeletal age using geometric morphometrics and three-dimensional cranial size changes. Int. J. Legal Med. 121, 439–443.
Brinkmann, B., 2007. Forensic anthropology. Int. J. Legal Med. 121, 431–432.
Bruner, E., Manzi, G., 2004. Variability in facial size and shape among North and East African human populations. Ital. J. Zool. 71, 51–56.
Bruner, E., Ripani, M., 2008. A quantitative and descriptive approach to morphological variation of the endocranial base in modern humans. Am. J. Phys. Anthropol. 137, 30–40.
Brůžek, J., Murail, P., 2006. Methodology and reliability of sex determination from the skeleton. In: Schmitt, A., Cunha, E., Pinheiro, J. (Eds.), Forensic Anthropology and Medicine: Complementary Sciences from Recovery to Cause of Death. Humana Press, Totowa, NJ, pp. 225–242.
Brůžek, J., Velemínsky, P., 2006. Sex diagnosis of the early medieval population of Great Moravia (9th to 10th century): proposed population specific discriminant functions for cranial measurements. J. Nat. Mus. Nat. Hist. Ser. 175, 39–52.
Buck, T.J., Vidarsdottir, U.S., 2004. A proposed method for the identification of race in sub-adult skeletons: a geometric morphometric analysis of mandibular morphology. J. Forensic Sci. 49, 1159–1164.
Buretić-Tomljanović, A., Ostojić, S., Kapović, M., 2006. Secular change of craniofacial measures in Croatian younger adults. Am. J. Hum. Biol. 18, 668–675.
Cattaneo, C., 2007. Forensic anthropology: developments of a classical discipline in the new millennium. Forensic Sci. Int. 165, 185–193.
Černý, M., Komenda, S., 1986. Reconstruction of body height based on humerus and femur lengths (material from Czech Lands),in: II Anthropological Congress of Aleš Hrdlička, Universitas Carolina Pragensis, pp. 475–479.
Corti, M., 1993. Geometric morphometrics: an extension of the revolution. Trends Ecol. Evol. 8, 302–303.
Davis, J.C., 1986. In: Statistics and Data Analysis in Geology. John Wiley and Sons, New York.
DeLeon, V.B., 2004. Fluctuating asymmetry in the human craniofacial skeleton: Effects of sexual dimorphism, stress and developmental anomalies. Ph.D. dissertation, Johns Hopkins University, Baltimore, Maryland.
Dryden, I.L., Mardia, K.V., 1998. In: Statistical Shape Analysis. John Wiley and Sons, Chichester, New York.
Fialová, L., 2004. Asymetrie dlouhých kostí dolní končetiny u velkomoravské a recentní populace [Lower limb bone asymmetry in Great Moravian and recent populations]. Master thesis, Faculty of Science, Charles University, Praha.
Franklin, D., Freedman, L., Milne, N., 2005. Sexual dimorphism and discriminant function sexing in indigenous South African crania. Homo 55, 213–228.
Franklin, D., Freedman, L., Milne, N., Oxnard, C.E., 2006a. A geometric morphometric study of sexual dimorphism in the crania of indigenous southern Africans. S. Afr. J. Sci. 102, 229–238.
Franklin, D., O'Higgins, P., Oxnard, C.E., Dadour, I., 2006b. Determination of sex in South African blacks by discriminant function analysis of mandibular linear dimensions. A preliminary investigation using the Zulu local population. Forensic Sci. Med. Pathol. 2, 263–268.
Franklin, D., O'Higgins, P., Oxnard, C.E., Dadour, I., 2007a. Sexual dimorphism and population variation in the adult mandible. Forensic applications of geometric morphometrics. Forensic Sci. Med. Pathol. 3, 15–22.
Franklin, D., Oxnard, C.E., O'Higgins, P., Dadour, I., 2007b. Sexual dimorphism in the subadult mandible: quantification using geometric morphometrics. J. Forensic Sci. 52, 6–10.
Franklin, D., Freedman, L., Milne, N., Oxnard, C.E., 2007c. Geometric morphometric study of population variation in indigenous Southern African crania. Am. J. Hum. Biol. 19, 20–33.
Frutos, L.R., 2005. Metric determination of sex from the humerus in a Guatemalan forensic sample. Forensic Sci. Int. 147, 153–157.
Gapert, R., Black, S., Last, J., 2009. Sex determination from the foramen magnum: discriminant function analysis in an eighteenth and nineteenth century British sample. Int. J. Legal. Med. 123, 25–33.
Giles, E., 1964. Sex determination by discriminant function analysis of the mandible. Am. J. Phys. Anthropol. 22, 129–135.
Giles, E., Elliot, O., 1963. Sex determination by discriminant function analysis of crania. Am. J. Phys. Anthropol. 21, 53–68.
Graham, E.A.M., 2006. Sex determination. Forensic Sci. Med. Pathol. 2, 283–286.

Gualdi-Russo, E., 2007. Sex determination from the talus and calcaneus measurements. Forensic Sci. Int. 171, 151–156.
Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PAST: Paleontological statistics software package for education and data analysis. Palaeontologia Electronica 4, p. 9. Available from: http://palaeo-electronica.org/2001_1/past/issue1_01.htm.
Hanihara, K., 1959. Sex diagnosis of Japanese skulls by means of discriminant function. J. Anthropol. Soc. Nippon 67, 191–197.
Henke, W., 1974. Zur Methode der diskriminanzanalytischen Geschlechtbestimmung am Schädel. Homo 24, 99–117.
Hennessy, R.J., Kinsella, A., Waddington, J.L., 2002. 3D Laser surface scanning and geometric morphometric analysis of craniofacial shape as an index of cerebro-craniofacial morphogenesis: Initial application to sexual dimorphism. Biol. Psychiatry 51, 507–514.
Hennessy, R.J., Stringer, C.B., 2002. Geometric morphometric study of the regional variation of modern human craniofacial form. Am. J. Phys. Anthropol. 117, 37–48.
Holland, T.D., 1986. Sex determination of fragmentary crania by analysis of the cranial base. Am. J. Phys. Anthropol. 70, 203–208.
Howells, W.W., 1964. Détermination du sexe du bassin par fonction discriminante: étude du matériel du Docteur Gaillard. Bull. Mem. Soc. Anthropol. Paris 7, 95–105.
Hudcová, B., 2006. Testování reliability kraniometrických metod: přímé měření lebek a 3D modelů, digitální měření fotografií a RTG snímků [Reliability testing of craniometric methods: direct measuring of skulls and of three dimensional models, digital measuring of photographs and of X-ray films]. Master thesis, Faculty of Science, Charles University, Praha.
İşcan, M.Y., 1988. Rise of forensic anthropology. Am. J. Phys. Anthropol. 31, 203–229.
Jantz, L.M., Jantz, R.L., 1999. Secular change in long bone length and proportion in the United States, 1800–1970. Am. J. Phys. Anthropol. 110, 57–67.
Jantz, R.L., 2001. Cranial change in Americans: 1850–1975. J. Forensic Sci. 46, 784–787.
Jonke, E., Prossinger, H., Bookstein, F.L., Schaefer, K., Bernhard, M., Freudenthaler, J.W., 2007. Secular trends in the facial skull from the 19th century to the present, analyzed with geometric morphometrics. Am. J. Orthod. Dentofacial. Orthop. 132, 63–70.
Kemkes-Grottenthaler, A., 2005. Sex determination by discriminant analysis: an evaluation of the reliability of patella measurements. Forensic Sci. Int. 147, 129–133.
Kemkes, A., Göbel, T., 2006. Metric assessment of the ''mastoid triangle'' for sex determination: a validation study. J. Forensic Sci. 51, 985–989.
Kimmerle, E.H., Ross, A., Slice, D.E., 2008. Sexual dimorphism in America: geometric morphometric analysis of the craniofacial region. J. Forensic Sci. 53, 54–57.
Klepinger, L.L., 1999. Stature, maturation variation and secular trends in forensic anthropology. J. Forensic Sci. 46, 788–790.
Krogman, W.M., İşcan, M.Y., 1986. In: The Human Skeleton in Forensic Medicine. Charles C. Thomas, Springfield, IL.
Kujanová, M., Bigoni, L., Velemínská, J., Velemínský, P., 2008. Limb bones asymmetry and stress in medieval and recent populations of Central Europe. Int. J. Osteoarchaeol. 18, 476–491.
Lazenby, R.A., 2001. Sex dimorphism and bilateral asymmetry: modeling developmental instability and functional adaptation. Am. J. Phys. Anthropol. Suppl. 32, 96.
Martin, R., Saller, K., 1957. In: Lehrbuch der Anthropologie. Gustav Fischer-Verlag, Stuttgart.
Masset, C., 1987. Recrutement d'un ensemble funéraire. In: Duday, H., Masset, C. (Eds.), Anthropologie Physique et Archéologie. CNRS, Paris, pp. 115–147.
Mays, S., Cox, M., 2000. Sex determination in skeletal remains. In: Cox, M., Mays, S. (Eds.), Human Osteology in Archaeology and Forensic Science. Greenwich Medical Media, London, pp. 117–130.
Meadows, L., Jantz, M.L., 1995. Allometric secular change in the long bones from the 1800 s to the present. J. Forensic Sci. 40, 762–767.
Meindl, R.S., Lovejoy, C.O., Mensford, R.S., Don Carlos, L., 1985. Accuracy and direction of error in the sexing of the skeleton: implication for paleodemography. Am. J. Phys. Anthropol. 68, 79–85.
Monticelli, F., Graw, M., 2008. Investigation on the reliability of determining sex from the human *os zygomaticum*. Forensic Sci. Med. Pathol. 4, 181–186.
Nagaoka, T., Shizushima, A., Sawada, J., Tomo, S., Hoshino, K., Sato, H., Hirata, K., 2008. Sex determination using mastoid process measurements: standards for Japanese human skeletons of the medieval and early modern periods. Anthropol. Sci. 116, 105–113.
Novotný, V., 1986. Sex determination of the pelvic bone: a systems approach. Anthropologie 24, 197–206.
Novotný, V., İşcan, M.Y., Loth, S.R., 1993. Morphologic and osteometric assessment of age, sex, and race from the skull. In: İşcan, M.Y., Helmer, R.P. (Eds.), Forensic Analysis of the Skull. Wiley, New York, pp. 71–88.
O'Higgins, P., Jones, N., 1998. Facial growth in *Cercocebus torquatus*: an application of three-dimensional geometric morphometric techniques to the study of morphological variation. J. Anat. 193, 251–272.
O'Higgins, P., Jones, N., 2006. Tools for statistical shape analysis. Morphologika 2.5. Hull York Medical School. Available from: http://hyms.fme.googlepages.com/resources.
Oettlé, A.C., Pretorius, E., Steyn, M., 2005. Geometric morphometric analysis of mandibular ramus flexure. Am. J. Phys. Anthropol. 128, 623–629.
Özer, I., Katayama, K., Sahgir, M., Güleç, E., 2006. Sex determination using the scapula in medieval skeletons from East Anatolia. Coll. Antropol. 30, 415–419.
Pachner, P., 1937. Pohlavní rozdíly na lidské pánvi [Sexual Differences in Human Pelvis]. Česká akademie věd a umění, Praha.
Perez, S.I., Bernal, V., Gonzalez, P.N., 2006. Differences between sliding semi-landmark methods in geometric morphometrics, with an application to human craniofacial and dental variation. J. Anat. 208, 769–784.
Pretorius, E., Steyn, M., Scholtz, Y., 2006. Investigation into the usability of geometric morphometric analysis in assessment of sexual dimorphism. Am. J. Phys. Anthropol. 129, 64–70.
Purkait, R., Chandra, H., 2004. A study of sexual variation in Indian femur. Forensic Sci. Int. 146, 25–33.
Richtsmeier, J.T., DeLeon, V.B., Lele, S.R., 2002. The promise of geometric morphometrics. Yrbk Phys. Anthropol. 45, 63–91.
Rohlf, F.J., 1996. Morphometrics spaces, shape components and the effects of linear transformations. In: Marcus, L.F., Corti, M., Loy, A., Naylor, G.J.P., Slice, D.E. (Eds.), Advances in Morphometrics. Plenum Press, New York, pp. 117–129.

Rohlf, F.J., 2003. Bias and error in estimates of mean shape in geometric morphometrics. J. Hum. Evol. 44, 665–683.
Rosas, A., Bastir, M., 2002. Thin-plate spline analysis of allometry and sexual dimorphism in the human craniofacial complex. Am. J. Phys. Anthropol. 117, 236–245.
Rösing, F.W., Graw, M., Marré, B., Ritz-Timme, S., Rothschild, M.A., Rötzscher, K., Schmeling, A., Schröder, I., Geserick, G., 2007. Recommendations for the forensic diagnosis of sex and age from skeletons. Homo 58, 75–89.
Ross, A.H., McKeown, A.H., Konigsberg, L.W., 1999. Allocation of crania to groups via the "new morphometry". J. Forensic Sci. 44, 584–587.
Ross, A.H., Kimmerle, E.H., Slice, D.E., Falsetti, A.B., 2006. What matters—size or shape? Three-dimensional analysis of craniofacial sexual variation among American populations [published abstract]. American Academy of Forensic Sciences, WA 12, 279.
Scheuer, L., 2002. Application of osteology to forensic medicine. Clin. Anat. 15, 297–312.
Schmeling, A., Olze, A., Reisinger, W., Geserick, G., 2001. Age estimation of living people undergoing criminal proceedings. Lancet 358, 89–90.
Sjøvold, T., 1988. Geschlechtsdiagnose am Skelett. In: Knussman, R. (Ed.), Anthropologie. Handbuch der Vergleichenden Biologie des Menschen. Gustav Fischer, Stuttgart, pp. 444–480.
Šlaus, M., Strinović, D., Škavić, J., Petrovečki, V., 2003. Discriminant function sexing of fragmentary and complete femora: standards for contemporary Croatia. J. Forensic Sci. 48, 509–512.
Slice, D.E., 1998. Morpheus et al.: Software for Morphometric Research, Department of Ecology and Evolution. State University of New York, Stony Brook, New York.
Slice, D.E., 2005. Modern morphometrics. In: Slice, D.E. (Ed.), Modern Morphometrics in Physical Anthropology. Kluwer Academic/Plenum Publishers, New York, pp. 1–45.
Slice, D.E., 2007. Geometric morphometrics. Annu. Rev. Anthropol. 36, 261–281.
Šmahel, Z., Šabík, D., Tomanová, M., Müllerová, Ž., 1998. Basic characteristics of the postnatal development of the human cranium. Anthropologie 36, 235–249.
Snow, F.J., 2004. Geometric Morphometry Analysis of the Scapula: Implications for the Determination of Sex and Ancestry. Ph.D. dissertation, University of Tennessee, Knoxville.
Spradley, M.K., Jantz, R.L., Robinson, A., Peccerelli, F., 2008. Demographic change and forensic identification: Problems in metric identification of Hispanic skeleton. J. Forensic Sci. 53, 21–28.
St. Hoyme, L.E., İşcan, M.Y., 1989. Determination of sex and race: accuracy and assumptions. In: İşcan, M.Y., Kennedy, K.A.R. (Eds.), Reconstruction of Life from the Skeleton. Alan R. Liss, New York, pp. 53–93.
Steyn, M., İşcan, M.Y., 1998. Sexual dimorphism in the crania and mandibles of South African whites. Forensic Sci. Int. 98, 9–16.
Steyn, M., Pretorius., E, Hutten, L., 2004. Geometric morphometric analysis of the greater sciatic notch in South Africans. Homo 54, 197–206.
Strádalová, V., 1972. Determination of sex from metrical characteristics of the sacrum. Folia Morphol. (Praha) 22, 408–412.
Stránská, P., Likovský, J., Velemínská, J., 2005. State of dental health and selected pathological conditions in the recent skulls from the Pachner's collection. Slovenská antropológia 8, 127–136.
Susanne, C., Vercauteren, M., Krasnicanova, H., Jaeger, V., Hauspie, R., Bruzek, J., 1988. Evolution séculaire des dimensions céphaliques [Secular evolution of cephalic dimensions]. Bull. Mem. Soc. Anthropol. Paris 5, 151–162.
Wahl, J., Graw, M., 2001. Metric sex differentiation of the pars petrosa ossis temporalis. Int. J. Legal Med. 114, 215–223.
Walker, P.L., 2008. Sexing skulls using discriminant function analysis of visually assessed traits. Am. J. Phys. Anthropol. 136, 39–50.
Williams, B.A., Rogers, T.L., 2006. Evaluating the accuracy and precision of cranial morphological traits for sex determination. J. Forensic Sci. 51, 729–735.
Wrobel, G.D., Danforth, M.E., Armstrong, C., 2002. Estimating sex of Maya skeletons by discriminant function analysis of long-bone measurements from the protohistoric Maya site of Tipu, Belize. Ancient Mesoamerica 13, 255–263.
Žaloudková, M., 2004. Asymetrie kostí horní končetiny u velkomoravské a recentní populace [Upper limb bone asymmetry in Great Moravian and recent populations]. Master thesis, Faculty of Science, Charles University, Praha.