Aus dem Institut für Rechtsmedizin

der Universität Würzburg

Vorstand: Professor Dr. med. Michael Bohnert

The Shape of the Frontal Bone

Inaugural - Dissertation

zur Erlangung der Doktorwürde der

Medizinischen Fakultät

der

Julius-Maximilians-Universität Würzburg

vorgelegt von

Laura Manthey

aus Leinefelde

Würzburg, April 2022

Referent: Prof. Dr. Michael Bohnert

Korreferent/in: Prof. Dr. Thorsten Bley

Dekan: Prof. Dr. Matthias Frosch

Tag der mündlichen Prüfung: 13.10.2022

Inhaltsverzeichnis

1 Introduction

1.1 The Frontal Bone

The frontal bone is one of the 22 cranial bones, attached posteriorly to both parietals, inferolaterally to the zygomatics and the sphenoid, and inferoanteriorly to the maxilla, the nasal bones, the ethmoids, and the lacrimal bones. Its shape has often been considered to be a reliable indicator for morphological sex estimation with male frontals thought to be inclined while the females' are observed as more pronounced[1] [1-3] (cited in [4]). As the frontal contains many highly reliable sexual dimorphic traits such as glabella, the supraorbital margins, and the supraorbital ridges (see also chapter 1.3 Sexual Dimorphism), the bone as a whole should be a comprehensive tool for sex estimation. Unfortunately, there is not much research on quantification and statistical evaluation of the forehead's shape differences.

Figure 1a: Male cranium. (Photograph taken by the author.)

[1] More vertical, rounded, convex, smooth, and broad. (Wilkinson, C., *Forensic Facial Reconstruction.* University Press, Cambridge, 2004.)

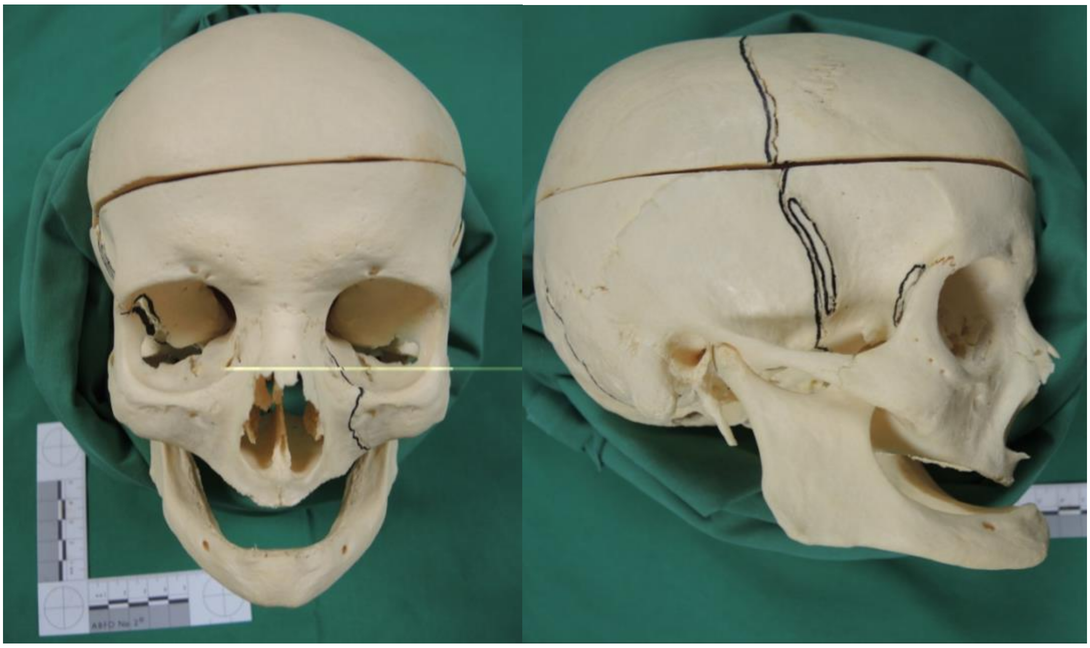


Figure 1b: Female cranium. (Photograph taken by Dr.Katharina Jellinghaus.)

Bulut et al. [4] have done a study to objectify the extent of sexual dimorphism on the frontal bone. Therefore, they have constructed 3D CAD[2] spheres for frontal bone models[3] to study their roundness. As could be expected, the distance between the sphere and the forehead was largest for glabella, supraorbital margins, zygomatic processes, superciliary arc, and the temporal face. More noteworthy is, though, that the general overlapping with the sphere was on average 43.2% in males and 33.9% in females which means that male frontal bones are much more rounded than female ones. This contradicts the commonly accepted assumption that female frontals would be the roundly shaped specimen. Bulut et al. attribute that fact to the "different expression and thickness of the supraorbital ridge and a different angle between the frontal area and the nose in males and females". According to them, the optic confusion might come from the eye-catching deviations[4] in males while the female's divergences from the sphere were spread out over large areas. Their study sample consisted of Turkish individuals which they say would be generally characterized by a relatively

[2] Computer Aided Design

[3] Extracted from CT scans.

[4] E. g. more prominent glabella and supraorbital ridges. (See also chapter 1.3 Sexual Dimorphism)

sloping forehead and might, thus, have influenced the results. This present work attempts to investigate shape differences between male and female frontals and might therefore support the general applicability of Bulut et al.'s findings.

1.2 Shape

Within the concept of geometric morphometrics, shape is defined as all the geometric features of a landmark configuration except for its size, position, and orientation. It can be extracted through Procrustes superimposition (see figure 2). As first step of this standardization process, all landmark configurations are scaled to unit Centroid Size[5] which is done by dividing all the landmark coordinates by the Centroid Size of the respective configuration. Next, variation in position needs to be removed through centering all the configurations on the same centroid being the origin of the coordinate system. The only diversifying component remaining other than shape is then the orientation of each object. It is eliminated by a process of minimizing the sum of squared distances between corresponding landmarks.

[5] Measure of size in geometric morphometrics, defined as the square root of the sum of squared distances of all landmarks from the centroid (center of gravity) of the respective configuration → Centroid Size= $\sqrt{x_1^2+x_2^2+x_n^2}$).

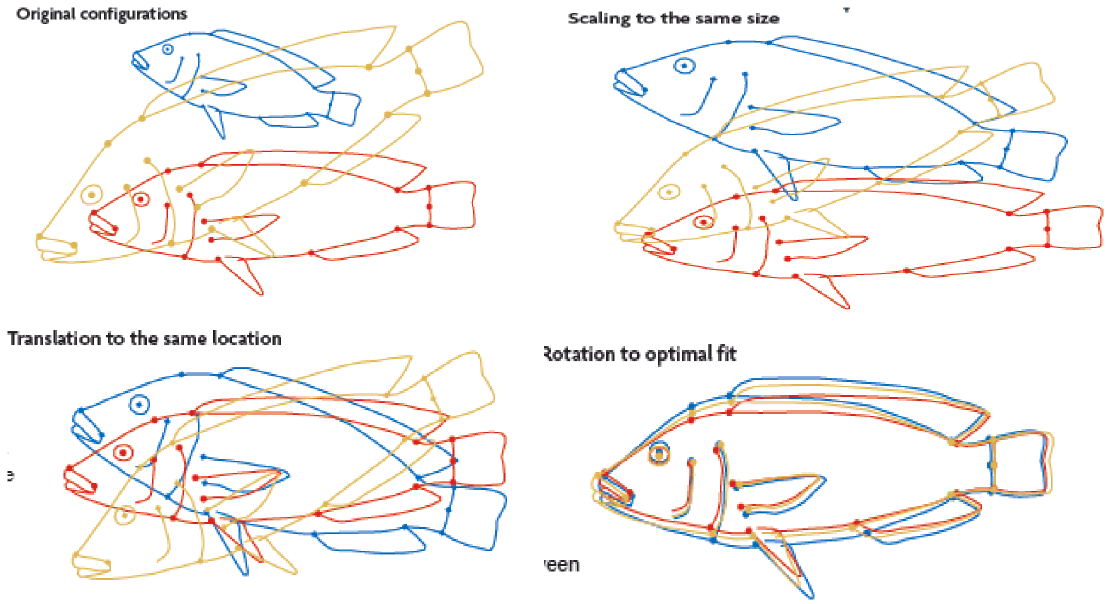


Figure 2: Procrustes superimposition. (Reprinted from [5] by permission from Springer Nature Customer Service Centre GmbH: Springer Nature. Nature Reviews Genetics. Evolution and development of shape: integrating quantitative approaches, Christian Peter Klingenberg, 2010, License Number 5124930809636.)

Software for analyses of geometric morphometric data is MorphoJ® [6]. After excluding shape through Procrustes superimposition there are various options to study coordinate data. The next step in the project tree should usually be searching for outliers. Furthermore, the program includes, among others, standard methods of multivariate analysis (such as principal component analysis, canonical variate analysis, and discriminant analysis with cross-validation) and techniques that compute covariation of shape with other types of variables (e.g. multivariate regression analysis for assessing allometry).

Shape can be independent of size which would be ideal for shape analysis and is called “isometry”. Nevertheless, the usual case in phylogenetic development is “allometry” where size and shape are correlated variables. There are different concepts of allometry, the two main schools being Gould-Mosimann [7, 8] (cited in [9]) and Huxley-Jolicoeur [10-12] (cited in [9]).

The base for the Gould-Mosimann approach are explicit definitions of size and shape. Size is a measure for the overall dimension of an object and can be quantified by a single number. Shape on the other hand gives information on the proportions of objects, expressed through vectors of ratios where each measurement is divided by the overall size of the object as standard size variable. Hence, the measurements of two conformations with the same shape differ by a constant factor. The explanation for allometry is then derived as covariation of size and shape. Tests of multiple correlation can distinguish between isometry and allometry.

In contrast, the Huxley-Jolicoeur [10-12] (cited in [9]) approach does not distinguish between size and shape and is viewing covariation among traits as a consequence of variation in size. The concept of allometry in this case originated from the frequent observation of constant ratios between the relative growth rates of different measurements of a conformation, which then form straight lines in pairwise plots. The slopes (see figure 3) are classified as negative allometry (m<1.0; blue line), isometry (m=1.0; grey line), and positive allometry (m>1.0; red line).

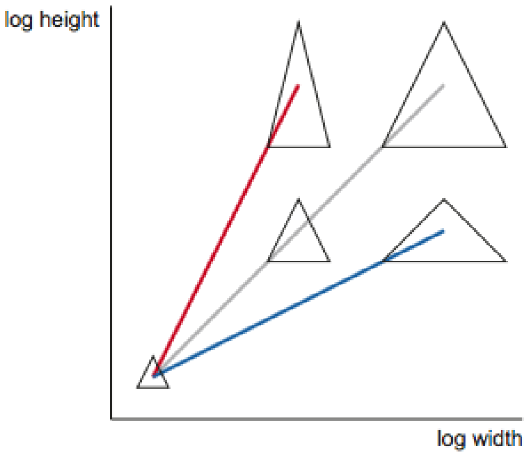


Figure 3: Bivariate allometry. Reprinted from [9][6].

Unfortunately, this method does only allow analyses of objects with two variables or would require considering all possible pairwise plots and is therefore rarely feasible. The solution for this problem is a multivariate generalization in the form of a multidimensional space. Within this space, each measurement corresponds to a respective axis. These lines can be measured through principal component analysis (PCA). Principal components (PC) are new axes that each align a measurement's variation in a respective direction, e.g. one PC aligns all variation in a direction 30° apart

[6] This is an open access article distributed under the terms of the Creative Commons CC BY license, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

from the x-axis in the xy-plain. PC1 accounts for the greatest possible proportion of the total variance and is thus an approximation of the allometric line. As each PC has its own direction within the multidimensional space, this direction needs to be measured for being used as an indicator in allometry analysis. To do so, a coefficient for each PC can be computed as the cosine between the coordinate axis for that variable and the respective PC axis. In case of isometry, all PC1 coefficients are equal since the proportions among the variables do not change along the allometric line.

All lines perpendicular to the allometric axis form a size-free space. It can be used to exclude the allometric effects of size. One should note that the size-free space does not represent complete shape variation which is first of all due to the fact that there is no size-shape concept in the Huxley-Jolicoeur school. Second, and more important, the allometric axis includes by definition size-related shape change, a part of shape variation that is thus not contained in size-free space.

1.3 Sexual Dimorphism

Estimating[7] the sex of an unknown adult[8] individual can be performed through various methods. The most established approaches are, in order of decreasing reliability, pelvic morphology, postcranial[9] morphometrics, and cranial morphology.

Pelvic morphology is usually examined using the Phenice traits [13, 14]: The general concept of the female innominate shape is to have a broad pelvis for giving birth. Therefore, it usually exposes a ventral arc[10], subpubic concavity[11], and a thin medial aspect of the ischiopubic ramus (versus robust in males) in greater or lesser extent respectively. As additional features to the Phenice traits the greater sciatic notch (broader in females, narrow in males), and the auricular surface (often raised with a preauricular sulcus in females) can be examined [15].

---

[7] One should note that the only way to “determine” sex on skeletal human remains is to perform a chromosomal analysis. All other approaches are “estimations”.

[8] Sex cannot be estimated morphologically or morphometrically on immature individuals because the development of male or female features on bones follows the hormonal status.

[9] All bones other than the cranium.

[10] A slightly elevated ridge of bone running inferiorly and laterally on the surface of the pubic bone.

[11] The ischiopubic ramus is concavely shaped at its end towards the pubic symphysis.

Morphometric analyses can be performed through Fordisc®. There are defined measurements [16] for all human bones that can be taken applying (depending on the respective measurement) a spreading or a sliding caliper, a tape measure, an osteometric board, or –in case of the cranium– a digitizer (see 2. Materials and Methods). Fordisc® 3.1 [17] is a software developed by Richard Jantz, PhD and Stephen Ousley, PhD at the University of Tennessee built to estimate ancestry, sex and stature of an unknown individual based on morphometric data. This tool is supposed to provide an easier and more reliable approach to creating a biological profile[12] than morphological analyses do. Its working technique is, generally speaking, to compare the studied case with the available samples on the program and to calculate the probability for its belonging to one of the given populations. Therefore, modern cranial measurements from all over the world are needed to make Fordisc® work universally on forensic cases.

To estimate sex and ancestry the program computes a new discriminant function for each analysis taking into account the chosen ancestries, centuries, sex(es), and measurements to compare the unknown individual's data with. One of Fordisc®'s most important advantages compared to other methods is its ability to use every possible combination of measurements for computation. It hereby increases the probability to identify the person represented by the examined remains even if major parts of the skeleton are missing. Stature estimation exemplifies an exception in the way the data is processed. By the means of linear regression for a chosen ancestry, the height measurement of one single postcranial bone[13] can be enough to get a stature value and its standard deviation. However, by having more bones and their respective measurements available the reliability of the result increases and the standard deviation shrinks.

Fordisc®'s dataset is based on the Forensic Data Bank (FDB) at the University of Tennessee, Knoxville. The main sources of which are bones from forensic cases and the

[12] The biological profile of a skeletal finding consists of the estimated ancestry, sex, age, and stature and is building the base of every forensic case report.
[13] Vertebra, sacrum, innominate, femur, tibia, or talus and calcaneus.

Anthropology Research Facility[14] [18]. As donations are derived from people throughout the United States of America the FDB and hence Fordisc® contain mostly data from African- and Euro-American, and Hispanic individuals. A few Polynesians and Asians have been added over the years. The software however still lacks sufficient samples, such as European, African, and Australian in order to put correct assessments on populations other than the previously named [19-21].

Cranial morphology as third of the important sexing criteria is easiest to apply with the "Walker traits" [22] (see figure 4). The examiner gives a score between 1 and 5 on the following highly dimorphic traits: nuchal crest, mastoid process, supra-orbital margin, supra-orbital ridge/glabella, and mental eminence. The average number is then calculated. A mean <3 suggests female, >3 male, and 3 means it remains unclear. This approach is unique in giving the opportunity for statistical analysis on morphological sex estimation through the scoring system.

[14] An outdoor research institution examining the decomposition of donated dead bodies at the University of Tennessee, Knoxville.

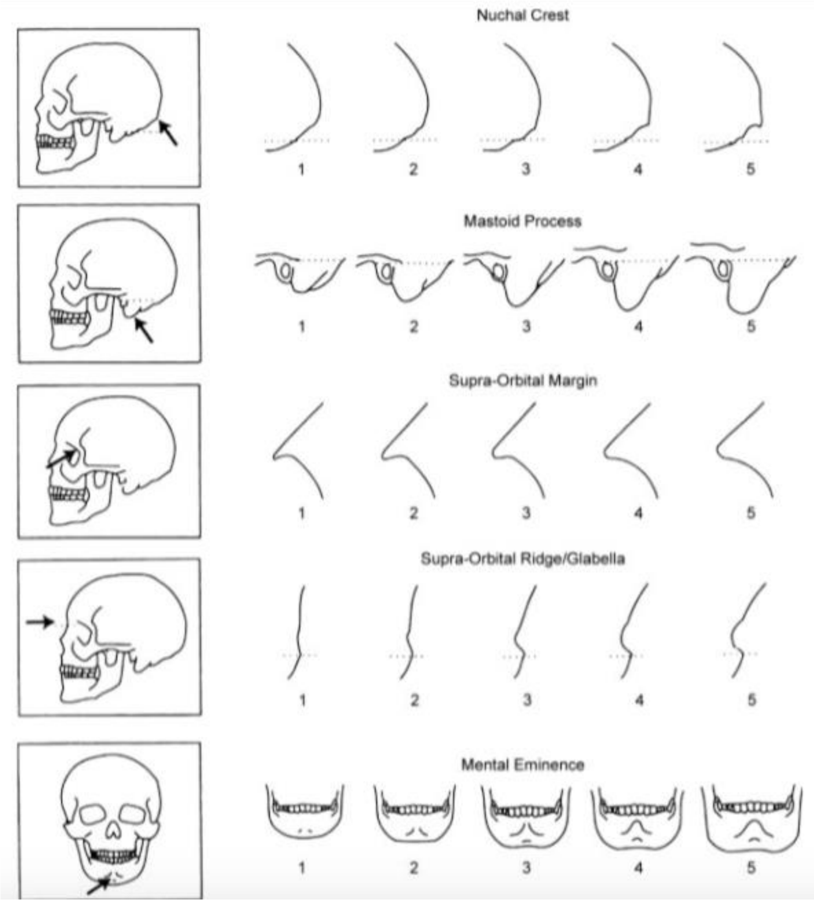


Figure 4: Walker traits. (Reprinted from [22] by permission from John Wiley and Sons. American Journal of Physical Anthropology. Sexing skulls using discriminant function analysis of visually assessed traits, Phillip L. Walker, 2008. License Number 5124931448628.)

However, it is noteworthy that this method has been developed on Euro-American, African-American (both 19th century), and English (18th century) samples and therefore needs to be handled carefully when applied on other populations. For the late 19th century, however, Euro-American dimorphism in GLS[15] and MDH[16] could be shown to be similar to that in German skulls [19] increasing the value of the Walker traits for 19th century Germans. This importance continues as they keep their amount of dimorphism through early 20th century [19]. Ramsthaler et al. [23] have been able to identify the most dimorphic morphologic cranial traits in 20th century central Europeans being (in order of decreasing reliability) supraorbital ridge, glabella, decline of frontal bone, upper edges of orbits, and mastoid process. This also represents a strong

[15] Glabella Subtense
[16] Mastoid Height

consistency with parts of Walker's findings. In this context it is important that Euro-American values for GLS and MDH increase significantly for both sexes between the late 19th and the early 20th century [19] which questions the Walker-applicability for 20th century Euro-Americans even though their ancestors have been part of the original study sample.

Cranial shape does of course influence facial shape. According to Kesterke et al. [24], male faces show more prominent nasal, supraorbital, and chin regions and less prominent orbital, malar, and forehead regions in the late 20th century European derived US population. The prominent supraorbital region is probably congruent with high Glabella projection but since Manthey et al. [19] have only shown dimorphism in size (GLS) sex differences in shape still need to be investigated. Garvin and Ruff [25] have found sexual dimorphism in the shape of the brow region though, which strongly suggests sexual dimorphism in Glabella shape. This thesis puts emphasis on the frontal bone and its dimorphism in terms of size and shape and does therefore include Glabella shape as well.

Another interesting fact in the context of facial dimorphism is that the prenatal testosterone level of a child influences its adult facial shape [26]. According to this study, a high testosterone level in the umbilical cord blood leads to a strongly masculine shaped face. This correlation is not present between adult testosterone levels and the adult face which leads to the assumption that facial shape and hence skull shape is mostly predetermined in utero.

The presence of sexual dimorphism leads to one of the most important discriminant factors for identification in forensic sciences: the individual's sex. If there is a reliable sex estimation, the number of possibly fitting missing people is reduced by approximately 50%[17].

Because of this importance and since the innominate or the (whole) cranium are not always present there is a vast amount of research performed on identifying dimorphism in other bones. Karakostis et al. [27] have found sexual dimorphism in proximal hand

[17] The male-female-ratio of forensic cases is usually not 1:1 and varies between different age groups. Hence, 50% can only be seen as an approximation.

phalanges of a modern Greek sample. They have shown that men do in general have larger proximal phalanges than women, with dimorphism rates up to 24.78% and the left-hand phalanges differing more between the sexes than the right ones. Another approach has put emphasis on the frontal sinus volume [28] and found significant sexual dimorphism, especially when using the total frontal sinus volume (sum of left and right FS volume). This way, they have been able to reach 72.5% correct sex estimation. Even though this is a remarkable finding its practical use in forensic sciences is questionable because CT scanners are rarely available in routine work.

1.4 Secular change

Over the centuries, multiple environmental factors have led to changes of size and shape in all human bones. As an example, the recent skull, especially the female, has become a lot more gracile compared to the Neanderthal. This overall fine shape, in contrast to the general robustness, allows estimating sex on modern individuals of most populations by the means of cranial morphology [22]. Furthermore, the results of secular change lead to the possibility of distinguishing bones from different centuries which is essential to decide between a skeletal finding's forensic or archaeological relevance[18].

Another well examined area is the secular change in height. Up from the colonial era, Euro-Americans used to be the tallest people in the world until they got passed by the Dutch in the 1930s. Nevertheless, there has been (and probably still is) a general increase in height for North America, and Western and Northern Europe [29]. Several factors are discussed to be responsible for these changes, such as eating habits/nutrition, the development of the social security system, advanced medical care, the economic situation in the respective country [29, 30], or genetics. Detailed research on these influences yet remains difficult since the real cause is most likely a compilation of various aspects. Secular change occurs highly variable and in diverse paces among different populations [19]. Hence, the most promising approach should be through

[18] For Germany, the forensically relevant time period is given as 30 years but has restrictions since murder does not come under the statute of limitations.

comparison of correlated changes in bone morphology and the environment in various populations. However, the lack of comprehensive data does make detailed research in this field challenging.

Nevertheless, Jantz and Meadows Jantz [30] and Jantz et al. [31] have been able to do studies on secular change of the cranium and the postcrania of Euro-Americans with ten year birth cohorts from early 19th through late 20th century and thus to conduct especially detailed analyses in contrast to the commonly applied half-century birth cohorts. For the cranial study they have used the measurements Glabello-Occipital Length (GOL), Basion-Bregma Height (BBH), Basion-Nasion Length (BNL)[19], Maximum Cranial Breadth (XCB), and Biauricular Breadth (AUB). What they found was that skulls "have become relatively higher, narrower, and larger with longer cranial bases". Furthermore, it was shown that the change in female individuals has occurred less marked than in males and that shape changes are a decade ahead of the alterations in size while they happen simultaneously with stature development. Besides the general study of morphological change, development in environmental factors has been investigated. This has led to the result that secular change relates to "improvements in health and nutrition, increasing wealth, and decreases in mortality and morbidity". The strongest correlation appeared between shape variables and infant mortality, being strongly negative for BBH-shape and strongly positive for XCB-shape. So the current development of a higher and narrower cranium comes while infant mortality decreases. A slightly lower correlation appeared between shape and higher calorie intake. Interestingly, shape development is lagging calorie intake by three to four decades. With regard to immigration rates it was additionally seen that the studied development relates to simultaneously shrinking immigration. Regardless of the remarkable findings, it seemed still not possible to identify the specific mechanisms of change.

For the postcranial skeleton Jantz et al. [31] found positive secular change in all bone lengths and stature. Moreover, there were similar discoveries for the crural and

[19] GOL as a measure for Maximum Cranial Length, BBH for Cranial Height, and BNL for Cranial Base Length.

brachial indices[20] which appears like the distal[21] limb bones had become relatively longer in relation to the proximal[22] ones. The assumption that absolute values would reflect this relative elongation is contradicted by the finding that the index change is mostly due to relatively shorter proximal limb bones. Jantz et al. [31] put the limb development in relation to stature. Hence, the index changes are for males in detail explained through positive allometry of tibia and fibula, isometry of the femur, and negative allometry of humerus, ulna, and radius (the humerus considerably more than the other two) compared to stature respectively. In females, as for the crania, secular change occurred generally less pronounced. Therefore, their upper limb bones and femur are negatively allometric, while tibia and fibula do not differ from isometry.

Jantz et al.'s discovery of secular change in all skeletal bones goes in line with Langley and Cridlin's [32] study about maximum clavicle length and maturation. This is not surprising since both have studied American individuals, even if it was only Euro-Americans for Jantz et al. For the clavicle, an interesting development could be seen as its length increased from 1840 through the breakpoint 1940 and decreased afterwards. This shrinking is congruent with the documented general narrowing of the American skeleton. Also, in the course of the 20th century, the fusion onset of the medial clavicle epiphysis was found to occur increasingly early, resulting in a late 20th century onset four years prior to the late 19th century. It is remarkable in this context that the age of complete fusion did not change significantly which means that the time period needing for fusion has increased. Langley and Cridlin assume that the onset of the epiphyseal fusion might be more sensitive to environmental factors while its completion would presumably be more dependent on genetic control. The medial clavicle epiphysis is the last one fusing in human beings and does thus determine maturation. The reported earlier onset leads to the conclusion that there would be an earlier start of maturation in general. This thought is supported through the finding of a decrease in the age at menarche of four to six months per decade over the past four to five decades [33-35] (cited in [32]) so roughly at the same time as the changes previously reported. Langley

[20] Distal bone length divided by proximal bone length.
[21] Tibia, fibula, radius, and ulna.
[22] Femur and humerus.

and Cridlin attribute this development among other things to an increased average BMI and a higher consumption rate of processed food with added vitamins, nutrients, and hormones in the US population. Like Jantz and Meadows Jantz [30] they have not been able to identify specific drivers behind the apparent development.

The studies reported to this point reflect the skeletal development in the US population. As a logical consequence of environmental influences being the reason for secular change, bone development should happen differently in other parts of the world. Manthey et al. [19] have been able to find differences in the secular trend between German and Euro-American crania even within the small amount of three studied measurements. The fact that these two groups both originate from the same ancestors supports the theory of a minor genetic but mostly environmental determination of short-term skeletal development. Moreover, another recent secular change study has been conducted on the crania of Mexican migrants who had died in the desert during the process of migration and had thus not been influenced by the American environment [36]. Their birth years ranged from 1944 through 1996. A few variables did in fact express significant secular change but these were mostly angles, fractions, subtenses, radii, and chords. Most variables, including the more general ones like height, breadth, and length, did not show any development. Nevertheless, these results do not allow to conclude there were never any changes in the Mexican skeleton. The study also compared the recent cohort with a 19th century Hispanic cemetery sample in which overall larger craniofacial dimensions have been found. Spradley et al. [36] do not attempt to explain their findings. The author of this work assumes that secular change could just occur more slowly in the Mexican population which might be through fewer environmental changes than the US population is and has been experiencing. On the other hand, bringing Mexican individuals into the American environment does actually lead to skeletal changes of their descendants as could be shown by Malina et al. [37] (cited in [32]).

1.5 Metopism

During fetal development, the forehead consists of a pair of two frontal bones divided by a fontanelle in the median sagittal plane. This gap usually fuses by the end of the second year after birth [38] (cited in [39]). In some occasions, there is no complete fusion but a persistence as an extra cranial suture which is then called "frontal suture" or "metopic suture/metopism". The frequency and the mechanisms of its occurrence are discussed intensively in the field of Anthropology.

As for the frequency of its occurrence, it has been found to appear mostly in European/European-derived populations [40], which makes the exact frequency in different parts of the world extremely variable. Hanihara and Ishida [41] have given a more general overview about a recent[23] sample of 81 populations. Their results have found metopism to be most common in Europeans (10-15%), especially frequent in the UK (up to 18%) and to be most seldom in Subsaharan African, Australian, and Pacific samples (0-1%). Beyond that, it could be shown that the occurrence of metopism and/or a biasterionic suture is related to the appearance of supernumerary ossicles.

There is no clear evidence of differences between the sexes [42] (cited in [39]). Metopic skulls have been shown to have a larger Minimum Frontal Breadth (WFB) [43] and to be mostly brachycephalic (cephalic index 81-86) or if being meso- or dolichocephalic (CI 76-81 or 71-76 respectively) having a higher average cephalic index than the corresponding non-metopic sample [39, 40]. The cephalic/cranial index is defined as Maximum Cranial Breadth (XCB) multiplied by 100 divided by Maximum Cranial Length (GOL) and does thus quantify the breadth-length-ratio of a skull.

Increased intracranial pressure and metopism as an inherited feature are the two most promising discussed mechanisms for the development of a persisting frontal suture [39]. The raised intracranial pressure could according to van Acken be a result of temporary interference in the homeostasis between growth of cranium and brain [43] (cited in [39]). Against Papillaut's [44] and LeDouble's [45] (both cited in [39])

[23] The exact time period is not given but as the paper dates to 2001 "recent" is probably meant as 19th and/or 20th century.

expectations, metopic skulls could not be shown to have an increased capacity [46] compared to the non-metopic.

Starting out from the theory of increased intracranial pressure, Weinholdt [47] assumed that hydrocephalic crania should show a greater incidence of metopism. Togersen [42] (cited in [39]) and Bolk [48] tried to prove this hypothesis but have not been able to find any coincidence of that kind. This absence of findings seems to refute the whole intracranial pressure theory and has been interpreted that way by many authors (e.g. Bolk [48]). Schmitt [39], however, does give an extraordinarily interesting explanation for this seeming inconsistency. Based on the functional anatomy of the supporting tissue [49, 50] (cited in [39]), he describes that cartilage can only develop under hydrostatic compressive stress while ossification needs absolute mechanic rest. As even a minimal temporary increased intracranial pressure causes tensile stress, there is no chance for the suture to ossify in that case. According to Böning [51] (cited in [39]), during brain growth there is a smaller difference in volume between the inner cranium and the brain than in later life. She states this situation was caused through skull growth being led by brain growth. If during this process disproportionally accelerated enlargement in a single part of the brain, the frontal lobe for example, occurred, there would be a short-term raised intracranial pressure as described above leading to connecting tissue development in the bone gap and hence a persistence of the frontal suture[24]. For hydrocephalic individuals Schmitt [39] explains how circumstances were different. Their increased cranial pressure was not temporarily but continuously developing. If there was another pressure peak, connective tissue would develop also on the outside of the cranium. The result was tension band wiring which opposed the intracranial pressure and thus further suture's dehiscence. Conditions for ossification were given. All in all, it seems likely that provisionally extended intracranial pressure during early childhood causes the development of a metopic suture.

The assumption of heredity as the other main cause for persisting frontal sutures is given through the observation of various cases within one family [42, 52, 53] (cited in [39]). Togersen [42] (cited in [39]) did furthermore find other anomalies like abnormal

[24] In case of the frontal lobe being grown larger.

development of the facial skull or Spina bifida occulta in this very same family he had studied which suggested a genetic influence of all his findings. On the word of Schmitt [39], both theories do not necessarily exclude one another since the mechanisms triggering intracranial pressure peaks could be genetically determined as well. Consequently, metopism might even be a means of identification if its presence in the family was known. However, it needs to be said that this skeletal characteristic is rarely known especially since it does not have any medical significance and could only be known through cranial x-rays or CT-scans, or, even more unlikely, through excavated ancestor skulls.

Schmitt [39] has studied two cranial samples, one from the institute for forensic pathology in Cologne (1968/69) and one from the institute for clinical pathology in Heidelberg (1973/74). He has been able to find 4-5% metopism in both collectives which is an excellent starting point for comparison with the present study sample. Besides these results, he also discovered as another remarkable finding in the Cologne sample slightly more than twice as many metopic sutures in suicide cases than in individuals with other causes of death (8.6% vs. 2.5%). This would agree with the observations of Materna and Gerhard [54], and Hess [55] (both cited in [39]) who have found increased rates of metopism in populations of individuals with psychiatric diseases. Nevertheless, these assumptions need to be handled carefully since the Cologne sample did only contain 214 crania and furthermore the studies involving mental illnesses date back to the time when Germany was under control of the Nazi regime and the original science of anthropology was abused. Schmitt's [39] results, although, are interesting and should be further investigated which can unfortunately not be performed through this work because the data set lacks appropriate information.

Another purpose of this thesis is, though, to investigate the relation between the frontal bone's shape and persistent frontal sutures. Metopism has already been found to be related to frontal curvature by Papillaut in the late 19th century [44] (cited in [56]).

The term frontal curvature means the ratio of frontal subtense[25] to frontal chord[26]. Papillaut has been able to prove it being greater in metopic skulls than in normal crania. Agreeing with that, Bryce and Young [40] have found shorter frontal chords in individuals with metopism and Hess [55] (cited in [56]) once described the frontal of these people as "high, vaulted or prominent". Woo [56] has done further investigation on the relation between frontal curvature and metopism. His main statements have been at first that Euro-Americans had the greatest frontal curvature[27]. Furthermore, he found that differences in the frontal curvature of his studied populations were mainly determined by the frontal subtense in contrast to sexual differences which were mostly determined by the frontal chord. In general, females had a greater frontal curvature than males. Finally, he has been able to confirm the greater frontal curvature in metopic skulls as found by Papillaut [44] (cited in [56]). The present study is looking for similar findings in the modern German population and comparing them to the Euro-Americans studied by Woo. The American sample used for this thesis does unfortunately not have any information on metopism.

1.6 Forensic Anthropology

Forensic Anthropology is defined by the American Board of Forensic Anthropology (ABFA) as "the application of the science of physical or biological anthropology to the legal process" [57]. It is a relatively young discipline within Physical Anthropology that launched in the early 1900s [58]. Physical Anthropologists are trained in estimating sex, age, ancestry[28][59, 60], and height of an individual. These skills are used to construct the biological profile of an unknown individual and hence provide law enforcement with the base for identification. The specialization towards Forensic

[25] Longest perpendicular distance between the frontal chord and the frontal bone.
[26] The straight line between Bregma and Nasion, Bregma being the intersection of the coronal with the sagittal suture and Nasion being the intersection of the naso-frontal suture with the mid-sagittal plane.
[27] His study sample consisted of "American Indians", "Mongoloids", "American Negros", and "American Whites".
[28] The author is aware of the ongoing discussion on whether "ancestry" or similar concepts should still be used in forensic case reports or not, but has not enough knowledge to determine a final position on that matter (see in-text citations for references). Analyses of population differences have been kept in this work.

Anthropology lies mostly within the emphasis on individualizing traits and evidence for cause and manner of death.

For identification purposes, the individualizing traits need to be known antemortem. These can be healed fractures, additional ribs, tooth fillings and crowns, missing teeth, features appearing on x-rays (e.g. frontal sinuses [61] and tooth roots), bone anomalies, or diseases that lead to alteration of the bone (e.g. diabetes [62], bone tumors [63, 64], rheumatoid arthritis [65] etc.).

For cause and manner of death there are two main characteristics of a trauma which need to be identified: What kind of trauma is it (e.g. blunt force, sharp force, gunshot) and was it caused ante-, peri-, or postmortem? An additional question might be: Are there signs of burning on the remains?

Broadly speaking, blunt force causes plastic deformation while sharp force results in incised wounds[29] and gunshot manifests as entrance and exit wounds with beveling indicating the direction of the bullet [66]. However, Kroman [67] (cited in[66]) stated that bone trauma was too complex to fit into these simple categories and suggested a physics-based trauma continuum.

Easiest to distinguish concerning the timing of an injury is antemortem trauma because its appearance is through signs of healing (callus formation, periosteal reaction, rounding of fracture margins) [68]. Perimortem, better stated as “at or near time of death”, and postmortem are much more difficult to tell apart. Both do not show any macroscopic remodeling. Macroscopically, the distinction is mainly whether the broken surface and the remaining bone have the same taphonomy[30] (perimortem) or the broken surface has a lighter color than the remaining bone (postmortem) [69]. However, this difference can be impaired by alteration e.g. through sunlight. The term “perimortem” is in any case quite unsatisfying because the timing of the trauma in relation to the death of the individual can range within a time period of days or sometimes weeks before and after decease. This is crucial when trying to determine

[29] These might even show characteristics that lead to the type of sharp instrument.

[30] Taphonomy is defined by Efremov as “the science of the laws of embedding” which means the effects on the bone caused by environmental impacts (e.g. animal scavenging, burial, bone weathering etc.) before its discovery. (Efremov (1940): *Taphonomy, a new branch of paleontology.* Pan-American Geologist 74:81-93)

whether the person was a crime victim or not. A pilot study performed at LABANOF[31] [70] could show histological signs of hemorrhaging and new bone formation on recent dry bone. They used fractures with known antemortem time between 34 minutes and 26 days of which all except for the oldest one did not show any macroscopical signs of healing and would thus have been classified as “perimortem” by the classical method. According to the authors, further research and development of this method might not only allow to decide more reliably between ante- and postmortem fractures but also to estimate the survival time of the individual.

Beyond the classical approach, the work fields of a Forensic Anthropologist are expanding. Nowadays, they include, apart from the skeleton, aging juvenile perpetrators, identifying bank robbers from videosurveillance (via superimposition), establishing whether presumed victims of pedopornography are under age, facial reconstruction and so forth [71]. Furthermore, mass disasters such as 9/11 bring new challenges in dealing with the identification of remains that show severe fragmentation, burning, or commingling [72]. However, the work on human remains should always be shared by all forensic disciplines (e.g. Anthropology, Pathology, Entomology, Odontology) with their respective expertise in order to have the most comprehensive means for identification of the person and the circumstances of their death [71].

1.7 Aim

The purpose of this thesis is to give a comprehensive overview of the frontal bone and its characteristics. Specifically, the author explores population differences between German and Euro-American crania, including sexual dimorphism and secular change for each group respectively. Beyond that, she puts emphasis on metopism as a special feature of the frontal bone. How often do we find it in the different groups and their sexes? Is this trait correlated to size and shape of the bone and how? Can its presence be predicted using measurements?

[31] Laboratorio di Antropologia ed Odontologia Forense (LABANOF), Istituto di Medicina Legale, Università degli Studi di Milano

For all of the topics, size and shape are considered separately and combined in order to see the impact of each of them on the respective differences. Do they qualify separately for distinction between groups and/or sexes? Are there even differences for each criterion?

A central question of this work as a contribution to the field of forensic sciences is the applicability of its results on the identification of an unknown individual. As described in chapter 1.6, traits of use are those known antemortem. Hence, they can be population and/or sex specific for classifying the individual into a certain group, and therefore minimize the number of suspects, or specific for the very individual.

2 Materials and Methods

	Early 19th	Late 19th	Early 20th	Late 20th	Century unknown	
Female	17	28	102	7	2	156
Male	48	58	149	25	7	287
	65	86	251	32	9	443

Table 1a: Distribution of the German sample.

	Late 19th	Early 20th	Late 20th	
Female	9	117	38	164
Male	23	160	95	278
	32	277	133	442

Table 1b: Distribution of the Euro-American sample.

This thesis performs comparative analyses between two populations named "German" and "Euro-American". All crania belong to positively identified individuals with known birth and death years. The criteria for classification as "German" include individuals with full German heritage who have spent most of their live in Germany. Nevertheless, admixture with other European or Non-European populations cannot be excluded since the information have been gathered postmortem from museum and donation records (nineteenth and twentieth century), cemetery data (nineteenth and twentieth centuries), and forensic cases (twentieth century).

The "Euro-American" group includes US-American citizens with known European ancestry. There is relatively little structure within this population in general since former ethnicities have lost their major influence on mating behavior [73]. However, according to Price et al. [74], genetic analyses show three important subgroups, being people with predominantly northwest or southeast European ancestry, and Ashkenazi Jews. In the present dataset, northwest European descendants build the majority (known from surnames and ancestry information). With Germany also belonging to northwest Europe a noteworthy common ancestry is given. Even though Euro-Americans and Europeans have been separate populations for several generations, genetic differences should be small enough that the present Euro-American data can be a reliable source for comparison with the Germans in terms of identifying environmental factors that cause secular change.

The German sample contains skulls from modern forensic cases in Mainz and Freiburg, from cemetery excavations near Würzburg (Bavaria) and in Inden (North Rhine-Westphalia), and from the following collections: Berliner Gesellschaft für Anthropologie, Ethnologie und Urgeschichte (BGAEU); Anatomisches Institut der Charité Universitätsmedizin Berlin; the Smithsonian Institution, National Museum of Natural History, Washington DC; the Morton Collection, University of Pennsylvania; donated collections in Aachen and Tübingen (Germany); and the Helmer Collection, University of Dundee.

Euro-American cranial data has been obtained from the Terry and Todd anatomical collections (nineteenth century), forensic cases at the Forensic Anthropology Center of the University of Tennessee, and the University of Tennessee donated collection (twentieth century). All are identified individuals with known birth and death years.

Samples were broken into seven groups as follows (see tables 1a and 1b): German early and late nineteenth and early and late twentieth century, American late nineteenth and early and late twentieth century. The term “early” is used meaning the years 00 through 49 of a century, whereas “late” has been defined as the years 50 through 99 of a century. The distribution in different centuries follows the birth year of the respective individual.

All cranial data have been taken with a MicroScribe G2X digitizer. This instrument is built as a base containing the origin (0/0/0) of a three-dimensional coordinate system connected to an arm with three joints and a stylus on top. The arm can be moved around an almost 360° radius. Its mode of operation is to save the respective three-dimensional coordinates of given landmarks on the skull. The software 3skull® [75] takes one through the whole digitizing process and computes a certain amount of cranial measurements out of the coordinate distances.

The landmark definitions by Howells and Martin and Knußmann [76, 77] (see tables 2 and 3 for landmarks and measurements used in this study) follow three different types. At first, there is the intersection of two sutures, e.g. the coronal with the sagittal suture ("Bregma"). These are usually easiest to find but due to human variation additional small bones on the suture ("sutural bones") or fused sutures are often making their discovery more difficult. The second type is the point of greatest extension or deepest incurvature within a certain area. Many of these can be found morphologically. Measurements like "Maximum Cranial Breadth" need to be determined with calipers prior to digitizing in order to find and mark their endpoints as landmarks on both lateral sides of the cranium. Third, there is the largest distance from a given point. "Opisthocranion" as an example for this type is furthest apart from "Glabella"[32] in the mid-sagittal plane. The distance between these two is then used as "Maximum Cranial Length". Furthermore, there is an additional type called semilandmarks. These do not have point definitions but are defined as continuous points spread between two defined landmarks.

In this study, the frontal arc and eight additional landmarks (see table 2) were used for analysis. The frontal arc is the line of semilandmarks between bregma and nasion. The number of collected points varies between different digitizing sessions and different crania. In order to make the frontal arcs comparable and to have an overseeable amount of points, resample® was applied to select ten equally spaced semilandmarks from the frontal arc for each individual, no. 1 always being bregma and no. 10 always being nasion. After that, the coordinates of the additional landmarks (left and right respectively) were added to the dataset.

The coordinate data was then imported into MorphoJ®, which is a program that allows creation of shape data from raw coordinates and to perform various analyses with the shape data. Initially, Procrustes Superimposition was performed in order to

[32] "The most anteriorly projecting point in the mid-sagittal plane at the lower margin of the frontal bone, which lies above the nasal root and between the superciliary arches." 76. Martin, R. and R. Knussmann, *Handbuch der vergleichenden Biologie des Menschen*. 1988, Stuttgart: Gustav Fischer.

extract shape data from the raw coordinates. After that, outliers selected by the program were taken out of the analysis sample and landmarks that were accidentally recorded out of order in some crania were repaired. As the last step before performing actual analyses, a Covariance Matrix was generated.

Principal Component Analysis was used to analyze directions of shape variation. The computed Principal Components (PCs) along with Centroid Sizes were then exported for the respective comparison and imported into Fordisc®. Fordisc® was used to compute classification rates for the respective analysis. The Canonical Variates Analysis used by Fordisc® for classification was also performed with MorphoJ in order to generate illustrations of the respective shape variation.

This work frequently uses the Mahalanobis distance as a means of comparing groups with each other or individuals with groups. It is a measure of the distance between two centroids standardized by the within group covariance matrix and expresses dissimilarity by using all measurements simultaneously. Canonical variates are a way to show Mahalanobis distances in graphical form [78].

For metopism analyses the frequencies were computed as simple ratios between metopic and all crania of the respective group. A discriminant function between metopic and non-metopic crania was computed with MorphoJ® in order to perform shape comparison. Microsoft Excel® was used to illustrate the relation between measurements and metopism. The development of a regressions formula to assess metopism was also attempted through calculations in Microsoft Excel®.

Landmark	Landmark definition
Bregma	The posterior border of the frontal bone in the mid-sagittal plane. Normally this is the meeting point of the coronal and sagittal sutures, on the frontal bone. (Howells 1973: 167).
Dacryon	The apex of the lacrimal fossa, as it impinges on the frontal bone (Howells 1973: 167).
Frontomalare anterior	[…] the most anterior point on the fronto-malar suture. (Howells 1973: 177)
Glabella	The most anteriorly projecting point in the mid-sagittal plane at the lower margin of the frontal bone, which lies above the nasal root and between the superciliary arches. (Martin and Knussmann 1988: 161).
Metopion	Intersection of a line connecting the two frontal tubera with the mid-sagittal plane. (Martin and Knussmann 1988: 162)
Nasion	The point of intersection of the naso-frontal suture and the mid-sagittal plane. As a general rule nasion is on the frontal bone. (Howells 1973: 169, Martin and Knussmann 1988: 165).
Frontotemporale	A point located generally forward and inward on the superior temporal line directly above the zygomatic process of the frontal bone. The right and left frontotemporale form the endpoints of the minimum frontal breadth measurement. (Martin and Knussmann 1988: 164).
Maximum frontal point	Points of Maximum Frontal Breadth (XFB): The maximum breadth at the coronal suture, perpendicular to the median plane. (Howells 1973: 172)

Table 2: Landmark definitions.

Measurement	Measurement definition
DKB: Interorbital Breadth	The distance between right and left dacryon (Howells 1973: 178)
FMB: Bifrontal Breadth	The breadth across the frontal bone between frontomalare anterior on each side, e.g., the most anterior point on the fronto-malar suture. (Howells 1973: 177)
XFB: Maximum Frontal Breadth	The maximum breadth at the coronal suture, perpendicular to the median plane. (Howells 1973: 172)
WFB: Minimum Frontal Breadth	The distance between the right and left frontotemporale (Hrdlicka 1920: 15; Martin and Knussmann 1988: 170, #9).
GLS: Glabella Subtense	The maximum projection of the midline profile between nasion and supraglabellare (Howells 1973:181).
STB: Bistephanic Breadth	Breadth between the intersections, on either side, of the coronal suture and the inferior temporal line marking the origin of the temporal muscle (Howells 1973:173).
FRC: Frontal Chord	The distance from nasion (n) to bregma (b) taken in the mid-sagittal plane (Figure 3.9, No. 20) (Howells 1973:181; Martin and Knussmann 1988: 174, #29).
FRS: Frontal Subtense	The maximum subtense, at the highest point on the convexity of the frontal bone in the midplane, to the nasion bregma chord (Howells 1973:181).
FRF: Frontal Fraction	The distance along the nasion-bregma chord, recorded from nasion, at which the nasion-bregma, or frontal, subtense falls (Howells 1973:181).

Table 3: Measurement definitions.

3 Results

3.1 Ancestry comparison between early 20th century Euro-Americans and Germans

3.1.1 Size and shape

For these analyses the early 20th century has been chosen because its data set is the largest in this work for both populations respectively. Fordisc®'s Forward Wilks stepwise analysis[33] has chosen 20 out of 29 variables composed from all principal components and Centroid Size. Figure 5 shows the classification table and the canonical structure coefficients for this population-sex-analysis between German and Euro-American males and females.

Classification Table

From Group	Total Number	Into Group (counts) AF	AM	GF	GM	Correct
AF	114	79	13	20	2	69.3 %
AM	149	16	120	1	12	80.5 %
GF	98	21	6	63	8	64.3 %
GM	136	7	17	18	94	69.1 %

Total Correct: 356 out of 497 (71.6 %) *** CROSS-VALIDATED ***[34]

[33] Stepwise analysis is a way to improve classification as it finds the most discriminating combination of variables for the current analysis by computing the best single discriminator or best discriminating combination of a certain number of variables (depending on the minimum number of variables set by the user) and then step by step adding the respective measurement out of the remaining ones that improves Wilks criterion the most (forward Wilks is the current default). This procedure continues until improvement in Wilks fails to meet the criterion established. The author used the default criterion, which is 0,002.

[34] Discriminant analysis investigates whether the data can be sorted reliably into different groups defined by distinct variables (e.g. sex, ancestry). Classification rates then get tested using leave-one-out cross-validation which means that each object is excluded from its respective group while being classified. This assures that classification rates are not biased. For example, object 1 has a measure x=7.5cm and a measure y=8.3cm. The means for group 1 are x=7cm, y=8cm and for group 2 x=8cm, y=8cm. Taking out object 1 from its group 1, the program is neutral and can classify the object in either group, depending on where it finds the best fit. If object 1 was still in group 1 it would be part of the group's mean and the program would have a higher tendency of classifying it there, which would create a false high classification rate.

```
Canonical Structure Coefficients

                          Can 1     Can 2     Can 3
 Log_Centroid_Size       0.6804   -0.2784   -0.0029
               PC3       0.3411   -0.1624   -0.1606
               PC2       0.3204   -0.5192    0.1627
               PC5      -0.1767   -0.3960   -0.1572
               PC1       0.1209    0.3940    0.4185
              PC11       0.3297    0.2068   -0.4207
              PC14      -0.1752   -0.2104    0.2085
               PC6       0.2939    0.0112    0.0556
              PC16       0.2214    0.1945    0.1728
              PC15       0.1633    0.2309   -0.3043
               PC8       0.3459   -0.0651    0.1476
               PC9       0.1312    0.1829    0.0477
              PC10       0.0846   -0.1947    0.0688
               PC4       0.1269   -0.2136    0.2301
              PC12      -0.1881    0.1497   -0.3185
               PC7      -0.1114    0.1880    0.1633
              PC13      -0.1144   -0.0989   -0.3492
              PC18       0.1573   -0.0505   -0.0394
              PC24      -0.0174   -0.1475   -0.1459
              PC28       0.0151    0.0159   -0.1666
```

Figure 5: Fordisc output for population-sex-discrimination including size and shape (A: Euro-American, G: German, F: female, M: male).

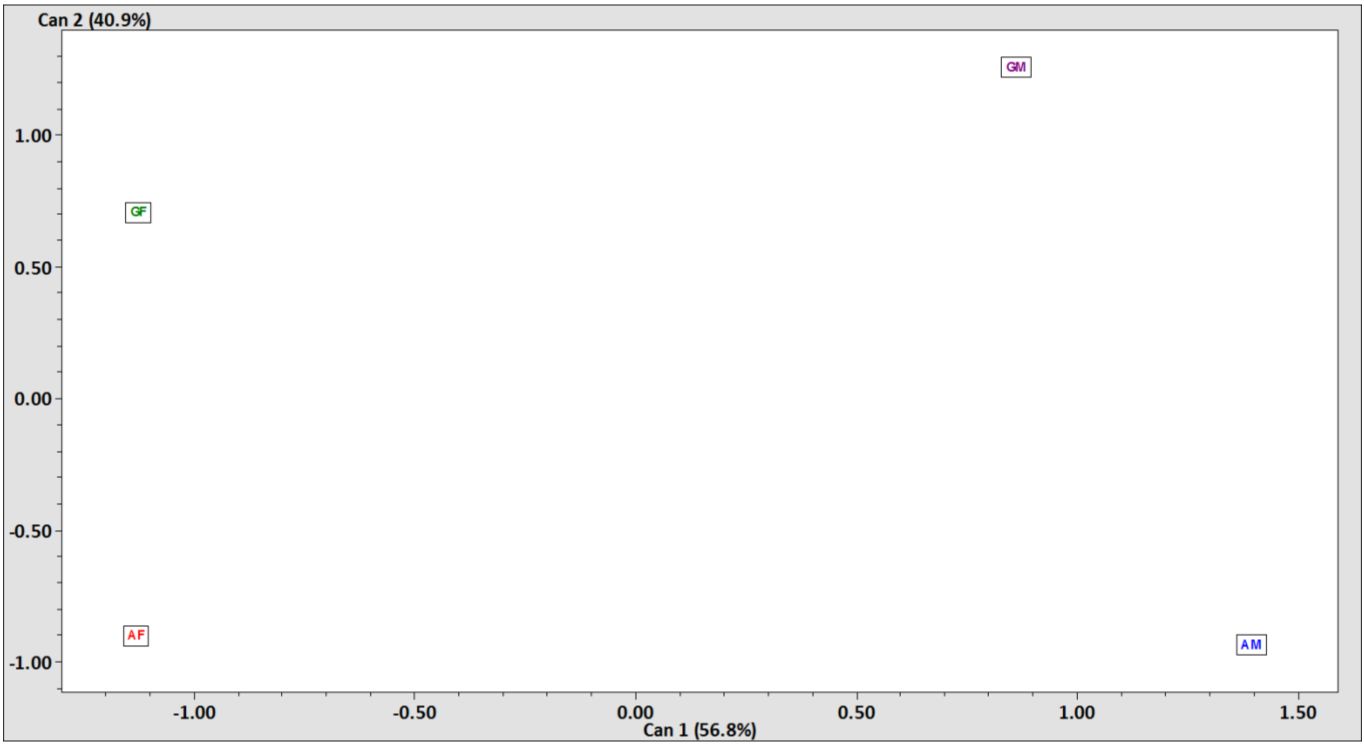


Figure 6: Fordisc graph for the analysis of figure 5.

The Fordisc graph (see figure 6) illustrates the Canonical Variates Analysis by showing Canonical Variate (Can) 1 and 2 which account together for 97.7% of the total variation. Since Can3 accounts for a very small amount of variation in all analyses, it can be disregarded in this study. As can be seen, Germans and Euro-Americans are separated on the y-axis (Can2) while there is a differentiation between males and females on the x-axis (Can1). Most importantly, Centroid Size (and hence size in general) is included in the analysis (see figure 5) and, regarding the Canonical Structure Coefficients, does even have the highest impact[35] on sex discrimination (Can1). PC2 is the most sensitive factor for distinguishing ancestry (Can2). With 71,6% shape and size combined have the highest overall discrimination rate of all analyses (shape: 65.2%, size: 43.7%).

3.1.2 Shape

Classification Table

From Group	Total Number	AF	AM	GF	GM	Correct
		Into Group (counts)				
AF	114	74	17	21	2	64.9 %
AM	149	23	109	3	14	73.2 %
GF	98	23	6	50	19	51.0 %
GM	136	7	14	24	91	66.9 %

Total Correct: 324 out of 497 (65.2 %) *** CROSS-VALIDATED ***

Mahalanobis Distance matrix

	AF	AM	GF	GM
AF	0.00	4.49	2.89	7.44
AM	4.49	0.00	6.78	5.27
GF	2.89	6.78	0.00	3.01
GM	7.44	5.27	3.01	0.00

Significance of Mahalanobis Distances

[35] Identifiable through the highest absolute value.

	AF	AM	GF	GM
AF	--	<0.001	<0.001	<0.001
AM	<0.001	--	<0.001	<0.001
GF	<0.001	<0.001	--	<0.001
GM	<0.001	<0.001	<0.001	--

Figure 7: Fordisc output for stepwise analysis of principal components[36] (A: Euro-American, G: German, F: female, M: male).

In the Forward Wilks stepwise analysis Fordisc has chosen 20 out of 28 principal components that discriminate best between the groups chosen. The overall correct classification is 65.2% (see figure 7).

The Mahalanobis Distance matrix of this Canonical Variates Analysis along with its significance table (see figure 7) shows that there are significant differences between all of the groups. The highest distance is found between German males and Euro-American females, followed by German females with Euro-American males, then (in decreasing order) both male groups, both Euro-American groups, both German groups, and both female groups.

[36] For definition see chapter *1.2.*

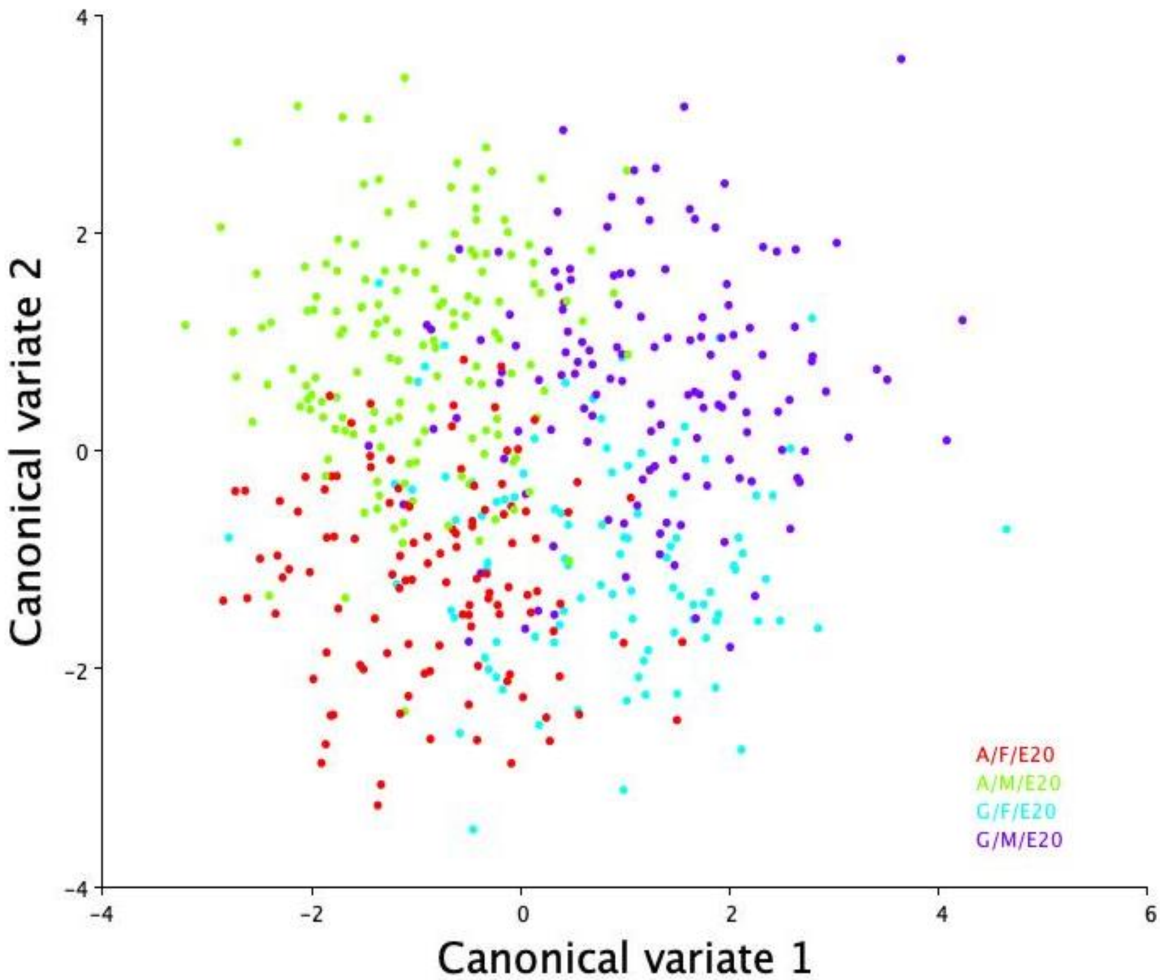


Figure 8: MorphoJ graph of Canonical Variates Analysis.

For illustration of the group variation Canonical Variates Analysis has been performed with MorphoJ as well. Figure 8 illustrates the distribution of the groups between Can1 and 2. The ancestries are separated on Can1 and the sexes on Can2. This is the opposite to figure 6 where Can1 separates the sexes and Can2 the populations, illustrating that without size Euro-American/German shape difference becomes the most important axis of variation. Wireframe graphs of Can1 are displayed below (see fig. 9 and 10) to illustrate population differences in detail. The corresponding landmarks to the numbers in the figures are given in table 4.

No.	Landmark	No.	Landmark
1-10	Drag Bregma-Nasion	**15**	Frontotemporale left
11	Dacryon left	**16**	Frontotemporale right
12	Dacryon right	**17**	Maximum frontal point left
13	Frontomalare anterior left	**18**	Maximum frontal point right
14	Frontomalare anterior right		

Table 4: List of landmarks corresponding to numbers used in MorphoJ (table with landmark definitions in Materials and Methods).

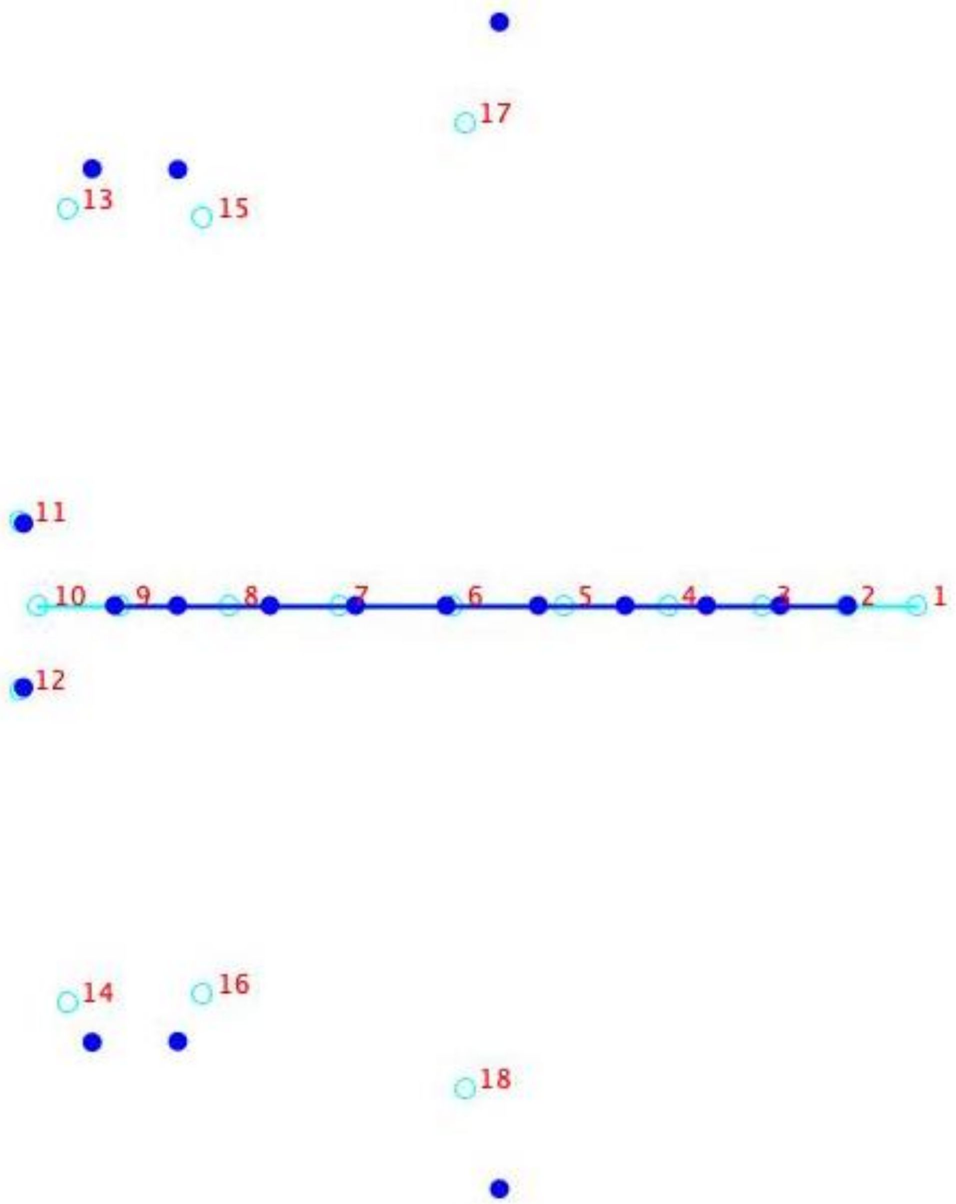


Figure 9: Canonical Variate 1 top view.

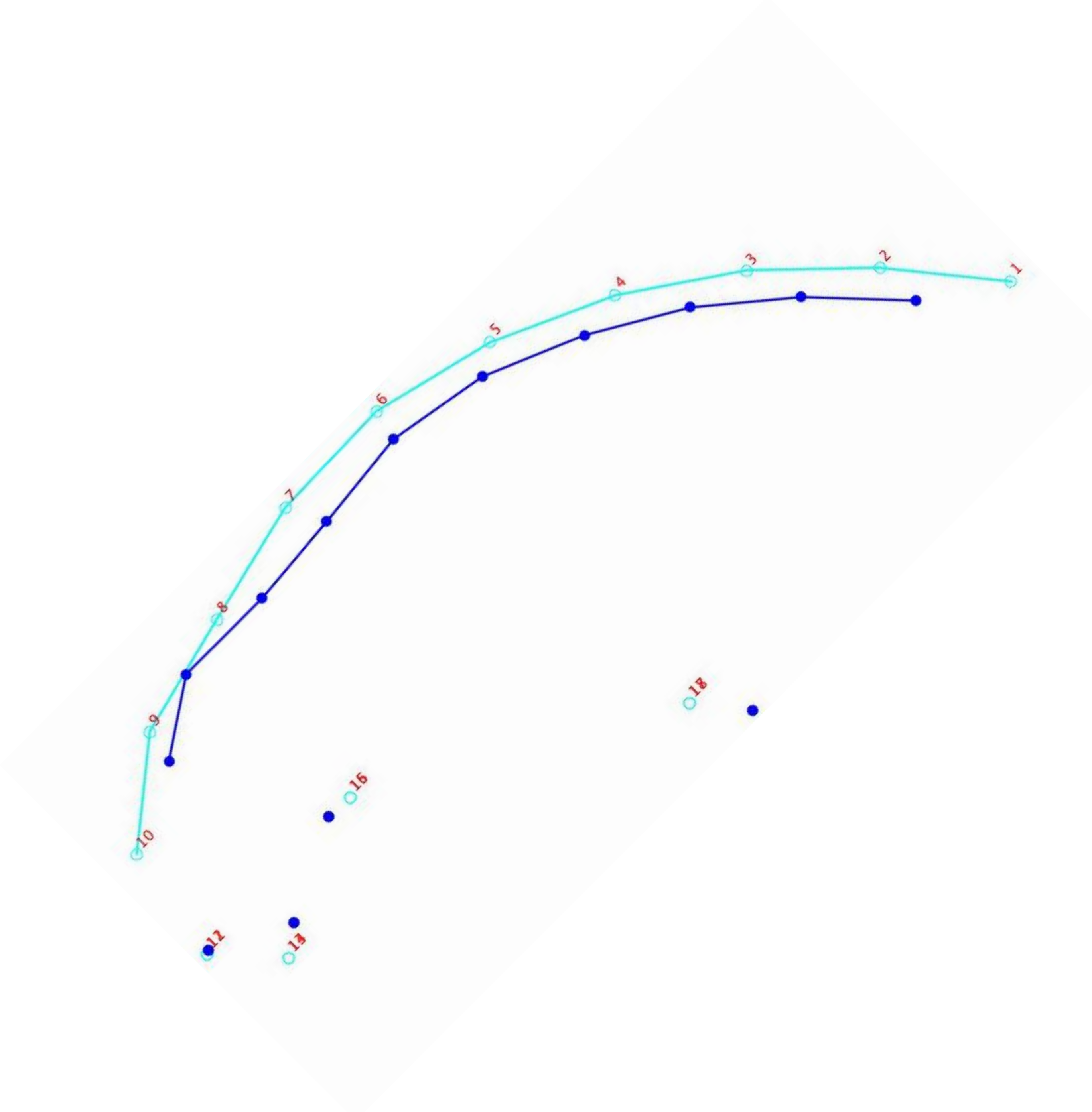


Figure 10: Canonical Variate 1 lateral view.

The wireframe graphs in figures 9 and 10 are designed to show the extent of shape variation in the respective analysis. So, in this case we can assume that we see the respective “extreme” Euro-American and German shape. Given what we already know about Euro-American and German cranial shapes (e.g. [79]), we can assume that the dark blue curve illustrates the German population and the light blue one the Euro-American population.

On the top view it can be seen that the dark blue (db) frontal arc is overall shorter than the light blue (lb) one with its single points being closer together. Interestingly, dacryon is almost in the same spot for both colors, showing a greater distance to nasion for db than for lb. Db not only is shorter but also broader than lb with all lateral landmarks being shifted more laterally.

The lateral view provides a better perspective to see the relation between dacryon and nasion, because dacryon is actually inferoposterior to nasion, not anterior. It also adds to the exact position of the lateral landmarks. Furthermore, glabella can be seen really well for both curves. It seems to be a little more pronounced for db than for lb.

3.1.3 Size

DFA results using 1 measurement:
Log_Centroid_Size

Classification Table

From Group	Total Number	Into Group (counts) AF	AM	GF	GM	Correct
AF	114	21	17	46	30	18.4 %
AM	149	10	98	13	28	65.8 %
GF	98	20	9	57	12	58.2 %
GM	136	23	44	28	41	30.1 %

Total Correct: 217 out of 497 (43.7 %) *** CROSS-VALIDATED ***

Mahalanobis Distance matrix

	AF	AM	GF	GM
AF	0.00	1.82	0.14	0.32
AM	1.82	0.00	2.99	0.62
GF	0.14	2.99	0.00	0.89
GM	0.32	0.62	0.89	0.00

Significance of Mahalanobis Distances

	AF	AM	GF	GM
AF	--	<0.001	0.006	<0.001
AM	<0.001	--	<0.001	<0.001
GF	0.006	<0.001	--	<0.001
GM	<0.001	<0.001	<0.001	--

Figure 11: Fordisc output for the discrimination between Germans and Euro-Americans of both sexes using only Centroid Size.

Regarding size only, classification rates are very low (see figure 11), especially for German males and Euro-American females. These two have the second lowest Mahalanobis distance after German and Euro-American females. While Mahalanobis distances are still significant, they are even lower than for the shape comparison. The highest ones are for Euro-American males with their females and for Euro-American males with German females. Remarkably, German males only have a Mahalanobis distance of 0.89 with their females. It is furthermore noteworthy that the rankings of Mahalanobis distances are different between size and shape analyses, except for German and Euro-American females which have the smallest distance in both cases.

3.1.4 Comparison with Fordisc Analysis of Regular Frontal Measurements

```
DFA results using 9 measurements:
 DKB   FMB   FRC   FRF   FRS   GLS   STB   WFB   XFB
 -------------------------------------------------

Classification Table

------------------------------------------------------------
 From     Total            Into Group (counts)
 Group    Number  AFE20  AME20  GFE20  GME20    Correct
 ------------------------------------------------------------
  AFE20    106      56     12     30      8     52.8 %
  AME20    144      16     94     10     24     65.3 %
  GFE20     94      32      9     40     13     42.6 %
  GME20    127      10     21     27     69     54.3 %
 ------------------------------------------------------------
 Total Correct:  259 out of 471 (55.0 %) *** CROSS-VALIDATED ***
 ------------------------------------------------------
```

Figure 12: Fordisc output for discrimination between Germans and Euro-Americans using standard measurements of the frontal bone[37].

In order to evaluate the value of shape analysis, an additional Fordisc® analysis has been performed (see figure 12) using the standard measurements that can be found on the frontal, namely DKB, FMB, FRC, FRF, FRS, GLS, STB, WFB, and XFB (see Materials and Methods for definitions). The overall classification rate for this analysis was 55.0%, which is less than for shape-size combined (71.6%) and shape only (65.2%) analyses and a little more than Centroid Size only (43.7%). Even though classical measurements do include size and shape, there is a lot more shape information in the principal components as they represent the shape of the whole landmark configuration.

[37] The number of individuals is lower for this analysis, because the measurement files could not be recovered for all crania and the data for all other analyses has been taken from coordinate files.

3.2 Sexual Dimorphism

3.2.1 German sexual dimorphism

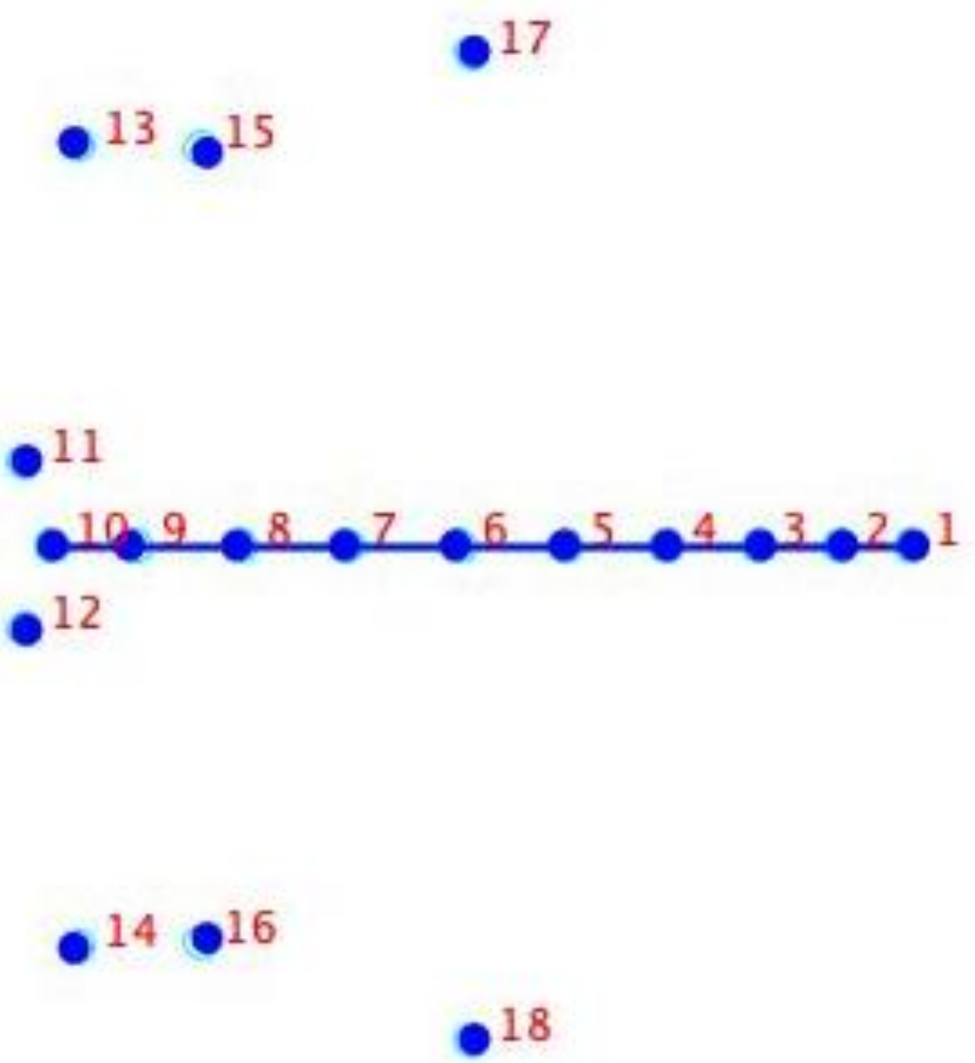
3.2.1.1 Size and shape

```
 --------------------------------------------------------------------
Classification Matrix

 --------------------------------------------------------------------
     From          Group          Into Group (counts)       Percent
     Group         Counts            GF           GM        Correct
 --------------------------------------------------------------------
        GF           98              85           13         86.7 %

        GM          136              24          112         82.4 %
 --------------------------------------------------------------------
     Total Correct:       197 / 234 ( 84.2 %) *** CROSS-VALIDATED ***

Discriminant Structure Coefficients
 Log_Centroid_Size  -0.5898
               PC3  -0.3247
               PC5   0.2156
              PC14   0.2755
               PC6  -0.2575
              PC11  -0.4634
               PC8  -0.2540
               PC1  -0.0733
              PC15  -0.2947
              PC16  -0.2000
              PC18  -0.1319
              PC24   0.0012
               PC9  -0.1504
```

Figure 13: Fordisc® output for size-shape analysis of German sexual dimorphism.

Sex analyses have also been performed with early 20th century data. For this stepwise analysis, Fordisc® has chosen 13 out of 29 measurements (see figure 13). Log_Centroid_Size is included and does again have the highest impact on discrimination (see Discriminant Structure Coefficients) as it had for the size-shape sex discrimination in the population comparison. Size and shape combined does again have the highest classification rate (84.2%), followed by shape (76.5%), and then size (70.1%). Classification rates are overall notably higher than for ancestry.

3.2.1.2 Shape



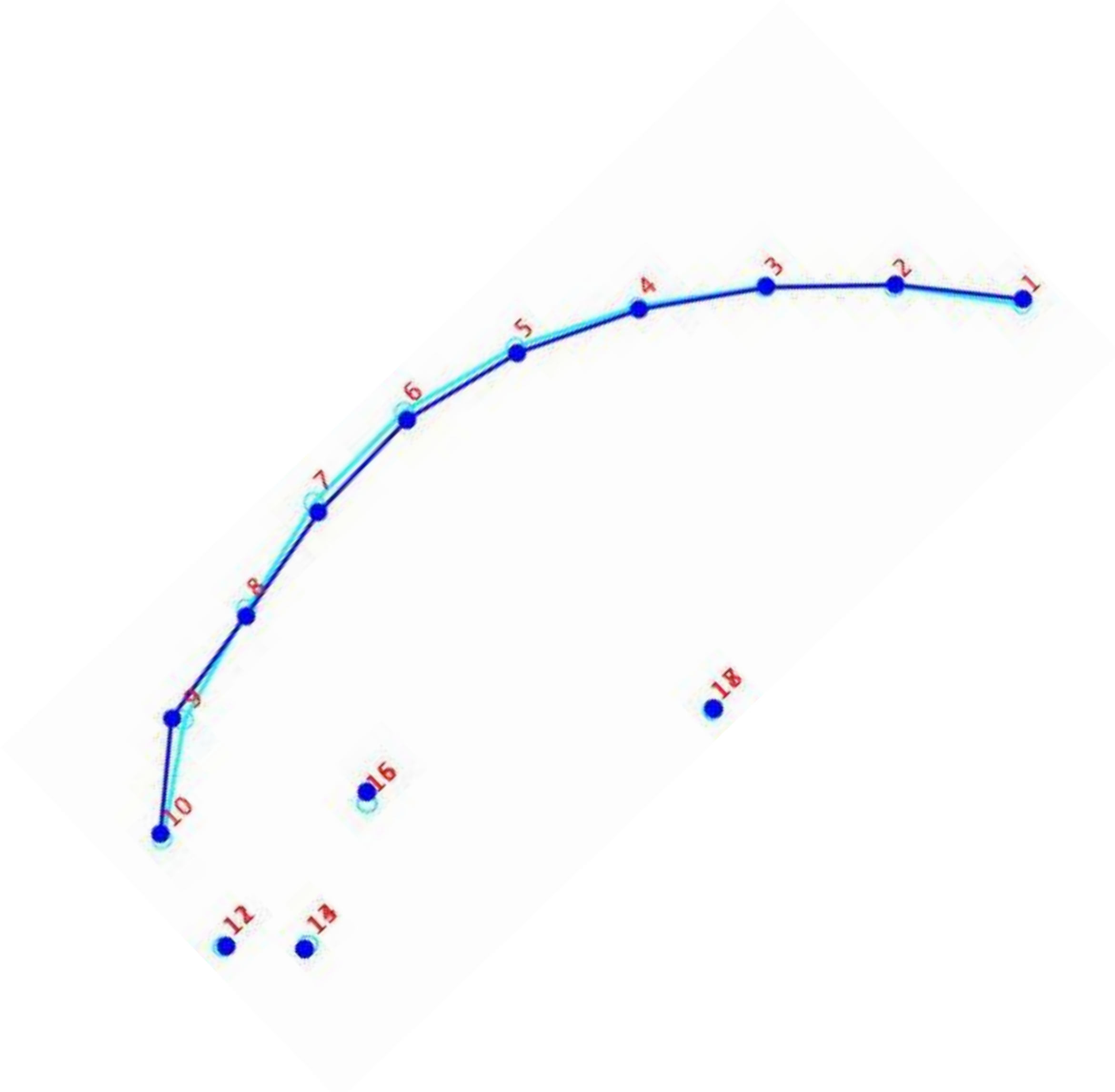


Figure 14: MorphoJ wireframe graph for German sex comparison, top view and lateral view (light blue: female, dark blue: male).

Classification Matrix

From Group	Group Counts	Into Group (counts) GF	GM	Percent Correct
GF	98	74	24	75.5 %
GM	136	31	105	77.2 %
Total Correct:	179 / 234 (76.5 %) *** CROSS-VALIDATED ***			

Figure 15: Fordisc output for stepwise discriminant function analysis of principal components of the German dataset.

For the German principal components Fordisc® is able to reach an overall correct sex classification of 76.5% (see figure 15). 20 out of 28 variables have been chosen in the stepwise analysis. The wireframe graphs (see fig. 14) have been gained by performing a discriminant function analysis in MorphoJ®. Looking at these, the shape of German male and female frontals seems very similar. The descriptions "sloping" and "vertical" for the male and female frontal respectively can only slightly be seen and their applicability seems debatable looking at these results. Nevertheless, these differences might be more apparent when size is included. Glabella and frontotemporale are the only spots showing a clear difference shape-wise.

3.2.1.3 Size

Classification Matrix

From Group	Group Counts	Into Group (counts) GF	GM	Percent Correct
GF	98	71	27	72.4 %
GM	136	43	93	68.4 %
Total Correct:	164 / 234 (70.1 %) *** CROSS-VALIDATED ***			

Figure 16: Fordisc® output for German sex discrimination using only Centroid Size as a discriminator.

The classification rate for size only is the lowest in this analysis, but with 70.1% (see fig. 16) still comparatively high. This again shows that size is quite influential for sexual dimorphism.

3.2.2 Euro-American sexual dimorphism

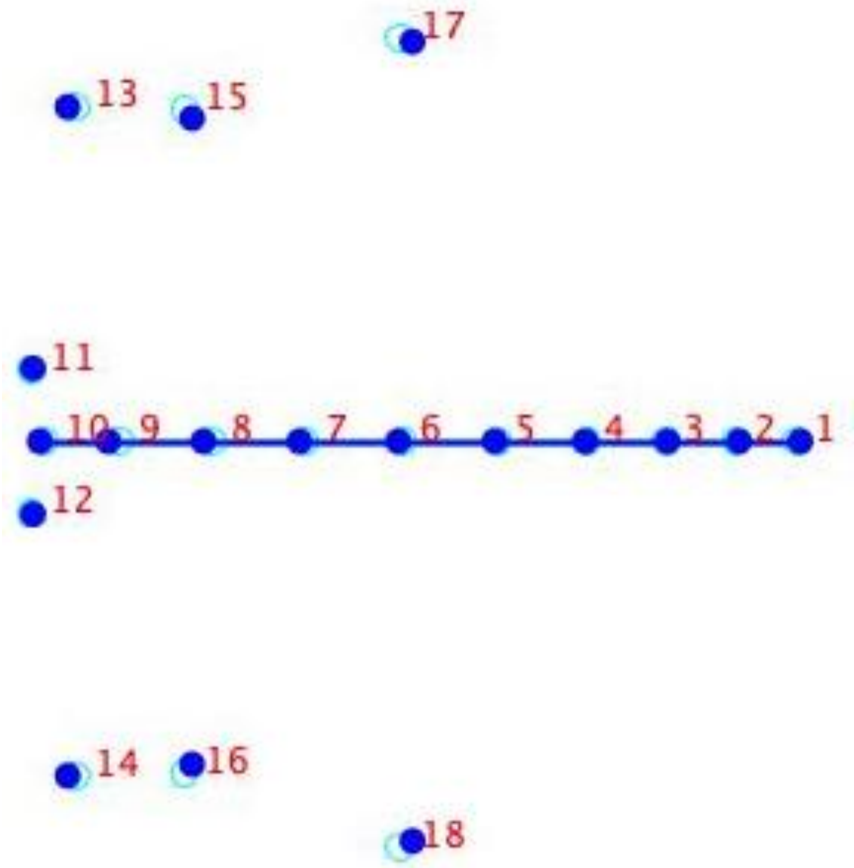
3.2.2.1 Size and shape

```
-------------------------------------------------------------------
Classification Matrix

 ------------------------------------------------------------------
     From          Group         Into Group (counts)      Percent
     Group         Counts          AF          AM         Correct
 ------------------------------------------------------------------
        AF          114            97          17          85.1 %

        AM          149            19         130          87.2 %
 ------------------------------------------------------------------
     Total Correct:       227 / 263 ( 86.3 %) *** CROSS-VALIDATED ***

Discriminant Structure Coefficients
 Log_Centroid_Size   -0.6975
              PC3   -0.3172
              PC6   -0.3090
             PC16   -0.2710
              PC1   -0.2346
              PC5    0.2343
              PC8   -0.3840
             PC14    0.1383
              PC9   -0.1495
             PC11   -0.2638
             PC26    0.0635
             PC22   -0.1237
              PC7    0.0816
              PC2   -0.4072
             PC10   -0.1088
             PC12    0.3104
             PC15   -0.1028
             PC18   -0.1657
```

Figure 17: Fordisc® output for size-shape analysis of Euro-American sexual dimorphism.

Again, early 20th century data has been used for analysis. Stepwise analysis chose 20 out of 29 variables and achieved a correct classification rate of 86.3% (see figure 17) with Log_Centroid_Size again having the highest impact on classification. Size-shape-analysis does again have the highest classification rate, followed by shape (82.9%), and then size (73.8%). Sex classification rates for Euro-Americans are higher than for Germans.

3.2.2.2 Shape



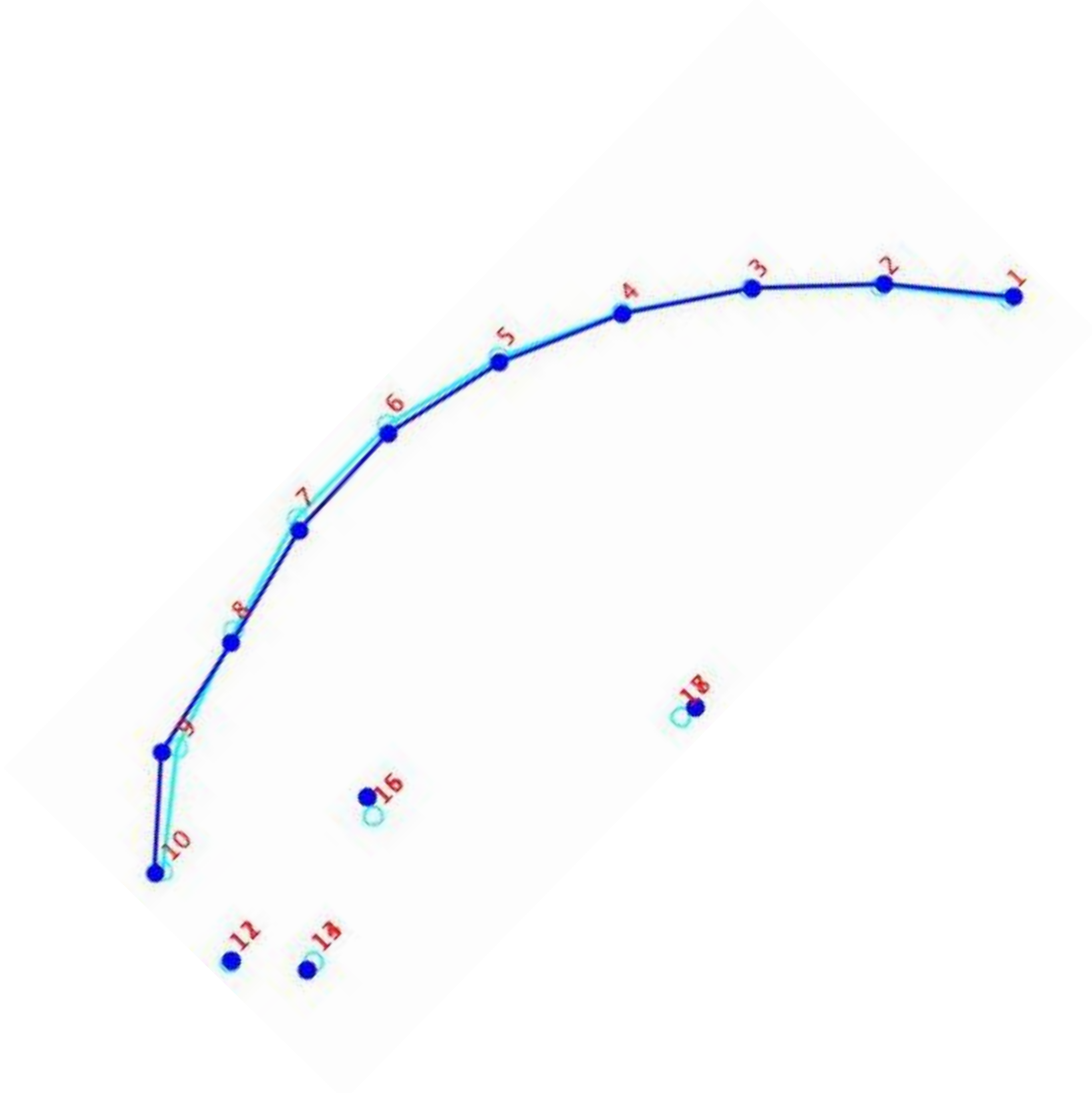


Figure 18: MorphoJ wireframe graph for American sex comparison (light blue: female, dark blue: male).

Classification Matrix

From Group	Group Counts	Into Group (counts) AF	AM	Percent Correct
AF	114	97	17	85.1 %
AM	149	28	121	81.2 %

Total Correct: 218 / 263 (82.9 %) *** CROSS-VALIDATED ***

Figure 19: Fordisc output for stepwise analysis of principal components of the Euro-American dataset.

In this stepwise analysis 20 out of 28 variables have been chosen. The overall classification rate for Euro-American sexual dimorphism was 82.9% (see figure 19). Looking at the wireframe graphs (see figure 18), it can be seen that the arcs are very much aligned. Clear differences can only be seen in the frontal half with females having a slightly rounder shape and less glabella projection. The side view is in this regard very similar to the German sexual dimorphism one. Further differences can be seen at Frontomalare anterior (13/14), Frontotemporale (15/16), and Maximum frontal point (17/18). Frontomalare anterior is more posterosuperiorly projected in females, Frontotemporale more anteroinferiorly, and Maximum frontal point more anteriorly. As Maximum frontal point is a type II landmark, its position can vary a lot more between individuals, and hence also individuals of the same sex, than the position of the other two. The apparent difference is thus presumably not a very reliable indicator of sexual variation.

3.2.2.3 Size

Classification Matrix

From Group	Group Counts	Into Group (counts) AF	AM	Percent Correct
AF	114	84	30	73.7 %
AM	149	39	110	73.8 %
Total Correct:		194 / 263 (73.8 %)		*** CROSS-VALIDATED ***

Figure 20: Fordisc® output for Euro-American sex discrimination using only Centroid Size as a discriminator.

Similar to the German analysis, size only has the lowest classification rate (73.8%; see fig. 20) for Euro-American sexual dimorphism. Using only one variable (Log_Centroid_Size), this classification rate is still quite high.

3.3 Secular change

3.3.1 Size and Shape

Classification Matrix

From Group	Group Counts	Into Group (counts) FE20	FL19	Percent Correct
FE20	98	69	29	70.4 %
FL19	23	8	15	65.2 %
Total Correct:		84 / 121 (69.4 %)		*** CROSS-VALIDATED ***

Classification Matrix

From Group	Group Counts	Into Group (counts) ME20	ML19	Percent Correct
ME20	136	110	26	80.9 %
ML19	53	16	37	69.8 %
Total Correct:		147 / 189 (77.8 %)		*** CROSS-VALIDATED ***

Canonical Structure Coefficients

	Can 1	Can 2	Can 3
Log_Centroid_Size	-0.5576	0.4557	-0.0320
PC3	-0.1523	0.1477	-0.4557
PC2	0.0514	-0.5948	-0.1791
PC1	0.1796	0.3491	-0.1692
PC11	0.4337	0.0684	0.1455
PC6	0.2104	0.2274	0.2677
PC5	-0.1218	0.0997	-0.3354
PC8	-0.3266	-0.0095	0.1642
PC14	-0.3636	0.0557	0.2140
PC15	-0.3141	0.1962	0.0355
PC18	-0.0758	0.3406	0.0934
PC16	-0.2641	-0.1449	0.1330
PC13	-0.0797	-0.1328	-0.1421
PC17	0.1436	0.2028	0.0870
PC20	-0.0172	-0.1266	-0.4768
PC12	-0.0183	-0.2392	0.1484
PC23	-0.0453	-0.2018	0.1305
PC7	-0.2046	-0.0240	-0.1125
PC9	0.0712	-0.0991	0.2846
PC4	0.1732	0.0658	-0.0808

Mahalanobis Distance matrix

	FE20	FL19	ME20	ML19
FE20	0.00	2.80	4.29	4.76
FL19	2.80	0.00	9.37	6.19
ME20	4.29	9.37	0.00	2.72
ML19	4.76	6.19	2.72	0.00

Significance of Mahalanobis Distances

	FE20	FL19	ME20	ML19
FE20	--	0.006	<0.001	<0.001
FL19	0.006	--	<0.001	<0.001
ME20	<0.001	<0.001	--	<0.001
ML19	<0.001	<0.001	<0.001	--

Figure 21a: Fordisc output for German secular change in size and shape.

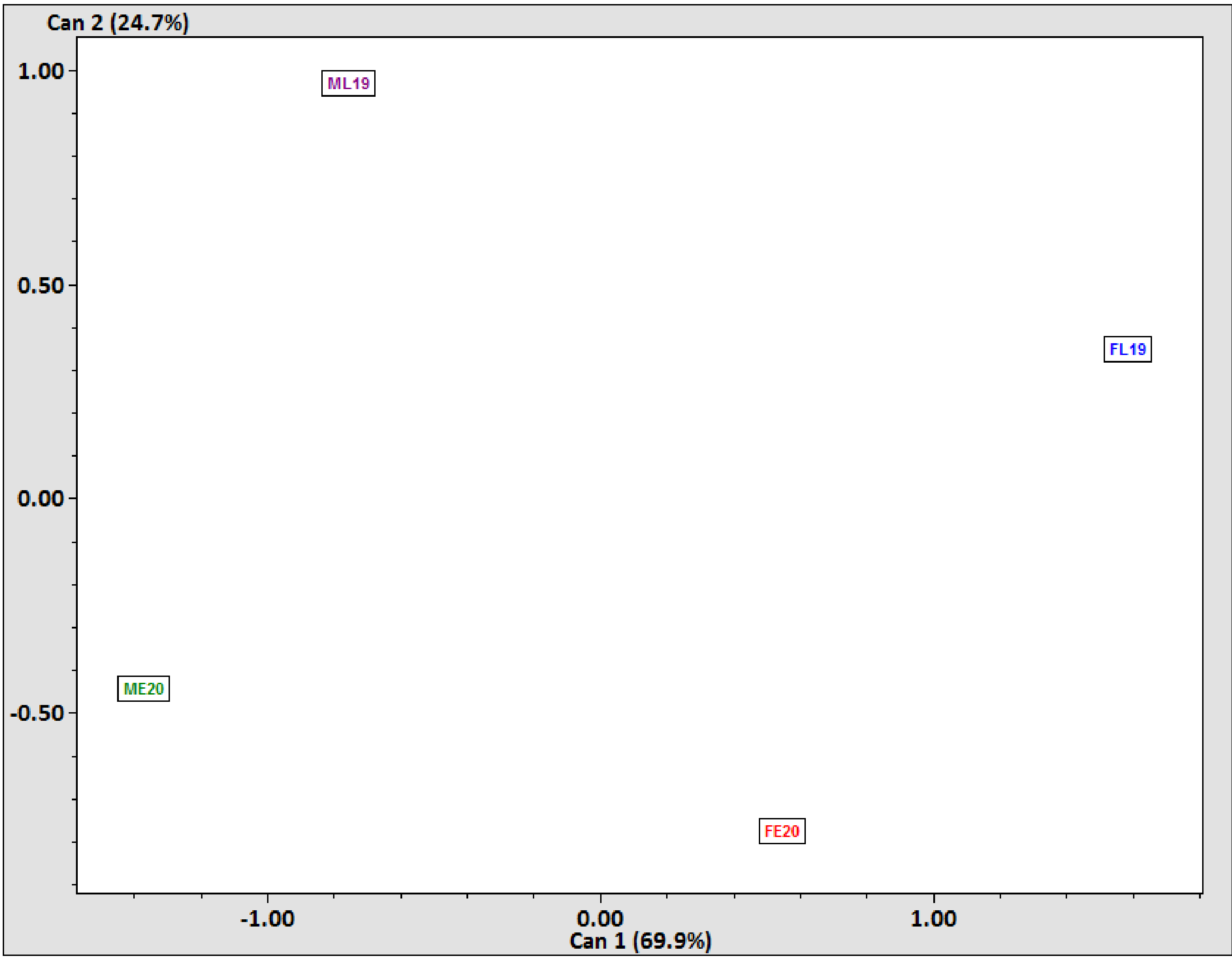


Figure 21b: Fordisc graph for German secular change in size and shape.

Again, the combination of size and shape results in higher Mahalanobis distances and therefore higher discrimination rates. For the Germans, males and females show almost the same amount of secular change with Mahalanobis distances of 2.72 and 2.80 respectively between late 19th and early 20th century (see figure 21a). The best discriminator on can1, so between the sexes (see figure 21b), is Log_Centroid_Size while the centuries are separated to a major extent by PC2 (can2). The time periods can be separated with classification rates of 69.4% for females and 77.8% for males. The better classification rate for males is probably due to their higher sample size, given that the Mahalanobis distances are almost equal. Furthermore, the classification rates for males are more unbalanced (69 and 80%) than for the females (65 and 70%). This might be because the 19th century males are more variable, which would lead to more misclassifications.

Classification Matrix

From Group	Group Counts	Into Group (counts) FE20	FL20	Percent Correct
FE20	114	80	34	70.2 %
FL20	34	16	18	52.9 %

Total Correct: 98 / 148 (66.2 %) *** CROSS-VALIDATED ***

Classification Matrix

From Group	Group Counts	Into Group (counts) ME20	ML20	Percent Correct
ME20	149	98	51	65.8 %
ML20	93	35	58	62.4 %

Total Correct: 156 / 242 (64.5 %) *** CROSS-VALIDATED ***

Canonical Structure Coefficients

	Can 1	Can 2	Can 3
Log_Centroid_Size	-0.7062	-0.0618	-0.1085
PC3	-0.3906	0.0908	-0.1950
PC16	-0.2196	-0.6429	0.0044
PC6	-0.3018	0.1001	-0.3509
PC8	0.4531	-0.2781	-0.2587
PC1	0.3279	0.0930	0.0958
PC11	-0.1970	-0.1472	0.0776
PC13	0.3145	-0.1045	0.1043
PC5	0.0972	0.1417	-0.5253
PC10	-0.1128	0.1643	0.3934
PC12	0.1262	0.0255	-0.3626
PC17	0.1242	-0.1821	0.0432
PC23	-0.0410	-0.2795	-0.0201
PC4	0.1630	0.2504	0.0601
PC7	-0.0742	-0.2508	0.0437
PC9	0.1412	0.2903	0.0986
PC15	-0.0513	0.0243	0.2534
PC19	0.0434	-0.2478	0.1500
PC2	0.0911	-0.0826	0.1062
PC28	0.0164	-0.0854	0.1348

Mahalanobis Distance matrix

	FE20	FL20	ME20	ML20
FE20	0.00	1.18	6.54	5.73
FL20	1.18	0.00	7.86	6.60
ME20	6.54	7.86	0.00	1.02
ML20	5.73	6.60	1.02	0.00

Significance of Mahalanobis Distances

	FE20	FL20	ME20	ML20
FE20	--	0.161	<0.001	<0.001
FL20	0.161	--	<0.001	<0.001
ME20	<0.001	<0.001	--	<0.001
ML20	<0.001	<0.001	<0.001	--

Figure 22a: Fordisc output for American secular change in size and shape.

Because of the small sample size for late 19th and a comparatively larger one for late 20th century, the early and late 20th centuries had to be chosen for this analysis. Unfortunately, with the small German late 20th century sample, this makes the two groups not comparable for this analysis. The American group has an overall small level of secular change within the 20th century (see figure 22a). The female change is not even significant in the four-group-analysis. Log_Centroid_Size is again the best discriminator for the sexes. PC16 is the most important variable for distinguishing the centuries. The different time periods of the sexes can be distinguished with an accuracy of 66.2% for females and 64.5% for males. The lower classification rates compared to the Germans fit well with the higher Mahalanobis distances in the German group.

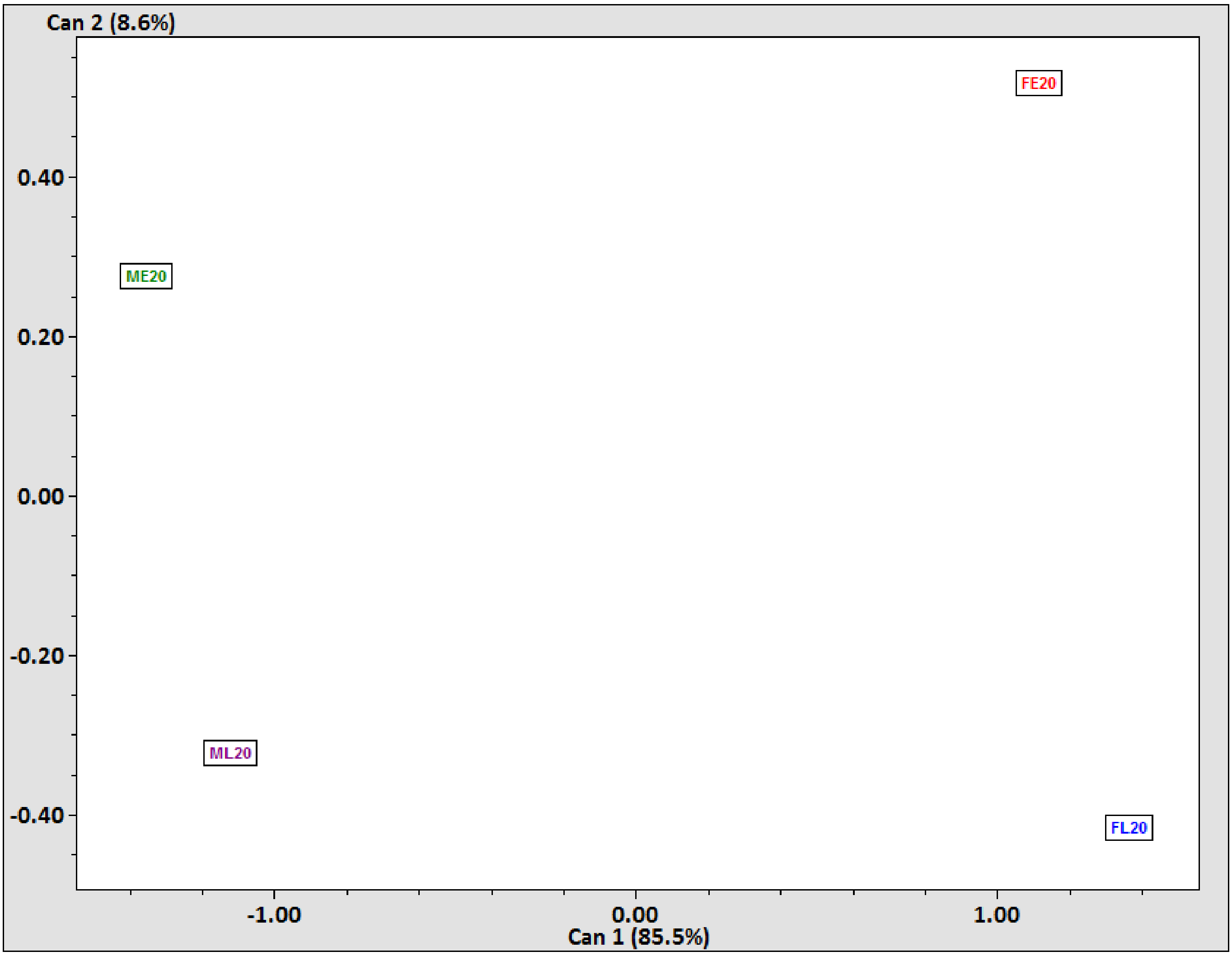


Figure 22b: Fordisc graph for American secular change in size and shape.

3.3.2 Shape

Discriminant Function Analyses have been performed with MorphoJ to calculate Mahalanobis distances between groups of different time periods. Tables 5a and b show that there is very little significant secular change in the shape of the frontal bone for both sexes from both populations respectively. The lack of significance for the non-significant groups is most likely due to small sample size and lack of change while their respective extent remains unknown.

Century	Sex	Mahalanobis distance	P-value
E19-L19	F	4.0540	0.2563
	M	1.3626	0.3423
L19-E20	F	**1.9144**	**0.0129**
	M	**1.8093**	**<.0001**
E20-L20	F	**3.4834**	**0.0232**
	M	**1.9866**	**0.0009**
E19-L20	F	6.4701	0.8455
	M	**2.5630**	**0.0220**

Table 5a: German secular change (significant changes in bold type).

Century	Sex	Mahalanobis distance	P-value
L19-E20	F	**2.6660**	**0.0400**
	M	**2.5211**	**<.0001**
E20-L20	F	1.4036	0.0693
	M	**1.0445**	**0.0036**
L19-L20	F	**5.5612**	**0.0277**
	M	**3.2073**	**<.0001**

Table 5b: American secular change (significant changes in bold type).

The German sample shows significant change between different time periods. Since both sexes are significant for L19-E20 and have the highest sample sizes there, these have been chosen for illustration (figures 23a and b). As expected from the small Mahalanobis distance, both sexes show very little and similar differences. In both cases, the frontal arc apparently has shortened over time. Furthermore, dacryon (11/12) has moved superiorly for both sexes, frontotemporale (15/16) moved inferoposteriorly for females and posteriorly for males, and maximum frontal point (17/18; again, very variable landmark) changed inferoposteriorly for both sexes.

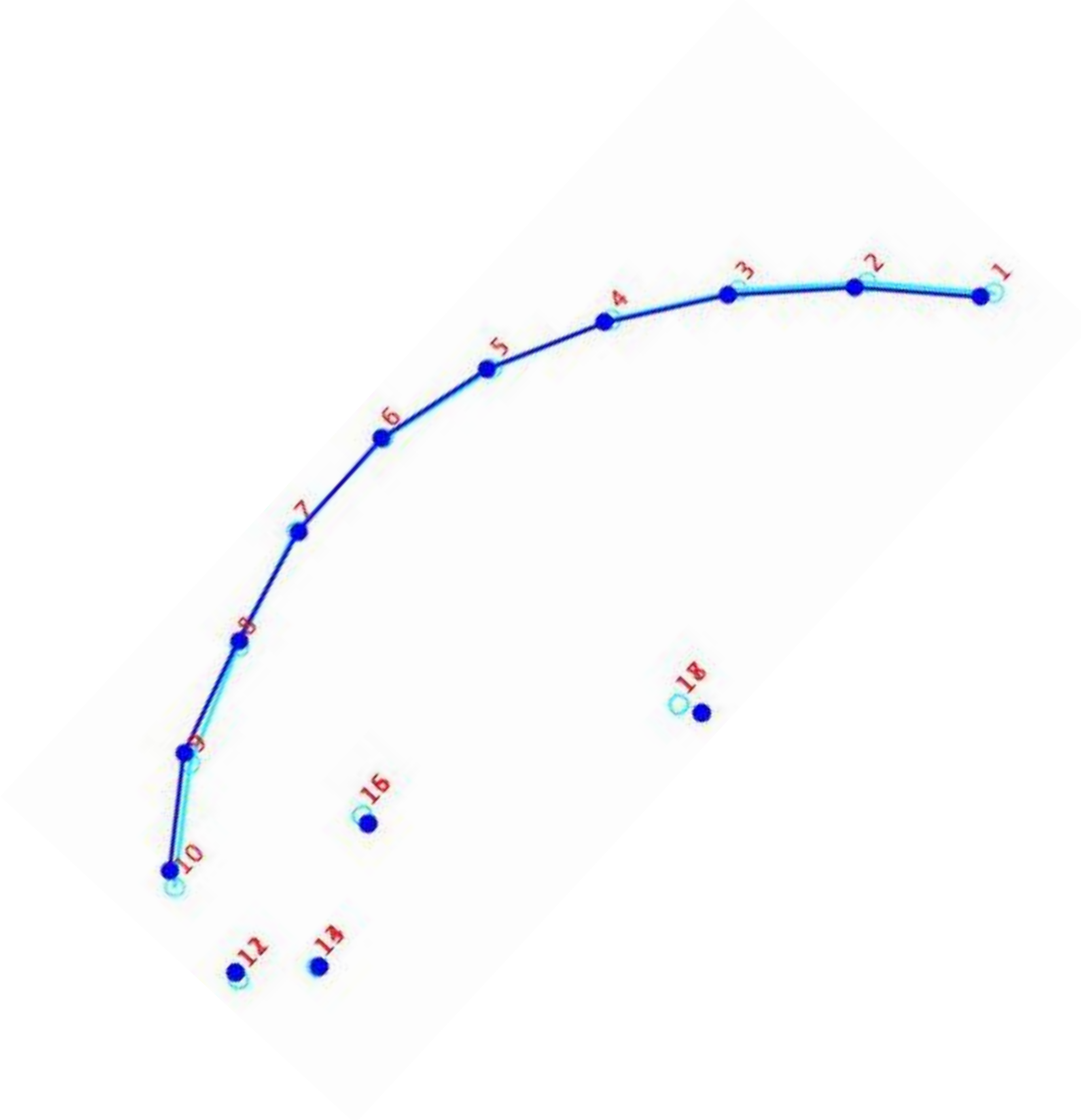


Figure 23a: German female L19 (light blue)-E20 (dark blue), lateral view.

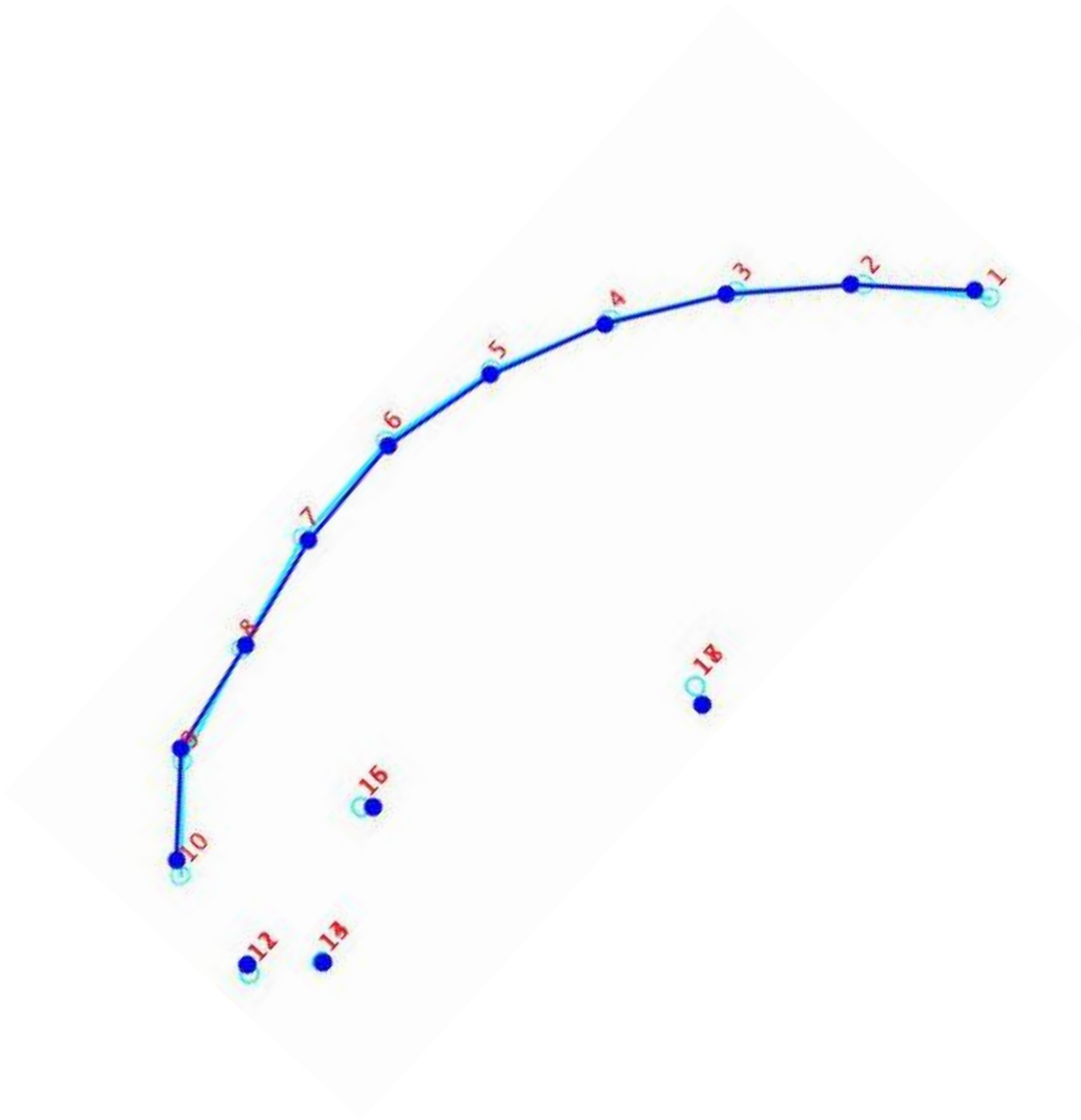


Figure 23b: German male L19 (light blue)-E20 (dark blue).

The highest significant Mahalanobis distance overall appears between American females of the late 19th and late 20th century (see table 5b). This example is illustrated in figure 24. Within one century, only frontomalare anterior (13/14; moved anteroinferiorly), frontotemporale (15/16; moved superiorly), and maximum frontal point (17/18; moved posteroinferiorly) have changed notably. Again, the difference at maximum frontal point should be regarded carefully due to its variable location.

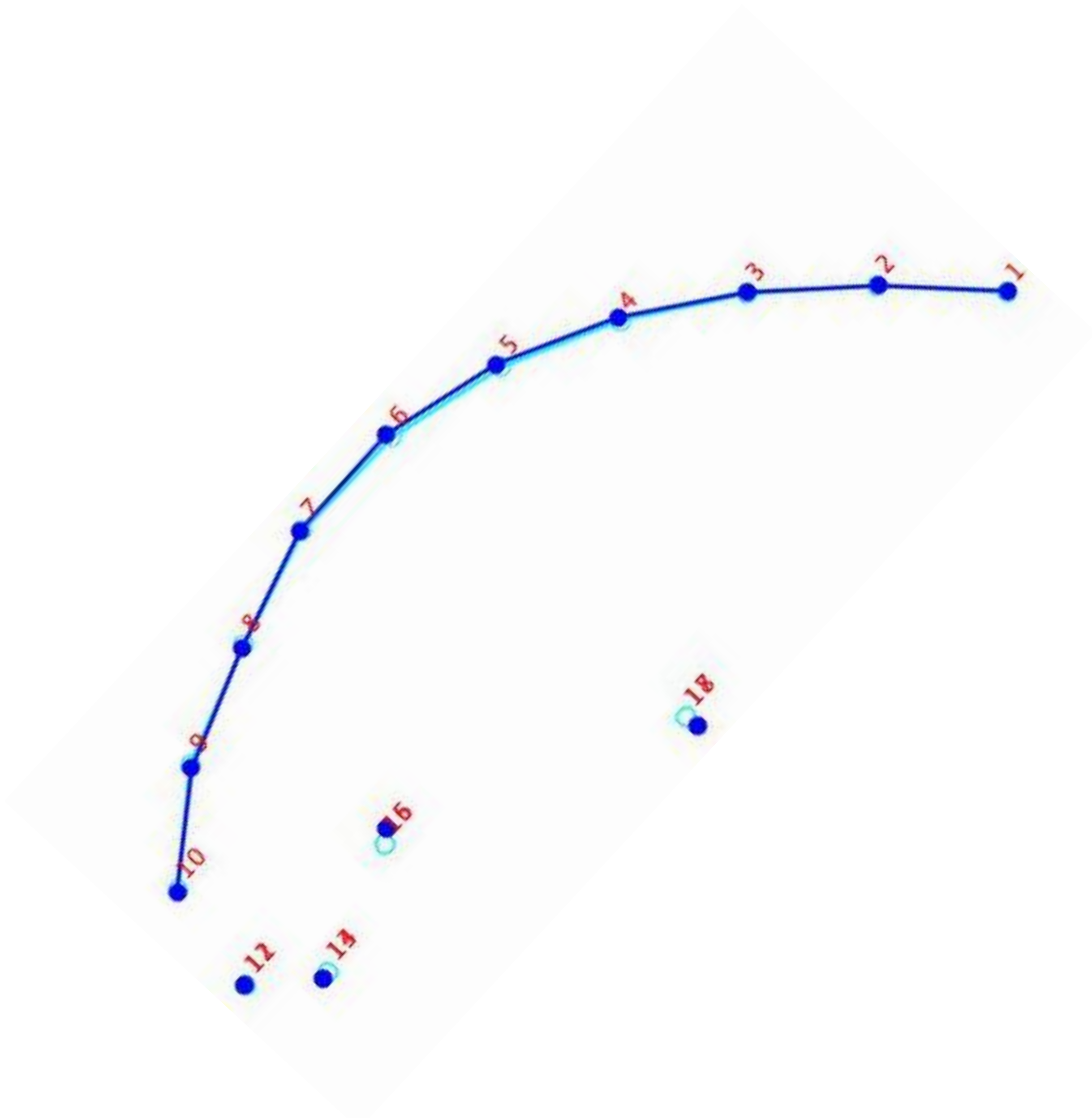


Figure 24: American female L19-L20, lateral view (light blue: late 19th, dark blue: late 20th).

The American male change from late 19th to late 20th century can be seen in figure 25. The changes are very similar to the females. Frontomalare anterior (13/14) has moved more directly inferiorly and there is an additional superior movement of dacryon (11/12).

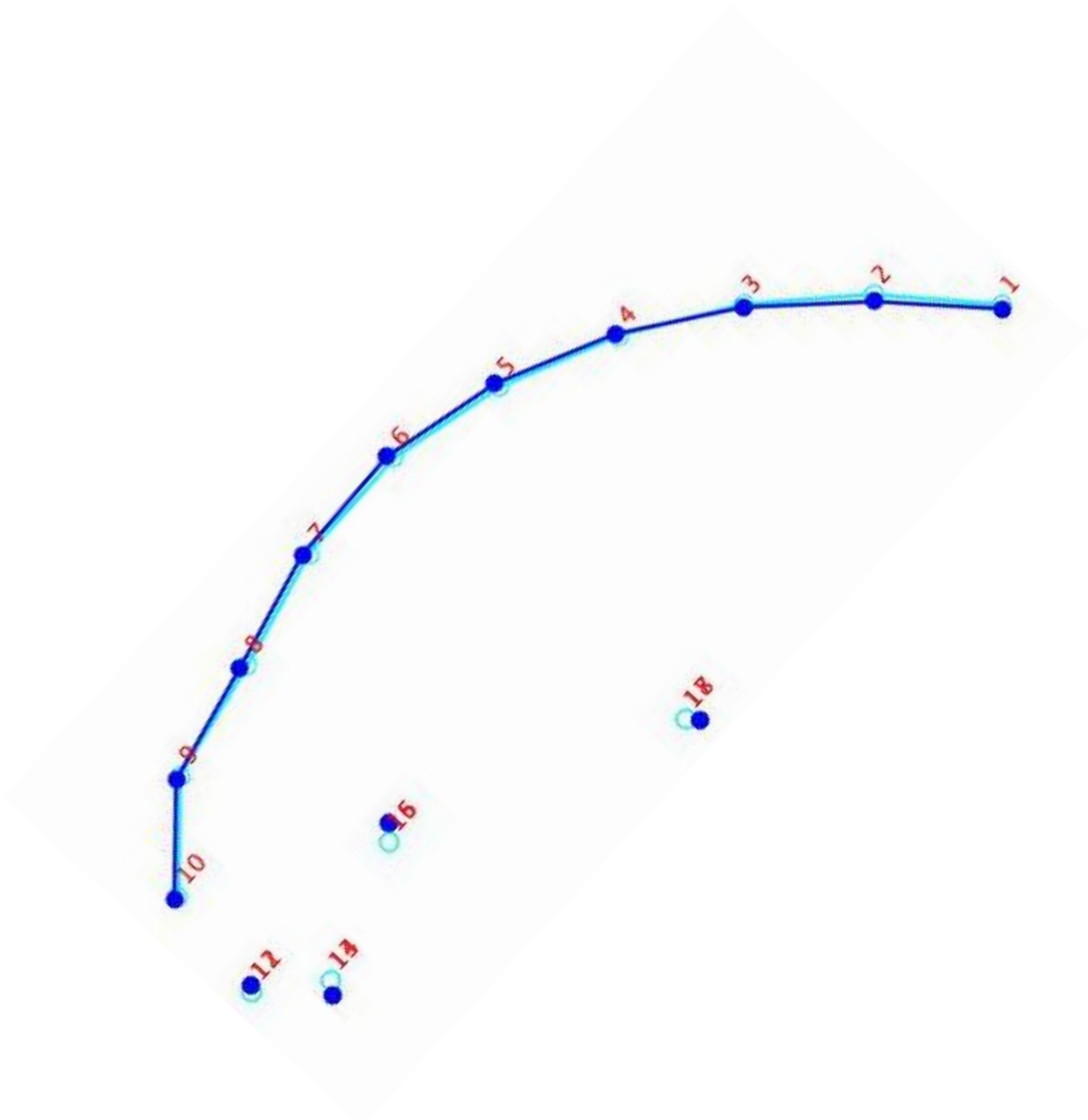


Figure 25: American male L19-L20, lateral view (light blue: late 19th, dark blue: late 20th).

3.3.3 Size

Mahalanobis Distance matrix

	FE20	FL19	ME20	ML19
FE20	0.00	0.00	0.89	1.66
FL19	0.00	0.00	0.91	1.69
ME20	0.89	0.91	0.00	0.12
ML19	1.66	1.69	0.12	0.00

Significance of Mahalanobis Distances

	FE20	FL19	ME20	ML19
FE20	--	0.967	<0.001	<0.001
FL19	0.967	--	<0.001	<0.001
ME20	<0.001	<0.001	--	0.033
ML19	<0.001	<0.001	0.033	--

Figure 26: Mahalanobis distance matrix for German secular change in size.

Mahalanobis Distance matrix

	FE20	FL20	ME20	ML20
FE20	0.00	0.01	1.86	1.46
FL20	0.01	0.00	2.11	1.68
ME20	1.86	2.11	0.00	0.02
ML20	1.46	1.68	0.02	0.00

Significance of Mahalanobis Distances

	FE20	FL20	ME20	ML20
FE20	--	0.646	<0.001	<0.001
FL20	0.646	--	<0.001	<0.001
ME20	<0.001	<0.001	--	0.238
ML20	<0.001	<0.001	0.238	--

Figure 27: Mahalanobis distance matrix for American secular change in size.

The time frames that had significant changes for shape (German: L19-E20, American: E20-L20) have been chosen for size and for size-and-shape analyses. Size analysis again was performed through a Fordisc run only using Log_Centroid_Size.

For both groups there are no significant changes for each sex respectively, except for German males. Their Mahalanobis distance of 0.12 is negligibly small though (see figures 26 and 27).

3.4 Metopism

3.4.1 Frequency

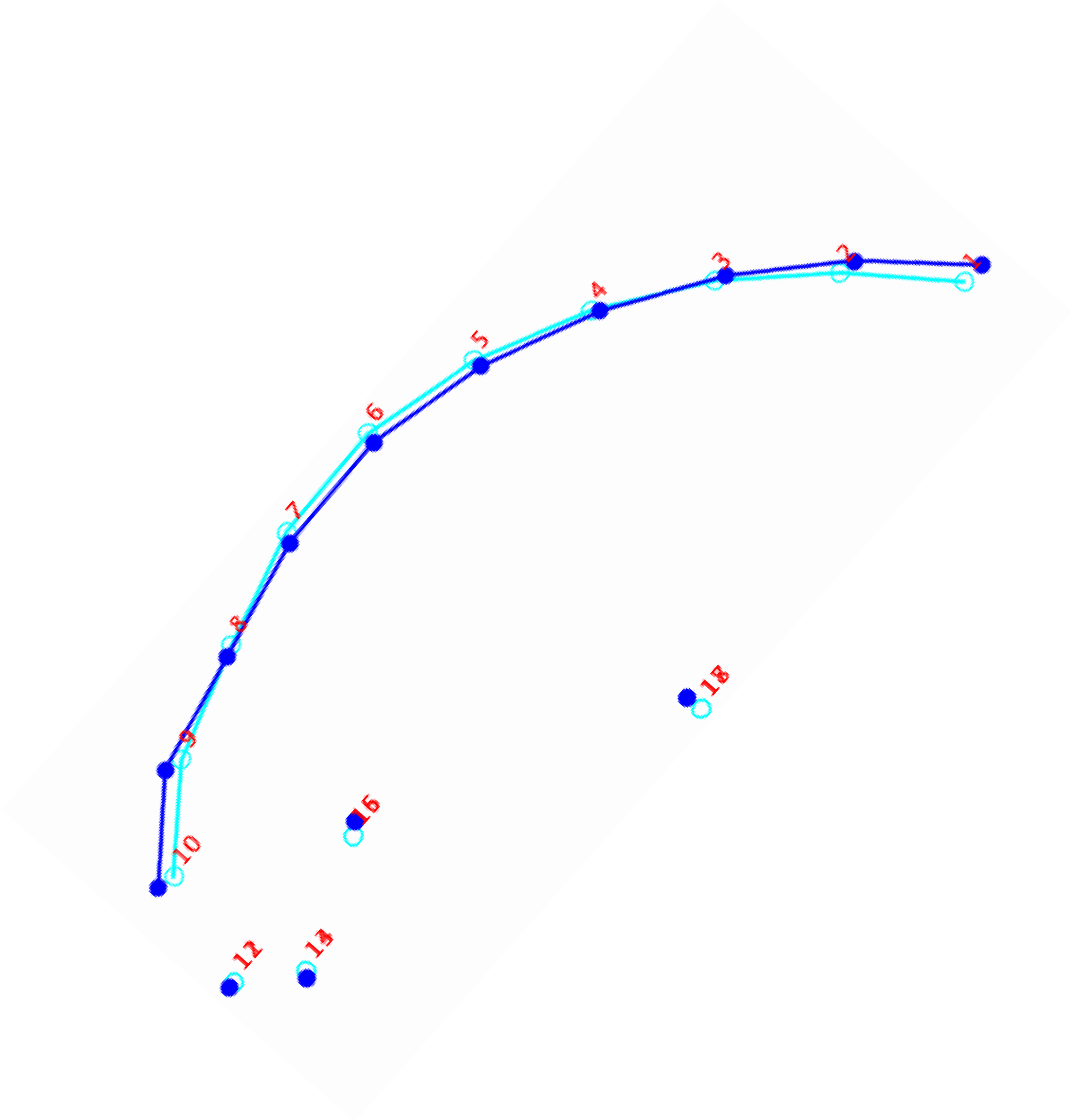
	Early 19th	Late 19th	Early 20th	Late 20th	Century unknown	Total
Female	3/17	0/28	4/102[38]	0/7	0/2	7/156
	17.65%	0.00%	3.92%	0.00%	0.00%	4.49%
Male	4/48	5/58	5/149	0/25	0/7	14/287
	8.33%	8.62%	3.36%	0.00%	0.00%	4.88%
Total	7/65	5/86	9/251	0/32	0/9	21/443
	10.77%	5.81%	3.59%	0.00%	0.00%	4.74%

Table 6: Frequency of metopism in the German sample.

For the presence of metopism only German data was available in this study. The frequency of metopic sutures is shown in table 6. Overall, 4.74% of the crania in the sample are metopic. Looking at the secular trend of the total frequency there is a decrease from early 19th through late 20th century. Nevertheless, sample sizes are low except for early 20th century, which is why this apparent tendency cannot be stated as certain.

[38] The presence or absence of metopism is unknown for one individual. In this table only sure cases of metopism have been taken into account.

3.4.2 Shape comparison



f -- no

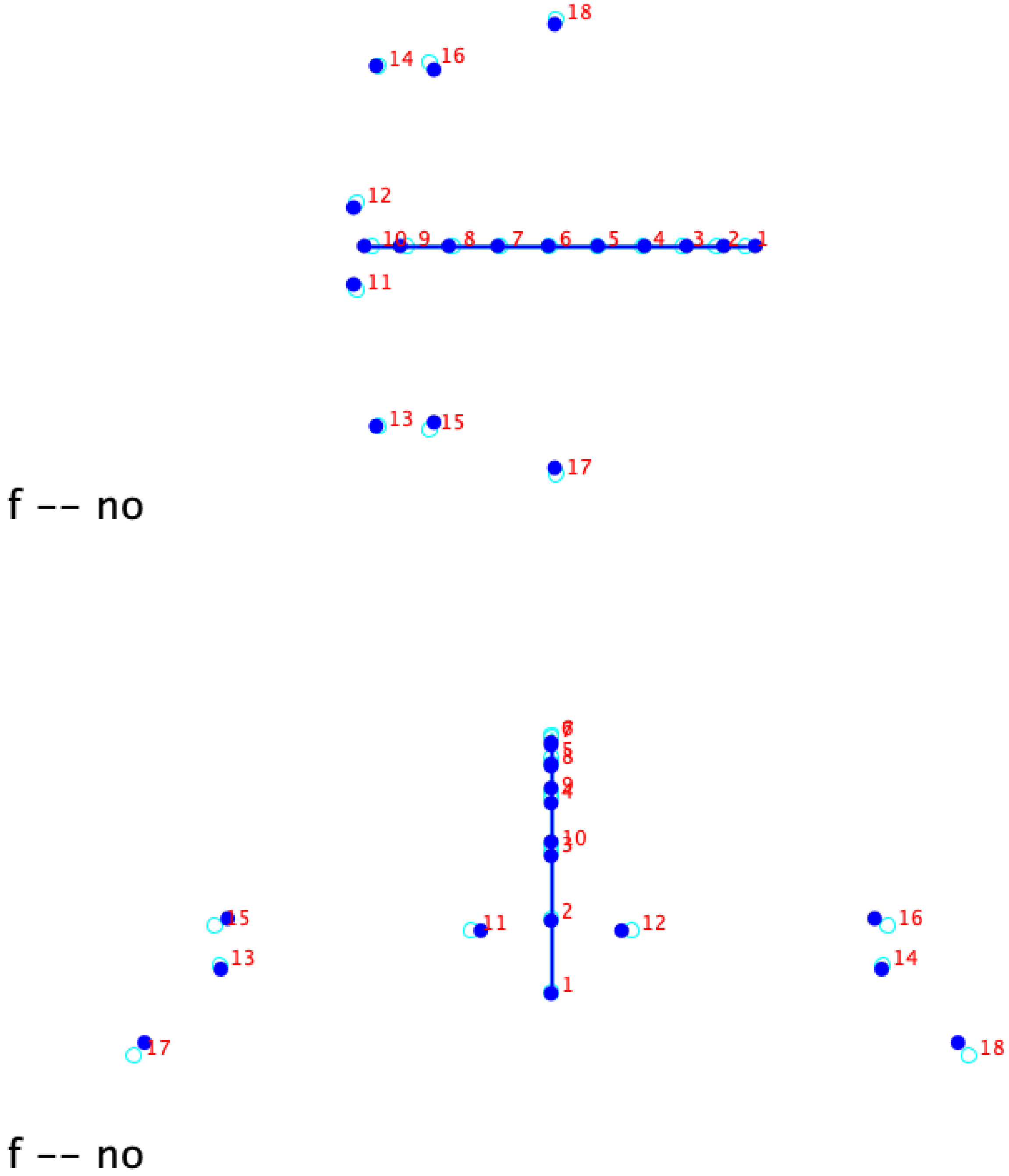


Figure 28: MorphoJ wireframe graphs for the discriminant function between full metopism (f: light blue) and no metopism (no: dark blue).

Figure 28 illustrates the shape differences between metopic (light blue) and non-metopic (dark blue) crania. On the lateral view there is not much difference. The metopic slope is a little bit more backwardly projected at nasion and glabella, then shows a slightly steeper incline before it crosses the other wireframe shortly after metopion and goes on, somewhat decreasing to bregma. Its course is overall a little bit shorter than the non-metopic one. Bigger differences occur at frontotemporale (15, 16) and maximum frontal point (17, 18), with metopic crania being broader in both locations. They cannot be specified in the lateral view but are also visible in the top view where for both aforementioned points as well as for dacryon (11, 12) metopic individuals have a broader shape. The frontal view confirms all the observations described above.

3.4.3 Discriminant function

For metopism analysis a discriminant function between the shapes of "full metopism" and "no metopism" has been computed in MorphoJ®. The two groups show a Mahalanobis distance of 2.6541 which is low but still highly significant ($p<0.0001$). Table 7 shows the classification. It can be seen that among the non-metopic crania the discrimination works well (87.4%) while there is no use for the function concerning the metopic individuals because their 50%-classification rate is equal to guessing. The overall classification rate is 68.7%.

True group	Allocated to			
	Full metopism	No metopism	Total	Classification rate
Full metopism	9	9	18	50.0%
No metopism	49	339	388	87.4%

Table 7: Cross-validated classification between the shapes of "full metopism" and "no metopism".

3.4.4 Relation between measurements and metopism

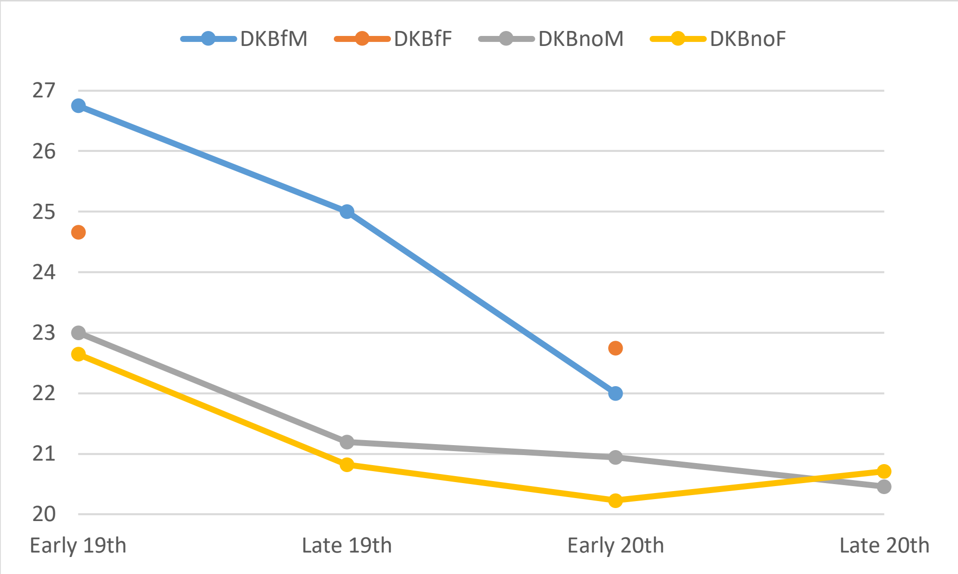
3.4.4.1 Comparison and secular trend of the mean values

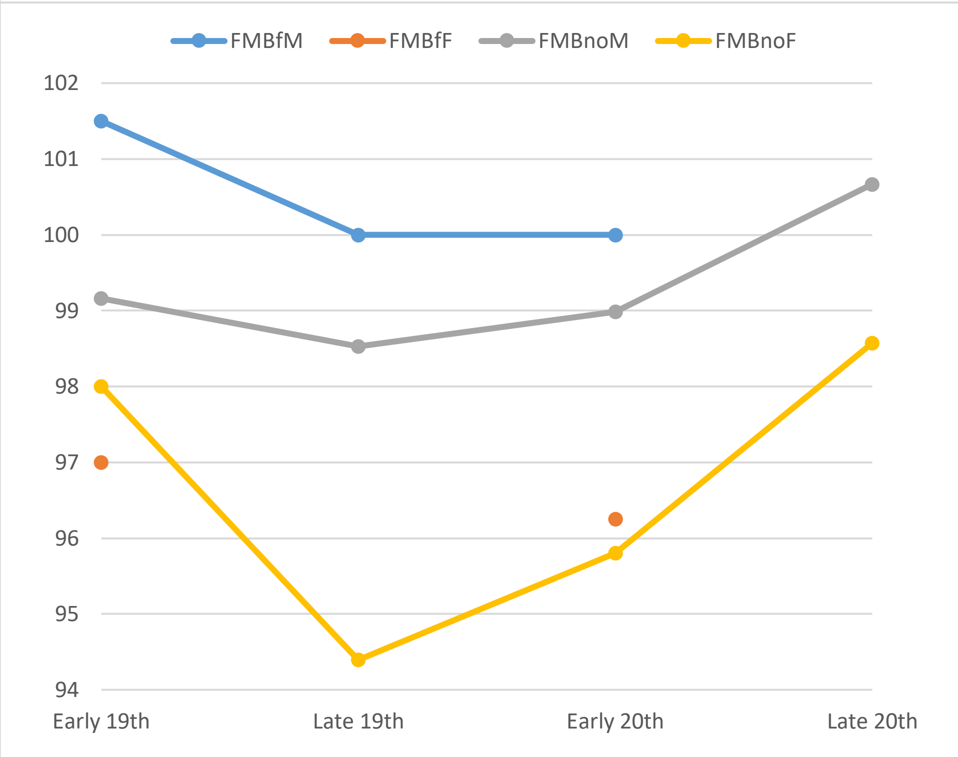
		Full Metopism			No Metopism		
		Male	Female	Total	Male	Female	Total
Early 19th	DKB	26.750	24.667	25.857	23.000	22.643	22.914
	WFB	101.750	98.333	100.286	97.773	97.071	97.603
	XFB	130.250	125.333	128.143	123.250	123.000	123.190
	FMB	101.500	97.000	99.571	99.159	98.000	98.879
	FRC	114.500	100.333	108.429	112.682	109.071	111.810
Late 19th	DKB	25.000	-	-	21.189	20.821	21.062
	WFB	103.600	-	-	95.981	92.714	94.852
	XFB	128.750	-	-	127.000	117.821	120.605
	FMB	100.000	-	-	98.528	94.393	97.099
	FRC	109.600	-	-	112.019	107.643	110.506
Early 20th	DKB	22.000	22.750	22.333	20.936	20.229	20.648
	WFB	98.000	99.000	98.444	96.734	94.656	95.900
	XFB	120.600	121.000	120.778	121.879	118.042	120.325
	FMB	100.000	96.250	98.333	98.986	95.802	97.702
	FRC	106.000	109.500	107.556	112.154	109.082	110.913
Late 20th	DKB	-	-	-	20.458	20.714	20.516
	WFB	-	-	-	98.458	93.714	97.387
	XFB	-	-	-	121.250	114.000	119.613
	FMB	-	-	-	100.667	98.571	100.194
	FRC	-	-	-	114.125	109.000	112.968

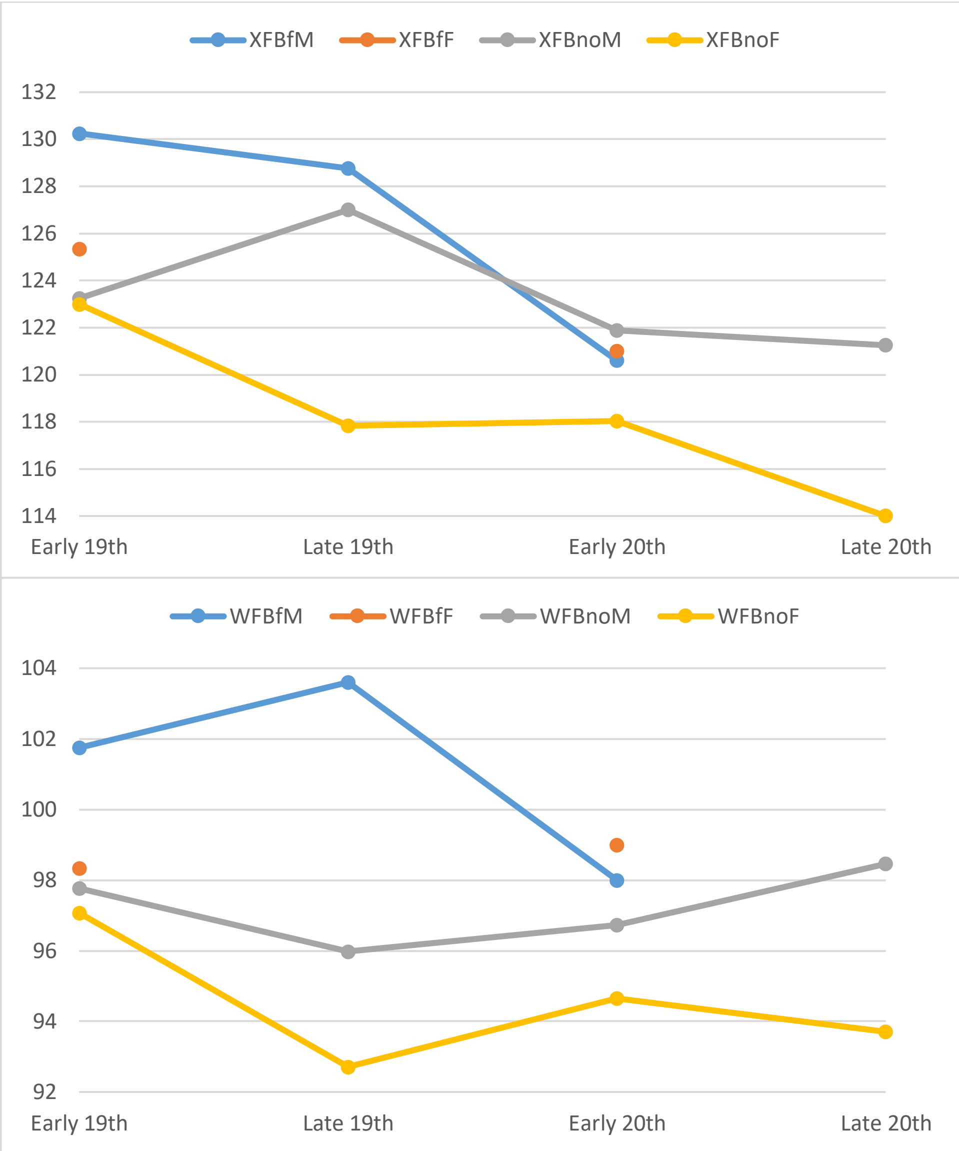
Table 8: Mean values for certain measurements of metopic and non-metopic crania (all values are given in mm, blank spaces where no data available in the sample).

As the values of table 8 and illustration of figure 29 show for breadth measurements, metopic crania of both sexes have constantly higher means for DKB and WFB than non-metopic ones. Also, for these two, metopic females have a higher value than metopic males for the early 20th century. For FMB metopic males are highest as well but both female groups are underneath both male groups and cross each other over the given centuries. XFB has non-metopic females as lowest for all four time periods. All of the other groups cross each other and are coming very close for the early 20th century. A trend towards closer mean values is present for all variables and would be in accordance with the decreasing frequency (see chapter 3.4.1).

The situation for FRC looks more complicated. It is clearly visible that there is almost no development for the non-metopic crania. The means for the metopic ones vary a lot around it. For the most part, the graphs give the idea of crania with full metopism having a tendency towards lower FRC values. Small sample size is a limit here and should not be forgotten as well regarding the other measurements.






XFBfM
XFBfF
XFBnoM
XFBnoF
132
130
128
126
124
122
120
118
116
114
Early 19th
Late 19th
Early 20th
Late 20th
WFBfM
WFBfF
WFBnoM
WFBnoF
104
102
100
98
96
94
92
Early 19th
Late 19th
Early 20th
Late 20th

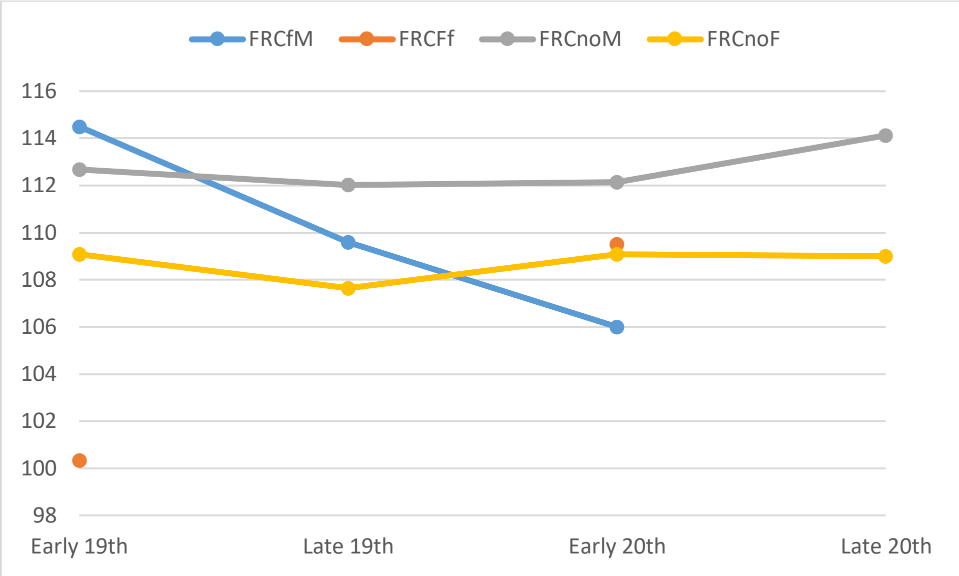


Figure 29: Comparison of the mean values of DKB, FMB, XFB, and WFB (for measurement definitions see Materials and Methods) between metopic and non-metopic crania and their respective secular trend (f: full metopism, no: no metopism, F: female, M: male).

3.4.4.2 Development of a regression formula

For the attempt of developing a regression formula to diagnose metopism from measurements, several steps were taken. The goal has been to develop a formula in the style of *"definitely no metopism < x < definitely metopism"*. Various tries have been made with the measurements from chapter 3.4.4.1 as single variables as well as as formulae computed from combinations of them. All ratios include FRC[39] as divisor because, as explained in the introduction (see 1.5 Metopism), metopic skulls are known to be rather brachycephalic and to have higher cephalic indices which means generally speaking that they are rather wide in relation to their length. Unfortunately, no ranges for "definitely metopism" could be found but only thresholds between "definitely no metopism" and "metopic/non-metopic mixed". These are given in tables 9a and b.

For single measurements, only the breadth variables showed a non-metopic range with Maximum and Minimum Frontal Breadth being the best discriminators, again showing the trend of metopic crania being broader. The most useful formula was

[39] FRC is a length measurement while all of the others are breadths.

"XFB/FRC x DKB/FRC", but also "DKB/FRC" as a simple quotition did perform considerably well. It is interesting to note that DKB cannot be applied effectively for discrimination as a single variable but does give the best results for the formulae.

Measurement	Overall Range (mm)	No Metopism (mm)	Number of Individuals in the Non-Metopic Range (out of 434)	Ranking
XFB	105-142	<117	98	1.
WFB	83-118	<93	92	2.
DKB	16-32	<18	21	3.
FMB	86-112	<91	18	4.
FRC	96-128	No range detectable	-	-

Table 9a: Measurement thresholds between "no metopism" and "metopic/non-metopic mixed" (Only individuals where all five measurements are present have been included for analysis.).

Formula	Overall range (rounded values)	No Metopism	Number of Individuals in the Non-Metopic Range (out of 434)	Ranking
XFB/FRC	0.9572-1.2885	<1.0400	70	6.
WFB/FRC	0.7187-1.0730	<0.7760	16	9.
DKB/FRC	0.1367-0.2783	<0.1730	111	5.
FMB/FRC	0.7542-1.0625	<0.8320	61	7.
XFB/FRC x DKB/FRC x FMB/FRC	0.1121-0.3598	<0.1686	153	2.
DKB/FRC x FMB/FRC	0.1075-0.2878	<0.1531	137	3.
XFB/FRC x DKB/FRC	0.1416-0.3394	<0.1964	174	1.
XFB/FRC x FMB/FRC	0.7350-1.3282	<0.8650	52	8.
(XFB x DKB x FMB)/FRC	1528.2162-3996.9392	<2003.6690	112	4.

Table 9b: Formula thresholds between "no metopism" and "metopic/non-metopic mixed" (Only individuals where all five measurements are present have been included for analysis.).

4 Discussion

4.1 Population Differences

Euro-American and German frontal bones are clearly distinguishable from one another. Size and shape combined have the highest overall classification rate of 71.6%, followed by shape only (65.2%), traditional measurements (55.0%), and size only (43.7%). The classification accuracies show that shape has a substantially higher impact on population differences than size does. Also, it can be seen that adding shape analysis improves the results substantially compared to just using standard measurements. Regarding the findings of Jantz and Meadows Jantz [30] that Euro-American crania have become relatively higher, narrower and larger in the course of the early 19th through the late 20th century, we can suspect that the light blue curve in figure 10 represents the Euro-American and the dark blue one the German shape, representing exactly the aforementioned trend. This population difference could reflect the development of the Euro-Americans apart from their European ancestors. It would of course only be true if Germans/Europeans had experienced a lot less secular change than the Americans or secular change in a different direction.

4.2 Sexual Dimorphism

As is usually the case, in this study the classification rates for sexual dimorphism are consistently higher than for population comparison (84.2%/86.3% for size and shape, 76.5%/82.9% for shape, and 70.1%/73.8% for size; all numbers being German/Euro-American). As Log_Cent_Size is the most important variable for classification in all of these sexual dimorphism analyses and classification rates for size-only consequently are considerably high, size seems to have a much higher impact on group differences in sexual dimorphism than it has for population analysis. This is in accordance with the results of Green and Curnoe [80] who found significant size dimorphism in their geometric morphometrics study on sexual dimorphism in southeast Asia. Chovalopoulou et al. [81] similarly found the best classification rates for sexual dimorphism with size and shape combined and also significant differences in size between males and females in the upper-face region. The classification rates for size-only are still lower than for shape-only, which is probably because size really is a single variable in this analysis, while several principal components are used for shape analysis, thus increasing the differentiation.

As has already been described by Manthey et al. [19], in this study 20th century Euro-American crania show greater sexual dimorphism than 20th century German crania. This is true for all three modes of testing. It is interesting to note that even though Log_Cent_Size is still the best single discriminator not only size but also shape differences are larger for Euro-Americans than for Germans.

4.3 Secular change

Both groups have experienced secular change within the 19th and 20th centuries. Unfortunately, because of the lack of Euro-American late 19th century data and German late 20th century data, the extent of secular change cannot be compared between the two populations. In general, very little secular change has happened in either group. There is some significant change in shape, but, except for a slight significant difference in German males, none in size. So, secular change of the frontal bone basically only happened in shape for these groups. Jantz and Meadows Jantz [30] found that Euro-American crania have become relatively higher, narrower, and larger with longer cranial bases between the early 19th and late 20th century. This trend is not visible for the Euro-American individuals in this study, probably because most of the change visible in their study happened in the 19th century.

Looking at the clear findings of secular change in Euro-American and German crania by Jantz and Meadows Jantz [30] and Jellinghaus et al. [79] for the shape of the whole cranium and Manthey et al. [19] for three sexually dimorphic variables on the cranium, who for the most part have used the same data sets as this study, it can be concluded that the frontal bone has experienced a lot less secular change in relation to the remaining cranium. The most comparable to the present study is probably the one by Jellinghaus et al. They investigated secular change of the cranial shape, size, capacity, and module from the early 19th through the mid 20th century in Euro-American and German individuals. Their findings show that significant changes in the cranial shape have occurred, with both groups becoming longer, higher, and narrower with a longer cranial base, while the differences between the populations stayed the same, Euro-Americans being higher, narrower, and with a longer cranial base than Germans.

4.4 Metopism

Metopism is present in almost five percent of the German crania in this study. The frequency has been decreasing continuously from almost eleven percent in the early 19th to zero percent in the late 20th century. This development might be in relation to the fact that the mean values of the breadth measurements have become closer to each other from early 19th through late 20th century between all non-metopic and metopic groups. Females show a higher tendency towards metopism for the early 19th and early 20th century. The lack of this trend in the late 19th century might be due to a lower sample size in females than in males for this time period. Sample sizes are generally a limit to the results of this study. Especially with the generally low frequencies of metopism, the percentages can change significantly with sample size.

Shape-wise, metopic frontals appear broader and shorter than non-metopic ones. This supports Schmitt [39] and Bryce and Young [40] who both have found metopic crania to be brachycephalic[40].

Additionally, the metopic frontal curvature is greater, almost circular, which has already been found by Papillaut [44]. The relatively shorter frontal chord[41] for metopic individuals seen by Bryce and Young [40] is also apparent in the present study.

Unfortunately, no new observations were made in this regard. The overall classification rate of 68.7% for the discriminant function that was calculated shows that there seems to be not much use in using discriminant analysis to assess metopism, since 68.7% is only slightly better than guessing.

[40] Rather broad in relation to their length.
[41] Linear distance between Bregma and Nasion.

The attempt of creating a formula with thresholds for metopic and non-metopic frontals has turned out very unsatisfying. It could be seen what was already known, that metopic crania are rather brachycephalic. The biggest limitation to finding definite morphological and morphometric correlations to metopism is probably the small amount of actual metopism cases in data collections.

4.5 Importance of the present results in the forensic context

Shape analysis to this day is not broadly being used in forensic analyses. We do, however, see from the results of this study that this type of analysis adds a new dimension of morphometric and morphological information that improves discriminant analyses. Hence, forensic sciences would greatly benefit from including standardized procedures using shape. One of the first approaches to implement shape analysis into forensic anthropology is the shape option in Fordisc®. It removes isometric size and is therefore somewhat close to Geometric Morphometric analysis. A software based on coordinates is 3D-ID [82], which uses geometric morphometrics to estimate sex and ancestry of an unknown individual. Further developments in this direction would greatly benefit future forensic work.

The use of metopism in forensic casework is surely questionable. Like for identification from the frontal sinuses [61], antemortem radiographs or CT scans of the cranium would be needed in order to a) know if the suspected individual actually had a persisting metopic suture and b) compare ante- and postmortem radiographs. We do furthermore not know how uniquely individual metopic sutures are shaped and if sutures can be distinguished well enough on radiographs.

5 Conclusion

The aim of this study was to provide a comprehensive overview of the frontal bone in the forensic context with special emphasis on its shape. Analyses on 19th and 20th century Euro-American and German crania were performed in terms of population differences, sexual dimorphism, secular change, and metopism.

It could clearly be seen that the frontal bone on its own already provides a lot of information toward the biological profile of an individual. Overall, using size and shape combined for analyses would always produce the best results, followed by shape only and then size only. Nevertheless, Log_Centroid_Size was the best sex-discriminating variable in the size-shape combined analyses for both populations. Population differences as well as sexual dimorphism could both be assessed (with varying accuracy) using size only and shape only respectively.

Very little secular change between the 19th and 20th century was found for the frontal in both groups respectively, with the secular change that could be seen mostly being shape variation.

Metopism analysis was only performed on German crania, because the presence or absence of a metopic suture was not documented for the Euro-American crania. Unfortunately, the results of these analyses were very limited due to too small sample sizes for the overall low percentage of metopism. The metopic frontal was once again found to be short in relation to its width and presenting a more rounded frontal curvature. The attempt of creating a formula to morphometrically assess the presence of metopism was not successful.

The results of this thesis suggest that forensic case work on skeletal remains would greatly benefit from a broader application of Geometric Morphometrics and consequently from larger databases containing shape data as well as more advanced and user-friendly software for this type of analyses.

6 Zusammenfassung

Ziel dieser Arbeit war ein umfassender Überblick über die Nutzbarkeit von Form[42]-Daten des Os frontale im forensischen Kontext. Hierzu wurden die Daten von euro-amerikanischen und deutschen Individuen (jeweils mit Geburtsjahren im 19. und 20. Jahrhundert) in Bezug auf Populationsunterschiede, Geschlechtsunterschiede, säkulare Veränderungen und das Auftreten einer Sutura metopica untersucht.

Es zeigte sich deutlich, dass das Os frontale allein eine Vielzahl an Informationen zur Erstellung des biologischen Profils eines Skelettfundes beinhaltet. Insgesamt erzielte die Nutzung von Form- und Größendaten gemeinsam in allen Untersuchungen die besten Ergebnisse, gefolgt von Form allein und Größe allein. Nichtsdestotrotz war die Größenvariable in beiden Populationen das einflussreichste Unterscheidungsmerkmal zwischen den Geschlechtern in der kombinierten Größen-Form-Analyse.

Das Os frontale zeigte in beiden Gruppen nur sehr wenige säkulare Veränderungen zwischen dem 19. und 20. Jahrhundert. Die vorhandenen Unterschiede fanden sich größtenteils in der Form.

Die Sutura metopica konnte wegen fehlender amerikanischer Daten nur für den deutschen Datensatz untersucht werden. Leider war auch der deutsche Datensatz im Verhältnis zum generell geringen Auftreten der Sutura metopica zu klein, um verlässliche Ergebnisse zu erzielen. Wie schon in früheren Studien zum Thema, war auch in dieser das Os frontale mit Sutura metopica relativ kurz in Relation zur Breite und die Form seiner Kurvatur runder als in Individuen ohne Sutura metopica. Der Versuch, eine Formel zur morphometrischen Bestimmung des Vorhandenseins einer Sutura metopica zu erstellen, scheiterte leider ebenso.

Die Ergebnisse dieser Arbeit zeigen deutlich, dass die forensische Analyse von Skelettfunden sehr von einer ausgedehnteren Einbeziehung von Form-Daten profitieren würde. Hierzu bräuchte es größere Datensätze, die Form-Daten beinhalten und bessere, nutzerfreundlichere Software für diese Art Untersuchungen. Die Grundvoraussetzungen sind bereits gegeben.

[42] Alle Informationen über ein Objekt, abgesehen von Größe, Position und Orientierung im Raum.

7 References

1. Iscan, M.Y. and M. Steyn, *The Human Skeleton in Forensic Medicine.* Charles C Thomas Pub Ltd, 2013.
2. Viciano, J., S. Lopez-Lazaro, and I. Aleman, *Sex estimation based on deciduous and permanent dentition in a contemporary Spanish population.* Am J Phys Anthropol, 2013.
3. Buikstra, J.E. and D.H. Ubelaker, *Sex determination*. Forensic Anthropology 2000-2010, ed. J.M. Bollag. 2011, Boca Raton, FL: CRC Press.
4. Bulut, O., et al., *Sexual dimorphism in frontal bone roundness quantified by a novel 3D-based and landmark-free method.* Forensic Science International, 2016.
5. Klingenberg, C.P., *Evolution and development of shape: integrating quantitative approaches.* Nature Reviews Genetics, 2010.
6. Klingenberg, C.P., *MorphoJ: an integrated software package for geometric morphometrics.* Molecular Ecology Resources, 2011.
7. Mosimann, J.E., *Size allometry: size and shape variables with characterizations of the lognormal and generalized gamma distributions.* J Am Stat Assoc, 1970.
8. Gould, S.J., *Allometry and size in ontogeny and phylogeny.* Biol Rev, 1966.
9. Klingenberg, C.P., *Size, shape, and form: concepts of allometry in geometric morphometrics.* Dev Genes Evol, 2016.
10. Huxley, J.S., *Constant differential growth-ratios and their significance.* Nature, 1924.
11. Huxley, J.S., *Problems of relative growth.* Johns Hopkins University Press, 1932.
12. Jolicoeur, P., *The multivariate generalization of the allometry equation.* Biometrics, 1963. **19**: p. 497-499.
13. Phenice, T.W., *A newly developed visual method of sexing the os pubis.* American Journal of Physical Anthropology, 1969. **30**: p. 297-301.
14. Klales, A.R., S.D. Ousley, and J.M. Vollner, *A revised method of sexing the human innominate using Phenice's nonmetric traits and statistical methods.* American Journal of Physical Anthropology, 2012. **149**(1): p. 104-114.
15. Buikstra, J.E. and D. Ubelaker, *Standards for Data Collection from Human Skeletal Remains*. Arkansas Archeological Survey Research Series. Vol. 44. 1994, Fayetteville, AR.
16. Langley, N.R., et al. *Data Collection Procedures for Forensic Skeletal Material 2.0*. 2016. University of Tennessee and Lincoln Memorial University.
17. Jantz, R.L. and S.D. Ousley, *Introduction to Fordisc 3*, in *Forensic Anthropology: An Introduction*, M.A. Tersigni-Tarrant and N.R. Shirley, Editors. 2012, CRC Press, Taylor and Francis Group: Boca Raton, FL. p. 253-270.
18. Meadows Jantz, L. and R.L. Jantz, *The anthropology research facility: The outdoor laboratory of the forensic Anthropology Center, University of Tennessee.*, in *The Forensic Anthropology Laboratory*, M.W. Warren and H.A. Walsh-Haney, Editors. 2008, CRC Press: Boca Raton, FL. p. 7-22.

19. Manthey, L., et al., *Secular change of sexually dimorphic cranial variables in Euro-Americans and Germans.* International Journal of Legal Medicine, 2016. **131**: p. 1113-1118.
20. Ramsthaler, F., K. Kreutz, and M.A. Verhoff, *Accuracy of metric sex analysis of skeletal remains using Fordisc (R) based on a recent skull collection.* International Journal of Legal Medicine, 2007. **121**(6): p. 477-482.
21. Guyomarc'h, P. and J. Bruzek, *Accuracy and reliability in sex determination from skulls: A comparison of Fordisc (R) 3.0 and the discriminant function analysis.* Forensic Science International, 2011. **208**(1-3): p. 180.e1-6.
22. Walker, P.L., *Sexing skulls using discriminant function analysis of visually assessed traits.* Am J Phys Anthropol, 2008. **136**: p. 39-50.
23. Ramsthaler, F., et al., *Digital forensic osteology: Morphological sexing of skeletal remains using volume-rendered cranial CT scans.* Forensic Science International, 2010. **195**(1-3): p. 148-152.
24. Kesterke, M.J., et al., *Using the 3D Facial Norms Database to investigate craniofacial sexual dimorphism in healthy children, adolescents, and adults.* Biology of Sex Differences, 2016.
25. Garvin, H.M. and C.B. Ruff, *Sexual dimorphism in skeletal browridge and chin morphologies determined using a new quantitative method.* American Journal of Physical Anthropology, 2012. **147**(4): p. 661-670.
26. Whitehouse, A.J.O., et al., *Prenatal testosterone exposure is related to sexually dimorphic facial morphology in adulthood.* Proc. R. Soc. B, 2015. **282**(1816).
27. Tanner, J.M., et al., *Relative importance of growth hormone and sex steroids for the growth at puberty of trunk length, limb length, and muscle width in growth hormone-deficient children.* J. Pediatr., 1976. **89**(6): p. 1000-1008.
28. Michel, J., et al., *Determination of Sex: Interest of Frontal Sinus 3D Reconstructions.* Journal of Forensic Sciences, 2015.
29. Komlos, J. and B.E. Lauderdale, *The mysterious trend in American heights in the 20th century.* American Journal of Human Biology, 2007. **34**(2): p. 206-215.
30. Jantz, R.L. and L. Meadows Jantz, *The Remarkable Change in Euro-American Cranial Shape and Size.* Human Biology, 2016. **88**(1).
31. Jantz, R.L., L. Meadows Jantz, and J.L. Devlin, *Secular Changes in the Postcranial Skeleton of American Whites.* Human Biology, 2016.
32. Langley, N.R. and S. Cridlin, *Changes in Clavicle Length and Maturation in Americans: 1840-1980.* Human Biology, 2016.
33. Bagga, A. and S. Kulkarni, *Age at menarche and secular trend in Maharashtrian (Indian) girls.* Acta Biol. Szegediensis, 2000.
34. Fredriks, A.M., et al., *Continuing positive secular growth change in the Netherlands 1955-1997.* Pediatr. Res., 2000.
35. Hoshi, H. and M. Kouchi, *Secular trend of the age at menarche of Japanese girls with special regard to the secular acceleration of the age at peak height velocity.* Human Biology, 1981. **53**(4): p. 593-598.
36. Spradley, K., K.E. Stull, and J.T. Hefner, *Craniofacial Secular Change in Recent Mexican Migrants.* Human Biology, 2016.

37. Malina, R.M. and A.N. Zavaleta, *Secular trend in the stature and weight of Mexican-American children in Texas between 1930 and 1970.* American Journal of Physical Anthropology, 1980. **52**(4): p. 453-461.
38. Martin, A. and K. Saller, *Lehrbuch der Anthropologie, Bd. I u. II*. 3. Aufl. ed. 1957, Stuttgart: Gustav Fischer.
39. Schmitt, H.P., *Ein Beitrag zum Problem der Sutura frontalis und Sutura mendosa persistens.* Virchows Arch. A. Path. Anat. and Histol., 1975.
40. Bryce, T.H. and M. Young, *Observations on metopism.* J. Anat., 1917.
41. Hanihara, T. and H. Ishida, *Frequency variations of discrete cranial traits in major human populations. II. Hypostoic variations.* Journal of Anatomy, 2001. **198**: p. 707-725.
42. Togersen, J., *Roentgenological study of metopic suture.* Acta Radiologica, 1950.
43. Acken, F.v., *Die Sutura frontalis im Röntgenbild.* Fortschr. Röntgenstr., 1933.
44. Papillaut, G., *La suture métopique et ses rapports avec la morphologie crânienne.* Mém. Soc. d'Anthropol., 1896.
45. Double, A.F.L., *Traité des variations des os du crâne de l'homme.* Paris: Masson, 1903.
46. Schultz, A.H., *The metopic fontanelle, fissure and suture.* Amer. J. Anat., 1929.
47. Weinholdt, H., *Untersuchungen über das Wachstum des Schädels unter pathologischen und physiologischen Verhältnissen.* Teil I u. II Beitr. path. Anat., 1922.
48. Bolk, L., *On metopism.* Amer. J. Anat., 1917.
49. Pauwels, F., *Der Schenkelhalsbruch. Ein mechanisches Problem. Grundriß einer Biomechanik der Frakturheilung. Eine neue Theorie über den Einfluß mechanischer Reize auf die Differenzierung der Stützgewebe.* Gesammelte Abhandlungen zur funktionellen Anatomie des Bewegungsapparates, 1965.
50. Kummer, B., *Biomechanik des Säugetierskelets.* Handbuch der Zoologie, 1959.
51. Böning, H., *Zur Kenntnis des Spielraums zwischen Gehirn und Schädel.* Z. Neurol. Psychiat., 1924.
52. Rössle, R., *Die pathologische Anatomie der Familie*. 1940, Berlin: Springer.
53. Schollmeyer, W., *Die Sutura frontalis (metopica) als Erb- und Identifizierungsmerkmal.* Dtsch. Z. ges. gerichtl. Med., 1965.
54. Materna, G.F. and F. Gerhard, *Der Metopismus und sein Vorkommen in Nordmähren-Schlesien.* Virchows Arch. path. Anat., 1936.
55. Hess, L., *The metopic suture and the metopic syndrome.* Human Biology, 1945.
56. Woo, J.-K., *Racial and sexual differences in the frontal curvature and its relation to metopism.*
57. ; Available from: www.theabfa.org.
58. Tersigni-Tarrant, M.A. and N.R. Shirley, *Brief History of Forensic Anthropology*, in *Forensic Anthropology. An Introduction*, M.T.A. Tersigni-Tarrant and N.R. Shirley, Editors. 2013, CRC Press, Taylor and Francis Group: Boca Raton, FL. p. 1-16.
59. Bethard, J.D. and E.A. DiGangi, *Letter to the Editor-Moving Beyond a Lost Cause: Forensic Anthropology and Ancestry Estimates in the United States Letter to the Editor-Moving Beyond a Lost Cause: Forensic Anthropology and Ancestry*

Estimates in the United States to the Editor — Moving Beyond a Lost Cause: For.
60. Stull, K.E., et al., *Commentary on: Bethard JD, DiGangi EA. Letter to the Editor-Moving beyond a lost cause: Forensic anthropology and ancestry estimates in the United States. J Forensic Sci. 2020;65(5):1791-2. doi: 10.1111/1556-4029.14513.* J Forensic Sci, 2021. **66**(1): p. 417-420.
61. Christensen, A.M., *Testing the reliability of frontal sinuses in positive identification.* Journal of Forensic Sciences, 2005. **50**(1): p. 18-22.
62. Biehler-Gomez, L., et al., *Diabetic bone lesions: a study on 38 known modern skeletons and the implications for forensic scenarios.* International Journal of Legal Medicine, 2018.
63. Biehler-Gomez, L., G. Giordano, and C. Cattaneo, *The appearance of breast cancer metastases on dry bone: Implications for forensic anthropology.* J Forensic Leg Med, 2019. **61**: p. 5-12.
64. Biehler-Gomez, L., G. Giordano, and C. Cattaneo, *The overlooked primary: bladder cancer metastases on dry bone. A study of the 20th century CAL Milano Cemetery Skeletal Collection.* Int J Paleopathol, 2019. **24**: p. 130-140.
65. Biehler-Gomez, L. and C. Cattaneo, *The Diagnostic Implications of Two Cases of Known Rheumatoid Arthritis from the CAL Milano Cemetery Skeletal Collection.* Journal of Forensic Sciences, 2018.
66. Berryman, H.E., N.R. Shirley, and A.K. Lanfear, *Low-Velocity Trauma*, in *Forensic Anthropology. An Introduction*, M.A. Tersigni-Tarrant and N.R. Shirley, Editors. 2013, CRC Press, Taylor and Francis Group: Boca Raton, FL. p. 271-290.
67. Kroman, A.M., *Fracture biomechanics of the human skeleton*, in *Department of Anthropology*. 2007, University of Tennessee, Knoxville, TN.
68. Barbian, L.T. and P.S. Sledzik, *Healing Following Cranial Trauma.* Journal of Forensic Sciences, 2008. **53**.
69. Ubelaker, D.H. and B.J. Adams, *Differentiation of perimortem and postmortem trauma using taphonomic indicators.* J Forensic Sci, 1995. **40**(3): p. 509-12.
70. Cattaneo, C., et al., *The Detection of Microscopic Markers of Hemorrhaging and Wound Age on Dry Bone. A Pilot Study.* Am J Forensic Med Pathol, 2010. **31**: p. 22-26.
71. Cattaneo, C., *Forensic anthropology: developments of a classical discipline in the new millennium.* Forensic Science International, 2007. **165**(2-3): p. 185-193.
72. Budimlija, Z., et al., *World Trade Center Human Identification Project: experiences with individual body identification cases.* Croatian Medical Journal, 2003. **44**(3): p. 259-262.
73. Alba, R.D. and R.M. Golden, *Patterns of ethnic intermarriage in the United States.* Social Forces, 1986. **65**: p. 202-223.
74. Price, A.L., et al., *Discerning the Ancestry of European Americans in Genetic Association Studies.* PLoS Genetics, 2008. **4**(1): p. e236.
75. Ousley, S.D. and A.H. McKeown, *Three dimensional digitizing of human skulls as an archival procedure*, in *Human Remains: Conservation, Retrieval and Analysis*, E. Williams, Editor. 2001, British Archaeological Reports: Oxford, England.

76. Martin, R. and R. Knussmann, *Handbuch der vergleichenden Biologie des Menschen*. 1988, Stuttgart: Gustav Fischer.
77. Howells, W.W., *Cranial variation in man: a study by multivariate analysis of patterns of difference among recent human populations*. Vol. 67. 1973, Cambridge, MA: Papers of the Peabody Museum of Archaeology and Ethnology, Harvard University.
78. Gower, J.C., *Measures of taxonomic distance and their analysis*, in *The Assessment of Population Affinities in Man*, J. Weiner and J. Huizinga, Editors. 1972, Clarenden Press: Oxford. p. 1-24.
79. Jellinghaus, K., et al., *Cranial secular change from the nineteenth to the twentieth century in modern German individuals compared to modern Euro-American individuals.* International Journal of Legal Medicine, 2018.
80. Green, H. and D. Curnoe, *Sexual dimorphism in southeast Asian crania: a geometric morphometric approach.* Homo, 2009. **60**(6): p. 517-34.
81. Chovalopoulou, M.E., E.D. Valakos, and S.K. Manolis, *Sex determination by three-dimensional geometric morphometrics of craniofacial form.* Anthropol Anz, 2016. **73**(3): p. 195-206.
82. Slice, D.E. and A.H. Ross, *3D-ID: geometric morphometric classification of crania for forensic scientists.* 2009.

Appendix

I Abkürzungsverzeichnis

ABFA:	American Board of Forensic Anthropology
A:	Euro-American
AUB:	Biauricular Breadth
BBH:	Basion-Bregma Height
BMI:	Body Mass Index
BNL:	Basion-Nasion Length
CAD:	Computer Aided Design
Can:	Canonical Variate
CI:	Cephalic Index
CT:	Computed Tomography
db:	dark blue
DKB:	Interorbital Breadth
E19/20:	early 19th/20th century
F:	female
f:	full metopism
FDB:	Forensic Data Bank
fig:	figure
FMB:	Bifrontal Breadth
FRC:	Frontal Chord
FRF:	Frontal Fraction
FRS:	Frontal Subtense
FS:	frontal sinus
G:	German
GLS:	Glabella Subtense
GOL:	Glabello-Occipital Length
L19/20:	late 19th/20th century
LABANOF:	Laboratorio di Antropologia ed Odontologia Forense
lb:	light blue
M:	male
MDH:	Mastoid Height
no:	no metopism
PC:	Principal Component
PCA:	Principal Component Analysis
STB:	Bistephanic Breadth
UK:	United Kingdom
WFB:	Minimum Frontal Breadth
XFB:	Maximum Frontal Breadth
XCB:	Maximum Cranial Breadth

II Abbildungsverzeichnis

III Tabellenverzeichnis