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DISSERTATION

GEOMETRIC MORPHOMETRIC CRANIOFACIAL ANALYSIS OF EARLY BRONZE AGE AUSTRIAN POPULATIONS

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This work id dedicated to my parents,
Renato Pellegrini and Ingeborg Rosa Stedtfeld,
and to my wife, Li Li Shao,
the love of my life.

CONTENTS

Abstract

Archeological data indicate that the early Bronze Age populations in Lower Austria did not present a cultural unity. They differed in three regional synchronous manifestations: North of the Danube was the area of the Únetice culture, south of the Danube the Unterwölbling culture (west of Wienerwald) and the Wieselburg culture (east of Wienerwald). These cultural groups shared a small geographic area and similar ecological conditions, but previous studies revealed significant population differences in their skeletal morphology. In this study, the cranial morphology of these Bronze Age populations is analyzed with a geometric morphometric approach in order to assess structure and migration patterns of these prehistoric groups, and to relate the results to recent archeological data.

58 three-dimensional craniofacial landmarks were located in skulls of 171 adult male and female individuals. A Principal Component Analysis (PCA) of shape coordinates in form space was performed in order to evaluate the pattern of craniofacial variation within the entire sample. This analysis showed conspicuous differences between the Wieselburg and the Únetice groups, whereas the Unterwölbling group overlaps with both of them. A PCA separately by sex provided evidence for a more heterogeneous cranial morphology in males than in females. Females of the three cultural groups differ in other morphological characteristics instead. Thin plate splines (TPS) interpolation functions reveal morphological differences among groups separately by sex, which concern mainly the breadth and the length of the crania, and the morphology of the mid-facial and occipital region.

This study confirms the previous evidence indicating that the morphological variation among populations corresponds to a cultural pre-defined subdivision. These phenotypic differences may have arisen from genetic differences due to partial or total endogamy. The analysis herein shows allometric variation within sexes and differences between cultural groups that had not been demonstrated by previous morphometric investigations. The morphological separation among males may be a result of a prolonged cranial growth of males as indicated by allometric analyses. Differences observed among females most likely arise from the female greater migration rate due to the presence of a patrilocal system, which is in agreement with the archeological evidence. Analyses of microevolutionary trends in craniofacial morphology of these early Bronze Age Austrian populations reveal a morphological separation of the chronologically younger Gemeinlebarn F population. This may be a result of a break-down of the isolation of populations due to intensified metallurgical trading.

Kurzzusammenfassung

Archäologische Forschungsergebnisse deuten an, dass die frühbronzezeitliche Bevölkerung in Niederösterreich keine kulturelle Einheit aufwies. Drei zeitgleiche Kulturgruppe sind im Raume Ostösterreichs dokumentiert: Nördlich der Donau war das Gebiet der Aunjetitzer Kultur, südlich der Donau und westlich der Wienerwaldes war der Bereich der Unterwölblinger Kultur, südlich der Donau und östlich des Wienerwaldes war die Gegend der Wieselburger Kultur. Diese kulturell differenzierten Gruppen besiedelten ein relativ kleines geographisches Gebiet unter ähnlichen klimatischen und (vermutlich) ökologischen Gegebenheiten. Bisherige anthropologische Untersuchungen belegten aber statistische Unterschiede in der Skelettmorphologie. In der vorliegenden Studie wird die Frage nach den phänetischen Unterschieden in der Cranialmorphologie neuerlich aufgegriffen und mittels der Geometric Morphometric Methode analysiert. Unter Einbeziehung neuerer archäologischer Erkenntnisse sollen damit die Ursachen dieses Phänomens besser eingeschätzt werden können.

58 drei-dimensionale kraniofazial Landmarks wurden an 171 erwachsenen männlichen und weiblichen Individuen, die aufgrund ihrer Grabausstattungen der frühen Bronzezeit zugeordnet wurden, digitalisiert. Zunächst wurde eine Hauptkomponente Analyse von shape-Koordinaten in „form space“ durchgeführt, um das Muster der kraniofazial Variation innerhalb der kompletten Stichprobe zu beleuchten. Diese Analyse zeigte auffällig Unterschiede zwischen der Wieselburger und der Aunjetitzer Kulturgruppe sowie eine Überlappung der Unterwölblinger Kulturgruppe mit den beiden anderen Gruppen. In der Hauptkomponentenanalyse, die unter Berücksichtigung des Geschlechts durchgeführt wurde, zeigten die männlichen Individuen eine deutlich heterogenere Schädelmorphologie als die weiblichen Individuen. Über Thin Plate Spline (TPS) Interpolationsfunktionen konnten morphologische Gruppenunterschiede

dokumentiert werden, welche hauptsächlich die Länge und die Breite der Schädel sowie die Morphologie des Mittelgesichtes und der Hinterhauptsregion betreffen.

Diese Studie bestätigt die vorherigen Untersuchungen, die morphologische Gruppenunterschiede zwischen kulturell definierten und räumlich (durch geographische Barrieren) abgegrenzten Bevölkerungen Ostösterreichs dokumentierten. Diese phänotypischen Abweichungen könnten auch genetisch bedingt sein, etwa durch Prozesse wie Endogamie. Die gegenständliche Analyse konnte allometrische Variation zwischen den Geschlechtern und Unterschiede zwischen den Kulturgruppen zeigen, die aus den bisherigen morphometrischen Untersuchungen nicht abzuleiten waren: Die allometrischen Analyse dokumentierte eine größere Heterogenität bei den männlichen Individuen sowie ein längeres Schädelwachstum im Vergleich zu den weiblichen. Die nachgewiesenen morphologischen Unterschiede zwischen den Frauen innerhalb der Kulturgruppen dürften am wahrscheinlichsten aus einem größeren Migrationsanteil auf der Basis eines patrilokalen Systems resultieren; letzteres ist mit archäologischen Indizien konsistent. Analysen von Mikroentwicklungstendenzen dieser frühenbronzezeitlichen Bevölkerungen zeigten, dass sich die chronologisch etwas jüngere Population von Gemeinlebarn F in Bezug auf die kraniofaziale Morphologie unterscheidet. Das könnte auf einen Zusammenbruch der Isolation dieser Gruppen (ev. durch verstärkte Handlesbeziehungen) und/oder eine verstärkte Bevölkerungsmischung hindeuten.

1 Introduction

Throughout the 20th Century, and right up until today, the Austria's Bronze Age populations have been the object of intensive investigations. Their archaeological and biological features have been studied for a long time thanks to a large collection deriving from numerous funeral places, but also from a number of single graves and settlement pits. In particular, the populations of eastern Austria, because of favourable sources, for instance the abundance of material, and the geographical fragmentation in synchronous groups, have been of particularly interest as far as the archaeological and biological aspects are concerned.

According to archaeological data (Neugebauer 1991, 1994; Sprenger, 1996; Lauermann, 1991a), the early Bronze Age populations of eastern Austria appear to present not a cultural unity, but they differ in three regional manifestations. The North of the Danube, in the Weinviertel, between Kamptal in the west and March in the east, was the domain of the Ùnetice culture. In the Southern region of the Danube Alps foreland, between Enns and the Wienerwald, especially along the tributary streams of the Danube, was the area of the Unterwölbling culture. The third regional manifestation is the Wieselburger or Gata group, which lay south of the Danube and east of the Wienerwald, and in the northern Burgenland.

Several anthropological investigations addressed these early Bronze Age populations. Early studies focused on the metrical and on the morphological features of a few populations in order to clarify questions of origin. (Zuckerkandl, 1875; Schürer and Waldheim, 1919; Pöch, 1922; Lebzelter, 1923; Szombathy, 1934; Tuppa, 1935; Weniger J., 1954; Weniger M., 1954; Ehgartner, 1959; Grefen-Peters, 1982). Other studies centered their interests on pathological and demographic issues to shed light on different population dynamic processes (Teschler-Nicola 1982-85; Teschler-Nicola, 1988; Schultz and Teschler-Nicola, 1989; Teschler-Nicola, 1989; Ziemann-Becker, 1992; Teschler-Nicola and

Prossinger, 1992; Kneissel et al. 1994; Teschler-Nicola and Prossinger, 1997; Teschler-Nicola and Gerold, 2001; Novotny, 2005).

Many of the investigations above mentioned have been carried out by some researchers of the Museum of Natural History of Vienna. These studies belong to one of the main projects of that institute, which concerns the topic of the anthropological and archeological features of the Bronze Age populations in Austria. Nevertheless, many of those studies are only fragments of light on locally focused thematic. In fact, despite the numerous investigations, a general sight of the Bronze Age in Austria is far from completion.

So far, to my best knowledge, the investigation carried out by Teschler-Nicola (1992) is the sole study that has examined the entire early Bronze Age collection. Teschler-Nicola explored the morphometrical characteristics of her sample with a classical morphometric approach on linear measurements. Along with these analyses, the skeletal material was searched for epigenetic and morphognostic traits. The study of Teschler-Nicola found significant differences among the inhabitants of the – *a priori* archaeologically characterized – Bronze Age populations. Teschler-Nicola interpreted this finding as the consequence of genetic dispositions due to the presence of geographical barriers, as, for instance, the river Danube and the Wienerwald.

Aim of the present study is to add the morphometrical issue searched by Teschler-Nicola by applying novel morphometric methods. The considerable Austrian early Bronze Age collection is investigated herein, for the first time with geometric morphometrics, in order to expand the knowledge of craniofacial morphology, mobility and population dynamics of early Bronze Age Austria.

In the field of morphometrics – the quantitative analysis of shape of organisms – a fundamental change began some years ago concerning handling and gathering of data. A new approach, called “geometric morphometrics”, considerably modified the ways in which variation of organisms has been measured and treated statistically (Rohlf and Marcus, 1993). Nowadays, geometric morphometrics offers a collection of approaches for multivariate statistical analysis usually on two-dimensional or three-dimensional coordinates of landmarks (Rohlf and Marcus, 1993; Slice et al., 1996; Adams, Rohlf and Slice, 2004). Those landmarks are anatomical points that correspond biologically form to form (Bookstein, 1991), and are recorded in order to provide the geometrical properties of the biological form that is being studied.

The main goal of my investigation is to integrate the toolkit of geometric morphometric with the archeological data that have been so far recorded, in order to asses the pattern of phenotypic craniofacial variation among the archaeologically pre-defined early Bronze populations of Lower Austria. The data here collected concern, therefore, two main sources of information: craniometrical and archeological data. Craniometrical data were recorded by means of geometric morphometrics techniques, in order to provide the quantification of craniofacial morphology, whereas archeological data provided the necessary information to reconstruct the cultural attributes of these populations.

The investigation is based on the analysis of a sample of human skulls stored at the Natural History Museum of Vienna. By including newly discovered remains excavated in recent years, the quantitative analysis of size and shape craniofacial variation addresses the following issues a) analyze morphological similarities and dissimilarities among pre-defined cultural groups in order to determine the extent of endogamy/exogamy of these populations, b) analyze morphological variation within cultural groups and between sexes in order to gain concerns regarding population structure and migration pattern of these prehistoric human groups, c) exploration of chronological effects on morphological variation.

Along with the former archeological and anthropological study, the purpose of this study is to enrich our knowledge of population biology, and population dynamic processes of the Bronze Age in Austria. Hence, in the next chapters, I will introduce the main findings discovered by archeological and anthropological investigations.

In chapter 2, I will review the archeological background of the Bronze Age in Austria. I will review history and development of the populations that inhabited the

Lower Austria in the early Bronze Age, in order to illustrate how and when cultural differences among groups of different geographical areas most likely arose. Furthermore, I will present archeological data that indicate which cultural attributes differentiate the regional groups. These archeological data comprises two main source of information. The first concern the types of burial, which most probably indicate spiritual or religious ritual practiced by these prehistoric populations; the second regards their pottery and metallurgy.

In chapter 3, I will illustrate the main findings obtained by the anthropological researches. I will introduce the findings gained by the early morphological studies of the first half of the 20th Century, which tried to clarify the question of origin of the Austrian Bronze Age populations. I will also present the results obtained by recently Paleopathological and Demographical investigations, which shed light on life condition and life expectancy in these populations. Besides, as the morphometrical investigation of Teschler-Nicola (1992) is of particular concern here, a long section of chapter 3 is dedicated to show methodology and results of that study.

Chapter 4 concerns the descriptions of the Austrian early Bronze Age collections analyzed in the present work. A detailed description of the material concerns its origin, and its chronological attributes.

The statistical and geometrical properties of the morphometric techniques herein applied are reviewed in chapter 5. This section encompasses a historical review of the morphometric methods that have been used in Anthropology so far, and a detailed discussion of the core techniques of modern geometric morphometrics.

The measurement and the handling of the data carried out in this study are presented in chapter 6. A detailed part of this section is dedicated to the definition of the landmarks digitized on the crania.

Finally, in chapter 7 and chapter 8 the findings gained in the present study are demonstrated and discussed.

2 Archaeology of the Bronze Age in Austria

2.1 The Bronze Age in East Austria

The term Bronze Age was introduced in 1836 by the archaeologist Christian Jürgensen Thomesen. The Danish archaeologist developed the three period system into which prehistory was divided: the Stone Age, the Bronze Age and the Iron Age. In this context, according to Felgenauer (1979), the Bronze Age represented the first temporal period of full production of the bronze, a copper-tin-alloy.

According to Strahm (1982), the intensification of the bronze metallurgy induced a revolution in the economic and social structure of the prehistoric societies. Part of the population was employed full-time in metal processing. Production and dressing of the ore, smelting and subsequent treatment were not possible without organization. Therefore, division and specialization of labor led to the formation of skilled and commercially oriented groups, which resulted in social differentiation. Furthermore, from those processes, formation of political institutions, systems of protection and security, and guiding leaders developed as well (Strahm, 1982; Neugebauer, 1991; 1994; Sprenger, 1996).

In Europe, the evolution of Cultures developed partially regionally and independently, and expressed itself in several societies with different socio-economic structures. According to Strahm (1982), the term Bronze Age can therefore not generally be defined, but must be concerned in a regional context instead. In order to trace the development of the numerous European cultural groups which evolved from those processes, several chronological systems have been established so far. Referring to the chronological system of Reinecke (1899), the middle Europe was divided in 4 stages (A = Early Bronze Age, B and C = Middle Bronze Age, D= Late Bronze Age). Besides, Ruckdeschel (1978) suggested a further differentiation of the stage A, resulting in 5 sub-phases by using a chronology of needles (A1a-A2c; see Figure 2.1). Absolute chronologically, calibrated C-14 data date the early Bronze Age between 2300 and 1500 BC (Neugebauer, 1994).

As far as the transitional period between the Stone Age and the Bronze Age is concerned, archeological data indicate that this occurred through a phase of the Copper Age, know as the Chalcolithic (Neugebauer, 1994). This phase was a part of the human cultural development, in which the use of early metal tools appeared alongside the use of stone tools (Strahm, 1982). Considering this aspects in Austria, the Neolithic groups belonging to the Corded Ware Culture and the Bell Beaker Culture, as well as the chronological older groups of early Bronze Age, have been chronologically attributed to the Chalcolithic phase (Neugebauer, 1994). According to Neugebauer (1994), in this period, no archeological differences between the groups which inhabited the east Austria already existed.

Nevertheless, in the early Bronze Age, the Lower Austria appeared culturally divided by regional district (Neugebauer, 1994). Following Neugebauer, the early Bronze Age populations in Lower Austria did not present a cultural unity, but they differed in three regional manifestations (see Figure 2.1):

- North of the Danube, in the Weinviertel, between Kamptal in the west and March in the east, was the domain of the Únetice Culture group. The core of this group was also partly dispersed in some region of Moravia, of the Czech Republic, of south-west Slovakia, Poland, and in the east of Germany. While in the neighboring south Moravia it was possible to observe a continuous development of the Únetice Culture from the bell Beaker Culture to the Veterov Culture, the circumstances in the Lower Austrian Weinviertel appear to be more complicated (Schubert, 1973). According to Schubert (1973), the Lower Austria Únetice Culture differed from the northern Únetice Culture of Moravia, and represented an advanced cultural phase of the early Bronze Age, with peculiar metallurgy and pottery.
- In the Southern region of the Danube Alps foreland, between Enns and the Wienerwald, especially along the tributary streams of the Danube, was located the area of the Unterwölbling Culture. In the upper Austria Alps foreland the element

of the Unterwölbling Culture with the ones of the Straubing Culture (the Linz Culture group) were combined.

- East of the Wienerwald, between the Danube in the north and the Raab in the south-east, lay the Wieselburg or Gata Culture group. This Culture was also dispersed in west Hungary in the settlement area of Gattendorf (ungar. Gáta).

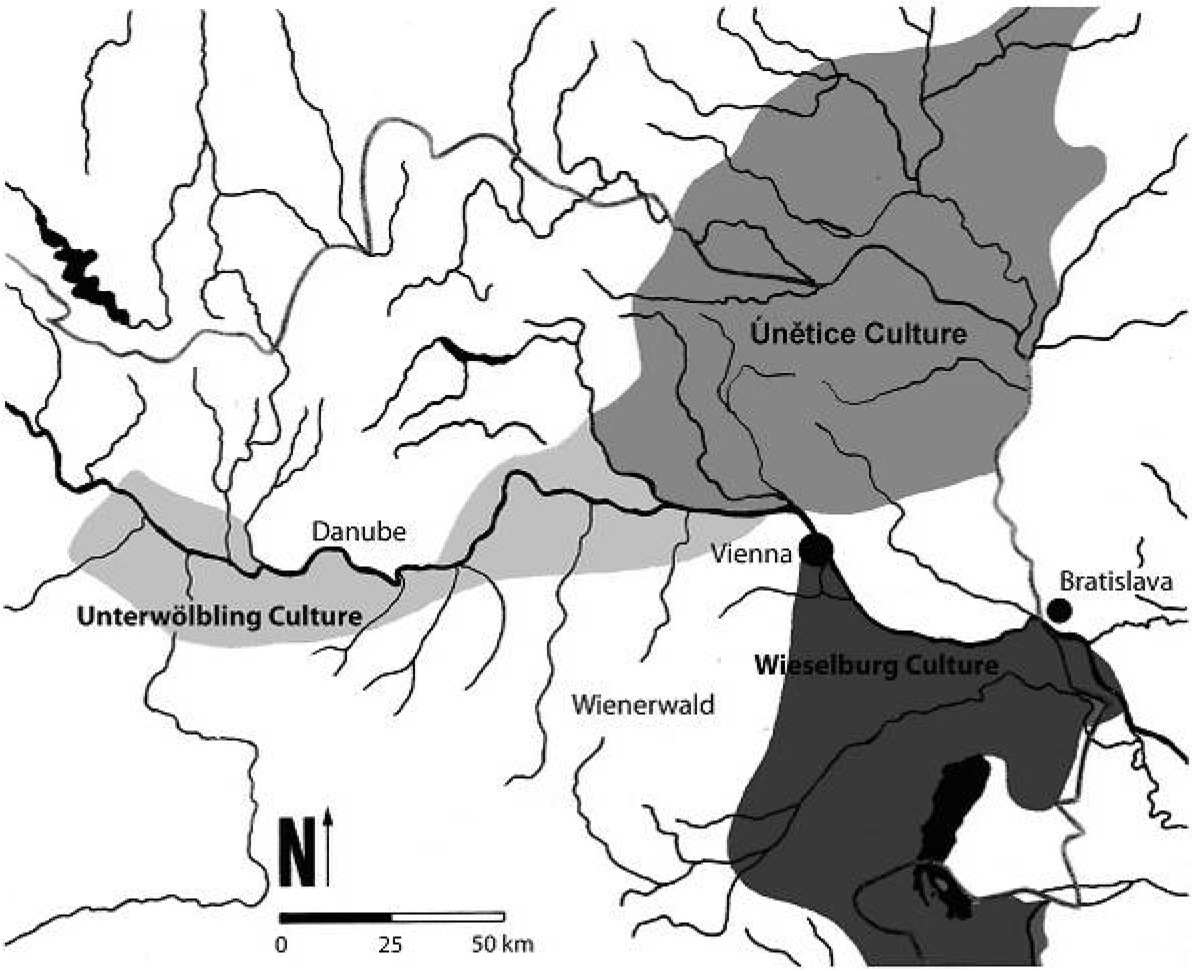

Figure 2.1. Spread of cultural groups of the early Bronze Age (2300-1500 B.C.) in Lower Austria. (From Neugebauer, 1994; Fig. 4).

2.2 Transitional period between the Neolithic and the Bronze Age

According to archeological data (Neugebauer, 1991, 1994), the early Bronze Age cultural groups of Lower Austria most likely evolved regionally from two local Endneolithic Cultures, namely the Corded Ware Culture and the Bell Beaker Culture.

At the end of the Neolithic, the Corded Ware Culture was one of the most important Cultures in Europe. The name of the Culture derived from the ornamental of its characteristic pottery: the ceramic were decorated with cordage, e.g. string. Absolute chronologically, this Culture date between 2900 and 2300/2200 B.C. According to numerous archaeologists, the origin of this Culture was the north-east of Europe. Through a strong expansion, groups belonging to this Culture encompassed most of the northern Europe and were dispersed over Poland, Germany, Bohemia, Moravia and Austria (see Figure 2.2). In the Corded Ware Culture, the dead were buried under flat ground or below small tumuli, in flexed position. Typical was a bipolar sex specialization. The males lied on their right side with the head towards the west whereas the females lied on the left side with the head towards the east. The view of both males and females were orientated to the south. Grave goods for men typically included stone battle-axes. Pottery in the shape of beakers and other types were the most common burial gifts. The ceramic were often decorated with cord, but also incisions and other types of impressions.

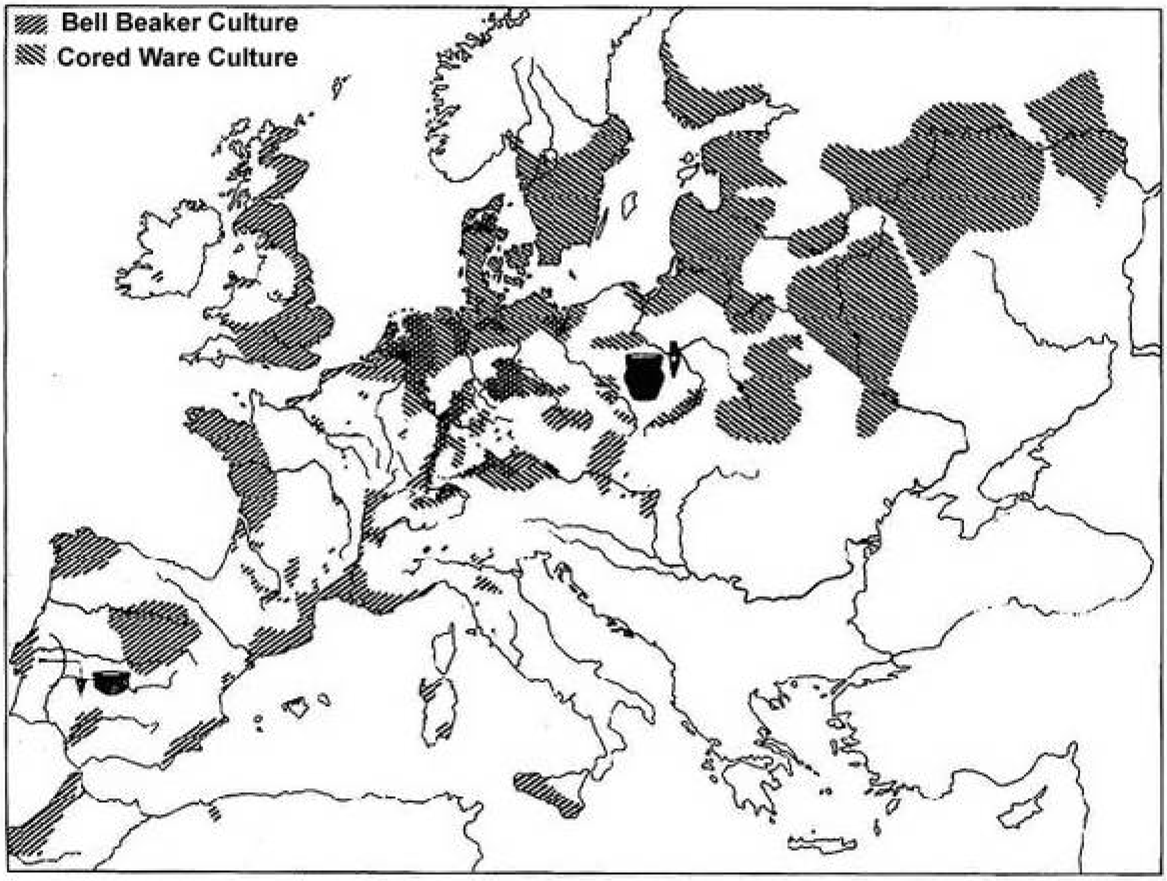

Figure 2.2. Spreading area of the Corded Ware Culture and Bell Beaker Culture.

The Bell Beaker Culture spread across the South- the West- and the Middle Europe around the 2600 BC till the 2200 B.C., thereby running in the first phases of the early Bronze Age. In 1900, the prehistorian Mainz Paul Reinecke applied the expression "Bell Beaker", because of its typical pottery - a beaker with a distinctive inverted bell-shaped. Many theories of the origins of the Bell Beakers have been put forward, and have subsequently been seriously challenged (Nicolis, 2001). So far, the Iberian Peninsula have been seen as the most likely place of Beaker origin. The Bell Beaker Culture spread into the British island, Denmark, France, Italy, reaching Poland and Hungary (see Figure 2.2). In Austria and in Bohemia, as well as in Moravia and Bayern, archeological findings witness the presence of this Culture in the Middle Europe block. According to archeological calibrated C-14 data, the Bell Beaker Culture date around the 2600/2500 BC. For 3 or 4 centuries was locally distributed in Austria, Bayern, Bohemia, and Moravia, and evolved parallel to the Corded Ware Culture (Strahm, 1990). Similarly to the Corded Ware Culture, in the Bell Beaker Culture the dead were buried in a flexed position with bipolar sex-specificity. In contrast with the Corded Ware Culture, however, the bodies were turned with a north-south direction. The males lied on their left sight with the head orientated to the north and the feet to the south; the females lied on their right side with the head orientated to the south and the feet to the north. The view of both males and females were orientated to the east. This typical burial rite will be also present in the early and middle Bronze Age southern Danubian Cultures (e.g. the Unterwölbling Culture and the Böheimkirchen Culture).

In Lower Austria, the inheritance both of the Corded Ware Culture, and of Bell Beaker Culture, was partially present till the first phase of the early Bronze Age. Numerous sites (e.g. Franzhausen I, Franzhausen II, Gemeinlebarn A) witness, in fact, the presence of the Corded Ware Culture in the Traisental Valley, which is located in the south–western Danubian area (Neugebauer, 1994).

In the northern Danubian area, the presence of the Bell Beaker Culture is supported by findings of Bell Beaker pottery in the site of Laa/Thaya. In the southern Danubian area, the presence of the Bell Beaker Culture was represented by a regional variant, which have been termed as the Ragelsdorf-Oggau group.

According to Neugebauer (1994), at the beginning of the early Bronze Age, from the unitary Ragelsdorf-Oggau group followed in Lower Austria several regional groups. In the southern-Danubian area east of the Wienerwald, the Ragelsdorf-Oggau group developed in the Leithaprodersdorf group. West of the Wienerwald, along with local groups of the Corded Ware culture, the Ragelsdorf-Oggau group evolved into the Unterwölbling group. In the northern Danubian area, paralleling to Ragelsdorf-Oggau group, groups of the Bell Beaker Culture, the Proto-Únetice groups, generated the older stage of the Únetice Culture (see Figure 2.3).

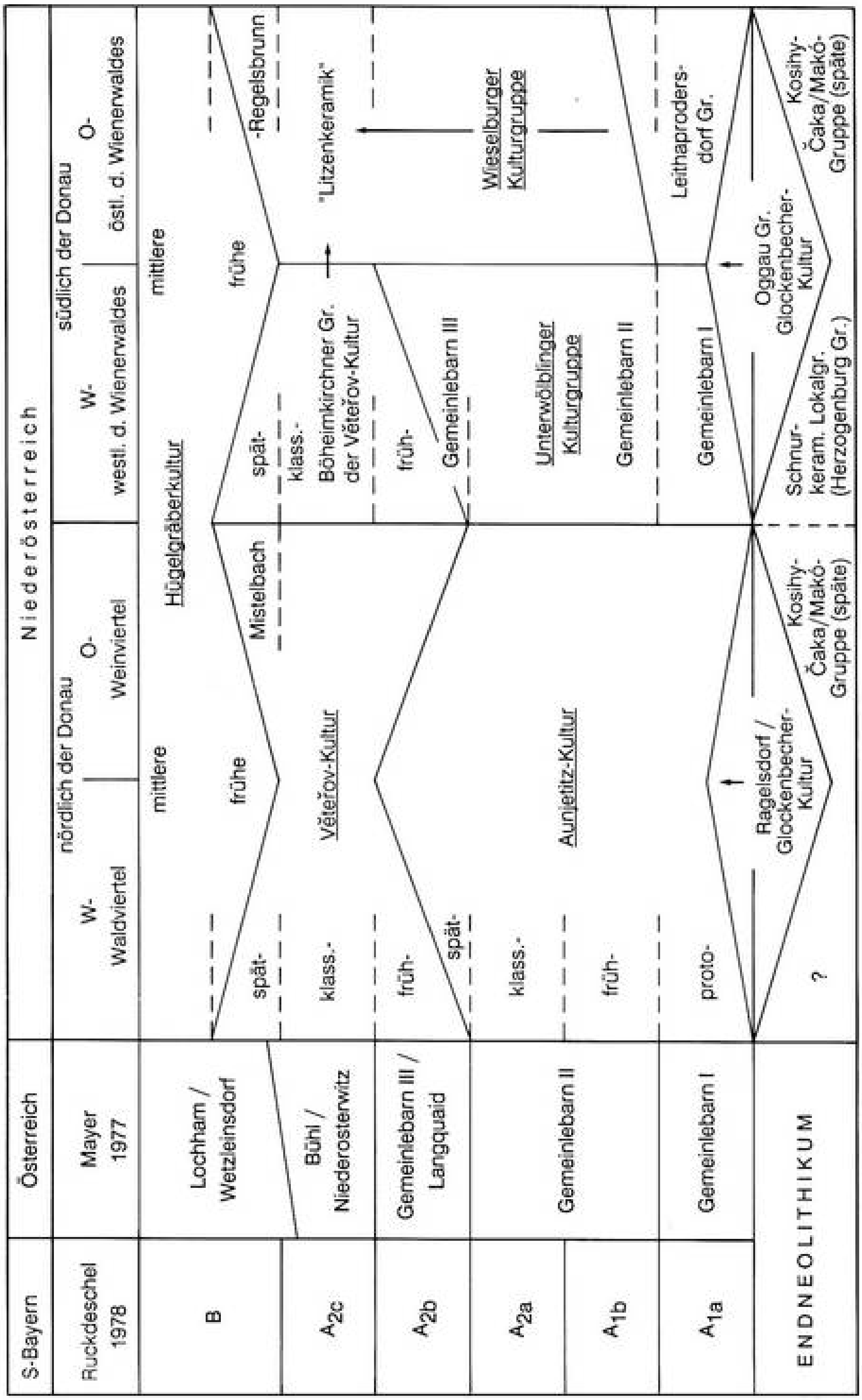

Figure 2.3. Chronology of cultural groups of the early Bronze Age in Lower Austria (From Neugebauer, 1994; Fig. 4).

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2.3 Early Bronze Age: the local Populations in east Austria

2.3.1 The Leithaprodersdorf group

At the beginning of the early Bronze Age (stage A1; see Figure 2.3), the Leithaprodersdorf group was widespread in Lower Austria in the southern Danubian area east of the Wienerwald. According to Ruttkay (1981), the groups evolved from the later phase of the Bell Beaker Culture under uncertain influences of south-eastern neighboring groups (e.g. Nitra groups and Nagyrèv Culture of west Hungary). The groups held a specific pottery, which showed a parallelization with the earlier stages of the Bohemian and Moravian Únetice Culture, and a similarity with the southern Danubian Unterwölbling group in the stage Gemeinlebarn I (Neugebauer, 1994). Their burial rite was similar to the Bell Beaker Culture for the presence of bipolar sex-specificity and a north-south orientation. Males and females lied in flexed position: the males on the left side with the head to north; the females on the right side, with the head to south. While the group settled the south-Danubian area in the stage A1, it seems likely that it was replaced by the Wieselburg group later on. The latter evolved a peculiar pottery and metallurgy, and characterized the early Bronze Age south-west danubian area along the stage A1b and A2b (Neugebauer, 1994).

2.3.2 The Wieselburg Culture

In the early Bronze Age, the Wieselburg Culture was located in Lower Austria east of the Wienerwald and between the Danube in the north, and the Raab in the south-east (Leeb, 1987). The Culture is also named Gáta Culture because of the material excavated in the site of Gattendorf (Burgend; ungar. Gata). According to Leeb (1987), traces of the presence of an Únetice-Wieselburg mixed group are identifiable in an area north of Bratislava in the Slovakia.

This Culture was archeologically separated from the other synchronous groups of eastern Austria (e.g. Únetice Culture, Unterwölbling Culture) by a specific metal inventory (sleeves head needles, globes head needles, bracelets, daggers) and a specific ceramics (funnel neck cups and funnel neck vessels, bails; see Figure 2.4).

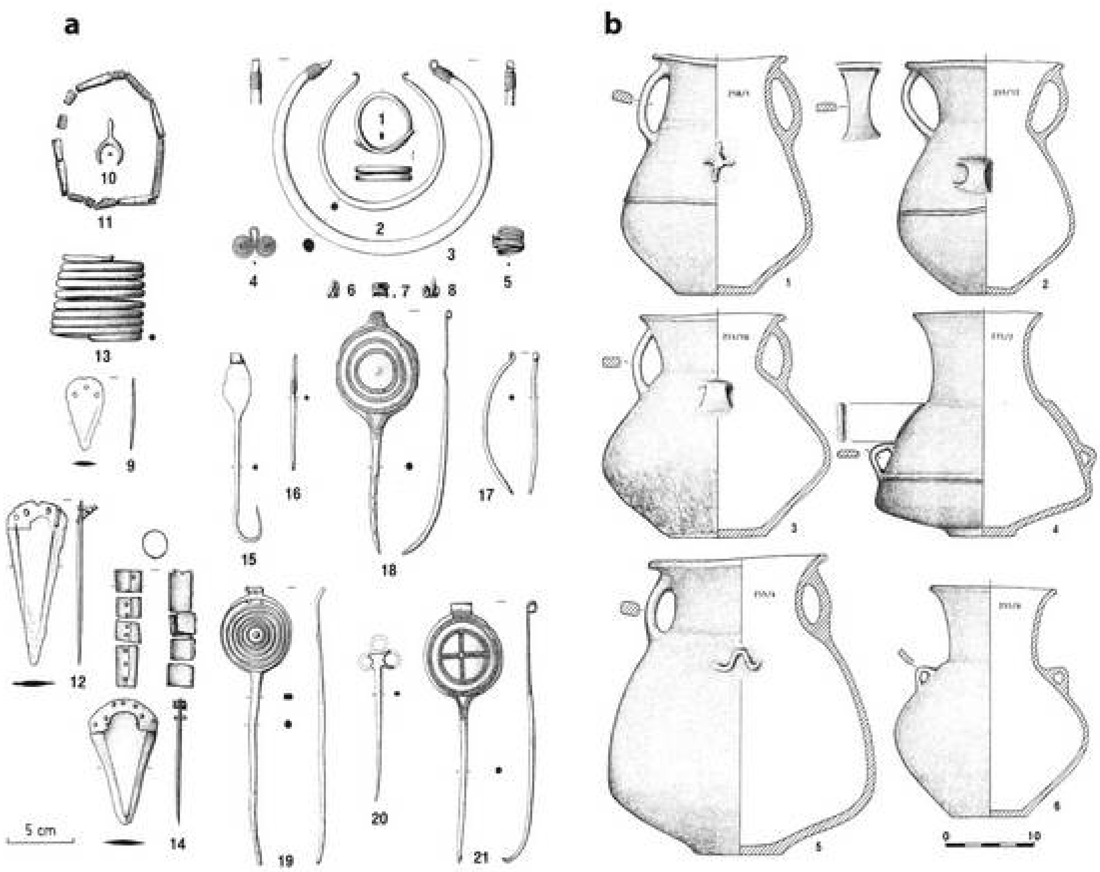

Figure 2.4. Grave goods belonging to the Wieselburg Culture (a) Metallurgy: site of Gattersdorf; (b) Pottery: site of Hainburg-Teichtal (From Neugebauer, 1994; Fig. 24, Fig. 31).

Similarly to the Endneolithic Cultures, the dead were buried in a flexed position. However, in contrast with the Corded Ware Culture and the Bell Beaker Culture, and the synchronous Unterwölbling Culture situated west of the Wienerwald as well, in this cultural group the bipolar sex-specific orientation is less consistent. The males lied mainly on the left side while the females lied on the right side. The head was orientated mainly to south-west and the body north-east; the view of the males was orientated to the north-west while the view of the females was orientated to the south-east. In Figure 2.5 a scheme proposed by Ehgartner (1959) is represented.

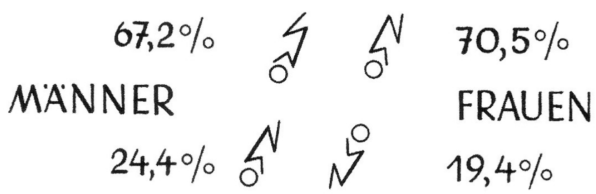

Figure 2.5. Representation of Ehgartner (1959) of the burial rite characterizing the Wieselburg Culture (From Neugebauer, 1994).

Referring to Neugebauer (1994), mixed inventories, which belong to the Leithaprodersdorf group and the Wieselburg group, have been found in burials discovered in the south-western Danubian areas. Following Neugebauer (1994), it seems likely that at the end of the A1 phase a temporary coexistence existed. According to Hicke (1987), however, a development of the Leithaprodersdorf group into Wieselburg group is not plausible because of the differences observed between the pottery and the metallurgic products between the two Cultures.

The more important necropolises representing the Wieselburg Culture are Gattendorf, Oggau, Mannersdorf and Hainburg-Teichtal. The dead were buried deep down into earth grave. Small tumuli ("Hügelgräber") were also generally used. In the sites of Hainburg-Teichtal and Mannersdorf, graves with wood internals and coffin were observed as well.

2.3.3 The Unterwölbling Culture

In the southern region of the Danube Alps foreland, between Enns and the Wienerwald, especially along the tributary streams of the Danube, was located the spreading area of the Unterwölbling Culture (Neugebauer and Neugebauer-Maresch, 1989). The name of this Culture was chosen by R. Pittioni, who analyzed the archeological material belonging to the site of Unterwölbling. However, the most important places of finding of this Culture are the site of Gemeinlebarn A and the two necropolises of Franzhausen (Franzhausen I and Franzhausen II), which have been the object of several study in the last 80 years. In particular, the Gemeinlebarn A site has been analyzed in its stratigraphy, in order to determine the chronological development of the southern Danubian cultural groups. In conjunction with the chronological system elaborated by the Ruckdeschel (1978), which divided the early Bronze Age in 5 stages in connection to a needle chronology of Bayern material, a parallel chronological system for Austria was elaborated by Mayer (1977). The latter divided the Austrian early Bronze Age in 3 phases, namely the Gemeinlebarn I, Gemeinlebarn II, Gemeinlebarn III phases (see figures 2.3).

Archeologically, the Unterwölbling Culture distinguished itself from the northern and the eastern south-Danubian groups by a special variation of the bronze jewellery (point-decorated coppers, bronze tin objects or neat pieces) and a specific type of ceramics (e.g., cups with division between neck and mouth seam and neck and body, dishes with grooves under the border and different top forms; see Figure 2.6).

Hitherto, the necropolis of Franzhausen I is the site which has been more deeply examined. In its north-eastern area, adjacent to early Bronze Age graves (stages Gemeinlebarn I and II), burials belonging to the Corded Ware Culture have been found. According to its stratigraphy, the early Bronze Age sites of Franzhausen I was occupied for about 700 years and encompasses nearly the full period of the early Bronze Age (2300/2200 till 1500 according to calibrated C-14 data). In the cemetery, the dead were buried in rectangular till oval cavities, whose dimensions were in relation to the living social status. The body lied in the lateral position in an extreme crouched position with a bipolar sex-specific orientation. The male lied on the left side with the head orientated to the north; the female lied on the right side with the head orientated to the south. The view of both males and females were orientated to the east. Therefore, the burial rite of the Unterwölbling Culture resembled strictly the one of the Bell Beaker Culture. Male and female graves have been determinate not just regarding the skeletal findings and the orientation of the body, but in relation to the grave goods too. Weapons as daggers, for example, were reserved to adult and young males. The bronze jewellery was carried by both males and females.

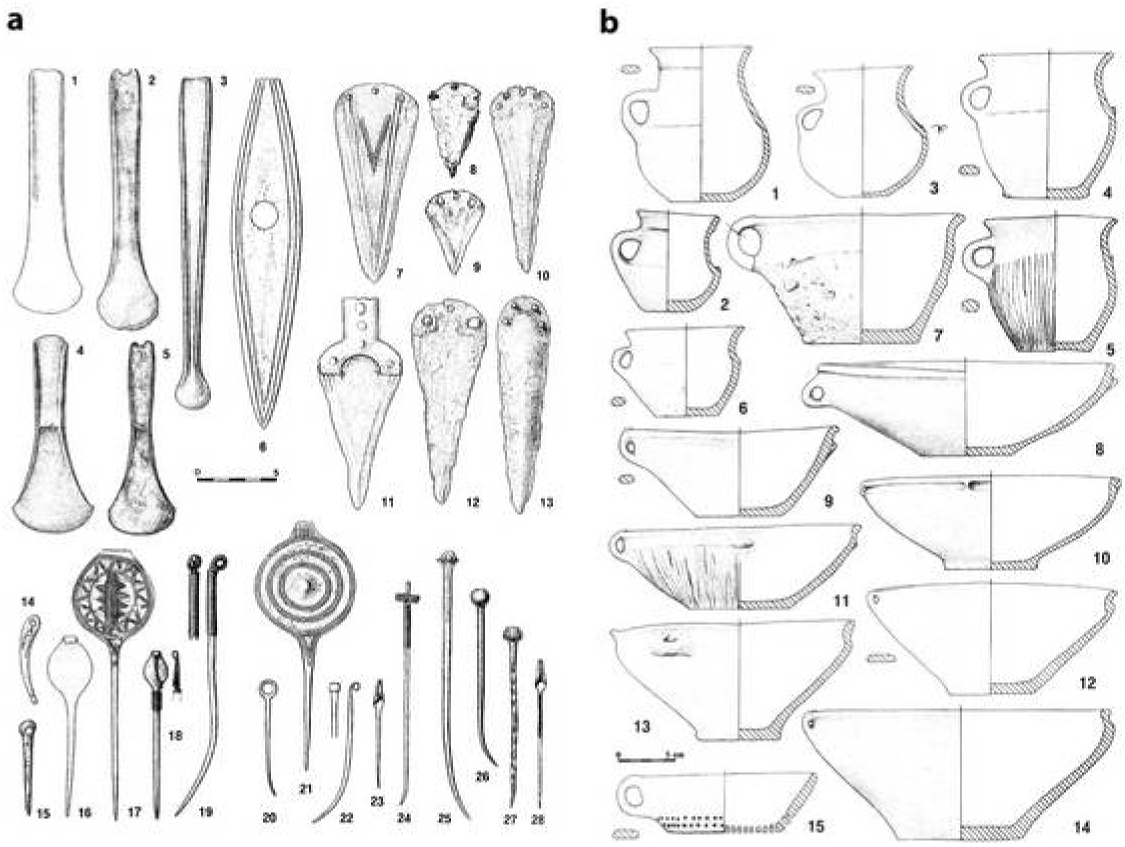

Figure 2.6. Grave goods of the Unterwölbling Culture (Franzhausen I). (a) Metallurgy. (b) Pottery (From Neugebauer, 1994; Fig. 33 and Fig. 35).

According to social-archeological analyses of that necropolis (Sprenger, 1996), types and numbers of the Bronze grave goods found in the burials are related to the social status of the individual. Referring to Sprenger (1996), the males with a higher social status were associated with the metallurgy. Following Sprenger, however, it is plausible that the Franzhausen I site was mainly a farming society, without a primary production of bronze artifacts. According to the convenient geographical position of the Franzhausen I site, it seems likely that the Traisental valley was a central point of trade processes. The latter brought primary metallurgic goods (e.g. copper) and basic material from the Slovakian and the east-alpine regions into the Unterwölbling province (Wind; Neugebauer-Maresch; Teschler-Nicola 1992; Neugebauer-Maresch, 1988) and witness the presence of interregional and intercultural relations between the regional cultural groups of Austria and Europe.

2.3.4 The Únetice Culture

In the early Bronze Age the Únetice Culture was widespread in most regions of middle Europe: Moravia, Bohemia, Saxony, Poland, and part of the eastern Austria. In the latter, the Únetice Culture was located north of the Danube, in the wine quarter, between Kamptal in the west and March in the east (Neugebauer, 1994). According to Neugebauer (1994), despite evidence of trade processes following the direction between the northern and southern Danubian area, there are few traces of the Únetice group in southern Lower Austria.

Concerning the archeological records examined in Moravia, 3 phases the Únetice Culture has been proposed (Stuchilovia and Stuchlik, 1989). The first phase, the Proto-Únetice belong to the Endneolithic. The second phase, the old-Únetice and the pre-Únetice, were collocated in the early stages of the early Bronze Age, namely the stages A1a and A1b. The third phase encompassed the classic- and the later Únetice Culture (stages A2a, A2b). In this development of the Únetice

Culture, connections with the Endneolithic Slovakian Caka-Mako and Nagyrév Cultures, as well as the Corded Ware and Bell Beaker Cultures, are also plausible (Neugebauer, 1994). According to Schubert (1973), however, the Lower Austria Únetice Culture differed from the northern Moravian Únetice Culture, and represented an advanced phase without a continuous development as the one observed in Moravia.

Up to now, in the Lower Austria Únetice Culture, no bigger grave fields have been found, but predominantly single findings and some small to medium-sized cemeteries, e.g. Bernhardstal, Schleinbach, Würnitz, Fels am Wagram, Größweikerdorf, Hippersdorf, Laa-Thaya (Scheibenreiter, 1953), are known. Archeologically, the Únetice Culture was characterized by a particular spectrum of pottery e.g. bowls, basins, pots, cups, small ceramic dishes (see Figure 2.7). Typical of the Austrian Únetice metal inventory were needles, nap rings, necklets and bracelets. The triangular daggers were usually weapons. (Figure 2.8)

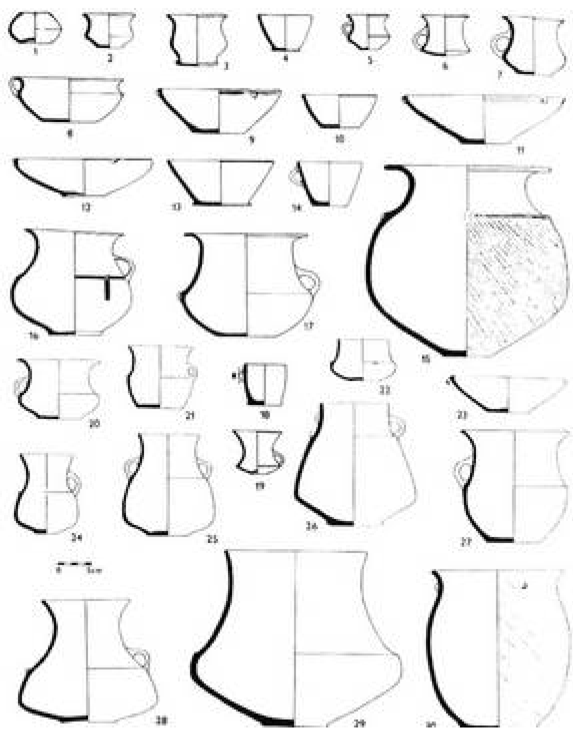

Figure 2.7. Spectrum of the pottery in the Únetice Culture: site of Bernhardstal. (From Neugebauer, 1994; Fig. 55).

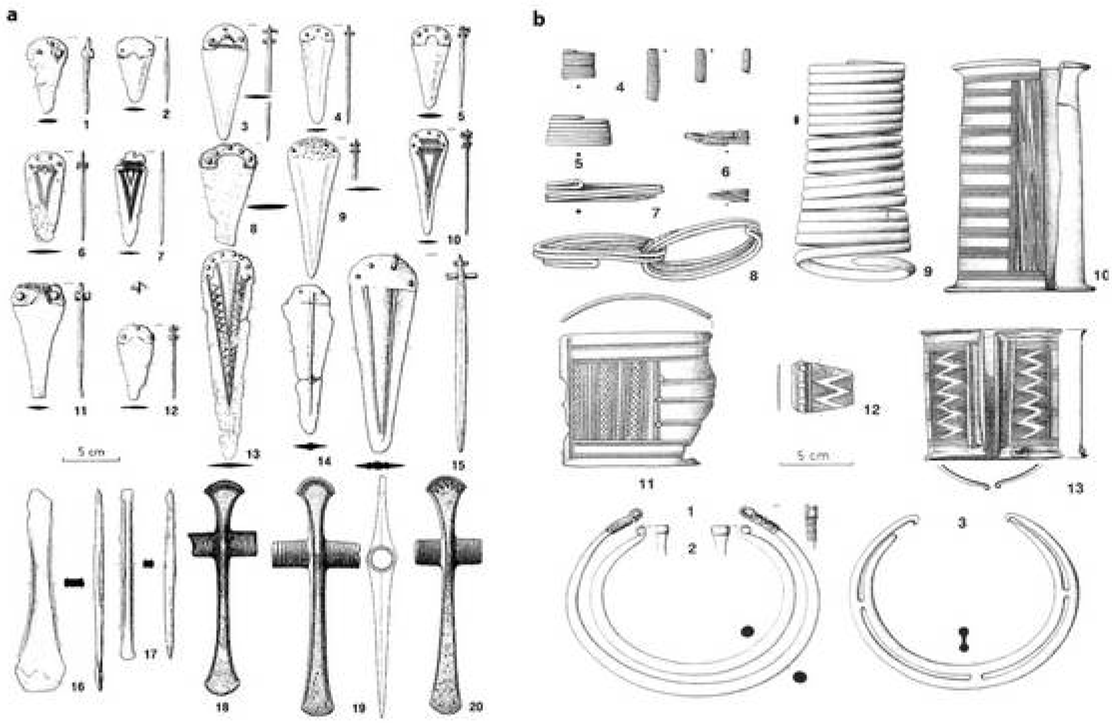

Figure 2.8. Metallurgy of the Únetice Culture. (a) Daggers and axes: site of Hippersdorf. (b) jewellery: site of Ebersdorf (From Neugebauer, 1994; Fig. 52, Fig. 53).

The grave had rectangular form and sometimes rounded edges. According to the result obtained by Lauermann (1991)**,** in the site of Unterhautzental (the most important sites of the Austrian Únetice Culture so far), the graves width and length, and in particular the depth and the use of coffins, were related to age, sex, and social status of the dead. Similarly to the south Danubian provinces, the dead were buried in the crouching position on one side. In analogy with the Bell Beaker Culture, the orientation of the bodies was the north-south direction with some deviations. Nevertheless, a bipolar sex-specificity was absent. Males and females lied both on the right side with the head orientated to the south. In the Únetice Culture the individual burials were common. According to Lauermann (1991), however, in comparison to the south-Danubian Cultures, a higher percentage of double or multiple burials has been found. Other special burials observed by Lauermann included bodies which lied in the extended and supine position.

2.3.5 Veterov Culture and Böheimkirchen group

In the later stages of the early Bronze Age, the Únetice Culture developed into the Veterov Culture. Referring to Neugebauer (1994), in 1929, the Austrian archeologist Herbert Mitscha-Märheim was the first archeologist to point out that in the transitional period between the early and middle Bronze Age a Culture with different characteristics from the Únetice Culture existed. This Culture was identified in the south-west Slovakia as the Mad`arovce Culture (Tocik and Vadlár, 1971). According to Tihelka (1960) elements of the presence of the later- Únetice Culture and the incoming Mad`arovce Culture were present in the east and south of the Moravian region. This Culture, which spread across the Moravian region in the phase between the early and the middle Bronze Age, was named “Veterov Culture” (Tihelka, 1960; 1961). Referring to Neugebauer (1994), in this transitional period, the groups who inhabited the northern Lower Austria belonged to the Veterov Culture as well. According to Neugebauer, the Veterov Culture had an impact in the south-west Danubian area, and developed into the regional Böheimkirchen group. However, it seems to be likely that the Veterov Culture did not replace the local Unterwölbling Culture, but influenced the latter at the end of the Stage Gemeinlebarn II.

The name Böheimkirchen group originates from the site of Böheimkirchen, which is located 10 kilometer from St. Pölten. Nevertheless, nowadays the most important site representing the Böheimkirchen group of the Veterov Culture is the necropolis F of Gemeinlebarn. The latter is situated 400 m easterly of the older site Gemeinlebarn A. The archeological materials excavated in the site of Gemeinlebarn F have been dated in the later phase of the early Bronze Age, namely the Gemeinlebarn III/Langquaid stadium (see Figure 2.3).

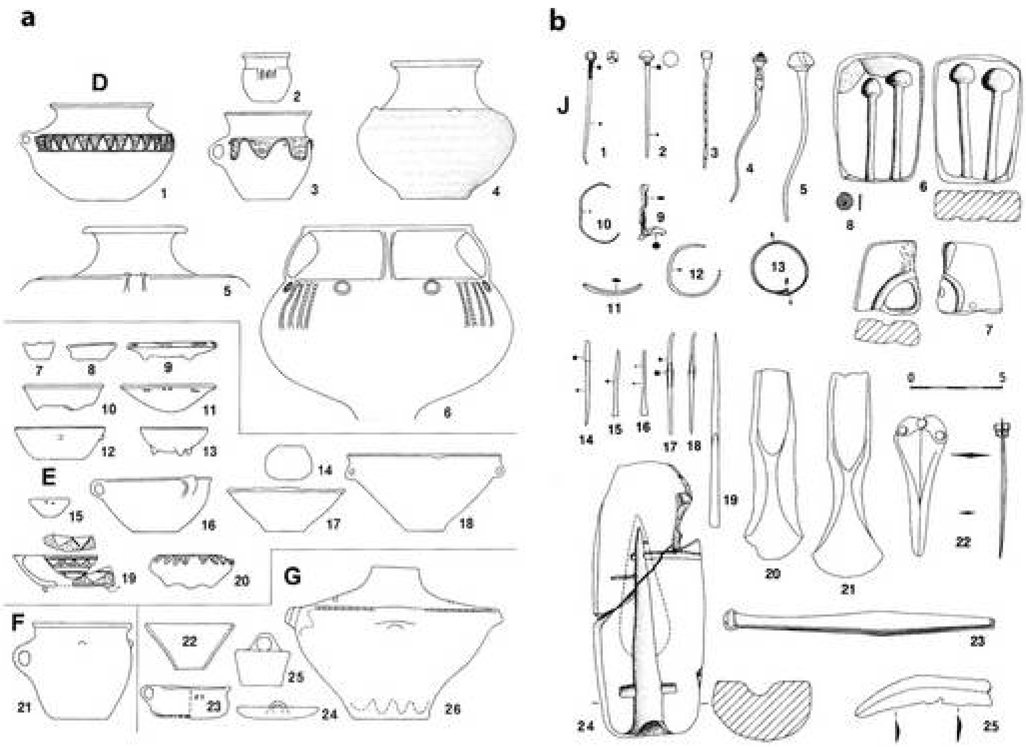

Figure 2.9. Grave goods of the Böheimkirchen group of the Veterov Culture. Site of Böheimkirchen. (a) Pottery. (b) Bronze objects (From Neugebauer, 1994; Fig. 68 and Fig. 70).

The pottery of the Gemeinlebarn F sites is typical of the Böheimkirchen group. The vessels were variedly decorated and showed vertical, horizontal and oblique incision. The form varied from keg cups to flagons, amphorae, bowls, dishes, funnels and filters (see Figure 2.9 a). The typical bronze object of the Veterov Culture excavated in Gemeinlebarn F regarded daggers, awls, bangles and garment needles (Figure 2.9b). The dead were buried in narrow, rectangular graves. The dimension of the burials, and their depth as well, were in relation with age, sex and social status of the dead. The burial rite was similar with the Bell Beaker Culture and the Unterwölbling Culture: the dead were buried in the crouching position in a north-south direction and a sex-specific orientation. In contrast with the Unterwölbling Culture, young males and young females were buried in the same way. The adult males were characterized by type of weapons (axes, daggers) and needles, while the adult females were characterized by the utensils for the leather handling and by the jewellery.

3 Anthropology of the Bronze Age in Lower Austria

3.1 Historical perspective

Referring to Teschler-Nicola (1992), the first anthropological studies on the Lower Austrian early Bronze Age populations date back to the end of the 19th and beginning of the 20th Century and focused on single places (Zuckerkandl, 1875; Schürer and Waldheim, 1919; Pöch, 1922; Lebzelter, 1923). According to the investigations of that time, these studies were predominantly focused on the recording on cranial features for "race" identification. Historically, the first broad investigation was carried out by Szombathy (1934), who examined the skeletal material allocated in the south-western Danubian province and archeologically assigned to the Unterwölbling Culture. Following the contemporary scientifically methodology, the author searched for "racial" features by applying anthropological concepts. Methodologically, he used a tabular composition in order to arrange the cranial skeleton according to their size, and the differences existing between them. The average morphology of the individuals was described as long and narrow, with a high cranial vault, a broad frontal bone, and a high and narrow face. Later on, Ehgartner (1959) could determine another morphological type in the south-eastern Danubian site of Hainburg, which have been assigned to the Wieselburg Culture because of its archaeological and cultural attributes. Following Ehgartner (1959), the morphological characters of the Hainburg population were, in comparison with the south-western Danubian population, a bigger breadth of the frontal bone, also apparent in the breadth of the face, and particular in lower height of the face. Regarding the Únetice Culture in northern Lower Austria, up to now smaller findings (Szombathy, 1934) or single findings have been excavated (Zuckerkandl, 1875; Schürer and Waldheim, 1919; Pöch, 1922; Lebzelter, 1923; Tuppa, 1935;

Weniger J., 1954; Weniger M., 1954; Grefen-Peters, 1982; Teschler-Nicola and Berner, 1991). Nearly all the investigations quoted at the investigation and identification of morphometrical characteristics of the Únetice people. The generalisation of the results of these investigations documents for this group elongated and narrow crania.

The previously mentioned study focused predominantly on the detection of the populations metrical and morphological variants in order to clarify questions of origin, but within the last decade, interest shifted to the analysis of type and frequency of pathological variation (Winkler 1985-86; Teschler-Nicola, 1987; Winkler and Groszschmidt 1987 a,b; Teschler-Nicola, 1988; Schultz 1988-89; Teschler-Nicola, 1988-89; Schultz and Teschler-Nicola, 1989; Teschler-Nicola and Berner, 1991; Pirsig, Ziemann-Becker and Teschler-Nicola, 1992; Teschler Nicola and Gerold, 2001; Novotny, 2005). The aim of these studies was the diagnosis of the type and frequencies of diseases, and the dispersion and developing of pathologies as well to shed light on living condition. To compare life expectancy of these prehistoric populations, further data based on the newly opened graves fields of the Traisen valley series with altogether 1228 burials have been acquired (Teschler-Nicola, 1992; Teschler-Nicola and Prossinger, 1992; Teschler-Nicola and Prossinger, 1997; Teschler Nicola and Gerold, 2001).

One of the most complete investigations about the entire Lower Austria series is the one conducted by Teschler-Nicola (1992). In her study, cranial and postcranial skeletal remains of 879 adult and sub-adult individuals were analyzed. The material was explored for metrical, epigenetic and morphognostic features, and paleodemographic investigations were carried out as well. The investigation of Teschler-Nicola provided descriptive analysis for the morphological attributes of each of the 79 sites analyzed, in term of interlandmark distances (e.g. maximum length or maximum width of crania) and distance ratios. Univariate and multivariate statistics were applied to these measurements in order to investigate the craniometrical differences among the inhabitants belonging to the main early Bronze Age Lower Austria cultural groups. Together with these studies, statistical analyses of epigenetic and morphognostic values described accurately the biological parameters of these populations. The results of Teschler-Nicola showed significant differences among the inhabitants of the – *a priori* archaeologically characterized – Bronze Age populations and were interpreted as the consequence of genetic dispositions and geographical barriers (e.g., the river Danube and the Wienerwald).

3.2 Paleopathological findings

Hitherto, the solely systematic analysis of populations' diseases and traumata of adult and subadult individuals is the one carried out by Novotny (2005). That study concerned the necropolis of Pottenbrunn-Ratzerdorf, which belongs to the south-western Danubian Unterwölbling Culture. Novotny was interested in the type and frequencies of population's diseases and traumata, and in the diagnostic criteria to define the timing of fracture events. The macroscopic, radiological and histological analyses of the skeletal material highlighted diseases due to nutrition problems, in particular Vitamin C deficiency. The latter was first identified by a modification of the alveolar area of the long bones and mandible in several individuals. This pathology was observed by 18.8% of the children and by the 50% of the adults. Anemic conditions were identified by Hyperostosis in the cranial vault and in the orbital area occurred in 58.6% of the individuals, and by Cribra orbitalia (50%). Vitamin C deficiency was also diagnosed by Pleuritis (16.6%) identified in the newly built bone structure of the ribs.

Important results gained by Novotny were achieved in analyses of sex-specific alteration of bone articulations. Examinations of the articular joints indicated increase of overstraining in the right shoulder, right elbow joint and ankle in males. In contrast, alterations of hand articulations were diagnosed in females. Following Novotny (2005), these results might indicate heavy work and high mobility in males (agriculture, hunting), and an overuse of the hand joint in females (e.g. handle and preparation of aliments).

Of great importance is also the investigation carried out by Ziemann-Becker (1992), which analyzed the frequencies of Otitis media in the necropolis of Franzhausen II. According to the results obtained, the males had higher frequencies inflammation of the ear ossicle. Following Ziemann-Becker (1992), this result may probably be caused by a higher mobility of males compared to females due to a more frequent stay in the open air, and hence, confirmed the findings obtained by Novotny (2005).

3.3 Demographical findings

During the last 15 years, many archaeological data have been acquired on the recently discovered graves of the Transley valley located in the south-western Danubian province. Referring to newly archaeological records, these graves have been assigned to the Unterwölbling culture (stage Gemeinlebarn II), and to the Böheimkirchen group of the Veterov Culture (stage Gemeinlebarn III). Besides archaeological studies, the skeletal materials belonging to four necropolises – Franzhausen I, Franzhausen II, Pottenbrunn-Ratzerdorf and Gemeinlebarn F- have been the object of several investigations (Berner, 1988; Berner and Wiltschke-Schrotta, 1992; Teschler-Nicola, 1992; Teschler Nicola and Gerold, 2001). Along with the identification of sex and age of individuals at death, demographic data collected over 1228 burials of these sites have been analyzed in order to shed light on life quality and life expectancy of these early Bronze Age populations (Teschler-Nicola and Prossinger, 1992; Teschler-Nicola and Prossinger, 1997).

Altersgruppe	Franzhausen I	Franzhausen II	Gemeinlebarn F	Pottenbrunn
	n=757	n=134	n=258	n=79
1	0,7	0,0	0,6	0,3
2	16,2	15,3	14,2	20,0
3	8,1	5,0	4,6	2,5
4	11,7	11,3	8,6	11,7
5	2,3	4,3	2,1	0,5
6	5,8	4,4	6,5	10,7
7	7,9	7,1	8,2	11,8
8	28,2	26,9	28,8	22,2
9	15,6	17,7	17,5	15,9
10	3,5	8,0	8,8	4,3

Table 3.1. Series of the Traisen Valley: mortality rates in age classes. The age classes are according to Heinrich and Teschler-Nicola (1991). 1= 0.2; 2= 0.2-6; 3= 6-8; 4= 8-13; 5= 13-15; 6= 15-19; 7= 19-22/24; 8= 22/24-40; 9= 40-60; 10 = 60-80. (From Teschler-Nicola and Prossinger, 1997).

According to their stratigraphy, the four sites differ in their chronology. The data collected were thus analyzed to yield insights into changes of life quality during the phases of the early Bronze Age. The site of Franzhausen I is the most representative necropolis of the territory and encompasses nearly the full period of the early Bronze Age (e.g. the stages Gemeinlebarn I, II, III). However, most of the graves analyzed by Teschler-Nicola and Prossinger (1997) were assigned to the middle phase of the early Bronze Age. At this stage were also dated the necropolis of Pottenbrunn-Ratzerdorf. The sites of Franzhausen II and Gemeinlebarn F were assigned to the late phase of the early Bronze Age instead.

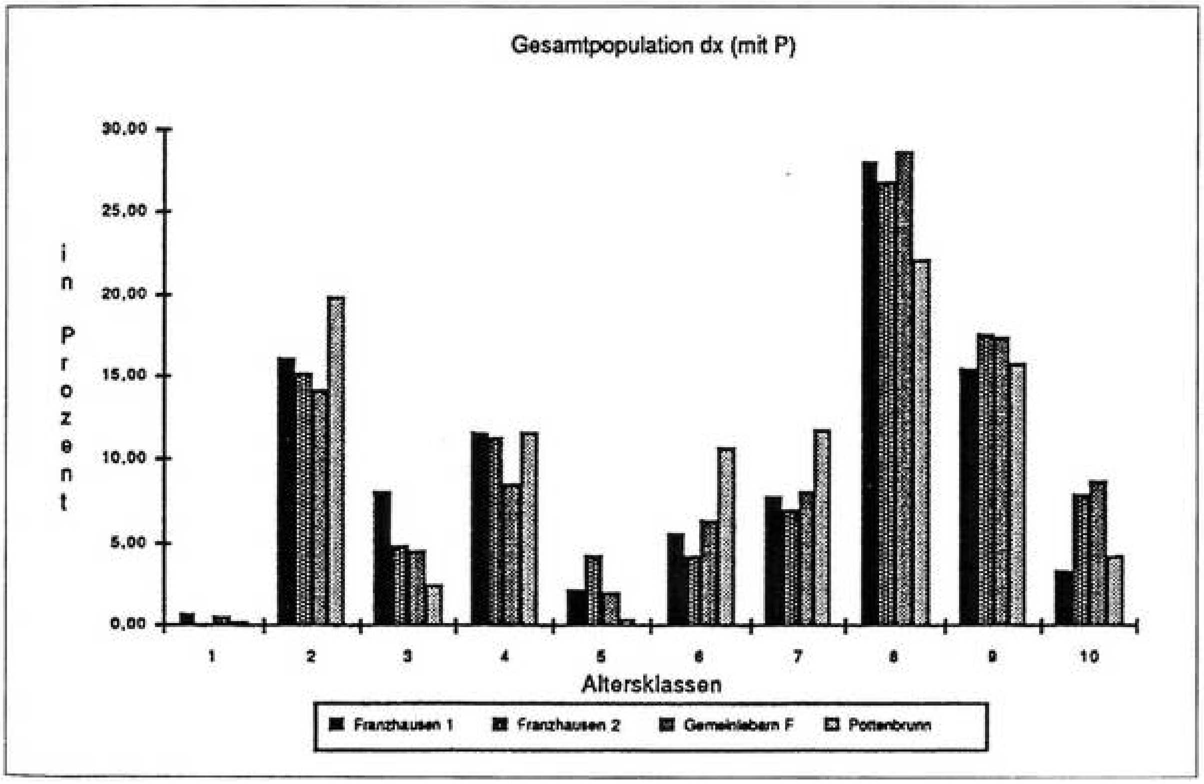

Figure 3.1. Mortality rates in the Traisen Valley. Age classes as in Table 2.1 (From Teschler-Nicola and Prossinger, 1997).

The results of the demographic analyses are summarized in Table 2.1 as well as in Figure 2.1 and Figure 2.2. The mortality rates of the sub-adults (0-19 years) varied between 36.6% (Gemeinlebarn F) and 45.7%. Considering the great amount of individual analyzed, all the four Necropolises showed a deficit of infants and young children. Following Teschler-Nicola and Prossinger (1997), such a deficit might be in relation to specific burial rites of the early Bronze Age population, as the children could have been buried in a particular place of the cemetery; on the other hand, excavation technique used in the territory could have destroyed part of the necropolis where infants and young were buried.

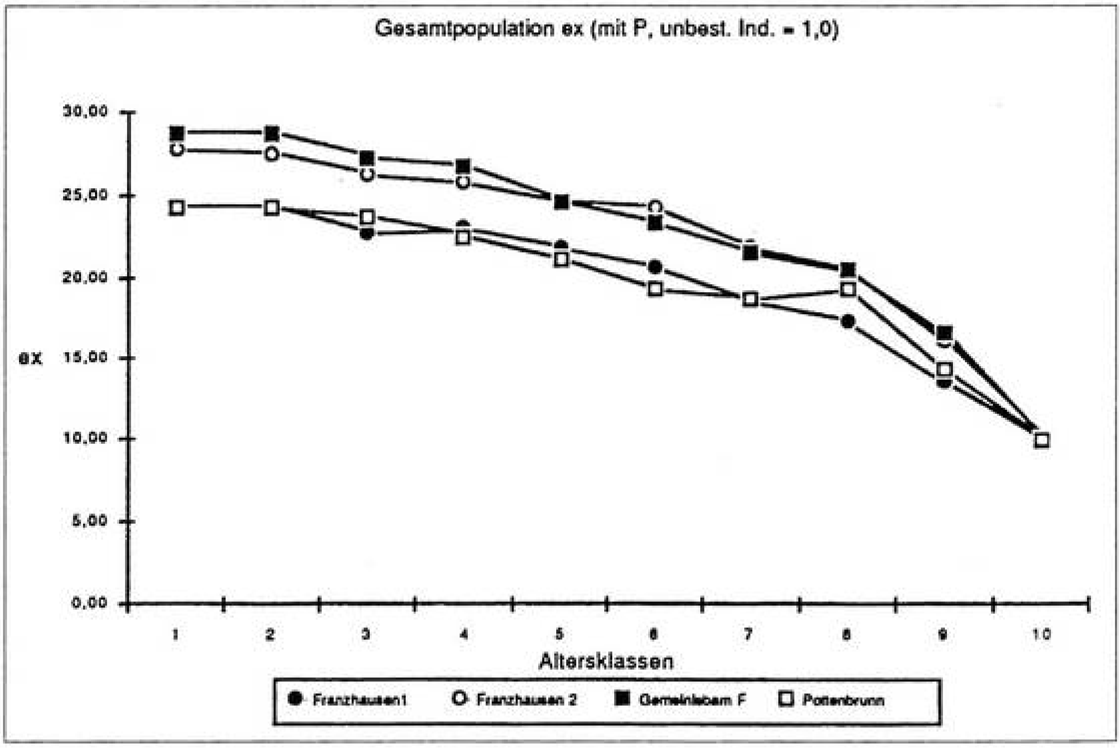

Figure 3.2. Early Bronze Age series of the Traisen Valley: life expectancy in each age classes. (From Teschler-Nicola and Prossinger, 1997).

These analyses indicated that the older populations represented by Franzhausen I and Pottenbrunn-Ratzerdorf had a life expectancy of 23.9 and 24.0 years, which is distinctly lower than the younger populations of Franzhausen II and Gemeinlebarn F, which had respectively expectancy of life of 27.2 and 28.9 years (see Figure 2.2). Following Teschler-Nicola and Prossinger (1997), these results may reflect an improvement of the life condition (e.g. ecological or alimental condition) in the later phase of the early Bronze Age. Nevertheless, according to Teschler-Nicola and Prossinger (1997), a statement about a generally improvement of the life conditions in the late early Bronze Age requires the analysis of additional skeletal material, and the analysis of the environmental condition in each early Bronze Age phases as well.

3.4 Craniometrical findings

Hitherto, the investigation conducted by Teschler-Nicola (1992) is the unique study which has examined the entire Lower Austria early Bronze Age series. As the morphometrical analysis of cranial skeletons carried out by Teschler-Nicola is of particular concern for the present study, methodology and results obtained by Teschler-Nicola are introduced in this chapter.

The craniometrical analysis of Teschler-Nicola was conducted with methods that used to be called "conventional multivariate morphometrics" (Blackith and Reyment, 1971). This style of morphometrics, which is nowadays frequently referred to "traditional morphometrics", is usually applied to a wide range of different measurements, such as linear distances and distance ratios, angles, areas and volumes (Marcus, 1990). In this tradition, the most frequently applied multivariate statistical tools have been principal components analysis, factor analysis, canonical variates analysis, discriminant function analysis, and cluster analysis. In her investigation, Teschler-Nicola provided descriptive analysis for morphological attributes of the individual analyzed, in term of interlandmark distances (e.g. maximum length or maximum width of crania) and distance ratios. Univariate and multivariate statistics were applied to these measurements in order to investigate biological differences between the archeologically pre-defined early Bronze Age Lower Austria populations.

The material investigated by Teschler-Nicola concerned mainly skeletal material belonged to the middle phase of the early Bronze Age (namely the Gemeinlebarn II stage). Three synchronous groups were considered: North of the Danube the Únetice Culture, south of the Danube the Unterwölbling Culture (west of Wienerwald) and the Wieselburg Culture (east of Wienerwald).

The descriptive craniometrical analysis was carried out by separating groups and sex. In Table 2.2 the values obtained for males are summarized. Of particular interest for our investigation are the cranial indices, which represent aspect of shape (see chapter 5.2.2). Regarding the length-breadth index, the Únetice and

Unterwölbling males were described as dolichocranic, while the Wieselburg as mesocranic. Concerning the breadth-height index, the Únetice and Unterwölbling males were marked by acrocrany and the Wieselburg group by metriocrany. No differences in shape between the three main groups were found in the length-height index that characterizes the populations as hypsicranic. The facial shape differences were described by the nasal index (leptorrhin for the Únetice males; chamaerrhin for the Unterwölbling males) and the maxilloalveolar index, which differentiates between the Únetice group (Brachyuranic) and the Unterwölbling group (Hyperbrachyuranic).

Besides descriptive statistic, Teschler-Nicola performed univariate analyses of many variables, testing whether the *a priori* archeological defined groups differed significantly for each variable. First, Teschler-Nicola conducted parametrical statistic tests: the Analysis of Variance and the Student-Newman-Keuls test (Table 2.3-2.4). Secondly, the non-parametric Kruskal-Wallis test, and the Mann-Whitney test were used to confirm the results of the first analyses (Tables 2.5-2.12). Regarding the males, the Analysis of Variance and the Student-Newman-Keuls test (Table 2.3) showed significant differences between populations in the length of the Neurocranium. Significant statistical differences between the males of groups were also found for variables such as the length of the foramen magnum, the palate length, the orbital breadth, the orbital sinew, and the breath of the mandible condyle.

Variable	G1	G2	G3
Größte Schädellänge	mittellang	mittellang	mittellang
Schädelbasislänge	lang	lang	mittellang
Größte Schädelbreite	schmal	mittelbreit	mittelbreit
Längen-Breiten-I.	dolichocran	dolichocran	mesocran
Kl. Stirnbreite	mittelbreit	mittelbreit	mittelbreit
Gr. Stirnbreite	schmal	breit	schmal
Basion-Bregma-H.	hoch	hoch	mittelhoch
Ohr-Bregma-Höhe	mittelhoch	hoch	hoch
Längen-Höhen-I.	hypsicran	hypsicran	hypsicran
Breiten-Höhen-I.	acrocran	acrocran	metriocran
Längen-Ohr-Bregmah.I.	orthocran	hypsicran	hypsicran
Breiten-Ohr-Br.höh.I.	metriocran	metriocran	metriocran
Schädelumfang	mittel	mittel	mittel
Mediansagittalbogen	groß	groß	mittel
Transversalbogen	mittel	mittel	mittel
Ganzgesichtshöhe	mittelhoch	mittelhoch	mittelhoch
Nasenhöhe	hoch	mittelhoch	-
Nasenbreite	mittelbreit	mittelbreit	mittelbreit
Nasal-Index	leptorrhin	chamaerrhin	-
Orbitalbreite	weit	weit	-
Orbialhöhe	nied./mitt.	nied./mitt.	nied./mitt.
Orbialindex	chamaecon.	chamaecon.	-
Mailloalveolar-I.	brachyuran.	hyperbrachyur.	-
Gaumenlänge	lang	kurz	-
Gaumenbreite	mittel	mittel	-
Gaumenindex	brachystaph.	hyperbrachyst.	-
Unterkieferwinkelbreite	mittel	mittel	eng

Table 3.2. Teschler-Nicola craniometrical descriptive analysis for males. G1= Únetice culture; G2= Unterwölbling culture; G3= Wieselburg culture. (From Teschler-Nicola, 1992).

Concerning the male craniometrical indices, the groups differed statistically in length-breadth index, and orbital index. In contrast, the Analysis of Variance and Student-Newman-Keuls test for females yielded fewer significant differences. Following Teschler-Nicola (1992), this result may be due to the smaller female sample size analyzed.

Ergebnisse der Varianzanalyse: Cranialmaße und Indizes, männliche Individuen.
G1 = nördlich der Donau, G2 = südlich der Donau und westlich des Wienerwaldes, G3 = südlich der Donau und östlich des Wienerwaldes, * = signifikante Unterschiede beim paarweisen Vergleich (Student-Newman-Keuls-Test)

Nr.	Maßbezeichnung	P(F) Zw.d.G	P(F) Hom.d.Var.	G1/2	G1/3	G2/3
9	Gr. Schädellänge	0,028	0,292		*	*
10	Glabella-Lambdalänge	0,008	0,674		*	*
11	Schädelbasislänge	0,045	0,136	*		
14	Größte Stirnbreite	0,039	0,764	*		
20	Länge For. magnum	0,001	0,808	*		*
22	Parietalsehne	0,050	0,296		*	
31	o-po (li.)	0,042	0,000			*
34	Mediansagittalbogen	0,059	0,553			*
45	Ohrjochbogenlänge (li.)	0,005	0,122		*	*
46	Untere Gesichtslänge	0,041	0,161	*		
72	Orbitalbreite (li.)	0,024	0,343		*	*
76	Orbitalsehne Os. front.(li.)	0,045	0,221		*	*
102	Gaumenlänge	0,035	0,533		*	*
103	Vord.max.Gaumenlänge	0,041	0,672	*		
117	Kondylenbreite d. UK	0,006	0,462		*	*
124	Kinnhöhe	0,050	0,431	*		
136	Kl. Asthöhe (li.)	0,009	0,644		*	*
147	Länge Cap.mand. (re.)	0,019	0,886			*
148	Länge Cap.mand. (li.)	0,000	0,400		*	*
151	For. mand.-Unterr. Corpus	0,018	0,881		*	*
168	M1-M2 d.Uk. (li.)	0,055	0,084	*		
195	o-mf (re.)	0,038	0,415	*		
196	o-mf (li.)	0,003	0,502	*		*
197	o-2 (re.)	0,028	0,129			*
198	o-2 (li.)	0,001	0,684	*		*
199	o-ek (re.)	0,007	0,133	*		*
200	o-ek (li.)	0,006	0,183	*		
202	o-4 (li.)	0,006	0,544	*		*
253	Occipitalneigungswinkel	0,022	0,705		*	
254	Stirnneigungswinkel	0,022	0,917		*	*
I1	Längen-Breiten-Index	0,039	0,689		*	*
I4	Längen-Ohr-Bregmahöhen-Index	0,001	0,358		*	*
I41	Orbital-Index (li.)	0,038	0,643		*	*
I48	Nasal-Index	0,021	0,871	*		
I58	Gaumen-Index	0,010	0,706	*		

Table 3.3. Analysis of Variance and Student-Newman-Keuls test for males. Significant differences ($p < 0.05$) obtained with pairwise comparison with the Student-Newman-Keuls test are signed with * (From Teschler-Nicola, 1992).

Significant differences between the females of the groups were found for variables concerning the dimensions of the viscerocranium, e.g. the interorbital breadth, the palate breadth, and the size of the mandible (Table 2.4).

Besides, for males and for females as well, the monovariate analyses performed with non-parametric test showed similar results to the ones achieved with the parametric test (Kruskal-Wallis test, and Mann-Whitney test; see Table 2.5-2.12). Summarizing these data, Teschler-Nicola (1992) concluded that the monovariate analyses of many variables indicated a high degree of statistically significant differences between the groups that were divided following their archeological attributes.

Ergebnisse der Varianzanalyse: Cranialmaße weibliche Individuen. G1 = nördlich der Donau, G2 = südlich der Donau und westlich des Wienerwaldes, G3 = südlich der Donau und östlich des Wienerwaldes, * = signifikante Unterschiede beim paarweisen Vergleich (Student-Newman-Keuls-Test)

Nr.	Maßbezeichnung	P(F) Zw.d.G	P(F) Hom.d.Var.	G1/2	G1/3	G2/3
30	o-po (re)	0,022	0,265	*		
65	Vord. Interorbitalbreite	0,000	0,278	*		
111	Vordere Gaumenbreite	0,097	0,056		*	
129	Dicke d.Cor.mand.For.ment(re.)	0,047	0,097	*		
139	Astbreite (re.)	0,015	0,073	*		*
161	Zahnbogenlänge UK	0,063	0,868	*		
163	Dentallänge UK.(re.)	0,023	0,727	*		
165	Molarenlänge UK. (re.)	0,049	0,967		*	
190	b-2 (li.)	0,004	0,603	*	*	*
203	mf-po (re.)	0,051	0,573	*		

Table 3.4. Analysis of Variance and Student-Newman-Keuls test for females. Significant differences obtained with pairwise comparison with the Student-Newman-Keuls test are signed with * (From Teschler-Nicola, 1992).

Ergebnisse des KRUSKAL-WALLIS-TESTS (männliche Individuen, *= die von der Varianzanalyse abweichenden Ergebnisse).

		N	X	P	
10	Glabella-Lambdalänge	96	7,08	0,03	
11	Schädelbasislänge	40	6,71	0,03	
14	Größte Stirnbreite	100	5,95	0,05	
20	Länge Foramen Magnum	30	10,69	0,00	
22	Parietalsehne	120	8,63	0,01	
25	Mediansaggitalsehne	63	6,23	0,04	*
45	Ohrjochbogenlänge (li.)	29	6,59	0,04	
102	Gaumenlänge	17	7,60	0,02	
103	Vordere max. Gaumenlänge	28	7,00	0,03	
117	Kondylenbreite d. Unterkiefers	67	6,54	0,04	
136	Kleine Asthöhe (li.)	71	10,36	0,01	
147	Länge d. Cap. mand. (re.)	37	6,81	0,03	
148	- " - (li.)	38	10,64	0,00	
152	For. mand. - Unterr. Corpus (li.)	98	6,76	0,03	
171	O-FMO (re.)	58	6,59	0,04	*
172	- " - (li.)	57	8,71	0,01	*
253	Occipitalneigungswinkel	20	6,61	0,04	
I 4	Längen-Ohr-Bregmahöhen-Index	88	12,7	0,00	
I48	Nasal-Index	39	6,26	0,04	
I58	Gaumen-Index	15	8,03	0,02	

Table 3.5. Kruskal-Wallis test for males. The results that differ from the analysis of variance are signed with * (From Teschler-Nicola, 1992).

Ergebnisse des KRUSKAL-WALLIS-TESTS (weibliche Individuen, *= die von der Varianzanalyse abweichenden Ergebnisse).

	N	X	P	
65 Vordere Interorbitalbreite	24	13,41	0,00	
111 Vordere Gaumenbreite	16	6,00	0,05	
153 Zahnbogenlänge OK.	9	6,00	0,01	*
161 Zahnbogenlänge UK	20	6,26	0,04	
163 Dentallänge UK (re.)	18	7,59	0,02	

Table 3.6. Kruskal-Wallis test for females. The results that differ from the analysis of variance are signed with * (From Teschler-Nicola, 1992).

Ergebnisse des MANN-WHITNEY-U-TESTS G1/2 - männliche Individuen (Maßnummer entspricht der Nummer im Befundbogen, *=die von der Varianzanalyse abweichenden Ergebnisse).

		N	z	p	
11	Schädelbasislänge	36	-2.19	0.03	
14	Größte Stirnbreite	89	-2.33	0.02	
20	Länge Foramen magnum	25	-2.69	0.01	
31	o-po (li)	46	-2.00	0.04	*
45	Ohrjochbogenlänge (li)	25	-1.95	0.05	*
56	Obergesichtsbreite	82	-2.09	0.04	*
102	Gaumenlänge	14	-2.40	0.02	*
103	Vord. max. Gaumenlänge	25	-2.56	0.01	
104	Gaumenlänge bis Sp.spina	10	-1.92	0.05	*
118	Cor. Br. d. Unterkiefers	36	-2.14	0.03	*
124	Kinnhöhe	111	-2.06	0.04	
149	For. Mand. - go	65	-1.95	0.05	*
168	M1-M2 Unterkiefer (li)	70	-2.26	0.02	
I48	Nasal-Index	37	-2.17	0.03	
I58	Gaumen-Index	12	-2.19	0.03	

Table 3.7. Mann-Whitney-U-Test between the Únetice culture (G1) and the Unterwölbling culture (G2) for males. The results that differ from the analysis of variance are signed with * (From Teschler-Nicola, 1992).

Ergebnisse des MANN-WHITNEY-U-TESTS G2/3 - männliche Individuen (Maßnummer entspricht der Nummer im Befundbogen, *= die von der Varianzanalyse abweichenden Ergebnisse).

		N	z	p	
10	Glabella-Lambdalänge	63	-2.23	0.03	
12	Größte Schädelbreite	49	-2.14	0.03	*
22	Parietalsehne	79	-2.62	0.00	*
34	Mediansagittalbogen	46	-1.95	0.05	
36	Parietalbogen	80	-1.93	0.05	*
45	Ohrjochbogenlänge (li)	19	-1.96	0.03	
72	Orbitalbreite (li)	18	-2.12	0.03	
136	Kleinste Asthöhe	46	-3.00	0.00	
148	Länge d. Cap. mandibulae (li)	21	-3.05	0.00	
152	For.mand.-Unterr.d.corp. (li)	60	-2.47	0.01	
253	Occipitalneigungswinkel	12	-2.14	0.03	*
254	Stirnneigungswinkel	15	-2.05	0.04	
I4	Längen-Ohr-Bregmahöhen-Index	58	-3.09	0.00	
I41	Orbital-Index (li)	13	-2.31	0.02	

Table 3.8. Mann-Whitney-U-Test between the Unterwölbling group (G2) and the Wieselburg group (G3) for males. The results that differ from the analysis of variance are signed with * (From Teschler-Nicola, 1992).

Ergebnisse des MANN-WHITNEY-U-TESTS G1/3 - männliche Individuen (Maßnummer entspricht der Nummer im Befundbogen, *= die von der Varianzanalyse abweichenden Ergebnisse).

		N	z	p	
10	Glabella-Lambdalänge	52	-2.61	0.03	
16	Basion-Bregmahöhe	24	-2.21	0.02	
20	Länge Foramen magnum	16	-2.56	0.01	*
22	Parietalsehne	64	-2.68	0.04	
25	Mediansagittalsehne	60	-2.11	0.05	*
36	Parietalbogen	64	-1.97	0.04	*
72	Orbitalbreite (li)	15	-2.09	0.02	
102	Gaumenlänge	8	-2.24	0.01	
117	Kondylenbreite d. Unterkiefers	46	-2.05	0.05	
132	Dicke d. Corp.i.N. v. M2 (li)	56	-2.22	0.03	*
136	Kleinste Asthöhe (li)	36	-2.96	0.02	
147	Länge d. Cap. mand. (re)	23	-2.39	0.01	*
148	Länge d. Cap. mand. (li)	21	-3.05	0.04	
152	For.mand.-Unterr.corp. (li)	55	-2.24	0.05	
166	Molarenlänge d. Unterk. (li)	44	-1.95	0.04	*
171	o-fmo (re)	31	-2.35	0.02	*
I1	Längen-Breiten-Index	44	-2.24	0.03	
I4	Längen-Ohr-Bregmahöhen-Index	44	-3.52	0.00	

Table 3.9. Mann-Whitney-U-Test between the Únetice group (G1) and the Wieselburg group (G3) for males. The results that differ from the analysis of variance are signed with * (From Teschler-Nicola, 1992).

Ergebnisse des MANN-WITHNEY-U-TESTS G1/2 - weibliche Individuen (Maßnummer entspricht der Nummer im Befundbogen, *= die von der Varianzanalyse abweichenden Ergebnisse).

		N	z	p	
65	Vordere Interorbitalbr.	22	-3.91	0.00	
120	Vordere Unterkieferbreite	33	-1.96	0.05	*
128	Höhe d.Corp.i.Niveau M2 (li)	31	-2.19	0.03	*
139	Astbreite (re)	25	-2.03	0.04	
153	Zahnbogenlänge d. Ok.	9	-2.46	0.01	*
161	Zahnbogenlänge d. Uk.	18	-2.22	0.03	
163	Dentallänge d. Uk. (re)	14	-2.32	0.02	
177	O-ZM (re)	8	-2.01	0.04	*
178	O-ZM (li)	9	-2.06	0.04	*

Table 3.10. Mann-Whitney-U-Test between the Únetice group (G1) and the Únetice group (G3) for females. The results that differ from the analysis of variance are signed with * (From Teschler-Nicola, 1992).

Ergebnisse des MANN-WITHNEY-U-TESTS G2/3 - weibliche Individuen (Maßnummer entspricht der Nummer im Befundbogen, *= die von der Varianzanalyse abweichenden Ergebnisse).

		N	z	p	
22	Parietalsehne	31	-2.23	0.03	*
77	Orbitalhöhe (re)	6	-1.99	0.05	*
168	M1-M2 d. Uk. (li)	18	-2.08	0.04	*
I1	Längen-Breiten-Index	26	-1.95	0.05	*

Table 3.11. Mann-Whitney-U-Test between the Unterwölbling group (G2) and the Wieselburg group (G3) for females. The results that differ from the analysis of variance are signed with * (From Teschler-Nicola, 1992).

Ergebnisse des MANN-WITHNEY-U-TESTS G1/3 - weibliche Individuen (Maßnummer entspricht der Nummer im Befundbogen, *= die von der Varianzanalyse abweichenden Ergebnisse).

		N	z	p	
9	Größte Schädellänge	36	-1.89	0.06	*
38	Transversalbogen	30	-2.03	0.04	*
101	Vordere Maxilloalveolarbr.	11	-1.89	0.06	*
111	Vordere Gaumenbreite	12	-2.31	0.02	
118	Coronoide Br. d. Unterkiefers	13	-1.96	0.05	*
150	For. mand. - GO (li)	25	-2.18	0.03	*
163	Dentallänge d. Uk. (re)	12	-2.21	0.03	*
165	Molarenlänge d. Uk. (re)	16	-2.17	0.03	*

Table 3.12. Mann-Whitney-U-Test between the Únetice group (G1) and the Wieselburg group (G3) for females. The results that differ from the analysis of variance are signed with * (From Teschler-Nicola, 1992).

The multivariate analyses of Teschler-Nicola included Cluster analysis and Discriminant analysis. Cluster analysis (Sneath and Sokal, 1973) is a method that analyses variables using ungrouped data sets and quantifies similarity or dissimilarity between individuals. Before proceeding to the analysis, a number of variables were chosen and reduced into a lower dimensionality of independent factors. The results of the cluster analysis are summarized in Figures 2.3-2.8. The first analysis of males (Figure 2.3) used 7 variables and showed a clear separation of the individuals in two main clusters, which were combined with a Δ E of 46.3 (where Δ E is a measure of the distance between two clusters; see Sneath and Sokal, 1973). A group-specific partitioning was not evident. Individuals of the same site, or same region, were closely associated instead. Similarly, in the first analysis of females (Figure 2.4), a separation in two main clusters was also present. The clusters, however, were combined with a Δ E of 16.8, which is lower in comparison with that achieved in males. In the second analysis 4 variables were used. In the males (Figure 2.5) two main clusters with a Δ E of 75.9 were present. However, they were heterogenic composed and it was not possible to remark any group-specific belonging. The second analysis of females (Figure 2.6) showed similar results in comparison to the males. In the last and third analysis 26 variables were examined. In the male analysis (Figure 2.7) any belonging of individuals to pre-defined archeological groups was observable. In the female analysis (Figure 2.8), just small clusters were noted, because individuals of the same site grouped together. In conclusion, looking at the results of the entire Cluster analyses, Teschler-Nicola (1992) stated that using this method any connection between the archeological subdivided groups and the craniometrical attributes of the individuals was detected. Nevertheless, Teschler-Nicola (1992) suggested that the results of the Cluster analysis could be influenced by the relative small sample size and by the choice of the variables.

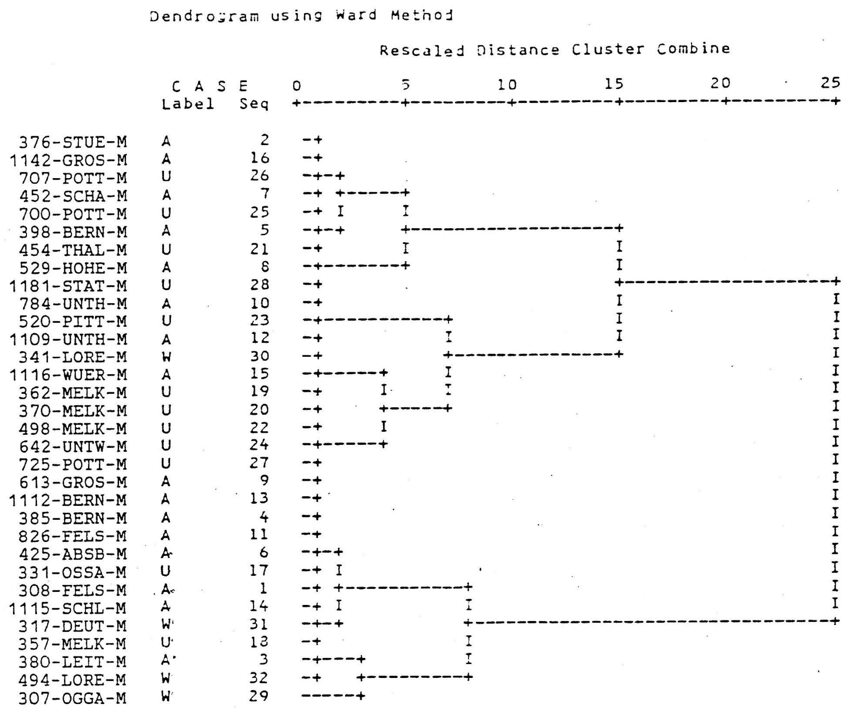

Figure 3.3. Cluster analysis for males using 7 variables. 2 Sub-clusters are noticeable. A= Únětice; U= Unterwölbling; W= Wieselburg. Group-specific partitioning is not evident. The 2 sub-clusters are separated by a Δ E = 46.3 (From Teschler-Nicola, 1992).

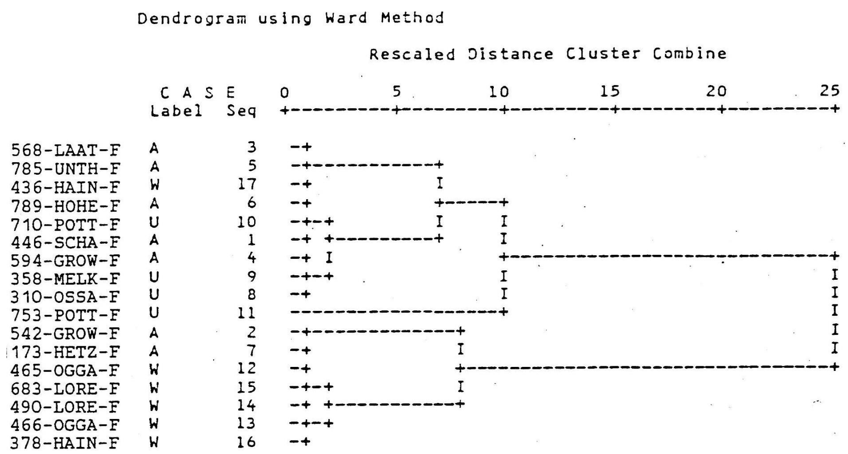

Figure 3.4. Cluster analysis for females using 7 variables. 2 Sub-clusters are noticeable. A= Únětice; U= Unterwölbling; W= Wieselburg. Similar to males, a group-specific partitioning is not evident. The 2 sub clusters are separated by a Δ E = 16.8. From Teschler-Nicola (1992).

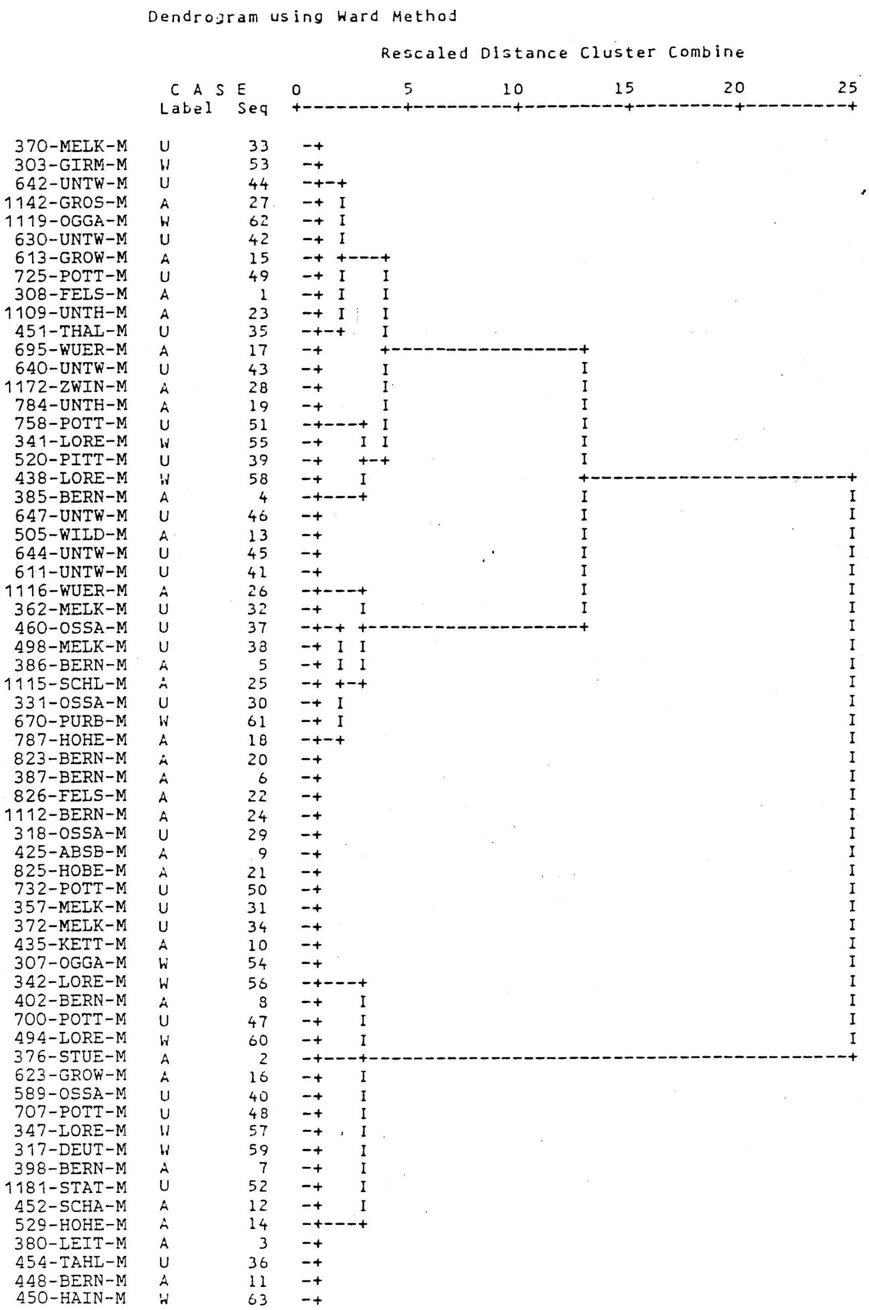

Figure 3.5. Cluster Analysis for males using 4 variables. Two main clusters with a Δ E = 75.9 are present (From Teschler-Nicola, 1992).

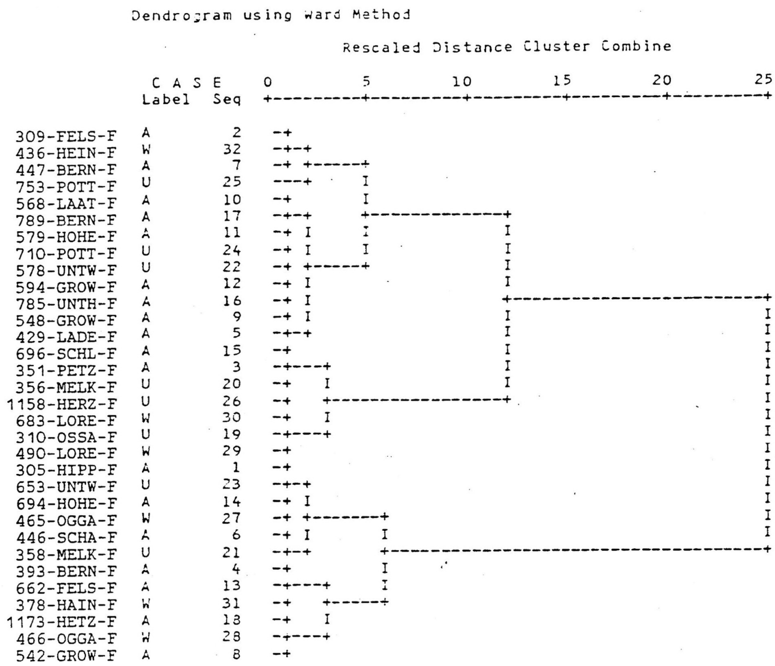

Figure 3.6. Cluster Analysis for females using 4 variables. Similar to males, two main clusters are present, but they are heterogenic composed. (From Teschler-Nicola, 1992).

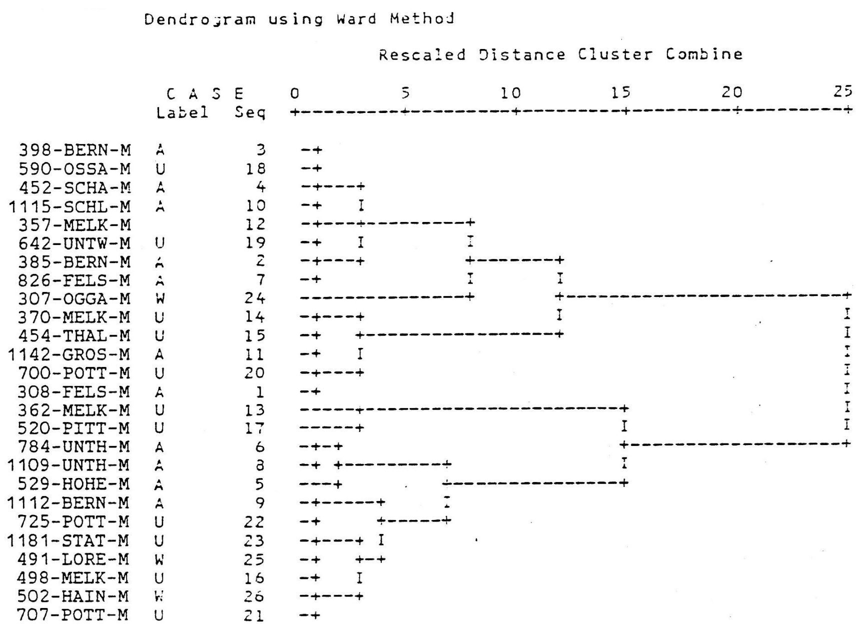

Figure 3.7. Cluster Analysis for males using 26 variables. No belonging of individuals to pre-defined archeological groups is observable (From Teschler-Nicola, 1992).

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Dendrogram using Ward Method

                          Rescaled Distance Cluster Combine

            C A S E     0         5        10        15        20        25
           Label  Seq   +---------+---------+---------+---------+---------+

309-FELS-F  A        1   -+---+
568-LAAT-F  A        3   -+   +-------------------+
594-GROS-F  A        4   -+---+                   +-----------------------+
785-UNTH-F  A        5   -+                       I                       I
358-MELK-F  U        8   -------------------------+                       I
310-OSSA-F  U        7   ---+---+                                         I
710-POTT-F  U        9   ---+   +---------------+                         I
789-HOHE-F  A        6   -------+               +-------------------------+
446-SCHA-F  A        2   -------------+---------+
436-HAIN-F  W       10   -------------+
```

Figure 3.8. Cluster Analysis for females using 26 variables. Similar to males, no belonging of individuals to pre-defined archeological groups is observable. Small cluster are present, because individuals of the same site are associated (From Teschler-Nicola, 1992).

In contrast with the Cluster analysis, the results obtained by Teschler Nicola in Discriminant analysis showed a clear connection, both for males and females, between the craniometrical individual’s features and their archeological attributes. Discriminant analysis is a multivariate method that classifies unknown objects in groups on the basis of their characteristics (Fischer, 1936; Schwidetzky, 1969). The method combines multiple variables into a single score through a linear combination. As with Cluster analysis, Discriminant analysis was performed with males and females separated. Before proceeding to the analysis, a set of variables were chosen and tested with Wilks Lambda (U-statistic) and Canonical Discriminant Functions. On the basis of these tests 8 variables were used (M1= length of the neurocranium, M2= breadth of the skull, M3= bigger breadth of the frontal bone, M4= smaller breadth of the frontal bone, M5= parietal sinew, M6= parietal arc, M7= upper face breadth, M8= chin height). The results of the Discriminant analysis are shown in Table 2.13 and Table 2.14.

CLASSIFICATION RESULTS -

ACTUAL GROUP		NO. OF CASES	PREDICTED GROUP MEMBERSHIP 1	2	3
GROUP	1	17	11 64.7%	3 17.6%	3 17.6%
GROUP	2	13	4 30.8%	8 61.5%	1 7.7%
GROUP	3	5	1 20.0%	0 0.0%	4 80.0%

PERCENT OF "GROUPED" CASES CORRECTLY CLASSIFIED: 65.71%

Table 3.13. Discriminant Analysis for males using 8 variables. The percentage of individuals assigned correctly to the a priori archeological-defined group is clearly higher in respect to a random classification. From Teschler-Nicola (1992).

CLASSIFICATION RESULTS -

ACTUAL GROUP		NO. OF CASES	PREDICTED GROUP MEMBERSHIP 1	2	3
GROUP	1	16	11 68.8%	3 18.8%	2 12.5%
GROUP	2	12	3 25.0%	9 75.0%	0 0.0%
GROUP	3	4	1 25.0%	0 0.0%	3 75.0%

PERCENT OF "GROUPED" CASES CORRECTLY CLASSIFIED: 71.88%

Table 3.14. Discriminant Analysis for females using 8 variables. The percentage of individuals assigned correctly to the a priori archeological-defined group is clearly higher in respect to a random classification. From Teschler-Nicola (1992).

For male and females, a high percentage of individuals assigned correctly to the a priori predefined archeological group was observable. This percentage was clearly higher in respect to a random distribution. Teschler Nicola concluded, therefore, that following this methods, the individuals craniometrical variation observed corresponded to the pre-defined archeological subdivision.

Concerning the biological variation within cultural provinces, the most interesting results obtained by Teschler-Nicola concerned a craniometrical analysis of the skeletal material belonging to the Unterwölbling culture in the sites of the Transley valley. In this study 7 necropolises were analyzed (Gemeinlebarn F, Gemeinlebarn A, Pottenbrunn-Ratzerdorf, Unterwölbling, Ossarn, Franzhausen I and Melk). The univariate analysis concerned 5 sites (Gemeinlebarn A, Pottenbrunn-Ratzerdorf, Unterwölbling, Ossarn and Melk) and was carried out with a Student-Newman-Keusls test. The investigation showed highly significant differences between males for variable concerning the breadth of the neurocranium. Concerning the multivariate analyses, the craniometrical features of the individuals were examined with a Cluster analysis. The male series regarded 6 sites: Gemeinlebarn F, Pottenbrunn-Ratzerdorf, Unterwölbling, Melk, Gemeinlebarn A and Franzhausen. The female series concerned 6 necropolises: Gemeinlebarn F, Melk, Gemeinlebarn A and Franzhausen. The results of the analyses are shown in Figure 2.9- 2.10 and Table 2.15-2.16. Two main findings were observed. Firstly, there was a separation between sites, indicated by the Δ E, which was proportional to the geographical distances. In particular, the site of Melk, which is the necropolis collocated north-west in the surrounding Upper Austria, represent a clear separated sub-cluster. Secondly, the males were more heterogenic in comparison to females, concerning their craniometrical values. Regarding this result, Teschler-Nicola (1992) suggested the presence of a bigger female's migration rate within the Unterwölbling district, due to the presence of a patrilocal system.

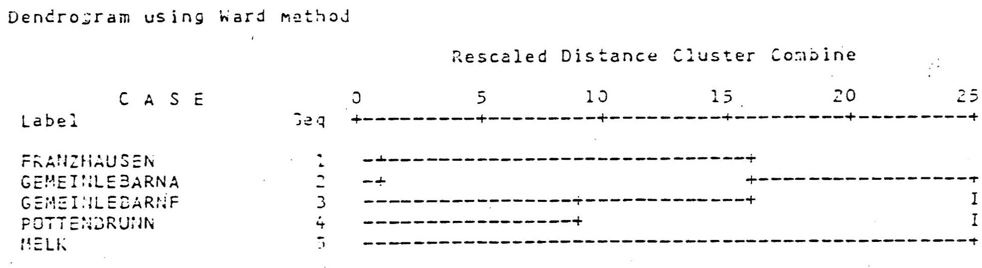

Figure 3.9. Cluster Analysis for males. The site of Melk represents a separated sub-cluster (From Teschler-Nicola, 1992).

Agglomeration Schedule using Ward Method

Stage	Clusters Combined Cluster 1	Cluster 2	Coefficient	Stage Cluster 1st Appears Cluster 1	Cluster 2	Next Stage
1	1	2	7.410000	0	0	3
2	3	4	36.679977	0	0	3
3	1	3	111.604874	1	2	4
4	1	5	263.247559	3	0	0

Table 3.15. Cluster Analysis for males. The Δ E between sites are proportional to geographical distances. From Teschler-Nicola (1992).

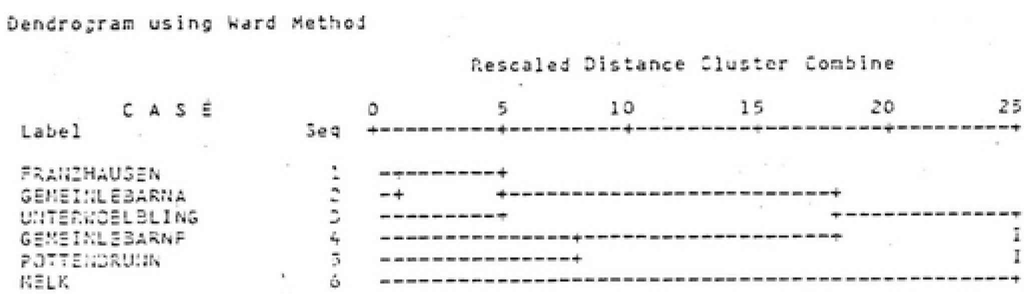

Figure 3.10. Cluster Analysis for females. Similar to males, the site of Melk represents a separated sub cluster.

Agglomeration Schedule using Ward Method

Stage	Clusters Combined Cluster 1	Cluster 2	Coefficient	Stage Cluster 1st Appears Cluster 1	Cluster 2	Next Stage
1	1	2	1.616338	0	0	2
2	1	3	6.514521	1	0	4
3	4	5	13.115277	0	0	4
4	1	4	26.717484	2	3	5
5	1	6	44.999954	4	0	0

Table 3.16. Cluster Analysis for females. Similar to males, the Δ E between sites is proportional to the geographical distances.

Summarizing the results obtained with monovariate and multivariate analyses, Teschler-Nicola (1992) concluded:

- Regarding their craniometrical attributes, numerous statistical tests indicate that there are significant differences between the *a priori* pre-defined archeological groups.
- There are morphological differences between the sites of the Unterwölbling group, whereby these differences are proportional to the geographical distances.
- Among the Traisen series, the females are more homogenic in their craniometrical characteristics, in respect to the males. These results may indicate the presence of a bigger marriage domain of the females.

4 The early Bronze Age collection of human remains

The material analyzed in this study consists of 171 skulls of adult individuals from 11 sites of Lower Austria. The skeletal remains have been chronologically dated applying the system elaborated by Mayer (1977) for the southern Danubian regions. This system divides the Austrian early Bronze Age into 3 phases, namely the Gemeinlebarn I, Gemeinlebarn II, Gemeinlebarn III stage (see chapter 2.3.3 and Figures 2.3). Concerning the Únetice culture located north of the Danube, a parallelism of the Mayer chronological system can be operated with the one of Ruckdeschel (1978), which divided the early Bronze Age into 5 stages in connection with a needles chronology of the Bayern archeological material. The stage A1a (Proto- Únetice) corresponds to Gemeinlebarn I; the stages A1b and A2a (old-Únetice classic-Únetice) correspond to Gemeinlebarn II; the stage A2b (later-Únetice) to Gemeinlebarn III.

In the next pages of this chapter will follow a brief description of the material (Teschler-Nicola, 1992). The bibliographies of the sites are shown in Table 4.1. Inventory numbers or graves protocol of the skeletal materials analyzed in the present work are shown in this table as well. The detailed chronology of the skeletal materials has been recently reanalyzed by Krenn-Leeb on the basis of the analysis of the graves archeological records (Krenn-Leeb, personal communication). All the specimens are stored at the Department of Anthropology in the Natural History Museum of Vienna.

Bernhardstal

The cemetery of Bernhardstal lies in the outermost northern part of Lower Austria called Weinviertel, in proximity of the border with the Czech Republic. The archeological records have been assigned to Únetice culture. The graves 1-6 were gathered in 1910 by K. Goat. The graves 16, 22 and 25 were discovered by G. and K. Spitzer. The Inv. Nr. NHM (Anthropology Department) 3593and 3602 belong to the collection of Mr. Wick and different other possessors in Bernhardstal and has been investigated by J. Szombathy. The Inv. Nr. NHM (Anthropology Department) 7385-7420 are Bronze Age skulls and skeleton remains from Bernhardstal. They were gathered from the local ministers of the Museum of Natural History. In the 24-4-1954 the Inv. Nr. NHM (Anthropology Department) 21885-21886 were discovered by O. Berger and L. Tihelka. The Inv. Nr. NHM (Prehistory Department) 70721-70737 has been collocated by the Prehistory department in 1981 in the collection Wadler.

Franzhausen

The cemetery of Franzhausen I was dug out and documented from the year 1981 to 1983 under the administration of J. W. Neugebauer by the Department for Ground Monument. Approximately 50 funerals were destroyed before the beginning of the rescue excavations in the east of the graves by the grit dismantling. A surface of 220x 140 ms was exposed. Near the early Bronze Age graves a double site of the natives Baden culture was excavated. The early Bronze Age cemeteries have been assigned to the Unterwölbling culture allocated south of the Danube, but also to the Böheimkirchen group to the Veterov culture. The chronology of the graves spans over 700 years. It encompasses the whole period of the early Bronze Age, namely from 2300-22000 to 1500 B C (data based on calibrated C-14).

Gemeinlebarn A

The graves field of Gemeinlebarn A is the old cemetery of the two Gemeinlebarn sites. The necropolis was described for the first time in 1929 by Szombathy. A recently analysis of the archeological records was carried out by Bertemes (1989). By the evaluation of the sepultures conditions Bertemes concluded, similarly to Szombathy (1929), that a robbery of the graves systematically happened due to the extraction of grave goods. According to archeological data, most of its graves date back to the first period of the early Bronze Age, the Gemeinlebarn I stage (Neugebauer, 1994).

Gemeinlebarn F

The necropolis of Gemeinlebarn F was excavated in the years 1973-75 and 1978-1981 by the Austrian department of Bodendenkmale des Bundesdenkmalamtes. The cemetery has a surface of 220 X 130 m (25.500 m² ca). The graves were buried in tumuli and were signed with the use of wood pillars or stones. The 258 sepultures (257 body's burials and a fire burial) have been archeologically assigned to the Böheimkirchen group of the Veterov culture (Neugebauer, 1994).

Großweikersdorf

The site of Großweikersdorf is located in the south of the Austrian Weinviertel. Archeologically, its graves belong to the Austrian Únetice culture. The Inv. Nr. NHM (Anthropology Department) 3370 was discovered in 1888 by J. Spöttl from a stool grave. The Inv. Nr. NHM (Anthropology Department) 6310 was salvaged in the 13-7-1927 in the vicinity of the brickworks Schneider. The Inv. Nr. 9422-9423: was excavated by K. Moßler in the 15-6-1929. The Inv. Nr. NHM (Anthropology Department) 9861-9862 was dug out in the 25-2-1930 and by a revision of the dating, it was assigned to the Únetice culture group. The Inv. Nr. NHM (Anthropology Department) 1309-13077 was salvaged by K. Moßler in the brickworks Groiß. Other specimens were received in 1987 in the NHM from E.

Lauermann who excavated a Bronze Age grave in the area of the brickworks Groiß in 1970.

Hainburg

The old material of the Hainburg necropolis was excavated in the years 1927 till 1939 in 3 different periods. In 1927, the first period, the graves 1-16 were dug out by F. Mühlhofer with the assistance of the Natural History Museum of Vienna. The graves were analyzed by E. Beninger and E. Geyer. The second excavation covered the graves 17-146 in the years 1930-1933 under the administration of the Natural History Museum of Vienna. In 1939, the third period, the graves 147-253 were excavated with the personal administration of E. Beninger and Ä. Kloiber. In 1982, 1985-86, 1980-90, under the administration of J.W. Neugebauer and the correspondent Alois Gattringer, through the analysis of the territory, 62 new early Bronze Age graves which belong to the old main necropolis and new cemeteries were discovered. According to recently archeological analyses, the cemeteries have been assigned to the Wieselburg culture.

Laa/Thaya

The necropolis of Laa is located in the northern Lower Austria and lies on the river Thaya. By an excavation of a sand cavity in the summer of 1932, were detected an early Bronze Age grave field. The graves 4-14 were systematically excavated by K. Müller and Kohlhauser. The sepultures belong to the Únetice culture.

Melk-Spielberg

The site of Melk-Spielberg lies on the Danube next to the Wachau valley. In 1969-70, under the direction of J. Offenberger 31 bodies burials were excavated. According to the archeological records, the graves have been dated uniformly in the stage Gemeinlebarn II. In 1928, the skeletal remains from the sand cavity Dober were acquired by the Natural History Museum. Archeologically, the graves goods have been assigned to the Unterwölbling culture.

Schleinbach

The necropolis of Schleinbach is located in the Austrian Weinviertel. All the burials are archeologically allocated in the Únetice culture. From 1926 to 1929, 10 body burials were detected in a funeral cavity by E. Hauser. In 1981, the skeleton remains were saved and exposed at the Museumverein of Stockerau and investigated by E. Lauermann.

Unterhautzental

The village of Unterhautzental is situated 37 Km north-west of Vienna. In the years from 1991 to 1992, 40 graves of the Únetice culture were found. So far, Unterhautzental is the biggest burial field of the northern Danubian area. During the archaeological excavation carried out by the Lower Austria Land Museum, directed by E. Lauermann, numerous settlement cavities of the middle Bronze Age and several graves of the early Bronze Age were exposed.

Würnitz

The site of Würnitz lies in the northern Lower Austrian part of the country nowadays known as the Korneuburg district. From 13-9-1931 till 14-10-1931, many graves dated in the early Bronze Age were dug out by K. Kriegler. The archeological grave goods belong to the Únetice culture.

Table 4.1. Material analyzed (dating according to Krenn-Leeb, personal comunication).

Necropolis	Inv. Nr. or Grave Nr.	References	Culture	Dating
Bernhardstal		Pittioni, 1925-29a; Berger and Tihelka, 1951-55; Pittioni 1929; Neugebauer, 1978.	Únetice	
	Inv. Nr. 3593			Classic Únetice
	Inv. Nr. 3594			Classic Únetice
	Inv. Nr. 7385			Classic Únetice
	Inv. Nr. 7386			Classic Únetice
	Inv. Nr. 7387			Classic Únetice
	Inv. Nr. 7388			Classic Únetice
	Inv. Nr. 7389			Classic Únetice
	Inv. Nr. 7390			Classic Únetice
	Inv. Nr. 7401			Classic Únetice
	Inv. Nr. 21885			Classic Únetice
	Inv. Nr. 21886			Classic Únetice
	Grave Nr. 16			Classic Únetice
	Grave Nr. 25			Classic Únetice
Franzhausen I		Neugebauer, 1991; Neugebauer and Neugebauer-Maresch, 1989; Sprenger, 1996.	Unterwölbling	
	Inv. Nr. 23650			Gemeinlebarn II
	Inv. Nr. 23661			Gemeinlebarn II
	Inv. Nr. 23683			Gemeinlebarn II
	Inv. Nr. 23703			Gemeinlebarn II
	Inv. Nr. 23713			Gemeinlebarn II
	Inv. Nr.23715			Gemeinlebarn II
	Inv. Nr. 23716			Gemeinlebarn II
	Inv. Nr. 23717			Gemeinlebarn II
	Inv. Nr. 23755			Gemeinlebarn II
	Inv. Nr. 23802			Gemeinlebarn II
	Inv. Nr. 23836			Gemeinlebarn II
	Inv. Nr. 23837			Gemeinlebarn II
	Inv. Nr. 23840			Gemeinlebarn II
	Inv. Nr. 23850			Gemeinlebarn I
	Inv. Nr. 23859			Gemeinlebarn II
	Inv. Nr. 23861			Gemeinlebarn II

Table 4.1. Material analyzed (continued).

Necropolis	Inv. Nr. or Grave Nr.	References	Culture	Dating
Franzhausen I			Unterwölbling	
	Inv. Nr. 23864			Gemeinlebarn II
	Inv. Nr. 23866			Gemeinlebarn II
	Inv. Nr. 23901			Gemeinlebarn II
	Inv. Nr. 23903			Gemeinlebarn II
	Inv. Nr. 23906			Gemeinlebarn II
	Inv. Nr. 23927			Gemeinlebarn II
	Inv. Nr. 23982			Gemeinlebarn II
	Inv. Nr. 23984			Gemeinlebarn II
	Inv. Nr. 23992			Gemeinlebarn II/III
	Inv. Nr. 24001			Gemeinlebarn II
	Inv. Nr. 24031			Gemeinlebarn II
	Inv. Nr.24080			Gemeinlebarn II
	Inv. Nr. 24107			Gemeinlebarn II
	Inv. Nr. 24155			Gemeinlebarn II
	Inv. Nr. 24162			Gemeinlebarn II
	Inv. Nr. 24164			Gemeinlebarn II
	Inv. Nr. 24166			Gemeinlebarn II
	Inv. Nr. 24189			Gemeinlebarn II
	Inv. Nr. 24193			Gemeinlebarn II
	Inv. Nr. 24201			Gemeinlebarn II
	Inv. Nr. 24207			Gemeinlebarn II
	Inv. Nr. 24219			Gemeinlebarn II
	Inv. Nr. 24221			Gemeinlebarn II
	Inv. Nr. 24226			Gemeinlebarn II
	Inv. Nr. 24254			Gemeinlebarn II
	Inv. Nr. 24266			Gemeinlebarn II
	Inv. Nr. 24280			Gemeinlebarn I/II

Table 4.1. Material analyzed (continued).

Necropolis	Inv. Nr. or Grave Nr.	References	Culture	Dating
Gemeinlebarn A		Szombathy, 1934; Bertemes, 1989; Sprenger, 1996.	Unterwölbling	
Inv. Nr.6102			Gemeinlebarn II	
Inv. Nr.6103			Gemeinlebarn II	
Inv. Nr.6110			Gemeinlebarn II	
Inv. Nr.6111			Gemeinlebarn II	
Inv. Nr.6115			Gemeinlebarn II	
Inv. Nr.6121			unknown	
Inv. Nr.6131			Gemeinlebarn II	
Inv. Nr.6132			Gemeinlebarn II	
Inv. Nr.6138			Gemeinlebarn II	
Inv. Nr.6141			Gemeinlebarn I/II	
Inv. Nr.6150			unknown	
Inv. Nr.6154			Gemeinlebarn II	
Inv. Nr.6159			Gemeinlebarn II	
Inv. Nr.6162			Gemeinlebarn II	
Inv. Nr.6165			Gemeinlebarn II	
Inv. Nr.6166			Gemeinlebarn II	
Inv. Nr.6251			Gemeinlebarn II/III	
Gemeinlebarn F		Gattringer and Neugebauer, 1976a and 1976b; Neugebauer, 1991; Heinrich and Teschler-Nicola, 1991; Teschler-Nicola, 1989.	Böheimkirchen	
	Grave Nr. 7		Gemeinlebarn III	
	Grave Nr. 29		Gemeinlebarn III	
	Grave Nr. 46		Gemeinlebarn III	
	Grave Nr. 54		Gemeinlebarn III	
	Grave Nr. 106		Gemeinlebarn III	
	Grave Nr. 126		Gemeinlebarn III	
	Grave Nr. 135		Gemeinlebarn III	
	Grave Nr. 150		Gemeinlebarn III	
	Grave Nr.191		Gemeinlebarn III	
	Grave Nr .212		Gemeinlebarn III	

Table 4.1. Material analyzed (continued).

Necropolis	Inv. Nr. or Grave Nr.	References	Culture	Dating
Großweikerdorf		Spöttl, 1889; Moßler, 1930-31; Lauermann, 1991b.	Únetice	
	Inv. Nr. 6310			Classic Únetice
	Inv. Nr. 12156			Classic Únetice
	Inv. Nr. 13070			Classic Únetice
	Inv. Nr. 13072			Classic Únetice
	Inv. Nr. 13077			Classic Únetice
Hainburg		Beninger, Mühlhofer and Geyer 1930; Geyer, 1930; Ehgartner 1959; Mays 1987; Teschler-Nicola, 1988-89; Neugebauer and Gattringer, 1985-86; Neugebauer and Gattringer, 1987; Neugebauer and Gattringer 1988b; Mayer, Neugebauer-Maresch and Neugebauer, 1989.	Wieselburg	
	Inv. Nr. 9709			unknown
	Inv. Nr. 9724			Gemeinlebarn II/III
	Inv. Nr. 9727			Gemeinlebarn II/III
	Inv. Nr. 9881			Gemeinlebarn II
	Inv. Nr. 9887			Gemeinlebarn II
	Inv. Nr. 12144			Gemeinlebarn II
	Inv. Nr. 12145			Gemeinlebarn II
	Inv. Nr. 12146			Gemeinlebarn II/III
	Inv. Nr. 12149			Gemeinlebarn II
	Inv. Nr. 13033			unknown
	Inv. Nr. 13036			Gemeinlebarn II/III
	Inv. Nr. 13040			unknown
	Inv. Nr. 13049			Gemeinlebarn II
	Inv. Nr. 13053			Gemeinlebarn II
	Inv. Nr. 13060			Gemeinlebarn II
	Inv. Nr. 13061			Gemeinlebarn II
	Inv. Nr. 13065			Gemeinlebarn II
	Inv. Nr. 13087			unknown
	Inv. Nr. 13112			Gemeinlebarn II
	Inv. Nr. 13114			Gemeinlebarn II
	Inv. Nr. 13117			Gemeinlebarn II

Table 4.1. Material analyzed (continued).

Necropolis	Inv. Nr. or Grave Nr.	References	Culture	Dating
Hainburg			Wieselburg	
	Inv. Nr. 13123			Gemeinlebarn II
	Inv. Nr. 13128			Gemeinlebarn II
	Inv. Nr. 21051			Gemeinlebarn II
	Inv. Nr. 21055			Gemeinlebarn II
	Inv. Nr. 21066			Gemeinlebarn II
	Inv. Nr. 21070			unknown
	Inv. Nr. 21071			Gemeinlebarn II/III
	Inv. Nr. 21076			Gemeinlebarn II
	Inv. Nr. 21077			Gemeinlebarn II
	Inv. Nr. 21081			unknown
	Inv. Nr. 21087			Gemeinlebarn II
	Inv. Nr. 21090			unknown
	Inv. Nr. 21091			Gemeinlebarn II
	Inv. Nr. 21095			Gemeinlebarn II
	Inv. Nr. 21097			Gemeinlebarn II
	Inv. Nr. 21102			Gemeinlebarn II
	Inv. Nr. 21103			Gemeinlebarn II
	Inv. Nr. 21111			Gemeinlebarn II
	Inv. Nr. 21116			unknown
	Inv. Nr. 21118			unknown
	Inv. Nr. 21123			Gemeinlebarn II
	Inv. Nr. 21125			Gemeinlebarn II
	Inv. Nr. 21126			Gemeinlebarn II
	Grave Nr. 258			Gemeinlebarn II
	Grave Nr. 271			unknown
	Grave Nr. 283			Gemeinlebarn II
	Grave Nr. 285			unknown
	Grave Nr. 288			unknown

Table 4.1. Material analyzed (continued).

Necropolis	Inv. Nr. or Grave Nr.	References	Culture	Dating
Laa-Thaya		Beninger, 1932; Scheibenreiter, 1953.	Únetice	
	Inv. Nr. 12124			Classic Únetice
	Inv. Nr. 12150			Classic Únetice
Melk-Spielberg		Offenberger, 1969; Wimmer, 1925-29.	Unterwölbling	
	Inv. Nr. 9863			Gemeinlebarn II
	Grave Nr. 1			Gemeinlebarn II
	Grave Nr. 5			Gemeinlebarn II
	Grave Nr. 17			Gemeinlebarn II
	Grave Nr. 20			Gemeinlebarn II
	Grave Nr. 23			Gemeinlebarn II
	Grave Nr. 25			Gemeinlebarn II
	Grave Nr. 26			Gemeinlebarn II
Schleinbach		Kriegler 1925-29; Kriegler 1925; Weninger M. 1954; Weninger, 1954; Lauermann, 1991b; Scheibenreiter, 1953.	Únetice	
	Grave Nr. 11			Classic Únetice
	Grave Nr. 18			Classic Únetice
	Grave Nr. 56			Classic Únetice
Unterhautzental		Lauermann 1988; Teschler- Nicola and Berner, 1991; Lauermann, 1991a.	Únetice	
	Inv. Nr. 24093			Classic Únetice
	Inv. Nr. 24096			Classic Únetice
	Inv. Nr. 24909			Classic Únetice
	Inv. Nr. 24911			Classic Únetice
	Inv. Nr. 24912			Classic Únetice
	Inv. Nr. 24914			Classic Únetice
	Inv. Nr. 24916			Classic Únetice
	Inv. Nr. 24920			Classic Únetice
	Inv. Nr. 24921			Classic Únetice
	Inv. Nr. 24926			Classic Únetice
	Inv. Nr. 24928			Classic Únetice
	Inv. Nr. 24934			Classic Únetice
	Inv. Nr. 24939			Classic Únetice

Table 4.1. Material analyzed (continued).

Necropolis	Inv. Nr. or Grave Nr.	References	Culture	Dating
Unterhautzental			Únetice	
	Inv. Nr. 24941			Classic Únetice
	Inv. Nr. 24944			Classic Únetice
	Inv. Nr. 24950			Classic Únetice
	Grave Nr. v93			Classic Únetice
Würnitz		Kriegler, 1930-31; Kriegler 1932; Weniger, 1954.	Únetice	
	Grave Nr.5			Classic Únetice
	Grave Nr. 6			Classic Únetice
	Grave Nr. 9			Classic Únetice

5 Morphometrics

5.1 An Historical Outline

Morphometrics is a field concerned with the quantitative analysis of the biological size and shape of organisms. The "fathers" of the nowadays Morphometrics were researchers of the 19th and 20th century, namely Francis Galton (1822-1911), Karl Pearson (1857-1936), and Ronald Fisher (1890-1962), who developed the standard statistics to analyze biological and morphological variations. Throughout the 19th Century, up until today, the measurements and analysis of human skeletal remains have been a central theme in Physical Anthropology (Slice, 2005). The works of the early Biometricians was of central importance for the development of statistical methodology in Anthropology as well (Mahalanobis, 1928, 1930; Pearson, 1903, 1933; Mornat, 1928, 1939). At the beginning, Morphometrics was restricted to the analysis of singles variables (univariate analysis). Early morphological studies also included the averaging of one or more measurable traits, which were compared among different groups (Adams et al., 2004). Further advances during the middle of the last century led to the development of statistical methods that allowed the analysis of many variables simultaneously (multivariate analysis). These analyses required the improvement of statistical methods such as the correlation coefficient (Pearson, 1895), and principal components analysis (Pearson, 1901; Hotelling, 1933). In the seventies and at the beginning of the eighties, the systematic application of the standard toolkit of multivariate statistics to the analysis of biological forms was established. This style of morphometrics, which were used to be called as "conventional multivariate morphometrics" (Blackith and Reyment, 1971) and nowadays referred to "traditional morphometrics", is usually applied to a wide range of different measurements, such as linear distances and distance ratios, angles, areas and volumes (Marcus, 1990). An example of variables analyzed with traditional morphometrics is shown in Figure 5.1.

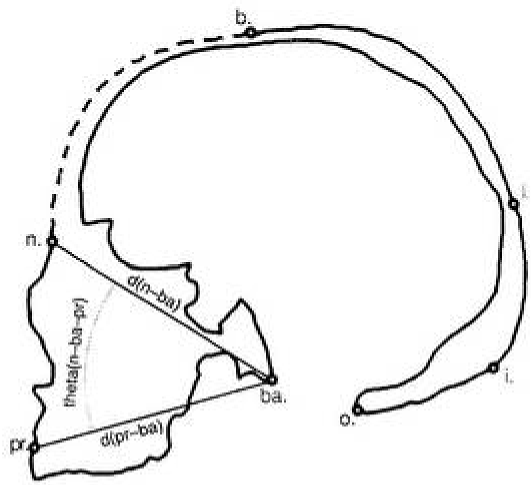

Figure 5.1. Variables analyzed in traditional morphometrics: distances, angles, ratio. Pictures copied from Slice (2005) with permission.

It is common to the statistical approaches of the seventies and early eighties to ignore the origin of data in the geometry of biological specimens. Multivariate statistics was applied to morphometric measurements just as to any other set of variables. Distances are the oldest and most familiar variables used for Morphometric analysis. They are measured by calliper, or other device, between two defined points. Even if well collected, distances alone cannot fairly describe the geometry of a measured object. Distance ratios or angles, however, allow the description of the geometrical attributes of a biological form more properly. Nevertheless, the combination of sets of distances, ratios and angles, mixing variables in different units, may cause a problem in multivariate statistics that use information about the variances and covariance of variables.

In the second half of the eighties, a new approach to quantify and analyze morphological data started to develop. This development led to a new style of morphometrics, which is nowadays called geometric morphometrics. It has been claimed that geometric morphometrics has caused an authentic “revolution” in the morphometric field (Rohlf and Markus, 1993). Geometric morphometrics is a landmark based method, which has been developed to analyze biological form variation and, therefore, morphological changes, in bi-dimensional or tri-dimensional spaces involving a growing corpus of statistical and graphical techniques for shape analysis.

One of the main points of geometrics morphometrics is the visualization of morphological changes as “deformation” by the use of deformation grids which are called Thin Plate Splines (Bookstein, 1991). Historically, the first attempt to fuse quantitative methods with qualitative analysis was by D'Arcy Thompson's (1917) with the pictorial approach of the Cartesian transformations. He constructed deformation grids to illustrate how a part of one creature may be described as a distortion of the same part in another individual (Figure 5.2).

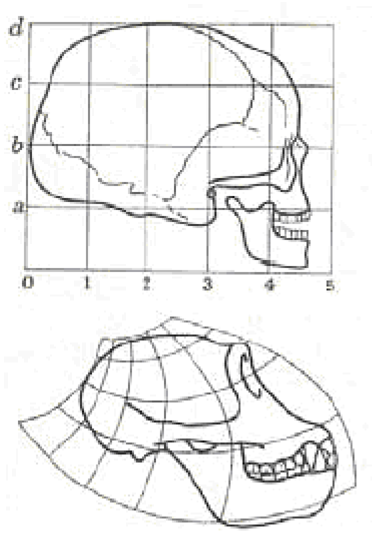

Figure 5.2. Cartesian transformation from D'Arcy Thompson's books (1917).

These deformation grids were, however, carried out by D'Arcy Thompson (1917) by hand. Several attempts have been tried out to construct the deformation grids on a mathematical basis such as polynomial trend surfaces (Sneath, 1967), or the method of biorthogonal grids (Bookstein, 1978). These methods, however, turned out to be not easily interpretable, either biologically or mathematically. In the last years of the eighties Bookstein (1989) introduced the methods of the thin plate spline interpolation function to show shape differences (see figure 5.3) between two biological form as deformations, in the style of D'Arcy Thompson Cartesian transformation. The name thin plate spline refers to a physical analogy involving the bending of infinitely thin, flat metal plate. This is constrained to adopt the form that minimizes the bending energy required to map a configuration of landmark points to another one. The differences in coordinates of one landmark configuration in the other are taken as vertical displacements of this plate perpendicular to itself, one Cartesian coordinate at a time. The bending energy of one of these out-of-plane changes is the energy that would be required to bend the metal plate, so that the landmarks were lifted with the least bending.

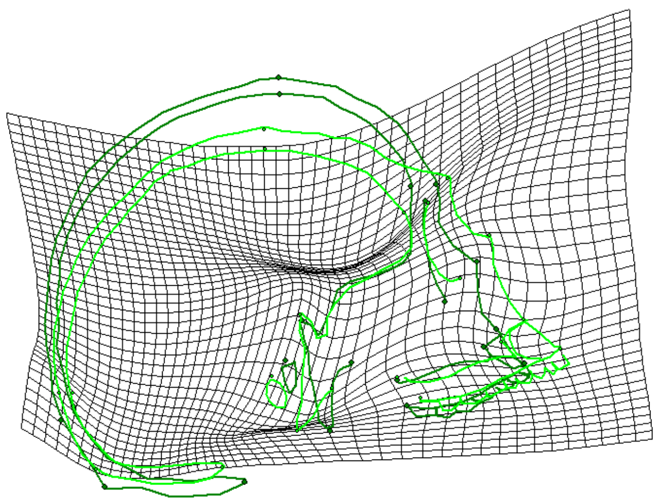

Figure 5.3. Thin Plate Spine deformation grids between a Pithecanthropus and a modern human. These deformation grids are drawn on a mathematical basis. Plot created with Morpheus et al. (Slice, 2008).

The notion of smoothness is approached by minimizing the bending energy of the deformation, which is the integral of second derivatives of that deformation. The thin plate spline turned out to have several convenient bio-mathematical properties and represented, together with the singular-value decomposition of fitted landmark configurations, the core of the modern morphometric synthesis.

5.2 The modern morphometric synthesis

5.2.1 Landmarks

In geometric morphometrics, the geometrical properties of the biological form being studied are recorded through two-dimensional or three-dimensional Cartesian coordinates of a landmarks set. These landmarks must be homologous between biological forms. That is, they must be present in all the sampled individuals and should represent some kind of biological correspondence between them (phylogenetic, structural, functional or biomechanical).

Homology concepts are in general a source of confusion because of the several definitions and use in different contexts. Evolutionary or taxonomic homology is the “sameness” defined by a common ancestor (De Beer, 1971). This includes retention in a more or less unchanged structure from an ancestral condition. Therefore the structure is in shared between two species derived from the same evolutionary ancestor. An alternative definition, operational homology, is most often use in Morphometrics study. Operational homology is a correspondence of landmark position from one form to another (Sneath and Sokal, 1973).

According to Bookstein (1991), landmarks are “Loci that have names” (bridge of the nose, tip of the chin) as well as Cartesian coordinates. The names are intended to imply true homology (biological correspondence) from form to form. That is, landmark points not only have their own locations, but also have the same locations in every other form of the study. In this context, following Bookstein (1991), homology must be considered as a mapping function, a correspondence relating points to points rather than parts to parts. Bookstein emphasizes that landmarks are the best choice of variables to delimit the explanations of effect on biological form because they describe the geometry of the data, are the base for the mathematics of deformation, and give the explanation of biology.

In the geometric morphometrics toolkit any definition of homology is defined *per se*: the choice of landmarks determines the kind of information that is homologous across the observed forms. Therefore, the researcher selects the level of homology that corresponds to the actual biological question. Bookstein (1991) described three principal types of landmarks (Figure 5.4):

- Type I landmarks are points defined by discrete juxtaposition of tissues, such as triple points of sutures intersections, such as the bony structures under the bridge of the nose in humans. Type I landmarks correspond to discrete anatomical structures, which are frequently considered to be biologically homologous, and are therefore the most desirable landmarks in morphometric study.
- Type II landmarks are curvature maxima associated with local structures usually with biomechanical implication. They include tips and valley of invaginations. Landmarks of this sort often serve as points of application of real bio-mechanic forces, pushes and pulls. Thought not as precisely as type I they are still defined in terms of biological structures.
- Type III landmarks are external points, like the endpoints of maximum length or breath defined to some distant structures or centroids, intersection of interlandmarks segments. These landmarks are well defined only in a single direction, but not in the one perpendicular to it (e.g. the Eurion, the two most lateral points on the neurocranium, is defined only in the lateral direction, but the exact three-dimensional position along the neurocranial surface cannot be well identified unambiguously. The homology of type 3 landmarks is usually based on vague geometric criteria and does not necessarily imply any biological correspondence.

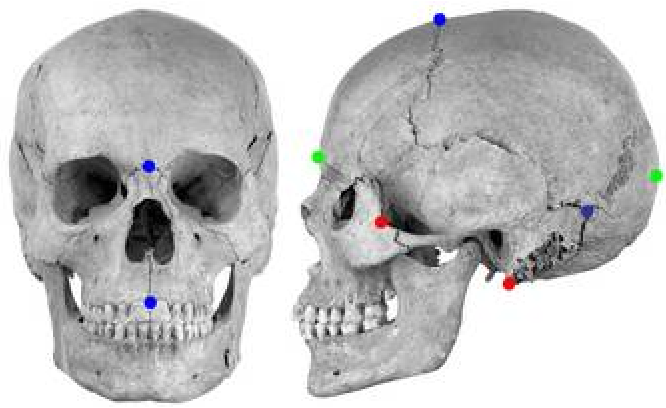

Figure 5.4. Typology of landmarks. Blue points indicate type I landmarks (nasion, prostion, bregma, asterion). Red points indicate type II landmarks (jugale, mastoidale). Green points indicate Type III landmarks (glabella, opistion) whose definition depends on the skull orientation.

5.2.2 Size and shape

The core concepts in geometric morphometrics are size and shape, which are the main features analyzed and quantified (Bookstein, 1991). An important improvement of geometric morphometrics is that it has provided specific definitions in the terms of size and shape, so that every researcher applies the same terminology. Moreover, geometric morphometrics aims to separate shape information from overall size and from nuisance parameters, like position and orientation of the specimens. In traditional morphometrics, the quantification of size has been controversial because the use of different measures yielded different results (Richtsmeier et al., 2002). The commonly used measures of size were body mass, length measures, areas and volumes. Geometric morphometrics concerns a specific measure of size, Centroid Size, which can always be obtained from a set of landmarks and is comparable between specimens.

While size refers to the magnitude and dimensions of the organism or one of its parts, shape refers to the essence of its figure, to its proportions and the relative positions of the parts that make it up. Even the simplest biological form has multiple aspects to be described because shape is an inherently multidimensional property (Klingenberg, 2004). Technically, shape is all the geometrical properties of a biological form that remains after removing the effects of size and position that is the nuisance parameters of scale, translation and rotation (Slice, 2005). These effects are removed by the transformation based on the Procrustes methods, which will be described in the next sections.

5.2.3 Procrustes superimposition

Geometric morphometrics aims to separate shape information from the overall size and nuisance parameters, like position and orientation of the specimens in the digitizing space. An earlier attempt to dissect landmark coordinates into shape components was the two-point shape coordinates or Bookstein shape coordinates (Bookstein, 1991). For a three landmark configurations, all configurations are translated, scaled, and rotated so that the first landmark is set to (0,0) and the second to (1,0). The shape of one triangle can then be expressed as the two coordinates of the third landmark (Figure 5.5).

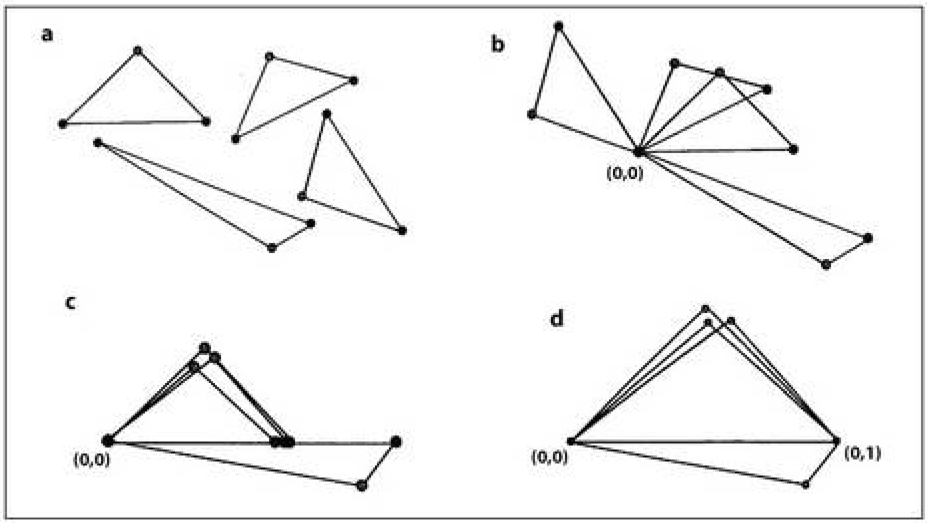

Figure 5.5. Bookstein shape coordinates. a) data set of triangles. b) translation to the origin. c) rotation to the x axe. d) scaling to the length of the baseline.

The principal disadvantage of the Bookstein shape coordinates is the absence of any corresponding shape distances. An analysis carried out with multivariate statistics, e.g. a principal component analysis, has no meaningful interpretation.

Nowadays, in geometric morphometrics the more common used method to extract shape variables from a set of raw landmarks is the so-called Procrustes superimposition. This is a least-squares method to optimally superimpose homologous landmark configurations discarding position, scale, and orientation of the raw data. Scale is saved as an explicit variable called Centroid Size. The resulting superimposed landmark, the Procrustes shape coordinates can be used as shape variables in further multivariate statistical analyses.

Procrustes superimposition is a three step procedures (Figure 5.6) based on Euclidean similarity transformations (Dryden and Mardia, 1998):

1. Translation of the landmark configurations, so that they share the same centroid (the coordinates average of the landmarks of one form). Usually, this common centroid is sent to the origin of the coordinate system.
2. Scaling of the landmark configurations, so that they all have the same Centroid Size (the square root of the summed squared deviations of the coordinates from their Centroid). This is the associated measure of scale for a landmark configuration which has been shown to be approximately uncorrelated with shape for small isotropic landmark variation (Bookstein, 1991; Dryden & Mardia, 1998). As a convention, Centroid Size is set to one for all landmark configurations.
3. One of the two centered and scaled configurations is rotated until the sum of the squared Euclidian distances between the homologous landmarks is minimal.

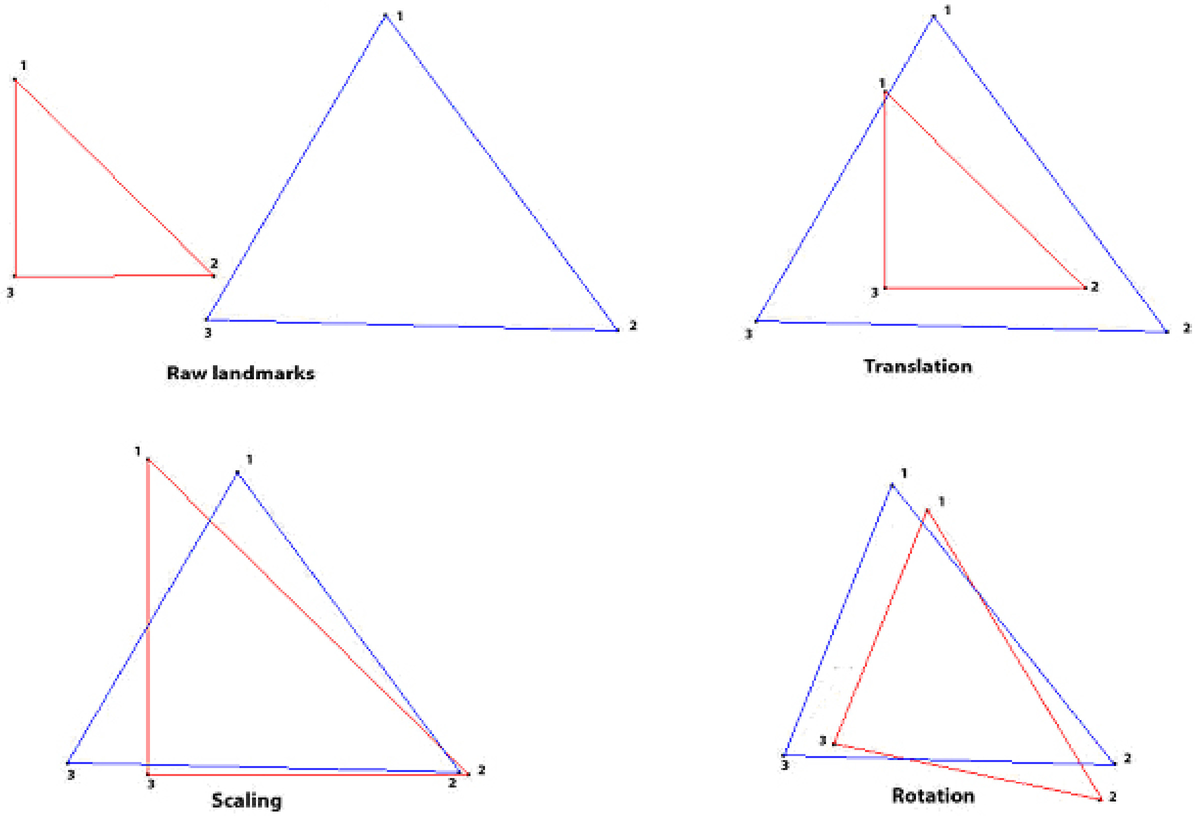

Figure 5.6. The three steps in Procrustes superimposition: Translation to the same centroid, scaling to the same Centroid Size, and rotation to minimize the summed squared distances between the corresponding landmarks.

In a general case a particular configuration of p landmarks in k dimension can be written as a $p \times k$ matrix. The perturbation model of Goodall (1991) is widely used to describe the variation in the positions of the landmarks around their mean. The individual's variation with regards to the mean is expressed in the following way:

$$\mathbf{X}_i = \alpha_i \mu + \mathbf{E}_i \mathbf{O} + \mathbf{1}\omega_i^t$$

where α_i is a scale factor (size of the ith specimen relative to the one of the mean), μ is the mean shape, $\mathbf{E}_i$ is a matrix of random errors (normally distribuited with means of zero), $\mathbf{O}$ is a $k \times k$ matrix describing the orientation of the *i*th specimens, **1** is k-dimensional vector of all ones, and ω_i is a k-dimensional vector specifying the location of the specimens in the space of digitization. Parameters α_i, **O,** and ω_i encode information unrelated to shape variation and are often called *nuisance parameters*. The nuisance parameters must be, however, estimate in order to valuate the extent of pure shape variation. Considering two specimens, shape variation and nuisance parameters are estimated with the algorithm of the Procrustes superimposition.

When more than two specimens are present, the algorithm of the Procrustes superimposition is extended to the so-called generalized Procrustes analysis (GPA) (Gower, 1975; Rohlf & Slice, 1990). The rotation step becomes an iterative algorithm. First, the centered and scaled landmark configurations are rotated to one of these configurations (usually the first one). The ensuing coordinates are averaged, and all configurations are then rotated to this new consensus. The resulting coordinates are averaged again to yield a new configuration to rotate to. The algorithm is iterated until convergence which is usually reached after a few repetitions. The resulting mean configuration is the shape whose sum of squared distances to the other shapes is minimal and is therefore the maximum likelihood estimate of the mean for certain statistical models (Dryden & Mardia 1993). The coordinates of the resulting centered, scaled, and rotated landmarks are called *Procrustes shape coordinates* and their difference from the average shape are called *Procrustes residuals*. The square root of summed squared differences between two sets of landmark configuration is referred as the *Procrustes distance*, and denotes the similarity or dissimilarity in shape between two landmark configurations.

5.2.4 Shape space

The transformation applied to landmark configurations by a generalized Procrustes analysis convert the landmark configuration of each specimen into a point in a shape space, which has been defined as Kendall's shape space. From the original recording space to Kendall's shape space the landmark configurations pass through several morphospaces, each with specific statistical characteristics and dimensionality.

Every measured specimen is characterized by p landmarks in k dimensions so that one landmark configuration can be described as a vector with kp elements. In the resulting kp-dimensional vector space, which is called *figure space*, a specimen can therefore be represented by a single point (Goodall, 1991). If the n objects are translated until their centroids are superimposed, these objects' coordinates correspond to points in a *preform space*, of dimensions $pk - k$ because the k coordinates of the centroid have been fixed for each object. After translation and rotation, the new coordinates characterize a *form space* of $pk - k - k\ (k - 1) / 2$ dimensions. If the centroids are superimposed and the Centroid Size of all configurations is set to unity, the coordinates characterize a *preshape space* of $pk - k - 1$ dimensions.

When the coordinates are translated, scaled, and rotated until the sum of squares between homologous landmarks is minimal, we finally arrive in the *shape space* which have $pk - k - k\ (k-1) / 2 - 1$ dimensions. This shape space has been called Kendall's shape space because this author defined and developed the statistical characteristics of the shape space (Kendall, 1981, 1984). This shape space is a non-Euclidean Riemannian manifold (Kendall, 1981, 1984); it has namely higher dimensions of a curved surface in three dimensions.

Landmark configurations can now be analyzed as a point lying in a multidimensional space. The distance between two points in shape space is the so-called Procrustes distance. According to Bookstein (1996) Procrustes distance is the sole statistically meaningful shape distance for landmark data.

As Kendall’s shape space is rather complex, the most common visualization of it concerns the shape of bi-dimensional triangles (p = 3; k =2). The dimension of this shape space is 6 – 2 – 1 – 1 = 2 and therefore this space can be described by two parameters. Kendall (1981, 1984) found out that this space is metrically equivalent to the surface of a sphere with radius 1 / 2. However, it has been shown that Procrustes aligned triangles lie in a hemisphere with radius one (Rohlf, 1999; Slice, 2001). Rohlf (1999) refers to this space as the preshape space of triangles aligned to the reference triangle. For k = 2 and p > 3, superimposed shapes lie on higher-dimensional hemispheres while for k = 3 the geometry is more complicated (see Dryden & Mardia, 1993, 1998; Small, 1996; Kendall, 1981, 1984).

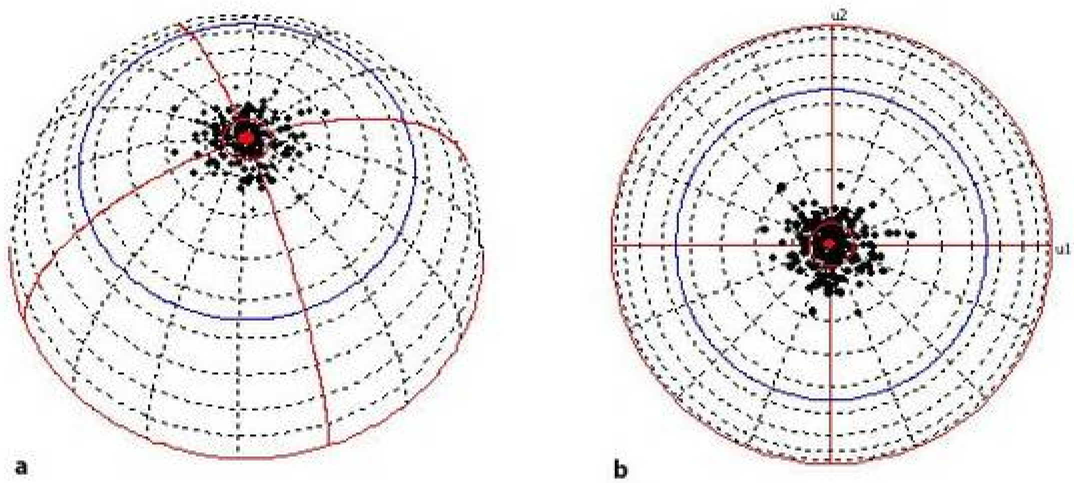

Figure 5.7. Preshape space of triangles aligned to the reference triangle. This shape space is a hemisphere with a radius of one. Each point on this hemisphere corresponds to one triangle. a) oblique view; b) view from the north pole.

Kendall (1984) demonstrated that if the vertices of a shape are independently and identically distributed in a spherical normal distribution, then the distribution of shape is uniform in Kendall's shape space. In Figure 5.7 it is shown the distribution of shape of triangles in the preshape space of triangles aligned to the reference triangle. Each point on the hemisphere represents a triangle. The triangles are distributed uniformly, but the two-dimensional shape space of triangles is not linear. Nevertheless, all the common statistical methods are based on linear models, and therefore in this curved shape space multivariate statistics can not be applied. In order to solve this pitfall, the Procrustes aligned landmarks are projected into a Euclidean tangent space. If the variation is relative small, this projection does not cause any significant bias in Procrustes data. The Euclidean tangent space has the same dimensions as shape space and can be viewed as tangent to it, where the point of tangency is at the reference shape. The Euclidean distances in this tangent space are close to the Procrustes distances in Kendall's shape space and the shapes projected into tangent space can be used for analysis with standard multivariate methods.

There are two different ways to construct a tangent space (see Figure 5.8). A stereographical projection is the projection of the point A into the tangent space and can be achieved by scaling the shapes to have Centroid Size 1 = cos ρ, where ρ is the Procrustes distance to the reference. However, the orthogonal projection of the point B into the tangent space is normally preferred. The resulting projections are called Kendall tangent space coordinates and lie in a linear space of kp –k – 1– k(k– 1) = 2 dimensions that is perpendicular to the direction corresponding to the reference. For triangles, an orthogonal projection simply corresponds to a view from above the pole as in Figure 5.7b (see for more details, Rohlf, 1999).

When the specimens are projected into the tangent space, the Procrustes distances between them are modified. The distortion is positive proportional to the distance to the tangent point. In the tangent space, the distances tend to be smaller than the Procrustes distances. If the mean shape is selected as a tangent point, than all the points in Kendall’s shape space are closer to the tangent point and the distortion is minimal. Because variation in biological shape is relatively small even when observed across a wide range of different organism, it is possible to make a good linear approximation to the tangent space (Marcus et al., 2000).

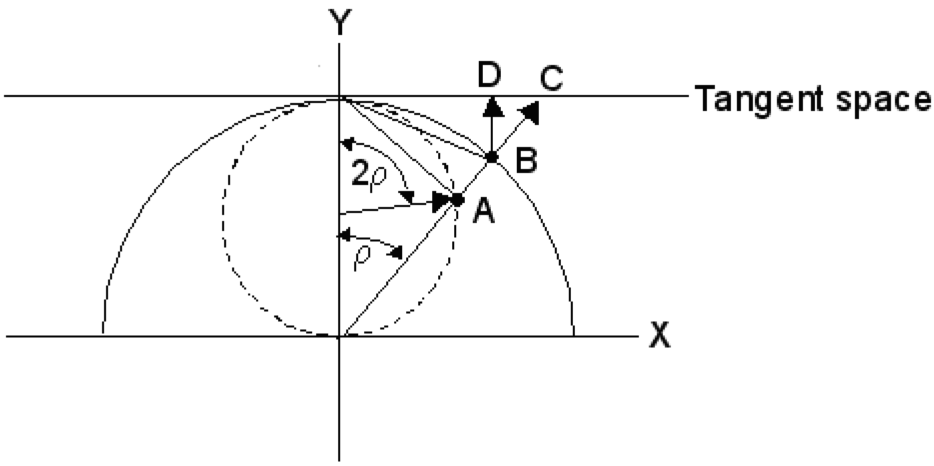

Figure 5.8. Tangent space. The circle is a cross section of Kendall's shape space for triangle which is a sphere with a radius of 1 / 2. The half-circle is a cross section the hemisphere of preshapes aligned to the reference (hemisphere a radius of 1). Point C is the stereographic projection of point A onto the tangent space. Point D is the orthogonal projection of Point B onto tangent space. The Procrustes distance of the indicated shape to the mean is ρ in radians (Rohlf, 1999).

5.2.5 Relative warps

In chapter 5.2.3 it has been shown how the standard Procrustes methods generate the correct distances between specimens (the Procrustes distances) to produce the substitute variables (the Procrustes shape coordinates) which are immune to nuisance parameters as positioning (or scaling), and are the variables commonly analyzed with multivariate statistics. In principle, all multivariate statistical methods familiar from traditional morphometrics can be applied to Procrustes shape coordinates or to equivalent basis of shape space. As in geometric morphometric, the data set consists usually in a lot of variables, often exceeding the number of cases, the common practice is a variable reduction carried out with a principal component analysis (PCA) which has been termed relative warp analysis by Bookstein (1991) in its application to Procrustes shape coordinates.

In geometric morphometrics, the superimposed data consists of k landmarks in p dimensions for n specimens. There are therefore pk Procrustes coordinates and n cases. This data set can be written as a matrix **M** which has the dimension n x (pk). Let be **C** the variance-covariance matrix of **M**. The matrix **C** can be expressed as a singular value decomposition: $\mathbf{C}=\mathbf{E}\boldsymbol{\Lambda}\mathbf{E}^t$ where $\boldsymbol{\Lambda}$ is a diagonal matrix of eigenvalues in descending order and $\mathbf{E}$ = (e1|e2| … |je$_{pk}$), the column matrix of corresponding eigenvectors, so that $\mathbf{E}\mathbf{E}^t = \mathbf{E}^t\mathbf{E} = \mathbf{I}$. The ith eigenvalue λ_i is the variance along the direction of the ith eigenvector Var($\mathbf{M}e_i$). The orthonormal matrix **E** is a rotation matrix so that **ME** yields the principal component scores. From the kp eigenvalues, just $kp - p - p(p - 1)$=2 – 1 will be nonzero (that is $2k - 4$ for bi-dimensional data and $3k - 7$ for three-dimensional data). This is due to the loss of degrees of freedom during Procrustes superimposition (p degree freedom for position, 1 for size, and $p(p - 1) = 2$ for orientation).

In a relative warps analysis, the computation of principal component scores of the Procrustes shape coordinates is, therefore, similar to that for other kind of data. However, in geometric morphometrics the visualization of the eigenvectors is unique and can be visualized as shape deformations, the corresponding relative warp (Bookstein, 1991). A convenient multiple of that partitioned eigenvector can be added to the average (the consensus configuration) and the shape deformation is usually represented as a thin plate spline deformation (Figure 5.9; see Bookstein et al., 2003), or average morphing (see Figure 5.10; Franklin et al., 2006), from the consensus configuration to the consensus configuration plus the eigenvector.

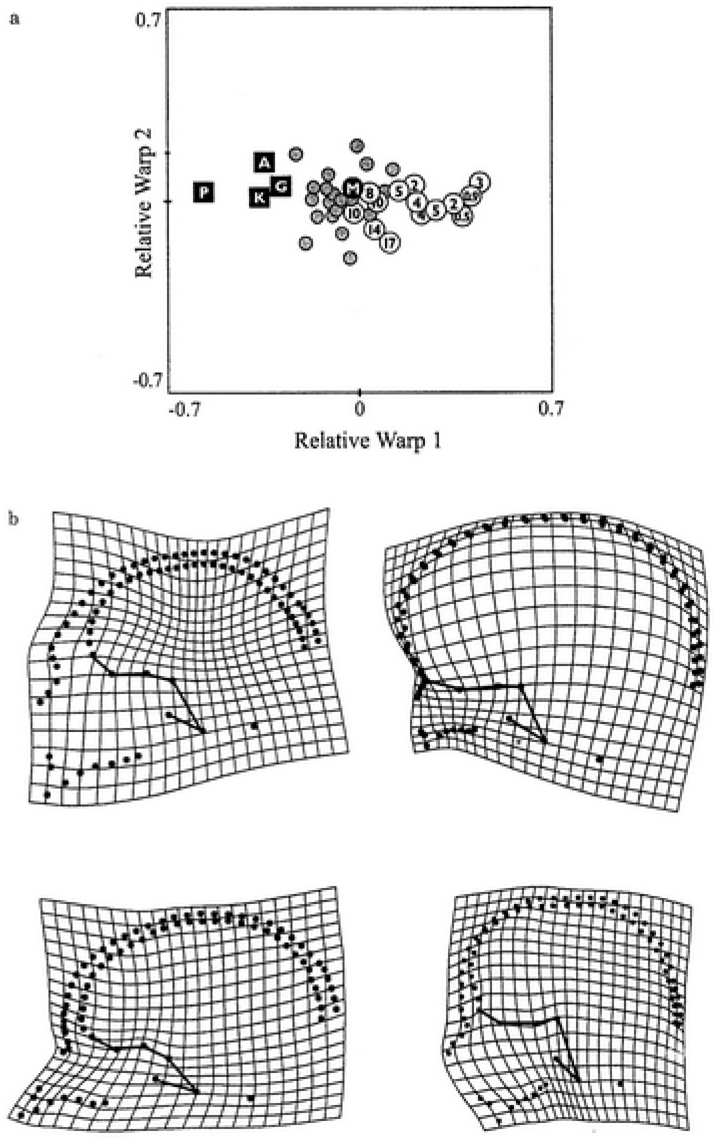

Figure 5.9. Relative warps 1 and 2 for a data set of 38 specimens with young and adult *H. sapiens* and middle Pleistocene Homo. (a) The first RW separates the archaic Homo from *H. sapiens*. (b) The grid of the thin plate spline indicates differences in the shape of the midface and thickness of the vault bones (first relative warp). The second relative warp shows differences in cranial length and alveolar Prognathism (From Bookstein et al., 2003).

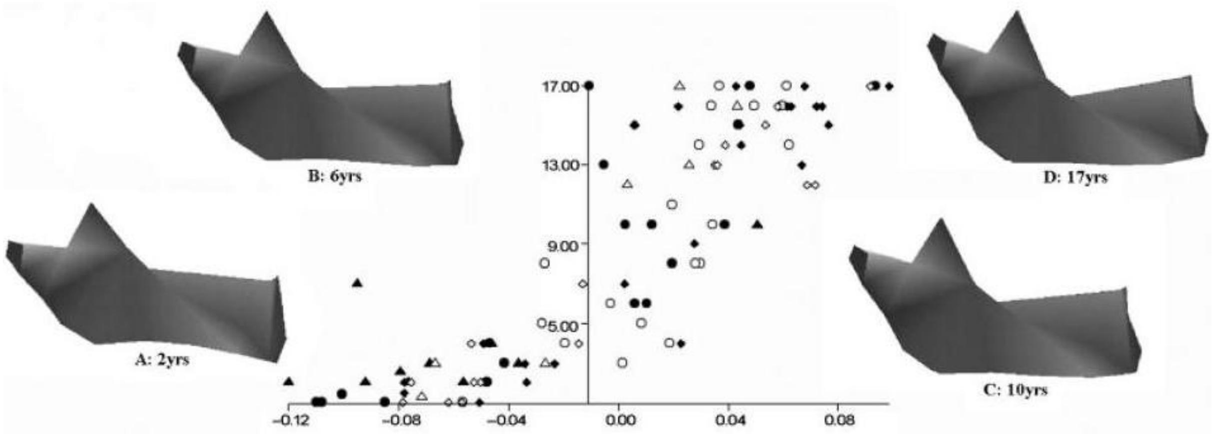

Figure 5.10. Relative warps 1 versus age in a data set of 96 subadult mandibles of both *H. sapiens* sexes. The relative warps are here shown as average morphing (from Franklin et al., 2006).

5.2.6 Procrustes form space

In most morphometric studies, size and shape are considered separately. However, in some situations the separation of size and shape is not desirable. Recently Mitteroecker et al. (2004) introduced an extension of the shape space augmented with size information. Initially this space has been termed size-shape space, but at the Vienna Morphofest 2006, an international workshop on geometric morphometrics, it was decided to call it Procrustes form space.

The main application of this space is in studies of groups' differences or development trends for which size could be a confining factor or the object of explanation. The Procrustes form space must be not confused with the "form space" introduced by Rohlf (1999) where the set of landmark are just centered and rotated. In Procrustes form space, instead of taking off size, the values of centroid are put back into the data after having carried out a generalized Procrustes analysis. This approach consists of a relative warp analysis not of the usual matrix of Procrustes shape coordinates (Bookstein, 1991; Rohlf, 1993) but instead of the matrix of those coordinates augmented by one single additional column for the logarithm of Centroid Size (CS).

The Procrustes form space (Figure 5.11) is therefore an extension of the shape space by one additional dimension of logarithm of Centroid Size. The resulting Euclidean metric is spherical (Figure 5.11) on the hypothesis of pure digitization error. In the limit of small variation of size and shape the appropriate column to add to the Procrustes shape coordinates is therefore the logarithm of Centroid Size because in the absence of any meaningful biological signal, the analysis of this data will yield no pattern. On the so-called offset isotropic Normal model of small identically distributed independent variation at every landmark in every Cartesian direction, centroid size is approximately uncorrelated with every dimension of the shape space (for more details see Mitteroecker et al., 2004)

In real biological data, when allometry is present, log CS will typically have by far the largest variance of any column of this matrix, and thus the first principal component of the form distribution will be closely aligned with size. But that is exactly analogous to the familiar fact that in any other allometric data set, the first principal component of any set of size-loaded measures is likewise very highly correlated with size however measured. In Procrustes form space, however, allometric shape and geometric size are reflected in a single size-shape component, which is the first principal component of this space (Mitteroecker at al, 2004, Schaefer, 2004). Therefore, only in Procrustes form space is decomposition into allometric and non-allometric component possible.

A principal component analysis in Procrustes form space shows scientific insights via high-dimensional scatter plots of the resulting component scores, followed by free rotation of those scatters to orientations that correspond to standard biological interpretations. The rotations will results into linear combinations of the principal components into new linear combinations of the original data which can be visualized as deformation by the usual method of thin plate splines. The latter can now have size included in some circumstances.

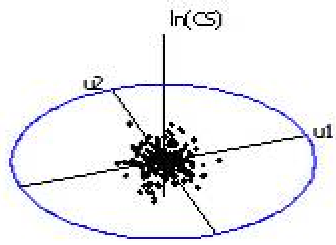

Figure 5.11. Procrustes form space. A sample of triangles differing by isotropic error at each landmark should correspond to a spherical distribution in this space.

5.2.7 Deformation

The visualization of shape variation as deformation using the singular value decomposition of the Procrustes shape coordinates constitutes the core engine of geometric morphometrics. In *On Growth and Form* (1917) D´Arcy Thomson showed diagrams as deformation to illustrate morphological differences between biological forms, but he left no instruction about how to produce these diagrams. In the late eighties Bookstein (1989, 1991) introduced the methods of the thin plate spline interpolation function to show shape differences between two biological forms as deformations, in the style of D'Arcy Thompson Cartesian transformation. The formalism is borrowed from physics, where it is applied to model infinitely thin and infinitely large metal plates under deformation. The “smoothness” of the resulting deformation is modeled as a minimization of the integral of the squared second derivatives perpendicular to the plate. Two shapes are compared by analyzing the deformation pattern obtained from the distortion of the first shape (the reference shape) onto the second on (the target shape). The decomposition is composed by affine and non-affine component (Bookstein, 1989, 1991).

Figure 5.12 shows the construction of the thin plate spline deformation grid. In the upper side a) there are two distribution of landmark differing only in the displacement of the central landmark on the target configuration. To produce the thin plate spline, interpolation formulae are computed separately for the *x* displacement and for the *y* displacement, b), and then combined, c).

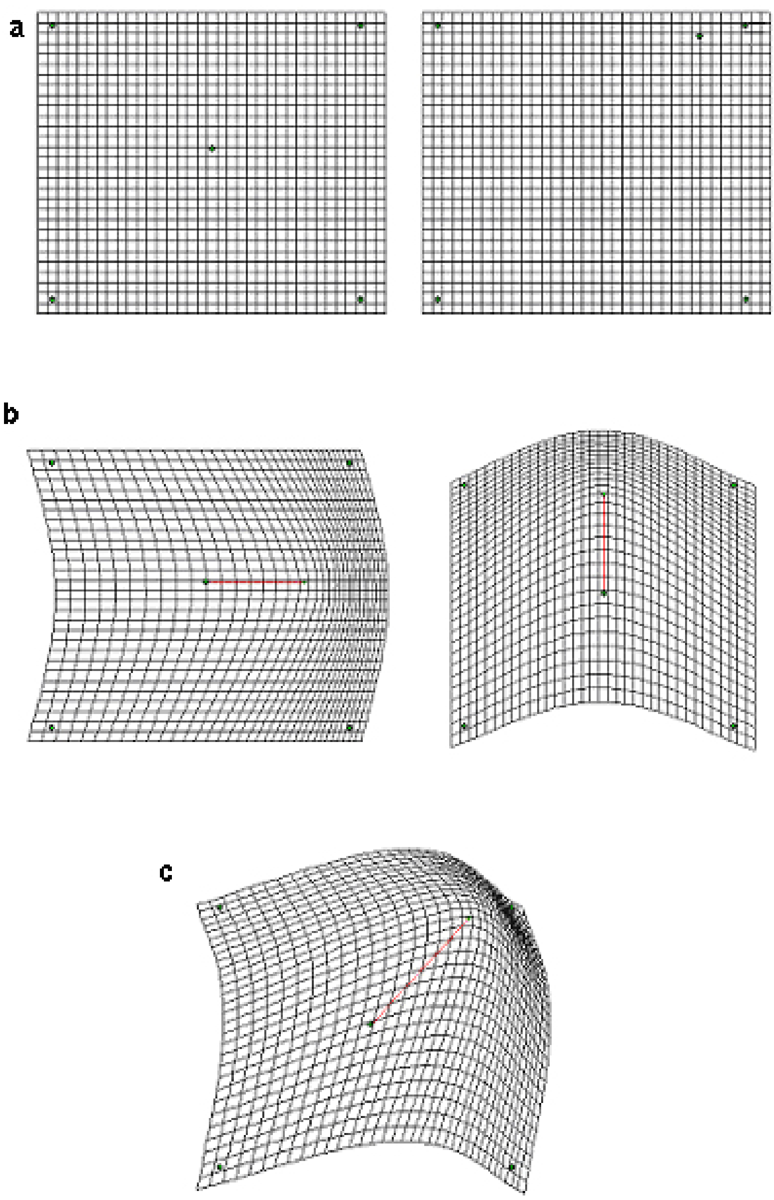

Figure 5.12. Construction of thin plate spline. a) two configurations differ just for the position of one landmark. b) displacements are computed separately for x and y dimensions. c) displacements are combined together. The construction work even if the configurations are not in Procrustes fit. Plots created with Morpheus et al. (Slice, 2008).

One configuration, usually the Consensus Configuration, is used as a reference, and the difference between the landmarks locations and those of another specimen, the target, are processed as displacements at right angles out of the planes of the reference configurations. The totality of differences between the two configurations is expressed as:

$$f(x,y) = a_1 + a_x x + a_y y + \sum_{i=1}^{p} w_i U((x_i, y_i) - (x, y))$$

This function maps a pair of coordinates (x , y) for each p landmarks, to a scalar that equals of height above or below the plane corresponding the coordinate differences between the references and the target. To compute the coefficients of this function, for configurations of p landmarks in k = 2 dimensions, we can construct a partitioned matrix:

$$\mathbf{L} = \left[\begin{array}{c|c} P_{pxp} & Q_{px3} \\ \hline Q^t_{px3} & 0_{3x3} \end{array}\right]$$

P is a symmetric matrix with zero on the diagonal. The off-diagonal the elements are:

$$p_{i,j} = p_{j,i} = U(r_{i,j}) = r^2_{ij} \ln(r^2_{i,j})$$

where r_{ij} is the Euclidean distances between the point i and j of the reference configuration. **Q** is a matrix of the landmarks coordinates of the reference with an initial column of zero. **0** is a matrix of zero. The required coefficients are obtained from the equation:

$$\mathbf{L}^{-1}\,\mathbf{Y}_{p+3,1} = (\mathbf{w}|a_1, a_x, a_y)^t$$

where **Y** is the vectors of differences between the references and the target configurations along the axis currently being considered, with three zero at the end. The elements of ***w*** are the w_i of the earlier equation. It is possible now to use the earlier equation and the new coefficients to compute the eight of the surface at any point in the plane of the reference.

The w_i used in the Thin Plate Spline computation provide the coordinates of an individual specimens wit respect to the eigenvectors of the bending energy matrix, which is the **P** upper-left p x p submatrix of the portioned matrix $\mathbf{L}^{-1}$. They describe the local, non-affine component of shape difference to the reference configuration. The reminder of the total shape difference is the affine or uniform component. The affine transformation shows shape difference as stretching or compressing in orthogonal direction and does not require bending energy. In Figure 5.13 it is shown an example of global or affine transformation, and an example of local or non-affine transformation.

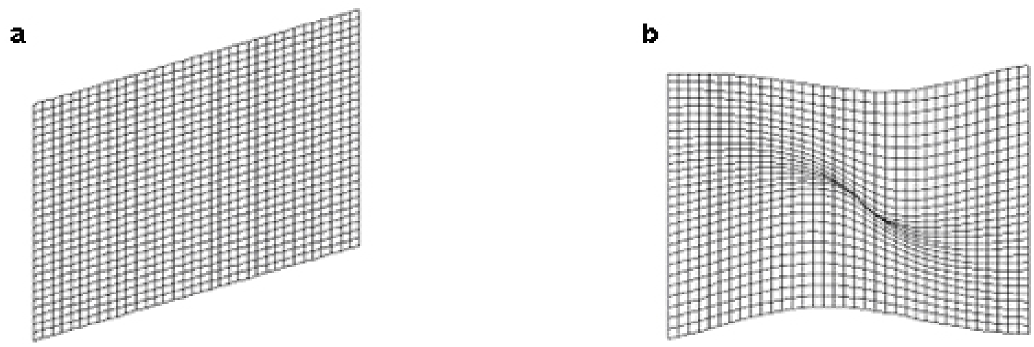

Figure 5.13. Affine and not affine component of thin plate spine interpolation function. a) affine transformation. b) non-affine transformation. Plots created with Morpheus et al. (Slice, 2008).

Slight modifications are necessary to produce interpolation functions for three-dimensional thin plate splines (Bookstein, 1991, appendix 1). In these cases the deformation grids shows volumetric shape changes of landmark configurations and the model is less intuitive compared with the bi-dimensional analysis (see Slice, 2005).

5.2.8 The uniform component

Any change in shape of a configuration of landmarks in two or three dimensions includes a uniform component, which is the component of the affine transformation. The formulas for estimating this component have been standardized for two-dimensions (Bookstein, 1996). Rohlf & Bookstein (2003), however, gave two different methods to estimate the uniform component that work for both two- and three-dimensional data. The component can be estimated by complementarities between the uniform component and the space of partial warps. Moreover, the uniform component can be estimated by regression in either one space or the other. These new methods can be used for both bi- and three-dimensional landmark data and thus generalize Bookstein's previous morphometrics (Bookstein, 1996).

Kendall tangent space S can be decomposed into a vector sum of the affine and the non-affine subspaces:

$$\mathbf{S} = \mathbf{U}+\mathbf{B}$$

where **U** is the subspace of affine or uniform transformations and **B** the subspace of those transformations that are pure bending (Rohlf & Bookstein, 2003). The symbol $\otimes$ indicates the direct sum of two vector spaces.

The first methods estimate the uniform component **U** by its perpendicularity with **B.** Construct a $p \times p$ matrix:

$$\mathbf{N} = \mathbf{I}_p - \mathbf{E}(\mathbf{E}^t\mathbf{E})^{-1}\mathbf{E}^t$$

where **E** is a p x (p –k –1) matrix of eigenvectors of the bending energy matrix and $\mathbf{I}_p$ is a $p \times p$ identity matrix. Multiplying the centered data matrix with N projects the data onto the uniform subspace that is perpendicular to the subspace spanned by the columns of E. Performing a singular values decomposition:

$$\mathbf{LSR}^t = \mathbf{V}(\mathbf{N} \otimes \mathbf{I}_{\mathrm{k}})$$

where $\mathbf{V} = \mathbf{X} - \mathbf{1}_n\mathrm{x}$, $\mathbf{1}_n$ is a column vector of n 1s, $\mathbf{I}_k$ is a k by k identity matrix, and indicates $\otimes$ the matrix direct product. The first k + ½ (k – 1) –1 columns of the product **LS** give scores for the uniform component of shape differences for the n specimens. The corresponding columns of **R** give the coefficients that define the uniform components as linear combinations of the *kp* coordinates.

The second method suggested by Rohlf & Bookstein (2003) is based on regressions of each specimen's Procrustes coordinates onto the coordinates of the reference shape. Computing

$$\mathbf{B}_x = (\mathbf{X}_c{}^t\mathbf{X}_{\mathrm{c}})\text{-}1\mathbf{X}_c\mathbf{X}_x{}^t$$

where $\mathbf{X}_x$ is the $n \times p$ matrix of x-coordinates of the aligned specimens, and $\mathbf{B}_y$ and $\mathbf{B}_z$ are defined similarly for the y and z coordinates. The regression coefficients are then combined into a single $n \times k^2$ matrix

$$\mathbf{B} = [\mathbf{B}_x{}^t|\mathbf{B}_{\mathrm{y}}{}^t|\mathbf{B}_z{}^t]$$

Performing a singular values decomposition of **B**

$$\mathbf{LSR}^t = \mathbf{B}(\mathbf{X}_c t \otimes \mathbf{I}_k):$$

In analogy with the first method the first k + ½ (k – 1) –1 columns of the product **LS** give scores for the uniform component.

5.2.9 Permutation test

Procrustes shape coordinates can be averaged in order to compare group differences visually by thin plate spline and to test for significance of group's shape difference by multivariate statistical tests. In principle, hypotheses about group differences can be tested with multivariate parametric test. However, resampling methods such as permutation tests are preferred in morphometrics. A permutation test, also called a randomization test, is a type of statistical significant test in which a reference distribution is obtained by calculating all possible values of the test statistic under rearrangements of the labels on the observed data. Permutation tests are designed to determine whether the observed difference between the sample means is large enough to reject the null hypothesis with a-level of significance that the two groups have identical probability distribution. Permutation tests exist for any test statistic, regardless of whether or not its distribution is known. Therefore, an advantage on the parametric test is that the previous knowledge of the distribution of the data is not necessary.

Good (2000) defined the basic steps of a permutation test:

1. Analyze the problem and choose a test statistic.
2. Compute the test statistic for the original labeling of the observations.
3. Rearrange (permute) the labels and recompute the test statistic for the rearranged labels. Repeat until you obtain the distribution of the test statistic for all possible permutations.
4. Accept or reject the hypotheses using this permutation distribution as a guide.

A problem with the permutation test is that it takes some time to compute all the possible permutation. An asymptotically equivalent permutation test can be created when there are too many possible orderings of the data to conveniently allow complete enumeration. This is done by generating the reference distribution by the

Monte Carlo sampling which takes a small (relative to the total number of permutations) random sample of the possible replicates. This type of permutation test is known under various names: approximate permutation test, Monte Carlo permutation tests or random permutation tests.

In geometric morphometrics we are interested in the significant level of group differences or correlation of a set of shape coordinate with independent variables. An appropriate test two group study is the Procrustes distance d between the mean configuration $\mathbf{M}_i$ of the groups i=1,2 with N_i specimens in the ith group:

$$\mathbf{M_i} = \frac{1}{\mathbf{N_i}} \sum_{\text{group } i} \mathbf{X}$$

$$d = (\mathbf{M1}-\mathbf{M2})\cdot(\mathbf{M1}-\mathbf{M2})$$

Assuming a linear dependence of the multivariate data on an independent variable, an appropriate statistic test is the explained variance summed over all the I variables:

$$\sum_{i=1}^{I} \rho^2 (\mathbf{vi}, \mathbf{u})\, \sigma^2 (\mathbf{vi})$$

Where ρ^2 is the squared correlation coefficient of the ith variable v_i and the indipendent variable $\mathbf{u}$, and σ^2 is the variance of the ith variable $\mathbf{v}i$.

5.3 Other morphometric methods

Besides traditional morphometrics and geometric morphometrics, a number of other morphometric methods have been suggested. Especially in the field of anthropology the method of Euclidian distance matrix analysis (EDMA), which was introduced in the early 1990s by Lele and Richtsmeier (Lele, 1993; Lele and Richtsmeier, 1991, 1992, 1995; Lele & Cole, 1996; Richtsmeier & Lele, 1993) is frequently applied. EDMA is a morphometric method that describe shape or form of landmark configuration in terms of the full set of interlandmark distances.

While EDMA also uses landmark coordinates as raw data, the form of each specimen is represented as the matrix of Euclidean distances between all possible pairs of landmarks, the so-called form matrix. In EDMA I a configuration A of k landmarks is described as a form matrix F M (A) = F M_{ij} (A) containing all k^2 interlandmark distances. The form matrix is an equivalent representation of the landmark coordinate data, which is invariant to nuisance parameters as translation, rotation and reflection (Lele and Richtsmeier, 1991). Lele and Richtsmeier (1991) proposed the use of a statistic T. First, form matrices consisting of the interlandmark distances for each specimen are computed and are averaged for each sample. A form difference matrix is then computed as the element-wise ratios of the average interlandmark distances in the average form matrices for the two samples. Their statistic T is the ratio of the largest to the smallest of the elements of the form difference matrix. The statistical significance of T is assessed by comparing the observed value to an empirical distribution of T values from a non-parametric bootstrap procedure (see Richtsmeier and Lele, 1993).

In EDMA II the shape matrix is obtained standardizing the form matrix by a scaling factor c, usually the geometric mean of all distances. The shape matrix of the landmark configuration A is therefore S M_{ij}(A) = F Mij(A)/c. The scaled interlandmark differences can be used to explore localized shape differences (Lele and Richtsmeier, 1995, 2001). This procedure shows which distances are significantly shorter or longer in the two configurations there are compared (Figure 5.14)

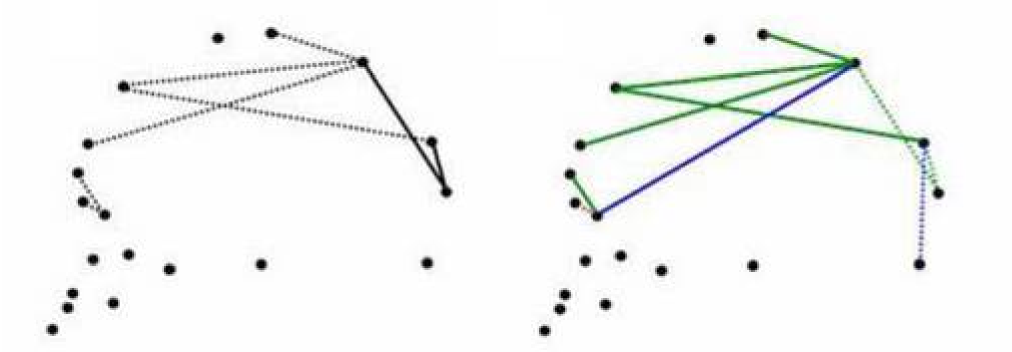

Figure 5.14. Visualization of shape differences with EDMA II. The green and the blue lines indicates interlandmark distances which are relatively smaller or larger between the two configuration (From Martínez-Abadías et al., 2006).

Lele and Cole (1995, 1996) described the procedures to test for significance in shape and size, based on the computation of the statistic Z, which is the maximum absolute value of the arithmetic difference between the two size-scaled average form matrices being compared. According to Lele and Cole (1996), the statistical significance of EDMA II) is tested on a parametric bootstrap procedure on an empirical distribution of the Z statistic. In this procedure, 100 pairs of multivariate normally distributed samples are generated with the same estimated mean and covariances as the observed data. *Z*-values are computed for each pair and sorted from low to high. A 100(1 – a)% confidence interval is given by the 100a/2 and 100(1 a/2) percentiles of this array (interpolating if necessary for a values such as 0.05). The null hypothesis of no difference in shape is rejected at the a a level of significance if the estimated confidence interval does not contain zero.

EDMA I and EDMA II are simple approaches mainly used in anthropology and craniofacial medicine. However, proponents of coordinate based morphometrics argue against distance based methods in principle (see Bookstein 1991). Others find the statistical properties of EDMA unsatisfactory (see for more details Rohlf, 2000a, b, 2003).

The rationale of EDMA is similar to traditional morphometrics. Nevertheless, in its statistical strategy, the usual EDMA application is much more limited than traditional morphometrics. While the latter approach employs the full arsenal of multivariate statistics, studies using EDMA rarely go beyond group mean comparisons or principal component analysis.

Besides, the main deficiency of the interlandmark morphometric is the absence of proper visualization tools such as, for instance, the thin plate spline used in geometric morphometrics. Hence, the interlandmarks based morphometrics lack accurate quantification and visualization of form and shape variation in biological organisms.

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6 Sample and Measurements

6.1 Sample

The crania examined in this study are part of the skeletal remains investigated by Teschler Nicola (1992), enhanced with new material excavated since then. The specimens chosen are a representative sample of the geographic range and age distribution of each population, with males and females approximately equally distributed (Table 6.1). Adulthood was assessed by the skeletal criterion of a fully closed spheno-occipital synchondrosis. Sex and age were determined using anthropological parameters on teeth, the cranium, and the postcranial skeleton according to previously investigations (see Berner and Wiltschke-Schrotta, 1992; Teschler-Nicola, 1992; Novotny et al., in preparation). All the specimens are stored in the Department of Anthropology of the Natural History Museum of Vienna. Inventory number, grave protocol, and fine dating of the specimens are indicated in Table 4.1 of chapter 4.

The sample was divided into four main groups according to cultural facts, temporal and geographical circumstances.

In the Wieselburg Culture, which was mainly dispersed south of the Danube and east of the Wienerwald, the necropolis of Hainburg was analyzed. Referring to the fine chronology of their graves (Kreen-Leeb, personal communication), according to the chronological system elaborated for the southern Danubian area by Mayer (1977), almost all the individuals examined belong to the middle phase of the early Bronze Age, the stage Gemeinlebarn II.

The skeletal materials representing the south-western Danubian area and belonging to the Unterwölbling Culture included three sub-groups: the sites of Franzhausen I, Gemeinlebarn A and Melk-Spielberg. According to their grave's fine chronology, nearly all the individuals have been allocated in the stage Gemeinlebarn II.

Among the Únetice Culture north of the Danube, six sub-groups (sites) were analyzed: Unterhautzental, Bernhardstal, Schleinbach, Würnitz, Großweikerdorf and Laa/Thaya. Chronologically, almost all the specimens belong to the stages A1b and A2a (old-Únetice and classic-Únetice) according to the chronological system developed by Ruckdeschel (1978). These stages correspond to the Gemeinlebarn II stadium of the southern Danubian provinces (see Figure 2.3).

The crania of the Gemeinlebarn F necropolis were also analyzed. This site represents the Böheimkirchen group of the Veterov Culture. Therefore, a sample of skeletal material concerning the south-western Danubian area in the later phase of the early Bronze Age, namely the Gemeinlebarn III stadium, was investigated.

Table 6.1. Number of specimens for each Culture, necropolis, and sex.

Culture	Necropolis	Male	Female
Wieselburg	Hainburg	22	27
	Franzhausen	19	25
Unterwölbling	Gemeinlebarn A	9	8
	Melk	5	3
	Unterhautzental	8	9
	Bernhardstal	9	4
Únetice	Schleinbach	2	1
	Würnitz	3	0
	Großweikersdorf	3	2
	Laa/Thaya	1	1
Böheimkirchen	Gemeinlebarn F	7	3
Total		88	83

6.2 Measurement protocol and data handling

To capture the overall craniofacial morphology, a total of 58 ectocranial three-dimensional landmarks on the viscerocranium, neurocranium and basicranium were digitized using a Microscribe 3DX. Their names and definitions are listed in Tables 6.2 and 6.3 and are illustrated in Figures 6.2.

The crania were mounted on plasticine and the measurements were taken in two separate sessions per skull (from the top and from the base) because not all landmarks could be reached in one orientation. The two sets of landmarks were fitted together by a least-squares superimposition of five fiducial points located in both sessions. Three-dimensional coordinates were recorded in a Microsoft Excel 2000 spreadsheet via the Inscribe utility (Immersion Inc., 2004), imported into Morpheus (Slice, 2008), and modified for Morphologika 2.5 (O'Higgins and Jones, 2006) for analysis.

The number of specimens that were examined in this study depended on the quality of skull preservation. In many specimens it was not possible to measure some landmarks because of damages. In these cases, the values of the missing point were estimated using a geometric reconstruction by warping the average of the complete cases to the specimens with missing data using a thin plate spline interpolation on the subset of observable landmarks (see Gunz et al. 2004). This was done in Morpheus.

Generalized Procrustes analysis, permutation test on Procrustes distances, and visualisation of shape variation as thin plate spline were carried out in Morpheus as well. Multivariate analyses of configuration in tangent space, and ordination analyses in Procrustes form space, were performed by using Morphologika 25.

Measurement errors in landmark acquisition were assessed by digitizing six different specimens on six different occasions. Using the method described by O'Higgins and Jones (1998), the six repeat sets of coordinate data from the test specimens were submitted to a generalized Procrustes analysis and analyzed with a relative warp analysis along with the total sample. This test showed that the repeated specimens clustered closely together on the relative warps in comparison with the variation between individuals.

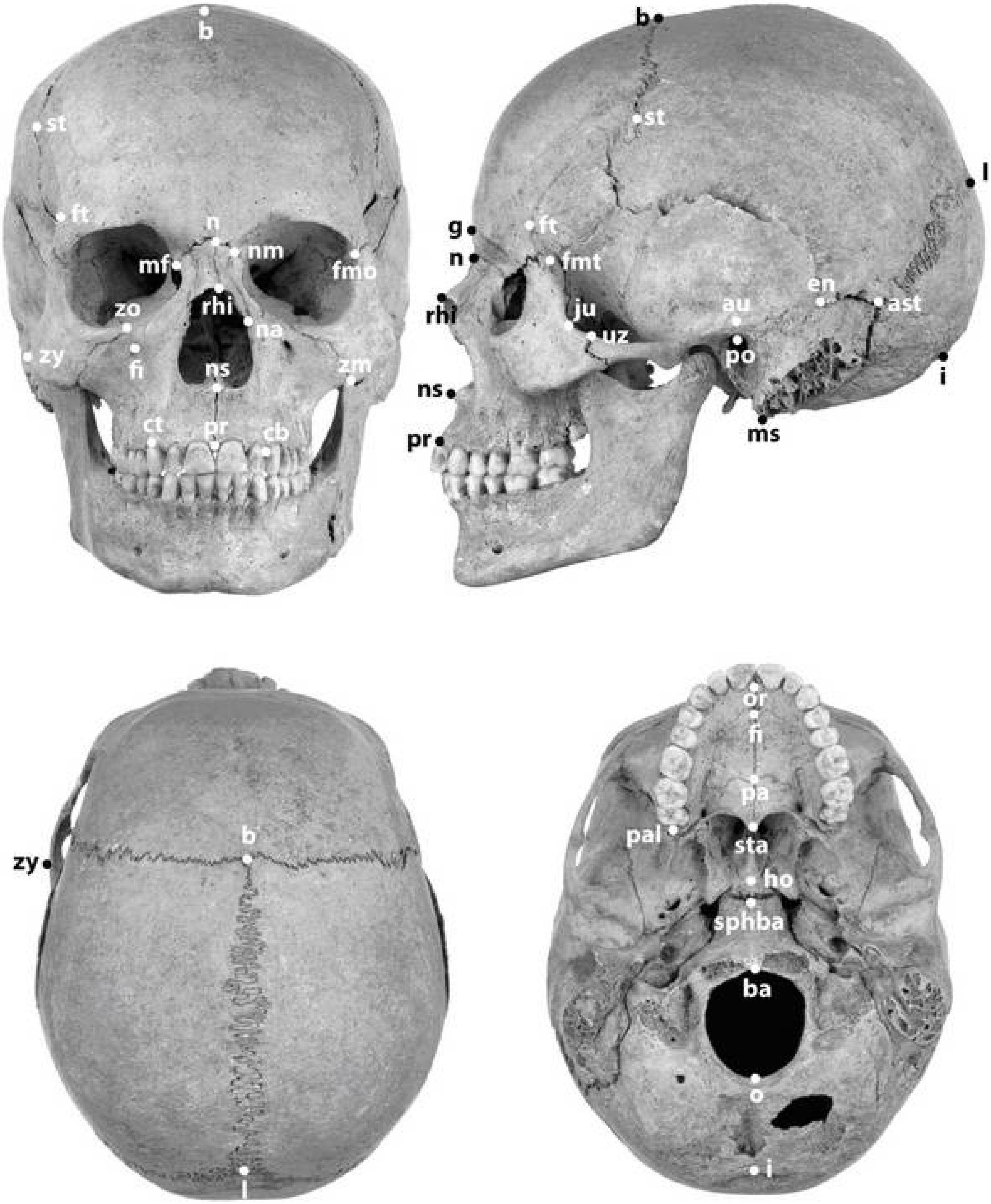

Figure 6.1. Anatomical landmarks located on the crania. Bilateral points were taken on both sides.

Table 6.2. Number, name, and definition of the midsagittal landmarks (classical landmarks are defined after Martin and Saller, 1957, and White, 1991). Landmark types after Bookstein (1991).

No.	Acr	Landmark	Definition
1	pr	Prosthion	Point on the maxillary bone where the midsagittal plane meets a tangent that goes through the alveolar margins of the central incisors. Type I
2	ns	Nasospinale	Point where the midsagittal plane meets the inferior inner rim of the nasal aperture (A-point). Type I
3	rhi	Rhinion	Midline point at the inferior free end of the internasal suture. Type I
4	n	Nasion	Midline point where the two nasal bones and the frontal intersect. Type I
5	g	Glabella	Intersection of the ridge curve on the arcus superciliaris with the midplane. Type II-III
6	b	Bregma	Midline point at the intersection of sutura sagittalis and sutura coronalis. Type I
7	l	Lambda	Point where the sagittal suture meet the lambdoid sutures. Type I
8	i	Inion	Midline point at the conuence of the lineae nuchae superiores. Type II-III
9	o	Opisthion	Midline point at the posterior margin of the foramen magnum. Type II
10	ba	Basion	Midline point on the anterior margin of the foramen magnum. Type II
11	sphba	Sphenobasion	Point where the midsagittal plane intersects the sphenooccipital suture. Type II
12	ho	Hormion	Most posterior midline point on the vomer. Type II
13	sta	Staphylion	Most posterior point on the interpalatal suture (B-point). Type II
14	pa	Palate	Intersection of medial and lateral palatal sutures. Type I
15	fi	Foramen incisivum	Point where the medial palatal suture meets the posterior margin of the foramen incisivum. Type I
16	or	Orale	Midline point on the hard palate where a line drawn tangent to the posterior margins of the central incisor alveoli crosses the midline. Type I-II

Table 6.3. Number, name, and definition of the bilateral landmarks (classical landmarks are defined after Martin and Saller, 1957, and White, 1991). Landmark types after Bookstein (1991).

No.	Acr	Landmark	Definition
17	cb	Canine base	Medial point on the outer alveolar margin of the canine. Type II
18	ct	Canine tip	Most mesial point on the outer alveolar margin of the canine. Type II
19	na	Pseudoalare	Point where the nasomaxillary suture meets the nasal aperture. Type I
20	nm	Nasomaxilla	Intersection of nasomaxillary and frontonasal suture. Type I
21	mf	Maxillofrontale	Point where the anterior lacrimal crest of the maxilla meets the frontomaxillary suture. Type
22	zo	Zygoorbitale	Point where the orbital rim intersects the zygomaticomaxillary suture. Type I
23	fmo	Frontomalare orbitale	Point where the frontozygomatic suture crosses the inner orbital rim. Type I
24	zm	Zygomaxillare	Most inferior point on the zygomaticomaxillary suture. Type I-2
25	st	Stephanion	The intersection of the coronal suture and the inferior temporal line. Type I
26	ft	Frontotemporale	Point where the temporal line reaches its most anteromedial position on the frontal. Type III
27	fmt	Frontomalare temporale	Point where the frontozygomatic suture crosses the temporal line or the orbital rim. Type I
28	ju	Jugale	Point in the depth of the notch between the temporal and frontal process of the zygomatic. Type II-III
29	zu	Upper zygomatic	Most superior point on the suture that separates zygomatic and parietal bone. Type I
30	zy	Zygion	Most inferior point on the suture that separates zygomatic and parietal bone. Type I
31	au	Auriculare	Point vertically above the center of the external auditory meatus at the root of the zygomatic process. Type III

Table 6.3. Continued.

No.	Acr	Landmark	Definition
32	po	Porion	Point on the upper margin of the external auditory meatus. Type II
33	ms	Mastoidale	Most inferior point on the mastoid process. Type III
34	fi	Foramen infraorbitale	External opening of the infraorbital canal on the front surface of the body of the maxilla. Type II
35	ast	Asterion	Point at the junction of the lambdoid suture and the occipitomastoid suture and the parietomastoid suture. Type I
36	en	Entomion	Point at the tip of the angular part of the parietal bone that articulates with the temporal bone Type II
37	pal	Postalveolare	Point on the most posterior end of the alveolar ridge. Type II-III

7 Results

7.1 Procrustes shape coordinates

In this study I applied the toolkit of geometric morphometrics (Bookstein, 1991; Marcus et al., 1996; Dryden & Mardia, 1998) to capture size and shape variation in the whole sample from the digitized landmarks. Shape information was captured by standard Procrustes methods (Dryden and Mardia, 1998). Size information was extracted by Centroid Size, which is the square root of the summed distances between the centroid and each landmark coordinate (Bookstein, 199; Dryden and Mardia, 1998).

I performed a Generalized Procrustes Analysis (Rohlf and Slice, 1990) to eliminate non-shape variation in the sample from the raw digitized landmarks. This process is a least-squares method that involves translating, rescaling, and rotating the configurations relative to each other so as to minimize a total sum of squares distances between corresponding points. The resulting Procrustes shape coordinates capture shape information only. The scaling procedure adjusts the landmark coordinates so that each configuration has a unit Centroid Size.

The scatterplot of the Procrustes shape coordinates labeled by group is demonstrated in Figure 7.1. Arrows are used to indicate arbitrarily selected coordinates, which appear more variable in position between groups. In lateral view (a) one can see differences in the location of the lambda (L), and the inion (I) between the four groups. Concerning the frontal portion of the skull, differences in localisation of the bregma (B) and the stephanion (ST) are visible; in the viscerocranium one can observe a wide variability of the maxillary alveolar morphology, in particular in the prostion (PR), and nasospinale (NS). In frontal view (b) a different position of landmarks is recognizable in the zygomatic region and in the frontal region at the level of the stephanion (ST), frontotempolare (FT), and frontomolare orbitale (FO). In vertical view (c), a different distribution of the mastoidale (MS) can be seen.

Figure 7.2 shows the scatterplot of the Procrustes shape coordinates of group mean configuration. The plot shows shape differences between groups for selected landmarks located in the occipital region in lateral view (a) and for the mid-facial region in frontal view (b), as well in vertical view (c).

The plot demonstrated in Figure 7.1 and Figure 7.2 shows shape variation between groups mainly recognizable for landmarks located in the viscerocranium and occipital neurocranium. To gain additional insight into the morphological variation within the sample, I operated multivariate statistical analyses on the Procrustes shape coordinates. These methods included analyses of Procrustes distances in shape space and in form space, and are shown in the next chapters.

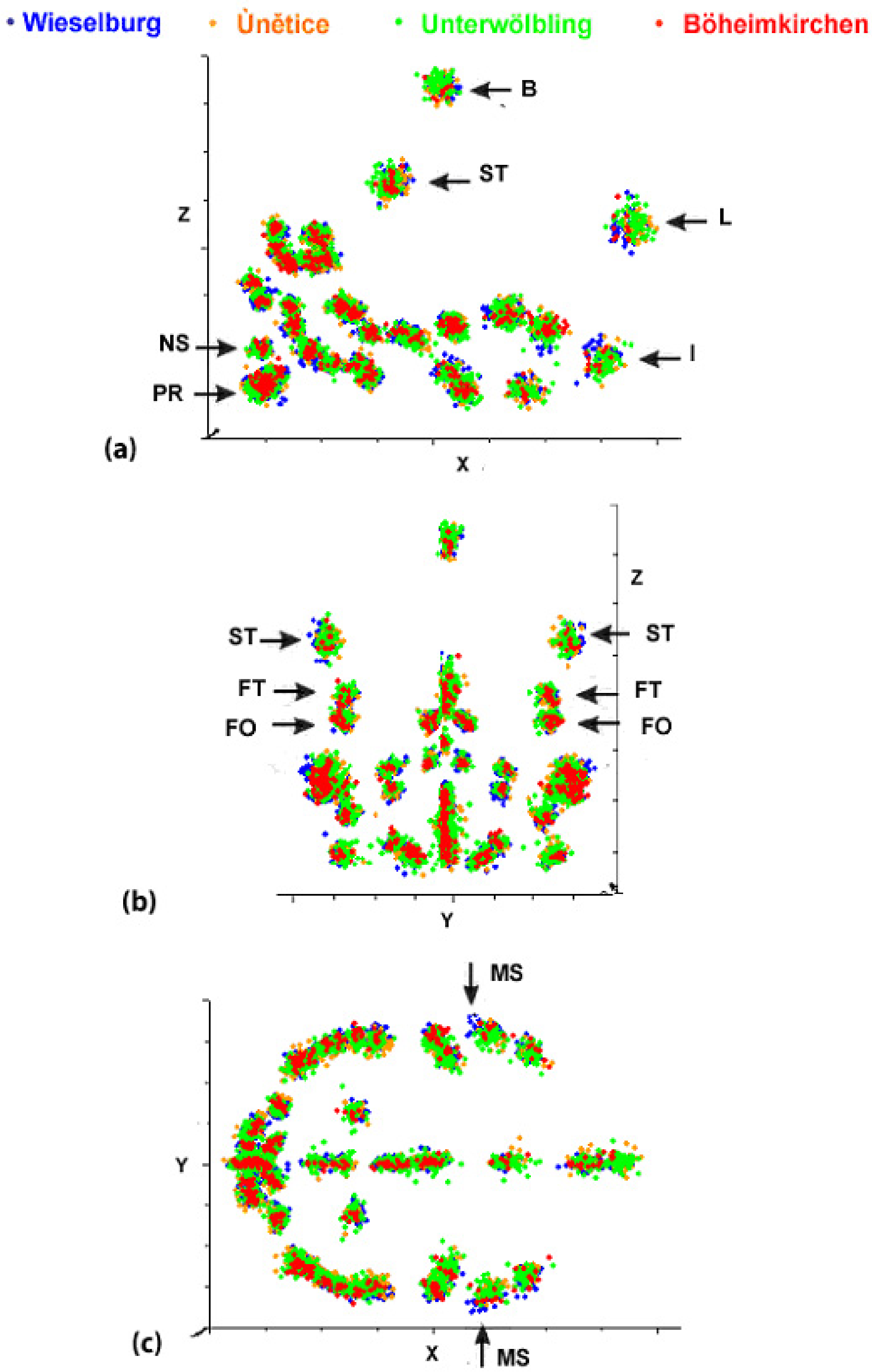

Figure 7.1. Plot of Procrustes shape coordinates labelled by group. (a) lateral view (b) frontal view (c) vertical view. The arrows indicate arbitrarily selected coordinates which appear more variable in location between groups.

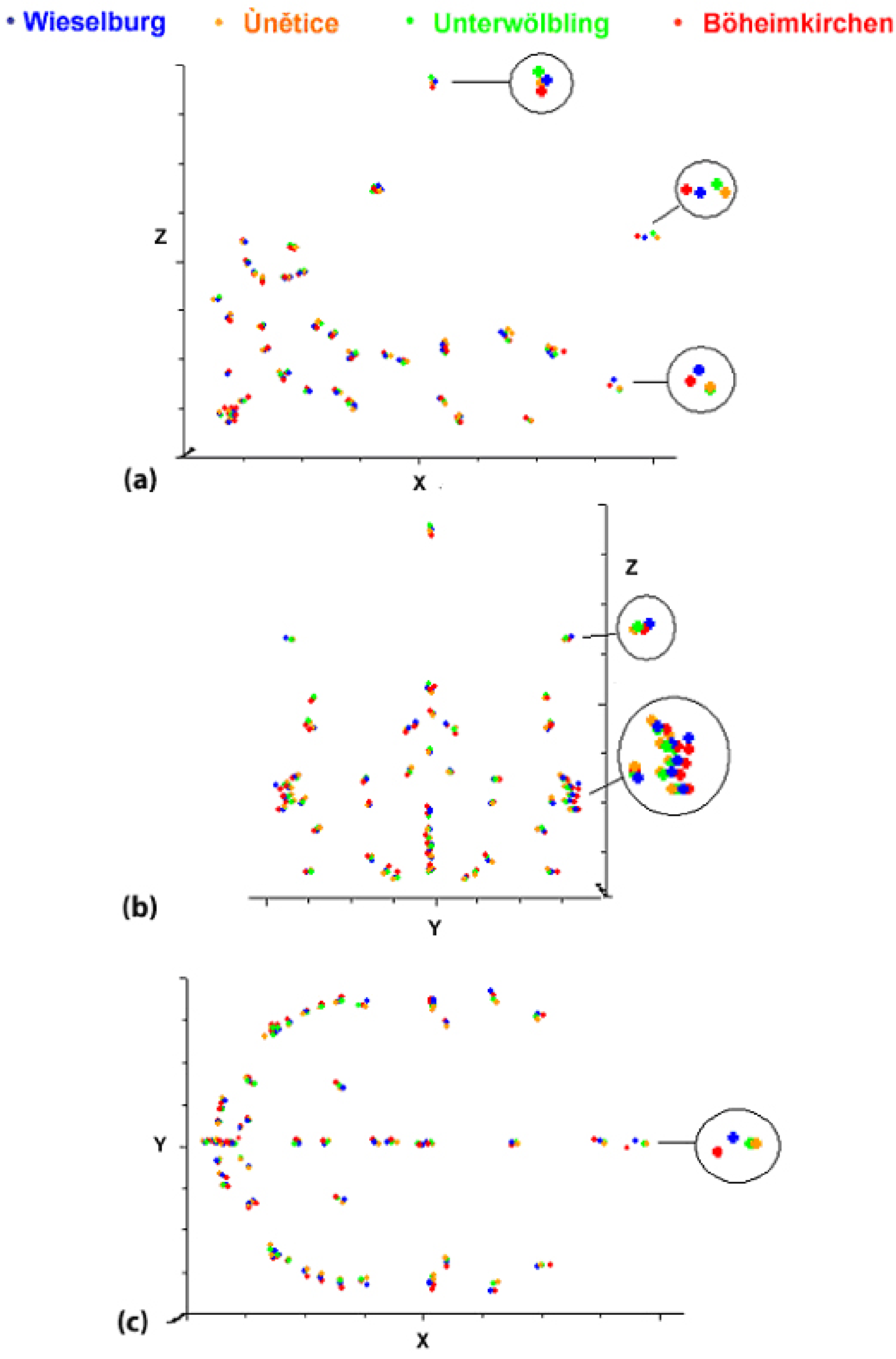

Figure 7.2. Plot of Procrustes shape coordinates of group mean configurations. (a) lateral view, (b) frontal view, (c) vertical view. Selected coordinates which appear more variable in position are shown with a higher magnification. Particularly different in position are the lambda, the inion, and the bregma.

7.2 Principal Component Analysis in Procrustes form space

The resulting fitted configurations lying in the non-Euclidean Kendall's shape space were projected into Kendall's tangent space by an orthogonal projection (see chapter 4.2.4); this specifically allowed statistical analyses to be performed using multivariate analytical techniques illustrated in the next chapters. Applying the methods of geometric morphometrics (Bookstein, 1991; Marcus et al., 1996; Dryden and Mardia, 1998; Mitteroecker et al., 2004), I constructed a size-shape space where the landmark configuration of each specimen is represented by a single point. Recently Mitteroecker et al. (2004) introduced an extension of the shape space augmented with size information[1], namely the Procrustes form space. In Procrustes form space, instead of taking off size, the values of centroid are put back into the data after having carried out a Generalized Procrustes Analysis. This approach consists of a relative warp analysis not of the usual matrix of Procrustes shape coordinates (Bookstein, 1991; Rohlf, 1993) but of the matrix of those coordinates augmented by one single additional column of the logarithm of Centroid Size (CS) instead. In most morphometrics studies size and shape are generally considered separately, but in some cases, for instance when allometry operates, a separation of size and shape is undesirable. In this study, allometry (the linear or linearized characterization of the dependence of shape on size; see for instance Bruner and Manzi, 2001; Rosas and Bastir, 2002; Mitteroecker et al., 2004; Rosas and Bastir, 2004; Berge and Penin, 2004) was examined by a principal components analysis (PCA) of the empirical data distribution in Procrustes form space. In biological data, when allometry is present, log CS has typically the largest variance of any column of this matrix, and thus the first principal component of the form distribution will be closely aligned with size. In Procrustes form space, therefore, allometric shape and geometric size are reflected in a single size-shape component, which is the first principal component of that space (Mitteroecker at al, 2004, Schaefer, 2004).

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[1]Initially this space was termed size-shape space, but at the Vienna Morphofest 2006, an international workshop on geometric morphometrics, it was decided to call it Procrustes form space.

Figure 7.3 shows the ordinated landmark configurations in Procrustes form space. The first PC explains 25.5% of net Procrustes form distances, whereas the second PC explains 8.6%. Along the first PC a separation of males and females can be observed. In this form space, the separation between males and females is due mainly to a generally larger geometric (and allometric) size of males compared to females.

The second PC points to a cultural separation. Interestingly, the Wieselburg group and the chronologically younger Böheimkirchen, which spread over the southern Danubian areas, separate from the Únetice group north of the Danube. The Unterwölbling group overlaps with the others. Eleven individuals from the Wieselburg Culture (recovered from the Hainburg site) have negative second PC scores and are clearly separated from the other specimens, which have mainly positive second PC scores. For this reasons, I investigated archaeological characteristics and findings, e.g. grave goods, to check their cultural background. Interestingly, 10 of the 11 specimens, which were morphologically separated from the Wieselburger group, have been attributed to the Únetice grave goods (Krenn-Leeb, personal communication). According to Leeb (1987), such result is consistent with traces of the presence of an Únetice-Wieselburg mixed group.

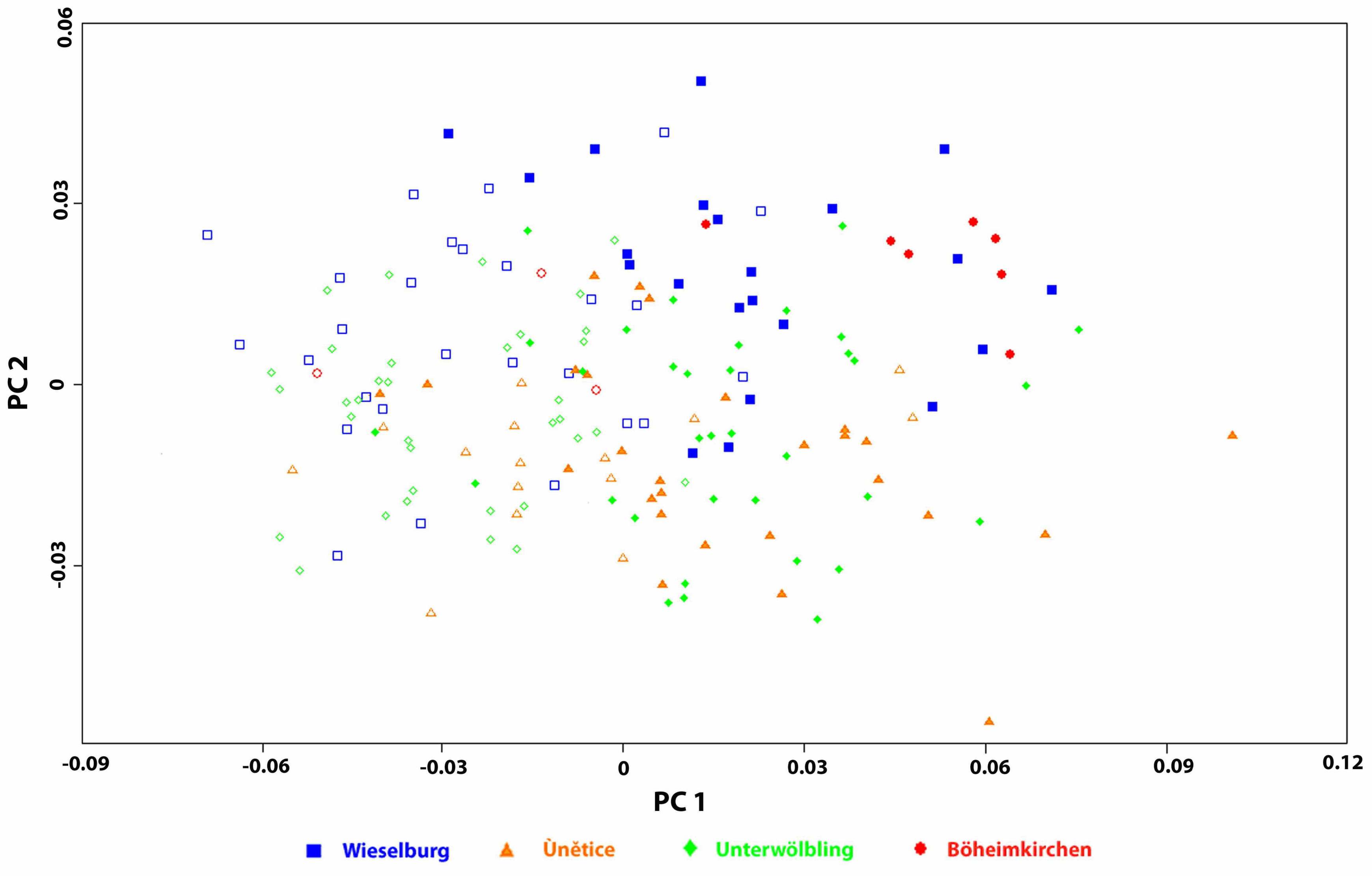

Figure. 7.3. Principal Components (PC) in Procrustes form space for the entire sample. Filled symbols: males. Empty symbols: females.

The shape variation among the sample is illustrated in Figure 7.4 and 7.5 as shape deformations along the first two eigenvector of the PCA (the corresponding relative warp). Here, the shape deformation is shown as an average morphing from the consensus configuration to the consensus configuration plus some multiple of the eigenvector.

In the first PC (Figure 7.4), in the direction of positive scores and increasing size, the deformation shows a relative big viscerocranium, compared to the relative small neurocranium. The shape of the cranium is elongated. In the viscerocranium the maxillary alveolar and the zygomatic region is relatively large compared to the other part of the face. The glabella and the nasal bone are prognathic. In the direction of negative scores and decreasing size the deformation shows a relative small viscerocranium, in comparison to the relative big neurocranium. The neurocranium is relatively enlarged especially in the parietal and occipital region. The shape of the crania is compressed, and the cranial vault is relative tall.

The shape deformation expressed by the second PC is shown in Figure 7.5. In the direction of positive scores, the deformation indicates a relatively short and broad cranium. Along with this features, the maxillary alveolar and the nasal bone are retrognathic. In the direction of negative scores, the deformation concerns a relatively elongated and narrow cranium; the maxillary alveolar and nasal bones are prognathic.

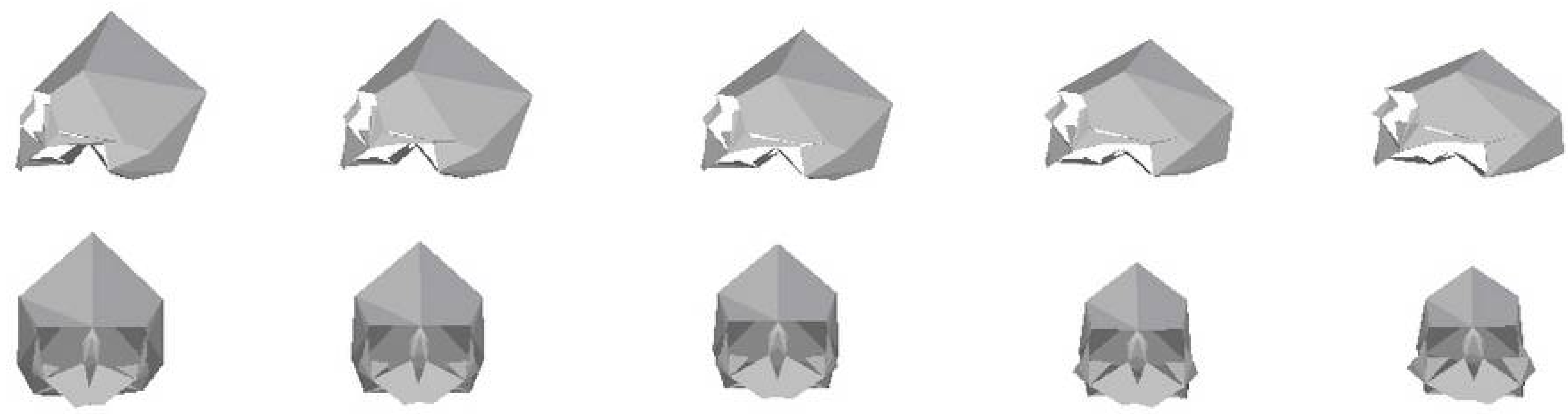

Figure 7.4. Shape deformation along the first PC of PCA for the entire sample. Right side: positive scores. Left side: negative scores. The average morphs illustrates differences in the relative size of the neurocranium and viscerocranium, in the the proportion of the part of the face, and in the length and breadth of the cranium. In Procrustes form space allometric shape and geometric size are reflected in a single size-shape component. The males with positive scores separate from the females with negative scores.

Positive scores are characterised by a relative big viscerocranium compared to a relative small neurocranium. The viscerocranium is relatively large in the maxillary alveolar and in the zygomatic region. The glabella and the nasal bone are more pronounced. The cranial shape is elongated.

Negative scores are characterised by a relative big neurocranium compared to a relative small viscerocranium. The neurocranium is relatively enlarged in the parietal and occipital region. The cranial shape is compressed and the vault is tall.

The shape deformations are arbitrarily magnified to ease interpretation.

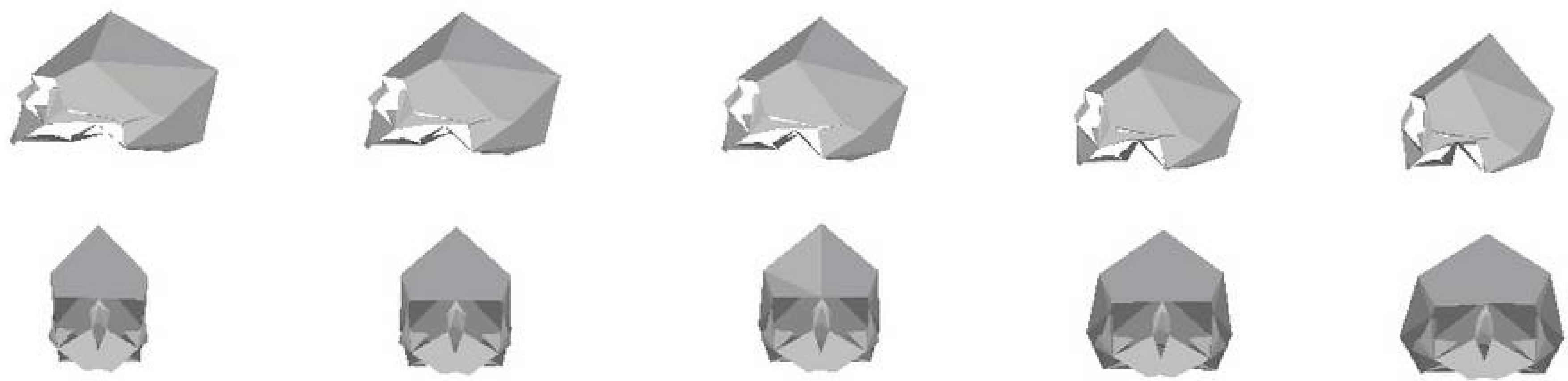

Figure 7.5. Shape deformation along the second PC of PCA for the entire sample. Right side: positive scores. Left side: negative scores. The average morphs shows differences in the length and breadth of the skulls. The second PC separates the Wieselburg and Böheimkirchen which have positive scores, from the Únetice and Unterwölbling witch have negative scores.

Positive scores are characterised by a short and broad skull. In the neurocranium the occipital region is relatively flat. The maxillary alveolar and the nasal bone are retrognathic.

Negative scores are characterised by an elongated and narrow skull. In the neurocranium the occipital region is particularly expanded. The maxillary alveolar and the nasal bone are prognathic.

The shape deformations are arbitrarily magnified to ease interpretation.

In this analysis, the first two PC explain 34.1% of net Procrustes form distances (Figure 7.6). Nevertheless, I found no clear separation between groups plotting the first two PC versus the successive PC, and hence I do not show the plots. In order to yield additional insight into the shape variation among the sample, I analyze below group mean configurations.

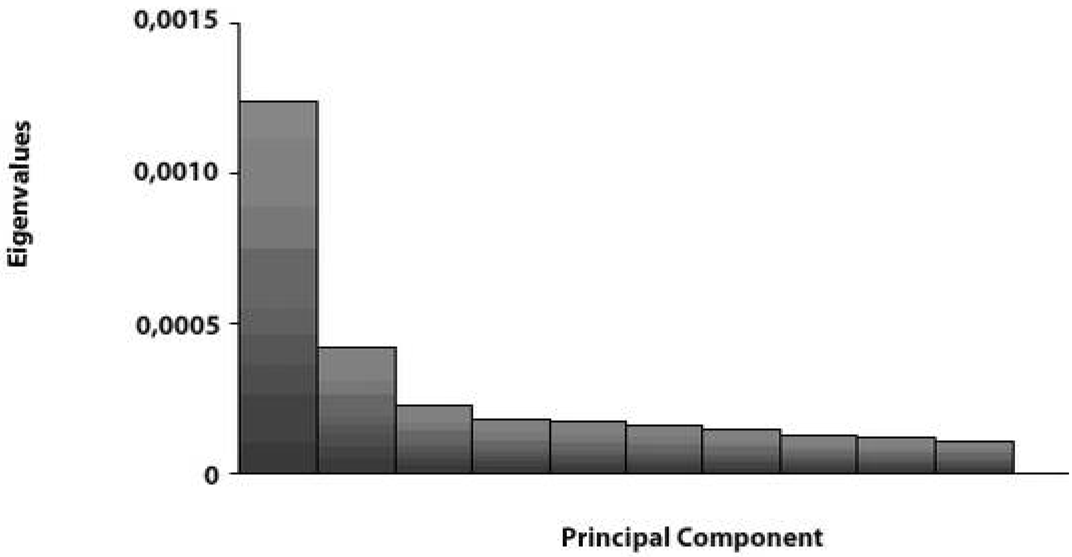

Figure 7.6. Screen plot of the first ten PCs. The first ten PC explain 60% of the total variance. The graphic shows the classical pattern, given by the fact, that the first two PC explain 34% of the sample variance.

7.3 Sex-specific PCA

In the overall PCA of Figure 7.3, the males are more variable than the females (the male variance along the first two PCs is 0.00142 whereas the female variance is 0.00086). In order to investigate this phenomenon, I performed PCAs of males and females separately. Figure 7.7 shows two PCAs of males and females.

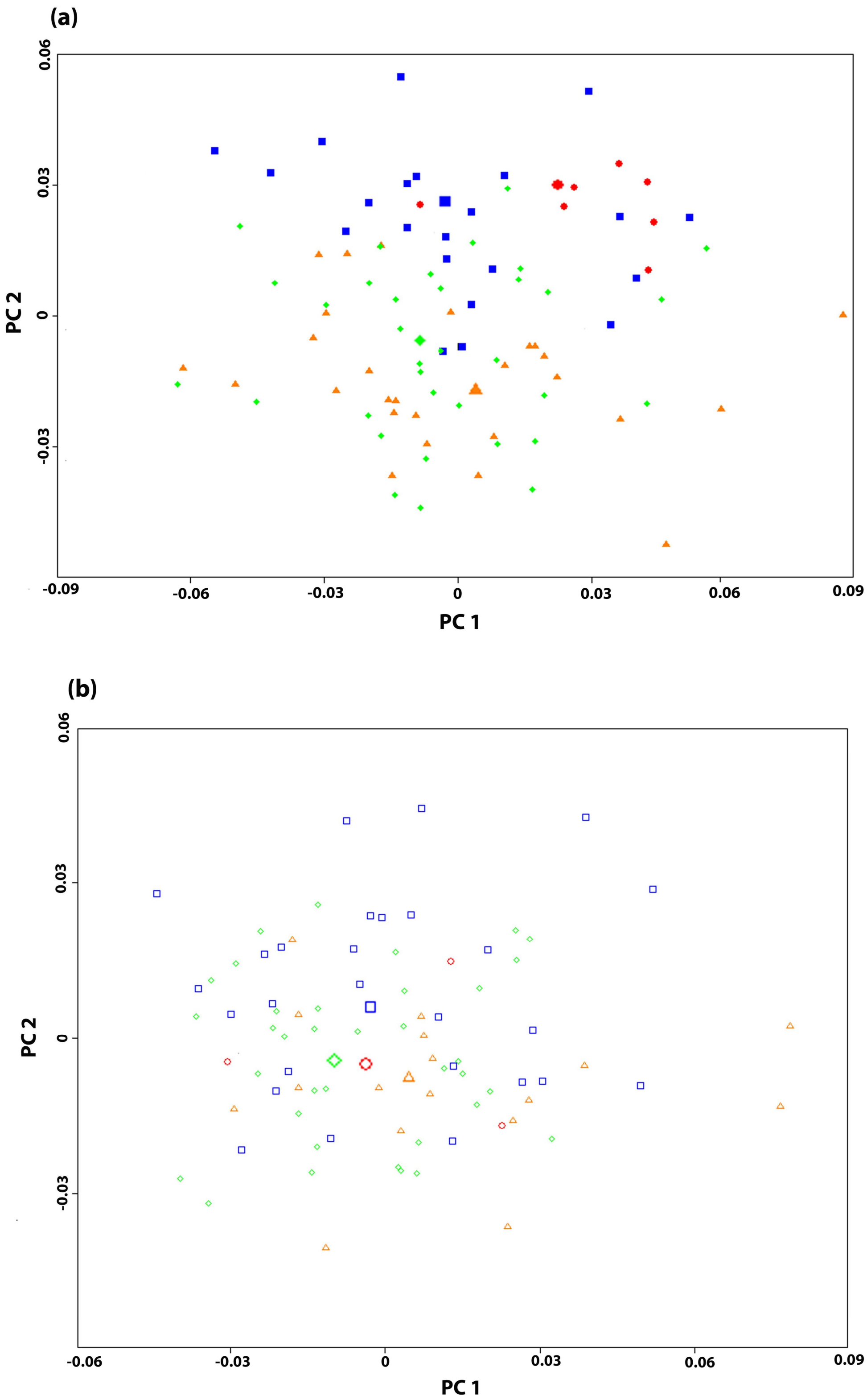

Figure 7.7. (a). The first two PCs of male mean configurations in form space. Legend as in Figure 7.3. Mean groups forms are indicated by large symbol. (b) The first two PCs of female mean configurations in form space. Note that compared to the males the females are less clearly clustered.

Again, the males are more dispersed than the females along the first PC, which is to say, they are more variable in size (variances of 0.00084 vs. 0.00066). There is also a greater culturally induced variation of males along the second PC (0.00054 vs. 0.00034).

Regarding this outcome, I formulated the hypothesis of a greater female rate. To evaluate this hypothesis, I carried out a PCA of sex-specific and site-specific group mean configuration. However, a prerequisite to validate the hypotheses is the investigation of a probable ontogenetic phenomenon, which is that the males tend to reach more variable craniofacial morphology than the females. The latter, in fact, show more evidence for craniofacial paedomorphosis (Shea, 1986; Perret et al., 1998; Rosa and Bastir, 2002; Bulygina et al., 2006). As we can see in Figures 7.3 and 7.7, the males have a greater allometric variation than the females.

7.4 Sex specific PCA of group mean configurations

According to their cultural attributions, sex specific PCA (Figures 7.7) has shown a greater separation in males than in females. To further explore this finding, I performed a sex-specific PCA of groups mean configurations separately by sites. Within the northern Únetice group I included the sites of Unterhautzental and Bernhardstal because of the small sample size of the other groups.

In the plot of PC1 vs. PC2 (Figure 7.8) the female mean forms appear to be more similar than in males (variance among male mean forms along the first two PCs 0.00052; female variance 0.00038). Considering the third PC, however, the females from Franzhausen I show more similarity to the other groups (Figure 7.9). Conversely, the males of the Melk-Spielberg site separate from the other populations.

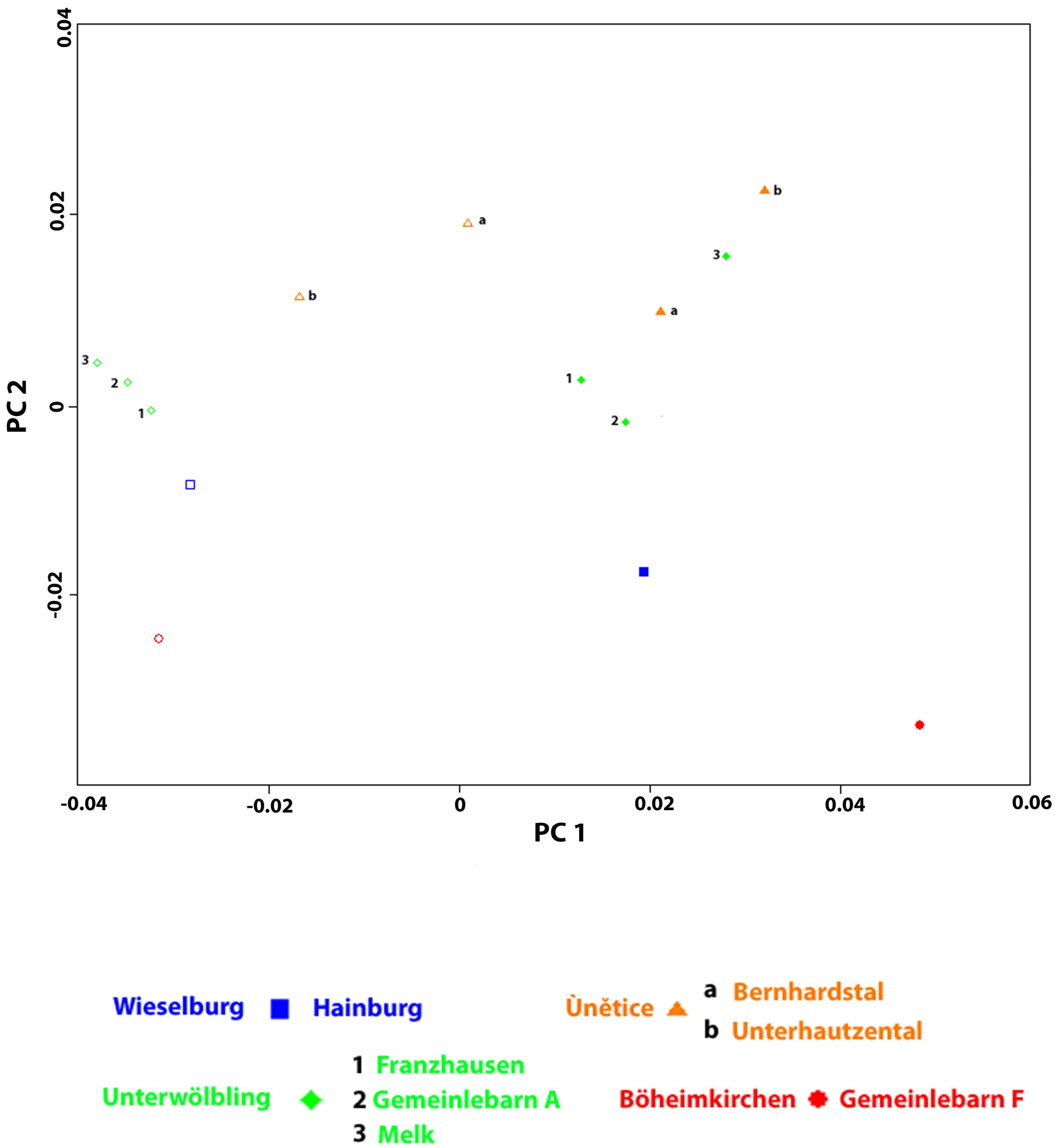

Figure 7.8. PC1vs. PC2 for sex-specific mean configurations in form space. Males and females separate along the first PC. Along the second component the males are more separated than the females. Filled symbols: males. Empty symbols: females.

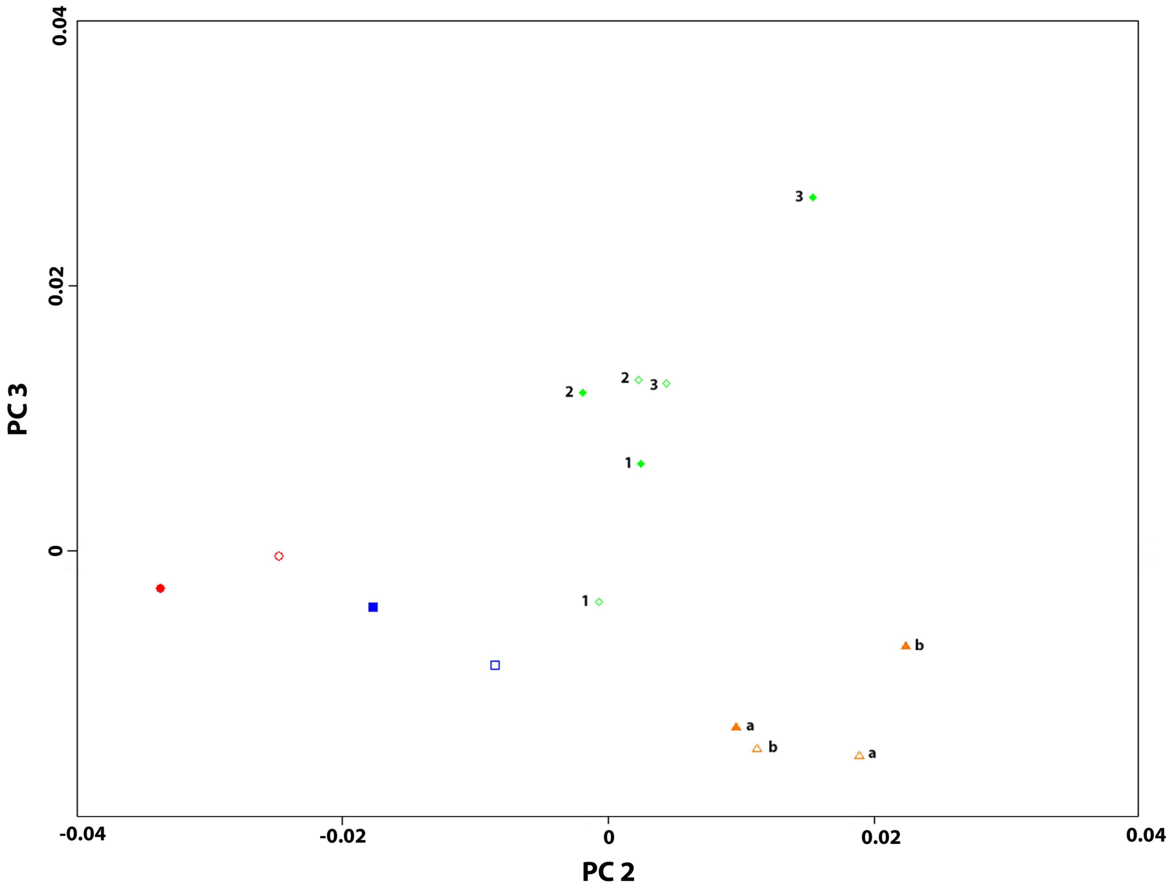

Figure 7.9. PC2 vs. PC3 for sex-specific Procrustes mean configurations in form space. Legend as in Figure 7.8.

In the component of size-shape space I have examined, males and females separate because of the larger geometric and allometric size of males. The first PC illustrates the deformation pattern of the allometric shape component of sexual dimorphism. The deformation (Figure 7.10) concerns differences in the proportion of the viscerocranium and neurocranium, the facial morphology, especially in the glabellar and nasal region expressed in a different degree of prognathism, and the breadth of maxillary alveolar and zygomatic region.

On the second PC, the south-eastern Danubian Wieselburg group separates from the northern Únetice group. On this PC, the south-western Unterwölbling group lies between the Wieselburg and the Únetice groups. Furthermore, the sample representing the Böheimkirchen group of the Veterov Culture, which was dispersed in the south-western area in the later phase of the early Bronze Age, separates from the chronologically older Unterwölbling group. The Böheimkirchen group shows, instead, a greater similarity with the Wieselburg group, as already observed in the above analyses.

Figure 7.11 shows the shape deformation illustrated by the second PC. Shape differences concern mainly length and breadth of the skull. In the direction of positive scores the morph shows a short and broad skull. The occipital region is relatively flat. The nasal and the maxillary alveolar bones are retrognathic. The baseline is short. In the direction of positive scores, the deformation shows an elongated and narrow skull. The occipital region is relatively pronounced. The nasal and the maxillary alveolar bones are prognathic. In the basicranium the baseline is elongated.

On the third PC, the sites belonging to the Unterwölbling group separates from the other groups. As observed, the separation is particular clear for the males of the Melk-Spielberg site. The latter is the farthest from the other sites, and it may be the one with a closer contact to the Bronze Age groups of the north and west, e.g. to the Straubing group in Upper Austria.

Figure 7.12 shows the shape deformation on the third PC. Variations are in the shape of the neurocranium and basicranium in the occipital region, in the morphology of the anterior parietal region, in the prognathism of the face, and in the shape of the basicranium along the baseline. In the direction of positive scores, the inion is shifted forwards whereas the opistion is shifted downwards, resulting in a flat basicranial occipital. In the basicranium, the segment basion-sphenobasion is relative short and the palate bone upwards displaced; in the face, the maxillary alveolar and zygomatic region are relatively large, the maxillary alveolar is prognathic, the frontomalare tempolare and frontomolare orbitale are shifted in the mid-sagittal line; the stephanion is displaced downwards. In the direction of negative scores the inion is shifted backwards while the opistion is shifted upwards, resulting in a globular occipital. In the basicranium the segment basion-sphenobasion is relatively long and the palate bone anterior inclined; in the face, the maxilla, and zygomatic bone are small, the alveolar retrognathic; the frontomalare tempolare and the frontomolare orbitale are displaced laterally; the stephanion is displaced upwards.

In the PCA of sex-specific and site-specific group mean shapes, the first PC accounts for 49.7% of the variation, whereas the second and the third 15.5% and 8.9% respectively. The screen plot of the entire eigenvalues of the PCA is shown in Figure 7.13. The first three eigenvalues explain 74.1% of net Procrustes form distances, and, hence, most of the size-shape variance within the sample.

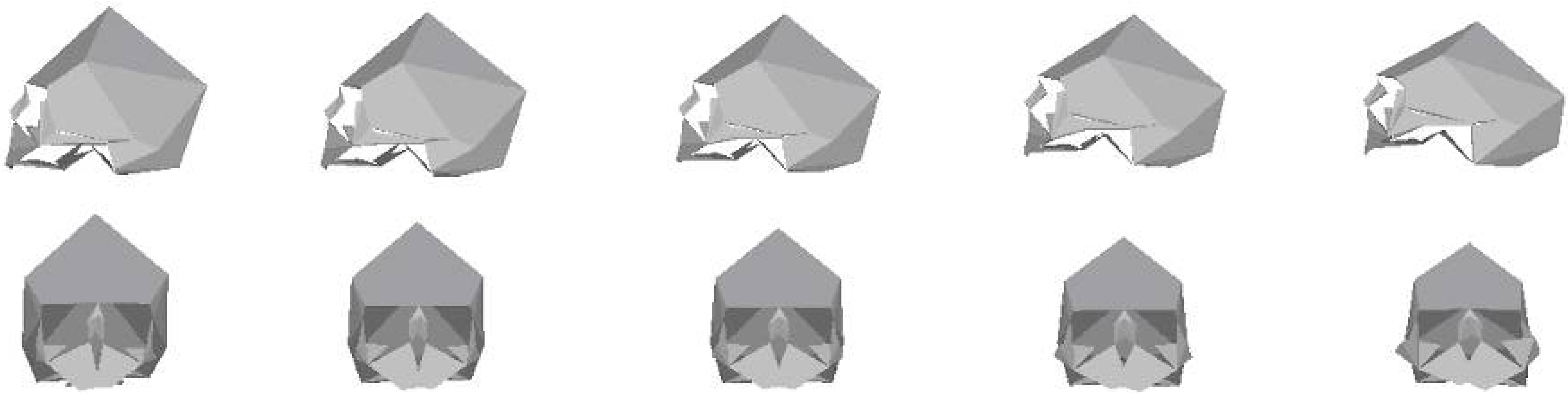

Figure 7.10. Shape deformation along the first PC of PCA for sex-specific mean configurations. Right side: positive scores a. left side: negative scores. The average morphs is similar to the shape deformation illustrated in 7.4 where the entire sample was used. Differences in shape are in the relative proportion of the viscerocranium and neurocranium, in the length of the baseline, and in the facial region.

The shape deformations are arbitrarily magnified to ease interpretation.

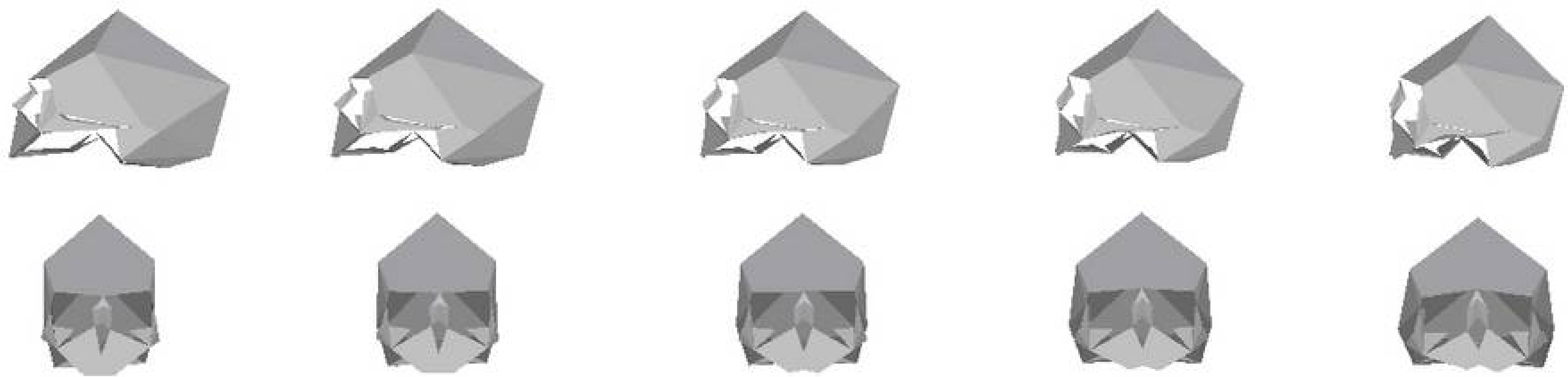

Figure 7.11. .Shape deformation along the second PC of PCA for sex-specific mean configurations. Right side: positive scores a. left side: negative scores. The average morphs is similar to the one shown in Figure 7.5 where the entire sample was used.

The average morphs illustrates shape differences in the length and breadth of the skull.

Positive scores are characterised by a short and broad skull. In the neurocranium the occipital region is short and flat. The maxillary alveolar and the nasal bone are retrognathic.

Negative scores are characterised by an elongated and narrow skull. In the neurocranium the occipital region is particularly expanded. The maxillary alveolar and the nasal bone are prognathic.

The shape deformations are arbitrarily magnified to ease interpretation.

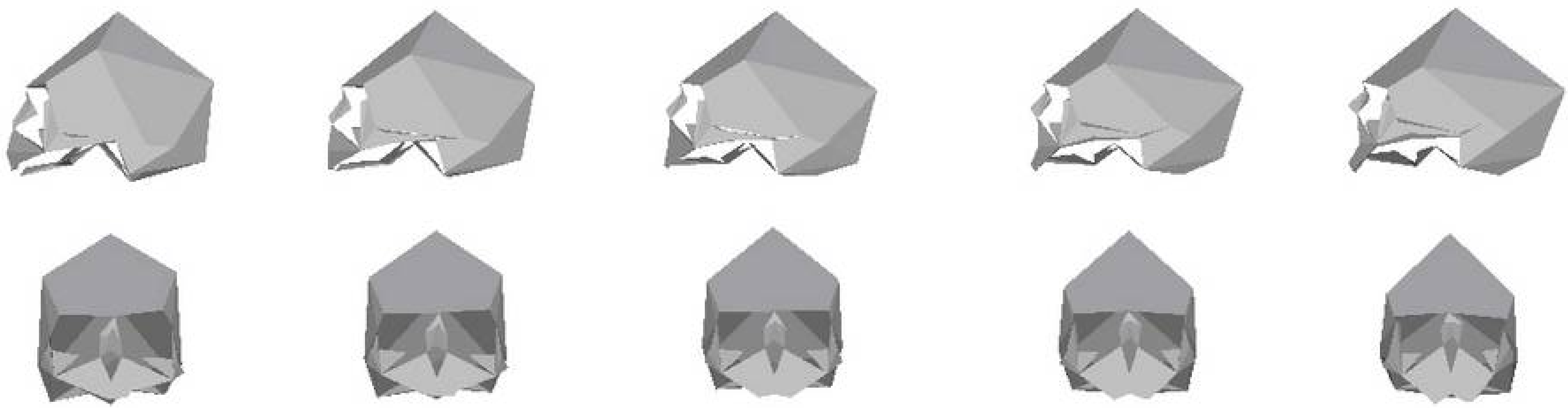

Figure 7.12. Shape deformation along the third PC of PCA for sex-specific mean configurations. Right side: positive scores a. left side: negative scores. The morphs expresses differences in the morphology of the neuro-basicranial region, the shape of the baseline, the shape of the face.

In positive scores the shape of the occipital basicranium is mainly characterised by the shift downwards of the opistion. In the face the maxilla and the zygomatic region are large and the maxillary alveolar prognathic. In the basicranium the segment basion-sphenobasion is relatively short and the palate bone upwards shifted. Frontomalare tempolare and frontomolare orbitale are displaced on the mid-line; the stephanion is shifted downwards

In negative scores the opistion is shifted upwards. The maxilla and zygomatic region are small. The alveolar bone is retrognathic. In the basicranium the segment basion-sphenobasion is relatively long and the palate bone downwards shifted. Frontomalare tempolare and frontomolare are displaced laterally; the stephanion is upwards shifted.

The shape deformations are arbitrarily magnified to ease interpretation.

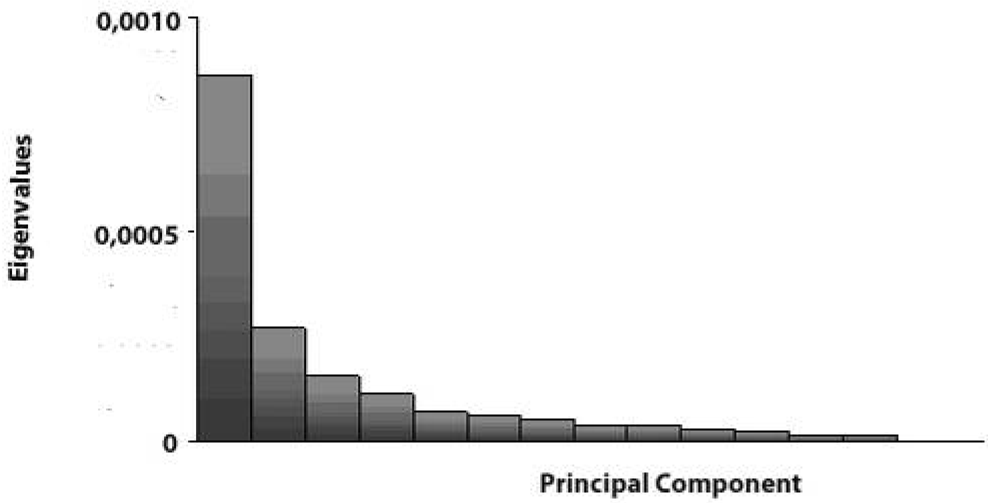

Figure 7.13. Screen plot of the eigenvalues of group mean configurations PCA in Procrustes form space. The first three PC explain describe 74.1% of net Procrustes form distances, and hence most of the size-shape variance within the sample.

7.5 Procrustes Shape Distances separated by sex

In the former chapter I ordinated sex-specific group mean configurations by a PCA in Procrustes form space. The analysis showed similarities/dissimilarities among groups in terms of the principal coordinates of Procrustes form distances. In this analysis, a greater variation in males than in females has been observed.

In this chapter I investigate this argument comparing Procrustes shape distances between sex-specific group mean configurations.

Table 7.1. Matrixes of Procrustes shape distances between males group mean configurations.

	Wieselburg	Böheimkirchen	Unterwölbling			Únetice	
	Hainburg	GemeinlebarnF	Franzhausen	GemeinlebarnA	Melk	Unterhautzental	Bernhardstal
Hainburg	-						
GemeinlebarnF	0.038	-					
Franzhausen	0.038	0.048	-				
GemeinlebarnA	0.043	0.044	0.031	-			
Melk	0.052	0.061	0.041	0.044	-		
Unterhautzental	0.051	0.060	0.042	0.045	0.047	-	
Bernhardstal	0.040	0.048	0.036	0.041	0.045	0.038	-

Table 7.2. Matrixes of Procrustes shape distances between females group mean configurations.

	Wieselburg	Böheimkirchen	Unterwölbling			Únetice	
	Hainburg	GemeinlebarnF	Franzhausen	GemeinlebarnA	Melk	Unterhautzental	Bernhardstal
Hainburg	-						
GemeinlebarnF	0.045	-					
Franzhausen	0.023	0.040	-				
GemeinlebarnA	0.043	0.042	0.036	-			
Melk	0.040	0.051	0.035	0.047	-		
Unterhautzental	0.035	0.050	0.030	0.044	0.046	-	
Bernhardstal	0.046	0.058	0.040	0.049	0.052	0.033	-

Table 7.1 and Table 7.2 show that Procrustes shape distances between male group mean shapes are in general larger as compared to those of females. However, larger distances between female mean shapes are observable between the sites of Franzhausen I and Gemeinlebarn A, which belong to the south-western Unterwölbling Culture. Conversely, concerning the Únetice sites of Unterhautzental and Bernhardstal, a greater similarity in females compared to males is evident.

Higher Procrustes distances are also observable between the female mean shapes of the southern Danubian groups Wieselburg and Böheimkirchen. This might imply a higher mobility of males in the southern Danubian area within the end phase of the early Bronze Age. This possibility is supported by recently archeological findings (Krenn-Leeb, in preparation).

7.6 Sexual Dimorphism

In order to gain additional insight into the morphological variation concerning these populations, I analyse in this chapter the pattern of sexual dimorphism in size and shape within each group and among groups.

Figure 7.14 shows the sexual dimorphism in size within each group. The most dimorphic is the Böheimkirchen group (Gemeinlebarn F site); the less dimorphic is the Únetice site of Bernhardstal.

In each group the males are not only larger than the females but also have a significantly different shape, as obtained by Permutation test on Procrustes distances between males and females in each group ($p < 0.001$). Figure 7.15 shows the sexual dimorphism in shape obtained as Procrustes distances between males and females mean shape in each group. The Unterwölbling site of Melk appear to be the most dimorphic in shape but such findings may be impaired by the small sample size analyzed (N males = 5; N females = 3). The Böheimkirchen group is also quite dimorphic in shape.

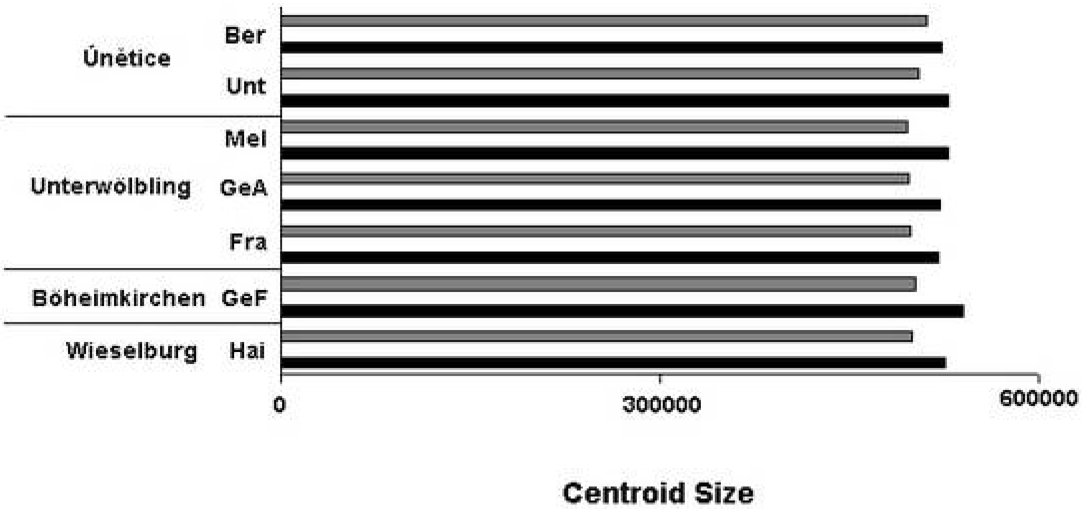

Figure 7.14. Sexual dimorphism in size in each group. The male are represented with black bars; the females with gray bars. (Hai = Hainburg; GeF = Gemeinlebarn F, Fra = Franzhausen; GeA = Gemeinlebarn A; Mel = Melk-Spielberg; Unt = Unterhautzental; Ber = Bernhardstal).

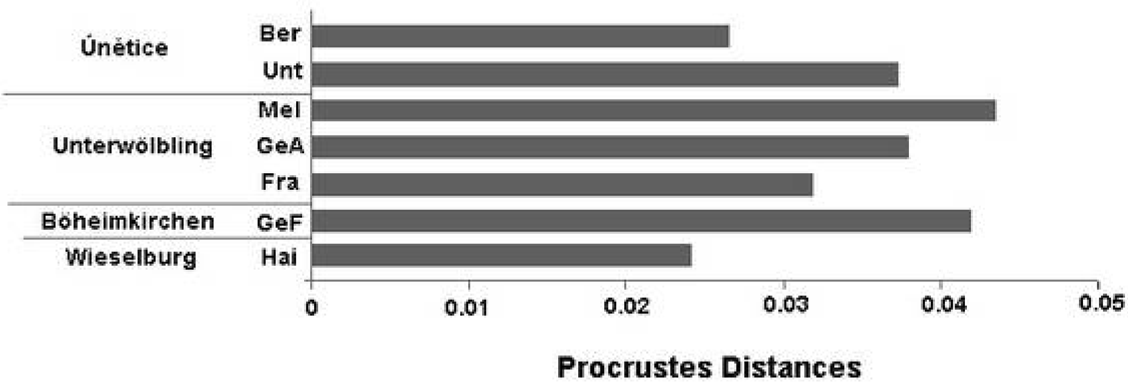

Figure 7.15. Sexual dimorphism in size in each group. (Hai = Hainburg; GeF = Gemeinlebarn F, Fra = Franzhausen; GeA = Gemeinlebarn A; Mel = Melk-Spielberg; Unt = Unterhautzental; Ber = Bernhardstal).

In order to analyse better magnitude and components of sexual dimorphism in each group I carried out an eigendecomposition analysis of craniofacial sexual dimorphism. I calculated a vector of sexual dimorphism for each group in form space as the difference of the PC scores between males and females mean configurations. In this analysis, similarly to a conventional PCA of fitted configurations in Procrustes form space, allometric shape variation and geometric size variation are both reflected in a single form component, namely the first component. For a graphical visualisation of the vector, I demonstrate in Figure 7.16 just the first three sexual dimorphism components (SDC). The components are shown in different orientation to visualize allometric and non-allometric component of sexual dimorphism. In Figure 7.16a, the second and third SDC are aligned along the first SDC, which is the allometric component. In Figure 7.16b, the axes are rotated so that the allometric component is pooled out.

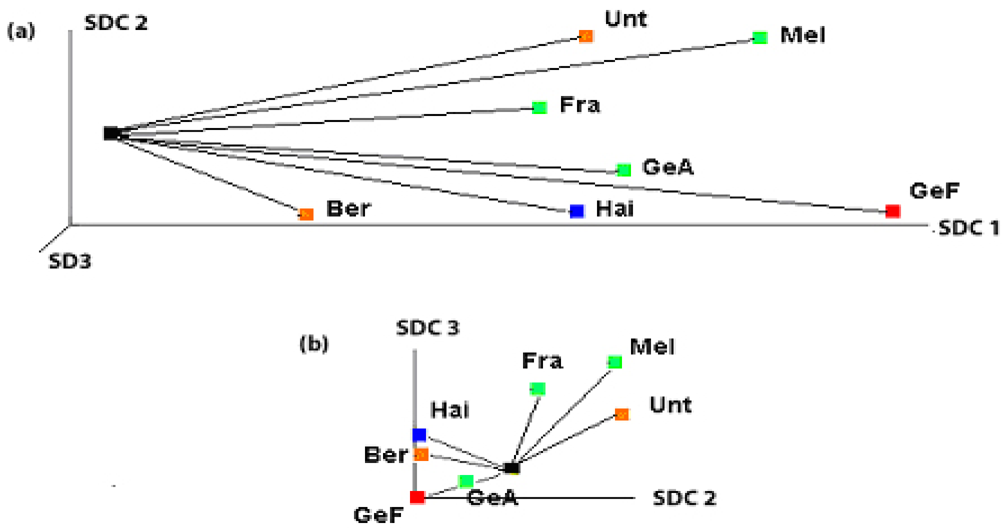

Figure 7.16 Eigendecomposition of sexual dimorphism. First three Sexual Dimorphism Component (SDC). (a) Alignment along the first SDC, the allometric component. (b) Rotation of the axes so that the allometric component is pooled out. (Hai = Hainburg; GeF = Gemeinlebarn F, Fra = Franzhausen; GeA = Gemeinlebarn A; Mel = Melk-Spielberg; Unt = Unterhautzental; Ber = Bernhardstal).

In Figure 7.16a the length of the vectors corresponds to the magnitude of the full sexual dimorphism in form space. The figure indicates that the Böheimkirchen group is the most dimorphic in form, whereas the least dimorphic is the Únetice site of Bernhardstal.

Once that the allometric component has been pooled out (Figure 7.16b), three main clusters of vectors are observable. The Unterwölbling sites of Franzhausen I and of Melk-Spielberg, and the Únetice site Unterhautzental, separates from the Wieselburg site Hainburg and the Únetice site Bernhardstal. Besides, the vectors representing the Unterwölbling site Gemeinlebarn A and the Böheimkirchen Gemeinlebarn F separate from the other groups.

Observing the orientations of the vectors, one may note that vectors representing the geographically close Unterwölbling Franzhausen I and Gemeinlebarn A point in different directions. Similarly, different vector orientations between the Únetice sites Unterhautzental and of Bernhardstal are noticeable.

Considering the two chronologically separated sites of Gemeinlebarn (Gemeinlebarn A and Gemeinlebarn F), one may observe in Figure 7.16a and Figure 7.16b that the orientation of the vector does not differ a lot. The vectors representing Gemeinlebarn A and Gemeinlebarn F differ mainly for their magnitude instead. That is, differences in sexual dimorphism between these sites are mostly affected by dimorphism in size.

7.7 Thin Plate Spline in Two-Dimension

In the preceding chapters we have visualized the morphological variation among the sample as shape deformations represented by the eigenvectors of the PCAs (the corresponding relative warps). The shape deformations have been shown as an average morphing from the consensus configuration to the consensus configuration plus some multiple of the eigenvector. In this chapter, I demonstrate shape differences between groups by computing thin plate spline (TPS) interpolation functions. As exposed in chapter 4.2.5, in geometric morphometric the TPS are the most common method used to visualize shape variation as deformation. Two shapes are compared by analyzing the deformation pattern obtained from the distortion of the first shape (the reference shape) onto the second one (the target shape).

TPS in three-dimensions are not always easy to interpret and one can appreciate but not at all understand shape differences between two configurations. To model shape differences as deformations, a subset of the 58 three-dimensional landmarks was analyzed as 2D data: sixteen landmarks were analyzed on the mid-sagittal plane and twenty-nine landmarks were analyzed for the face (Figure 7.17 and

Figure 7.18; Table 7.3 and 7.4). The sub-set of the three-dimensional landmarks data was projected into a plane which is fitted to the landmarks using a least square criterion (the projected landmark are the first two principal components of the coordinates of the landmarks subset). To analyse shape differences between groups, I computed the TPS functions between sex-specific group mean configurations and the Grand Mean.

In Figure 7.19 a-c and Figure 7.19 d-g the grid deformation of the mid-sagittal plane landmarks are shown (lateral view of the cranium). To enhance the visualization, the splines are exaggerated by a factor of 5. Along with the affine and non-affine component of the TPS, vectors are shown to visualize differences in landmark locations between the mean of groups (the target shape) and the Grand Mean (the reference shape). Differences between the means of the groups are seen in general shape of the neurocranium and specific portions, such as the occipital basicranium and baseline shape, but also in the mid-facial region.

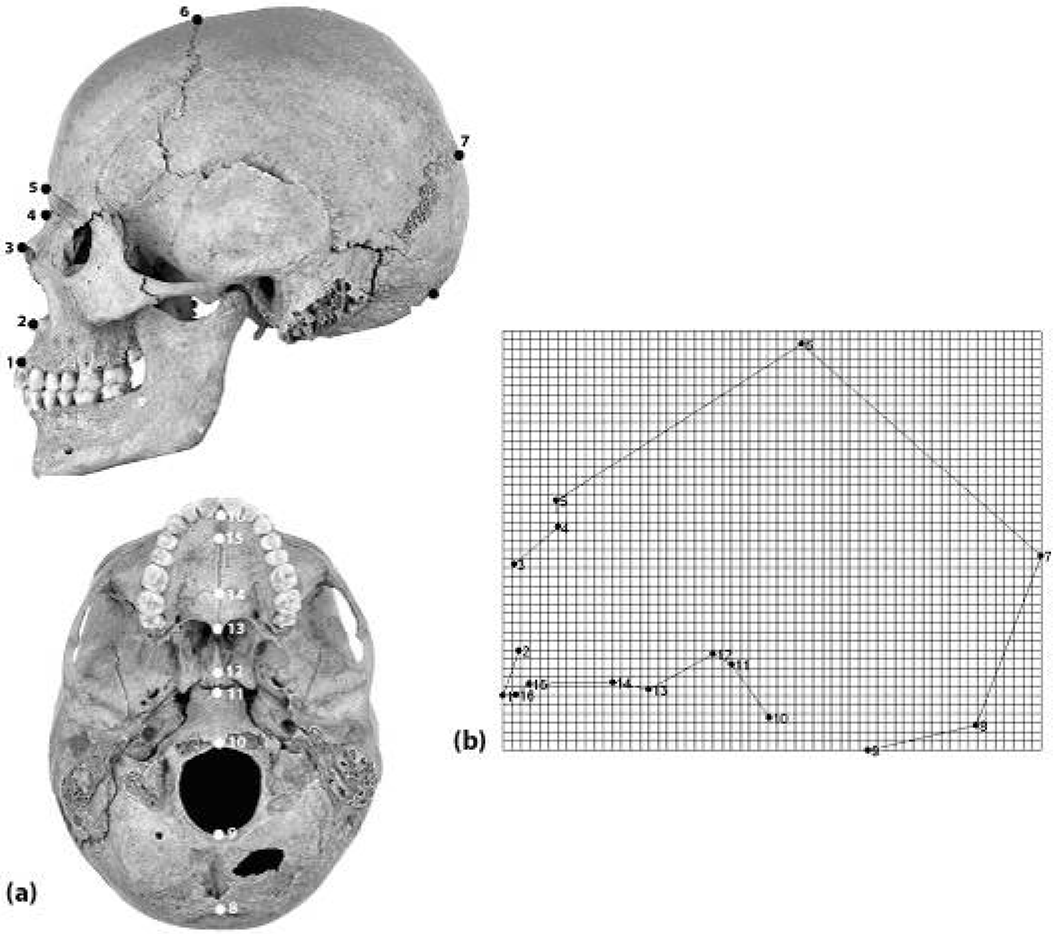

Figure 7.17. Landmarks on the midsagittal plane. (a) landmarks location on skull. (b) landmarks location on TPS.

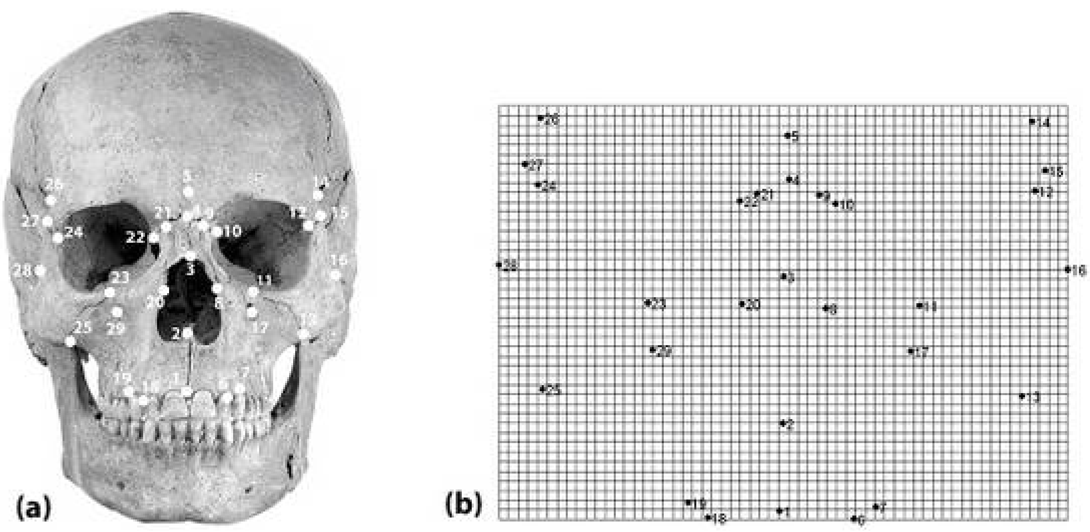

Figure 7.18. Facial landmark. (a) landmarks location on skull. (b) landmarks location on TPS.

Table 7.3. Landmarks on the midsagittal plane.

No.	Landmarks
1	prosthion
2	nasospinale
3	rhinion
4	nasion
5	glabella
6	bregma
7	lambda
8	inion
9	opisthion
10	basion
11	sphenobasion
12	ormion
13	staphylion
14	palate
15	foramen incisivum
16	orale

Table 7.4. Facial Landmarks.

No.	Landmarks
1	prosthion
2	nasospinale
3	rhinion
4	nasion
5	glabella
6	left canine base
7	left canine tip
8	left pseudoalare
9	left nasomaxilla
10	left maxillofrontale
11	left zygoorbitale
12	left frontomalare orbitale
13	left zygomaxillare
14	left frontotemporale
15	left frontomalare temporale
16	left jugale
17	left foramen infraorbitale
18	right canine base
19	right canine tip
20	right pseudoalare
21	right nasomaxilla
22	right maxillofrontale
23	right zygoorbitale
24	right frontomalare orbitale
25	right zygomaxillare
26	right frontotemporale
27	right frontomalare temporale
28	right jugale
29	right foramen infraorbitale

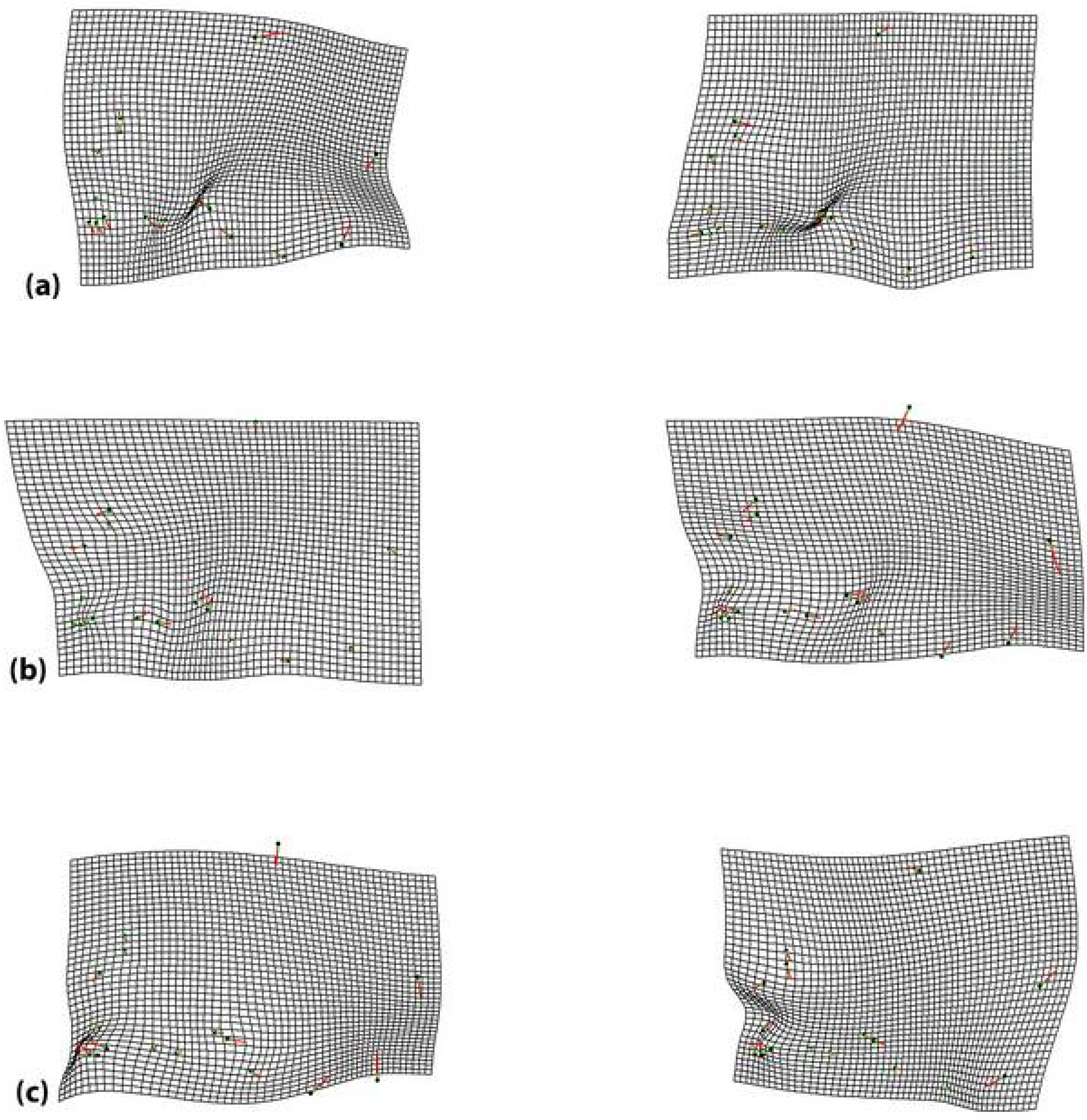

Figure 7.19 a-c. TPS of mid-sagittal sex-specific group mean configurations from the Grand Mean. On the right the males of each group are shown. The females are shown on the left. (a) Hainburg, (b) Bernhardstal, (c) Unterhautzental. Splines exaggerated by a factor of 5.

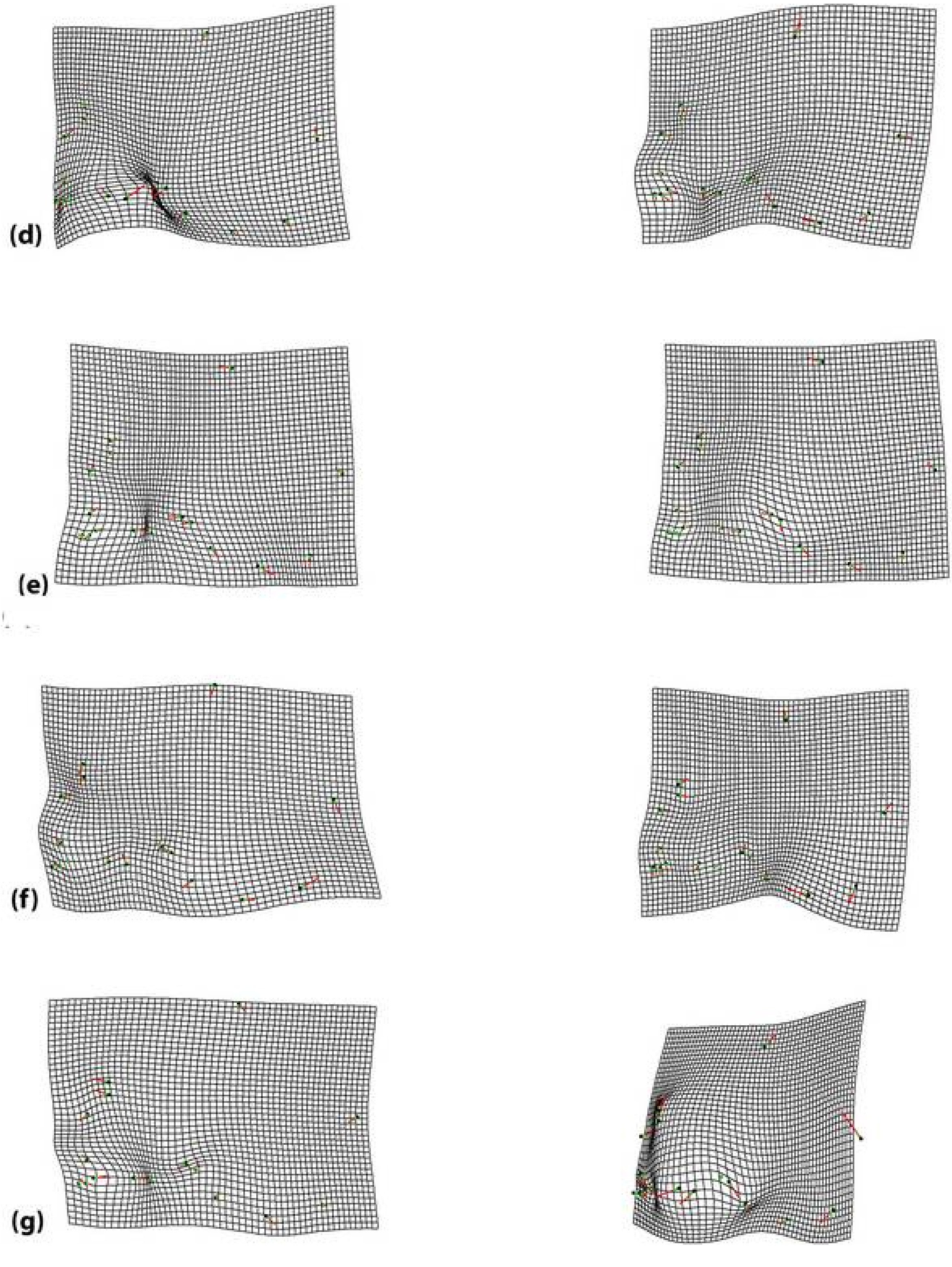

Figure 7.19 d-g. TPS of mid-sagittal sex-specific group mean configurations from the Grand Mean. On the right the males of each group are shown. The females are shown on the left. (d) Franzhausen, (e) Gemeinlebarn A, (f) Melk, (g) Gemeinlebarn F. Splines exaggerated by a factor of 5.

Hainburg site of the Wieselburg Culture (Figure 7.19a): the crania, both in males and in females, have a relatively short shape. In the neurocranium a relative flat occipital can be visualised by a backwards displacement of the lambda and an upwards displacement of the inion. As a result, the occipital is relatively small in comparison to the rest of the skull, especially the viscerocranium, where the face is enlarged. In the basicranium, the palate bone is relatively long but the baseline between the segment staphylion-sphenobasion is short and compressed, with an inclination backwards and upwards of the sphenobasion. Differences between males and females shape from the Grand Mean are mainly in the viscerocranium, due a greater alveolar prognathism in females, and greater nasal and glabella prognathism in males.

Bernhardardstal site of the Únetice Culture (Figure 7.19b): males and females share a common elongated shape of the crania. In this instance, the affine component of the TPS consists in stretching on lateral direction. Local differences shape differences between the Bernhardstal mean configuration and the Grand Mean are in the lambda position, in the length of the palate, the length of the nasal bone and in maxillary prognathism. In the neurocranium the occipital is elongate due to the backwards shift of the lambda. Along with this features the bregma is shifted downwards, and the inion and the opistion shifted upwards and backwards. The crania are therefore long and low. In the basicranium the baseline is elongated due a relative long palate bone. In the viscerocranium the nasal bone is relatively long and the maxillary alveolar prognathic. The shape of the neurocranium is less globular in females due to a more intensive deformation of females from the Grand Mean compared to males.

Unterhautzental site of the Únetice Culture (Figure 7.19c): similarly to Bernhardstal, males and females of the Unterhautzental site have elongated crania. The pattern of deformation of males and females is similar, but they differ for the vault height and occipital region. The shape of males strictly resembles the shape of males and females of the Unterhautzental site. The shape of females differs, instead, mainly in the neurocranium, due to an upwards displacement of the bregma, and the upwards shift of the lambda and downwards shift of the inion. The occipital region of females in the neurocranium is, as a consequence, more globular, and the cranial vault higher.

Franzhausen site of the Unterwölbling Culture (Figure 7.19d): the shape of the crania is relatively elongated but not as elongated as observed in the one of the Únetice Culture. In the females a high cranial vault can be noticed. Due to the displacement of lambda, inion and opistion, the shape of the females' neurocranium is globular and resembles the neurocranium shape observed in the females of Unterhautzental. In contrast, the males are characterized by a flatter occipital compared to females. Moreover, males and females differ for the baseline shape. In males the viscerocranium the palate bone is relatively long but the segment staphylion-sphenobasion is short, due a compression between palate and staphylion and between sphenobasion and ormion. In both males and females, the nasal bone is relatively short and the piriform aperture relatively large; the maxillary is slightly retrognathic.

Gemeinlebarn A site of the Unterwölbling Culture (Figure 7.19e): males and females share a common sagittal relatively elongated morphology. The cranial vault is relatively high. The downwards displacement of the inion and the opistion results in a globular occipital neurocranium. Similar to Franzhausen, the nasal bone is short and the piriform aperture relatively large.

Melk site of the Unterwölbling Culture (Figure 7.19f): similar to the other site of the Unterwölbling Culture, males and females of the Melk site have a relatively elongated shape of the crania. Besides, males and females of the Melk site share a short nasal bone and a relatively large piriform aperture. Males and females of Melk differ, instead, for their occipital neurocranial shape due to the different positions of the lambda, the inion and the opistion. The crania of males are relatively low and elongated, and in their basicranial region the palate bone is relatively long, as we have seen in all elongated crania.

Gemeinlebarn F site of the Böheimkirchen group of the Veterov Culture (Figure 7.19g): the crania are relatively short in males and very short in females. The sex-specific pattern of deformation from the Grand Mean shape shows that the cranial mid-sagittal plane in highly dimorphic. In particular, in females the facial and occipital regions are very flat in comparison with the other part of the mid-sagittal crania. Concerning the males, the occipital region is relatively flat as a consequence of a backwards shift of the lambda. Besides, in males the nasal bone and the glabella are relatively prognathic.

In Figure 7.19 h-j and Figure 7.19 k-n the TPS of the facial landmarks (in frontal view) are demonstrated. To enhance the visualization, the splines are exaggerated by a factor of 5. As asymmetry phenomena (e.g. ontogenetic or post-mortem processes; see for instance Schaefer et al., 2004b) may affect the facial shape, each group configuration was mirrored and averaged with its reflection. Here as well differences between the mean configurations of groups exist in the general shape of the viscerocranium, in particular the breadth of the face, and the morphology of the maxillary alveolar bone.

Hainburg site of the Wieselburg Culture (Figure 7.19h): the crania of both males and females are characterised by a relative broad face. The deformation shows slight contractions in the maxilla in the zygomatic area at the level of the zygomaxillare, and expansions in the frontal bone at the level of the frontomalare tempolare. The nasal bone is narrow and long, as the nasomaxilla is shifted in the mid-line and the rhinion shifted downwards (yet, for a better visualisation of the nasal length, the nasal bone angulations in the mid-sagittal plane TPS must be considered). In the females, a smaller maxilla alveolar area can be observed compared to the one noted in males, though males and females share similar deformation from the Grand Mean.

Bernhardstal site of the Culture (Figure 7.19i): males and females of this group are both characterized by a very narrow face. The maxilla alveolar is relatively big and expanded compared to the zygomatic area. A slight compression is present in the frontal bone at the level of the frontomalare orbitale. At the level of the sutura frontonasalis and the sutura frontomaxillaris, the nasomaxilla and maxillofrontal are shifted upwards. The nasal bone is relatively long, enlarged at the level of the nasomaxilla and enclosed at the level of the pseudoalare. Particularly in females, a short face can be visualized, due to the downwards displacement of the glabella.

Unterhautzental site of the Únetice Culture (Figure 7.19j): the face of males is relatively narrow, whereas the face of females is relatively broad. Males and females share a common nasal bone morphology, which is similar to the one observed in the Únetice site of Bernhardstal. In males’ temporal area, similarly to the shape deformation observed in Bernhardstal, slight compression at the level of frontotemporale, frontomalare orbitale and frontomalare temporale can be seen. In contrast, expansions are observed in these landmarks in females. Besides, males and females differ in the morphology of the orbital area due to a different location of the zygoorbitale, and in the morphology of the maxillary alveolar bone, which is more expanded in males.

Franzhausen site of the Unterwölbling Culture (Figure 7.19k): the crania of this group have a relative narrow face in males and a relative broad face in females. In both males and in females, the nasal bone is large and short, and the piriform aperture relatively big. Moreover, a contraction between the foramen infraorbitale and the orbit is present in both sexes. In females, the maxilla is relatively expanded in the zygomatic region compared to the alveolar bone, whereas in males a relatively smaller zygomatic region can be observed.

Unterwölbling Gemeinlebarn A (Figure 7.19l): the mean face morphology of this group is similar to the morphology observable in the Unterwölbling site of Franzhausen. In fact, males and females of this group have large and short nasal bones, a relatively big piriform aperture, and contraction between the foramen infraorbitale and the orbit. In males and females of Gemeinlebarn A, however, the shape of the maxilla is characterized by an expanded zygomatic region compared to the alveolar bone. Moreover, shape differences from the site of Franzhausen I are in the location of glabella, and in the relative position of frontomalare orbitale, frontotemporale and frontomalare temporale.

Unterwölbling Melk (Figure 7.19m): the females of the site Melk share a similar facial morphology with the one shown by the females of Franzhausen and Gemeinlebarn A. The males of Melk, instead, appear to have a particular facial morphology especially in the frontal and zygomatic area. The frontomalare orbitale is shifted upwards while frontotempolare and frontomalare tempolare are shifted laterally. That is, the facial morphology of the Melk males differ the most from the common facial morphology shown by males and females belonging to the Unterwölbling Culture.

Gemeinlebarn F site of the Böheimkirchen group of the Veterov Culture (Figure 7.19n): the face of the crania belonging to the Gemeinlebarn F site is relatively broad in females and extremely broad in males. Similar to the chronologically older Gemeinlebarn A, in both sexes of Gemeinlebarn F a large and short nasal bone, a relative big piriform aperture and a contraction between the foramen infraorbitale and the orbit can be observed. In the mean facial shape of males and females of Gemeinlebarn F, however, an extreme short and small maxilla can be noticed. Along with this features, in males the maxilla is expanded at the zygomaxillare level. Moreover, in both sexes the facial shape of the Böheimkirchen is conspicuous because of the position of frontotempolare, frontomalare tempolare, frontomolare and zygoorbitale observed in the frontal and zygomatic area.

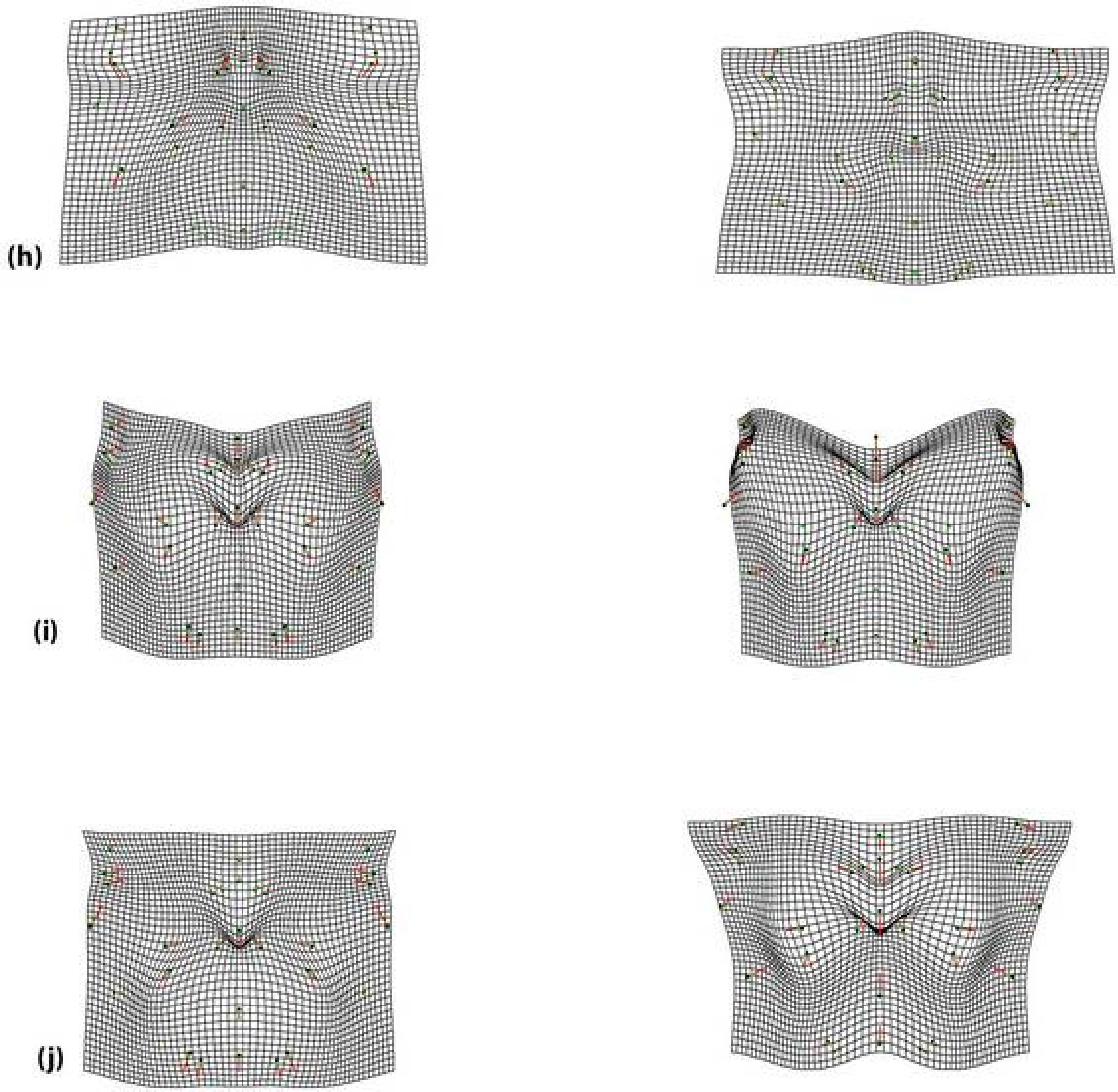

Figure 7.19 h-j. TPS of facial landmarks sex-specific group mean configurations from the Grand Mean. On the right the males of each group are shown. The females are shown on the left. (h) Hainburg, (i) Bernhardstal, (j) Unterhautzental. Splines exaggerated by a factor of 5.

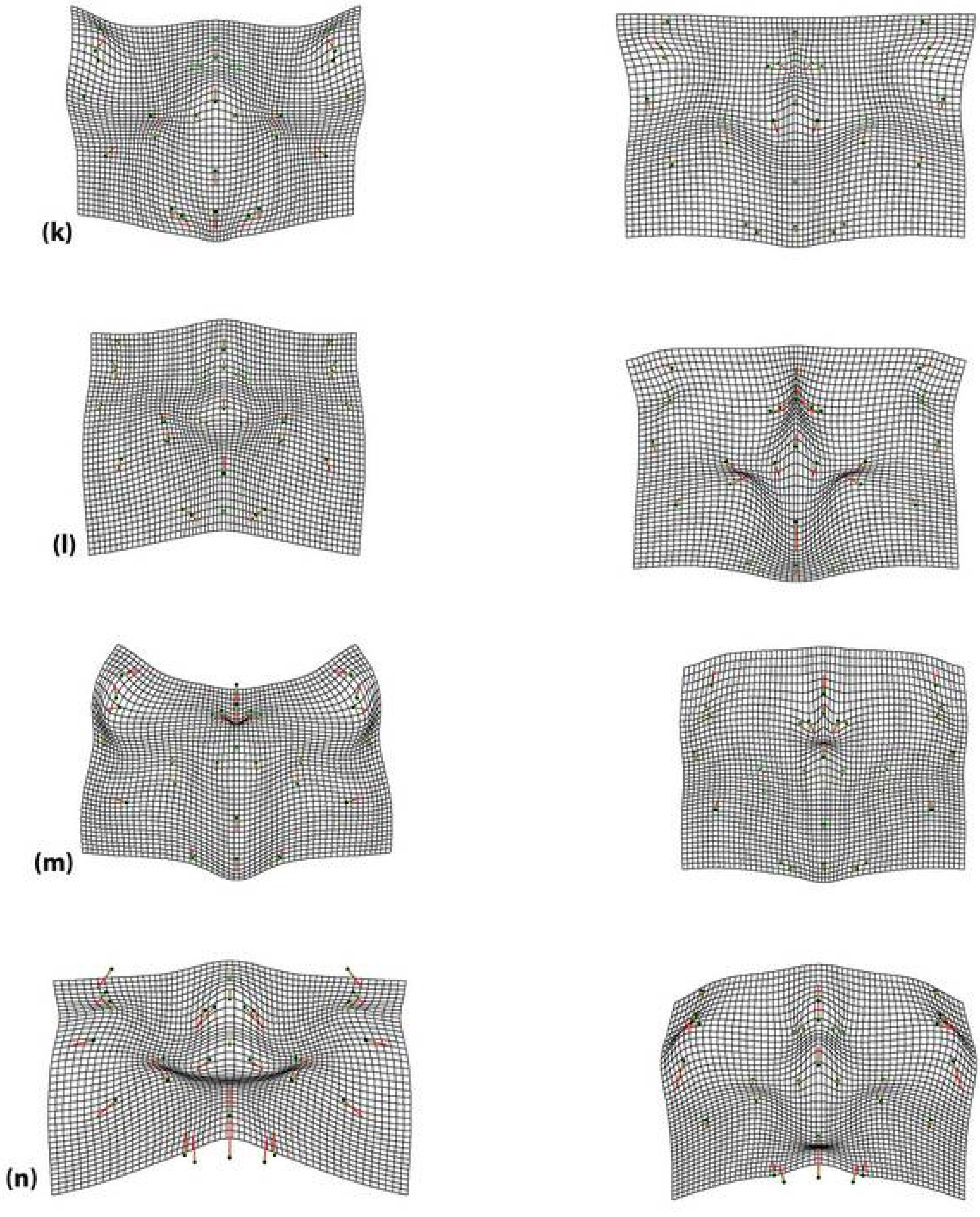

Figure 7.19 k-n. TPS of facial landmarks sex-specific group mean configurations from the Grand Mean. On the right the males of each group are shown. The females are shown on the left. (k) Franzhausen, (l) Gemeinlebarn A, (m) Melk, (n) Gemeinlebarn F. Splines exaggerated by a factor of 5.

8 Discussion

Along with the present study, a wide range of anthropological researches have been focused on issues concerning the biological parameters of the early Bronze Age populations in Austria. Though a lot of investigations have been carried out to shed light on thematic such as origin, life condition and population dynamics, a general sight into those matters is far from completion. Actually, most of our knowledge on the Lower Austria Bronze Age concerns highlights about life conditions and life expectancy regarding the south-eastern Danubian groups, (Wiltschke-Schrotta, 1988; Teschler-Nicola, 1992; Teschler-Nicola and Prossinger, 1992; Teschler-Nicola and Prossinger, 1997; Teschler Nicola and Gerold, 2001; Novotny, 2005). Otherwise, the northern and the south-western Danubian groups have been less analyzed in these matters (Schultz, 1988-1989; Winkler and Groszschmidt, 1987 a,b; Teschler-Nicola and Berner, 1991). Currently, it is therefore not possible to establish whether differences on those parameters existed between the groups of Lower Austria. On the other hand, a systematic exploration and confrontation on morphometrical, epigenetic and morphognostic traits on these populations has been carried out. Indeed, the investigation of Teschler-Nicola (1992), with the analysis of 879 individuals of 79 sites of Lower Austria, has amply analyzed these issues. Teschler-Nicola (1992) reported a significant amount of morphological differences among the - *a priori* archaeologically characterized – Bronze Age populations. These findings were interpreted by Teschler Nicola as the consequence of genetic disposition, and geographical barriers, e.g. the river Danube and the Wienerwald.

By applying novel morphometrics on craniofacial morphology, the study herein added the thematic concerning the phenetical variation among these populations, in order to verify the results obtained by Teschler-Nicola and to yield additional insight into issues such as populations structure and migration patterns.

In spite of the inclusion of newly discovered remains, most of the geometric morphometric analyses carried out in this study confirm the previous evidence indicating that the morphological variation among populations corresponds to a cultural pre-defined subdivision.

Morphological variation among populations showed by PCA

The pattern of morphological variation within the analyzed sample has been shown by the ordination analysis of Procrustes distances in form space (Figure 7.3). The Wieselburg cultural group, which was located south-west of the Danube, separates almost completely from the Únetice cultural group north of the Danube. This supports previous indicating that those groups were culturally and genetically separated (Neugebauer, 1991; Teschler-Nicola, 1992; Neugebauer, 1994; Sprenger, 1996; Krenn-Leeb, in preparation). Yet 10 individuals buried in the territory of the Wieselburg groups match morphological and archeological attributes of the Únetice group. According to Leeb (1987), traces of the presence of an Únetice-Wieselburg mixed (cultural) group have been already identified in an area north of Bratislava. The results obtained here are supported by new archeological findings suggesting that an Únetice-Wieselburg mixed (cultural) group existed in the territory of the Wieselburg Culture, in particular in the most northeastern located area, including Hainburg and the southwestern Slovakian sites (Krenn-Leeb, in preparation)**.**

In this analysis of morphological parameters, the Unterwölbling group, spreading over the south-western Danubian area, overlaps with both the Wieselburg cultural group and the Únetice cultural group. Inasmuch as the main source of the Unterwölbling groups is the site of Franzhausen I, this result could be due to a chronological issue, as the site of Franzhausen I encompasses nearly the whole period of the early Bronze Age (Neugebauer, 1991; Sprenger, 1996). Nevertheless, according to the dating of the selected specimens, my sample of Franzhausen I belongs to the Gemeinlebarn II stage, and is therefore synchronous with the sample of the Wieselburg and Únetice groups. On the other hand, the reported morphological pattern may also be due to the geographical localisation of the Unterwölbling group. The Franzhausen I site was mainly a farming society without a primary production of bronze artifacts (Sprenger, 1996). But based on the exceptional number of bronze objects used as grave goods, Sprenger (1996) argued that the Traisental valley was a central point of trade processes, which primarily brought metallurgic goods (e.g. copper) and basic materials from the Slovakian and the eastern alpine regions into the Unterwölbling province. This might have caused intensive contacts with the neighbour groups (see also Neugebauer, 1991; Neugebauer, 1994).

The Böheimkirchen group of the Veterov Culture, inhabiting the south-western Danubian area in the later phase of the early Bronze Age (Gemeinlebarn III stage) separates completely from the chronologically older Unterwölbling group. In this analysis, the Böheimkirchen group shows a higher morphological similarity with the Wieselburg group instead. According to recent archeological arguments (Krenn-Leeb, in preparation), this might imply a higher mobility between these populations within the end phase of the early Bronze Age, probably for economic reasons (e.g., intensified trade processes).

Extent of endogamy/exogamy between populations

According to the archeological data the early Bronze Age cultural groups of Lower Austria most likely evolved regionally from two local Endneolithic Cultures, the Corded Ware Culture and the Bell Beaker Culture (Neugebauer, 1991; Neugebauer, 1994). While contacts between regional groups due to trade process are evident (Neugebauer, 1994; Sprenger, 1996), it seems likely that these groups evolved independently (Neugebauer, 1991, Neugebauer, 1994; Leeb, in preparation). Given the small geographic area inhabited by these groups and their relatively small population size, it is likely that genetic drift (stochastic evolutionary processes) considerably influenced the evolution of these populations. Moreover, in small populations, genetic variation is also influenced by inbreeding, which tends to increase homozigosity among individuals over time (Falconer and McKay, 1996). Inasmuch as the populations were semi-isolated by the presence of barriers such as the river Danube or the Wienerwald, a low amount of admixture is plausible between those groups.

Yet one might consider that craniofacial features are determined not only by genetic, but also by environmental factors acting on development. The estimation of the genetic and non-genetic components underlying the phenotypic variation of the human skull has long been a main focus of anthropological studies (Boas, 1912; Kohn, 1991; Konigsberg, 2000). Numerous studies have estimated the heritability of craniofacial traits (Wylie, 1944; Kraus et al., 1959; Sneath, 1967; Nakata et al., 1976; Cheverud et al., 1982; Byard et al., 1985; Hauspie et al,. 1985; Devor et al., 1986; Richtsmeier and Cheverud, 1986; Devor, 1987; Nikolova, 1996; Sparks and Jantz, 2002; Carson, 2006, Martínez-Abadías et al., 2009). The general conclusion is that human craniofacial traits have moderate to high degree of genetic variation, but also are influenced by environmental factors. Such environmental influences on morphology are particularly apparent in secular trends of the improvement of life conditions (Boas, 1912; Hunter and Garn, 1969; Smith, et al., 1986; Jantz and Jantz, 2000; Buretic-Tomljanovic et al., 2003; Wescott and Jantz, 2005).

However, the synchronous Austrian early Bronze Age populations inhabited a relatively small geographic area and hence shared very similar ecological environments. Therefore, their phenotypic differences most likely arose from genetic drift and were maintained by partial or total endogamy.

Craniofacial morphological variation showed by deformations

In this study, landmarks were selected in order to reveal the overall craniofacial morphology of the crania. The craniofacial variation within the sample has been shown as shape deformations, by morphing the average configuration along the eigenvectors of PCAs in form space, and by computing TPS interpolation functions in two dimensions between sex-specific mean shape of groups.

Differences in craniofacial morphology have been seen in the global structure of the crania as well as in locally positioned features. The analysis herein reported differences which mainly concerned parameters as breadth and length of the crania, the morphology of the mid-facial and occipital region, and the baseline shape.

The ordination analysis of Procrustes distances for the entire sample, and its associated shape deformations along eigenvectors, reveals a distinct craniofacial morphology between the northern Únetice group and the southern Danubian groups Wieselburger and Böheimkirchen (Figure 7.3; Figure 7.4). The former is principally characterized by elongated and narrow crania, while the latter are mainly marked by short and broad skulls. Further morphological variation regards the maxillary alveolar and the nasal bone morphology, which appear more prognathic in the Únetice group. In addition, TPS interpolations functions show a conspicuous cranial morphology of the Únetice group, which is apparent in the low cranial vault, and in the elongated basicranial morphology of its mean group shapes.

The PCA for the entire sample reports a high similarity in the craniofacial morphology of the Wieselburger and Böheimkirchen groups, but TPS deformation grids between sex-specific mean configurations reveal some local shape differences between these groups (Figure 7.19a, Figure 7.19g, Figure 7.19h, and Figure 7.19n). These differences concern the basicranium morphology, which appear peculiar in the Wieselburg group because of a relatively short and compressed baseline in the staphylion-sphenobasion segment expressed in both males and females. Besides, the Böheimkirchen group shows a greater sexual dimorphism in its mid-sagittal group mean shapes, as in females the facial and occipital regions are relatively flat in comparison with those of males. Furthermore, in the Böheimkirchen group an extreme short and small maxilla has been noticed, along with an increased facial breadth, especially expressed in males.

The PCA of site- and sex-specific group mean configurations, and its related visualization of shape variation as deformation, shows differences in craniofacial morphology between the south-western Unterwölbling group and the other populations, which concern the morphology of the anterior parietal region, the shape of the basicranium along the baseline, the globularity of the occipital region, and the morphology of the maxillary alveolar and zygomatic region (Figure 7.12; Figure 7.19 d-f Figure 7.19 k-m). TPS deformation grids show that the Unterwölbling sub-groups share a relative short nasal bone and a relative large piriform aperture (Figure 7.19 k-m), even though the facial morphology of the Melk males differ in the morphology of the frontal and zygomatic area.

When the results of the descriptive morphological analysis here obtained are compared with those achieved by the classical morphometric approach of Teschler-Nicola (1992), it turns out that similarities but also differences between the two analyses are noticeable (see Table 2.2). Differences in shape descriptions between the present and the former investigation are seen in parameters such as length and breadth of crania, and in local shape difference as well, e.g. the morphology of the mid-facial and occipital region. While the investigation of Teschler-Nicola (1992) reported a dolichocranic morphology of the Unterwölbling group, the present study demonstrates that the morphology of that group vary from long and narrow till short and broad crania. Besides, no differences between groups have been detected by Teschler-Nicola concerning the length-height index, but my analysis demonstrates clearly a particular morphology of the Únetice group, because of the low structure of their vault.

The results here gained present, in my opinion, the benefit to show more elegantly global and local shape differences, which could be not be demonstrated by traditional methods. Differences between these two morphometric studies are not unexpected, since the present analysis departed from different data. Furthermore, inconsistencies between my results and the former might also arise mainly from the use of a different sample and its subdivision. In accordance with new chronological dating, the present study considered the Gemeinlebarn F site as belonging to the chronologically younger Böheimkirchen group. The Gemeinlebarn F site was analyzed by Teschler-Nicola together with the Unterwölbling group instead. Additionally, this study analyzed a considerable sample of the Wieselburg site of Hainburg, whose skeletal material has been recently excavated.

In comparison with the investigation of Teschler-Nicola (1992), the present study lacked, however, the analysis of important sites of the Wieselburg culture, e.g. the site of Mannersdorf, because the skeletal remains were too fragmentary for a geometric morphometric analysis. It was impossible for the Mannersdorf site to estimate some missing points because in all the specimens the viscerocranium was strongly damaged. Therefore, in order to shed light on the morphological variation within the Wieselburg group, and hence, on the biological and cultural relationship of this group to the others of Lower Austria, further analysis based on sufficiently well preserved cranial remains suitable for geometric morphometric analyses are requested.

Mobility and populations dynamics

While ordination analyses are usually performed in shape space, the analysis in form space permits the exploration of the allometric variation within the sample. In the analysis carried out with the entire sample, one can observe in Figure 7.3 a greater allometric shape variation in males than in females. Similarly, the ordination analyses separately by sex (Figure 7.7a and Figure 7.7b) demonstrate that the males are more dispersed than females on the first PC (the allometric component). Furthermore, those analyses show a greater separation in males according to their cultural attributions (the second PC). This may be explained as a consequence of a longer ontogenetic development in males than in females. Males tend to reach more variable craniofacial morphology than the females, whereas the females tend to be more paedomorphic (Shea, 1986; Perret et al., 1998; Rosa and Bastir, 2002; Bulygina et al., 2006).

On the other hand, a greater separation of male groups as compared to females might be rooted in a greater female migration rate. Similarly, in an investigation concerning the Unterwölbling group, Teschler-Nicola (1992) found a higher variability of average craniometrical traits in males than in females. Teschler-Nicola argued that a greater female migration rate within the Unterwölbling district may have existed, and interpreted these results as evidence for the presence of a patrilocal system. In such a system, females had a larger marriage domain and could have originated from different geographical areas in comparison to the males, who were local instead. Accordingly, the archeological records suggest that the patrilocal system was widespread in early Bronze Age societies. This assumption is mainly based on sex/cultural specific grave goods (e.g., several female graves excavated at the Melk site are equipped with objects typically for the Franzhausen site, which belong to the Unterwölbling group) but is also supported by the settlement sizes (rather small sites) and demographic parameters (Krenn-Leeb, personal communication).

Also in the PCA of site- and sex-specific group mean configurations the female mean forms seem to be more similar than those of males (Figure 7.8 and Figure 7.9), hence supporting the hypothesis of a patrilocal system within and among cultural groups. Along PC 3, Franzhausen I females show a pronounced morphological distance to the females from Gemeinlebarn A in spite of their close geographic proximity (4 Km), which might again be a result of high female mobility.

Because of small sample size, group mean forms of the Únetice group could only be computed for the sites of Unterhautzental and Bernhardstal. As indicated by the Procrustes distances (Table 7.1 and 7.2), female mean shapes are more similar than that of males. Given the larger geographical distance between these two sites (about

40 Km), it is plausible that the males were largely isolated. Morphological similarity in average females might again indicate an interchange of females between the sites and a patrilocal system within the Unterwölbling group. However, given the small sample, a general statement about this issue is difficult.

Chronological effect on morphological variation

The present study aimed to investigate microevolutionary trends in craniofacial morphology of the early Bronze Age Austrian populations. Though most of the analyzed remains have been dated to the middle phase of the early Bronze Age, namely the Gemeinlebarn II stage, the skeletal remains belonging to the site of Gemeinlebarn F have been allocated to a later phase instead (the Gemeinlebarn III stage).

The analysis herein revealed different patterns of craniofacial morphology in the Gemeinlebarn F site, which has been assigned to the Böheimkirchen group, and the sites belonging to the Unterwölbling group, which inhabited the same geographical area in an earlier phase. In the PCAs of form space, the two south-western Danubian groups clearly separate (Figure 7.3; Figure 7.8 and Figure 7.9). This is especially apparent when the sites of Gemeinlebarn A and Gemeinlebarn F are compared, as the sites were temporally separated by a few decades only and are geographically closely adjacent (for the other sites attributed to the Gemeinlebarn III stage the sample size is not representative).

So far, no exhaustive explanations are available for such an issue. It is arguable that change in environment condition, or genetic factor, may have contribute to the observed pattern. There is evidence that life conditions may have changed during the early Bronze Age as indicated by increase of life expectancies (Teschler-Nicola and Prossinger 1992, 1997). Such modifications of environmental conditions are likely to induce morphological changes, which are documented by many other studies on secular trends (Boas, 1912; Hunter and Garn, 1969; Smith, et al., 1986; Buretic-Tomljanovic et al., 2003; Jantz and Jantz, 2000, Wescott and Jantz, 2005).

However, the changes in craniofacial morphology in the later stage of the early Bronze Age could also be due partly to gene flow. It has been proposed that in this phase a break-down of the isolation of cultural groups caused by intensification of metallurgical production and ampler trade may have happened (Krenn-Leeb, in preparation), thus increasing the mobility between the Wieselburg and the Böheimkirchen groups. The relatively small Procrustes distance between males of these groups as compared to females (Table 7.1 and Table 7.2) point to a higher male migration rate, probably because they were more frequently involved in trade processes.

Pattern of sexual dimorphism

The eigendecomposition of sexual dimorphism in form space reveals different direction of vectors in populations belonging to the same cultural group. Observing the pattern in form space demonstrated in Figure 7.16, one may note that vectors representing the geographically close Unterwölbling Franzhausen I and Gemeinlebarn A sites point in different directions. Similarly, different vector orientations between the Únetice sites of Unterhautzental and Bernhardstal are noticeable. Again, this pattern might indicate a patrilocal system in which the females could have originated from different geographical areas in comparison to the males, who were mainly autochthons.

The Melk-Spielberg population appears to be the most dimorphic group in shape, as indicated by Procrustes distances between males and females mean configurations. This high dimorphism in shape has been also demonstrated in PCAs (see Figure 7.8 and Figure 7.9) and by the use of TPS interpolation functions (Figure 7.19f and Figure 7.19m). Also this pattern of morphological variation may be the consequence of a patrilocal system. As the site of Melk-Spielberg is geographically the farthest from the other sites (see Krenn-Leeb, 1994), this dimorphism could be the effect of a higher isolation in males than in females. The latter share, in fact, similarity with the females of the other groups (Figure 7.8 and Figure 7.9). However, considered the small sample size analyzed conclusions about this argument are far from completion.

The population of Gemeinlebarn F is the most dimorphic population in size (Figure 7.14) and it is also quite dimorphic in shape (Figure 7.15). In particular, the males of Gemeinlebarn F hold an extra position for their greater Centroid Size (Figure 7.8; Figure 7.15). However, the orientation of the Gemeinlebarn F sexual dimorphism vector does not differ a lot from that of the chronologically younger Gemeinlebarn A. They differ mostly for the magnitude of the allometric component instead. That is, differences in sexual dimorphism between these populations appear mostly affected by dimorphism in size due to bigger crania in males of the chronologically younger Gemeinlebarn F sites. So far, no certain arguments are available for a sophisticated interpretation of such a result. Socio-economic factors and the role of each sex may have had a bearing on issues such as a higher migration rate of males in the later phase of the early Bronze Age (Neugebauer, 1991; Neugebauer, 1994; Sprenger, 1996; Krenn-Leeb, in preparation). Otherwise, changes of life conditions may have contribute to the observed change of pattern of sexual dimorphism, for instance acting on the longer ontogenetic development in males, in contrast with the paedomorphis of females, which has been observed in this study.

Further perspective

A main goal of this investigation was to integrate the toolkit of geometric morphometrics with the archeological data that have been so far recorded. This study analyzed principally Procrustes coordinates and the associated phenetic similarity and dissimilarity among individuals of the analyzed sample. These analyses have reviewed extensive evidence that Procrustes distances match other sources of information about the early Bronze Age populations of Lower Austria, for instance their cultural and geographical disposition.

The illustrated morphological differences among pre-defined cultural populations most likely arose, as hypothesized, from genetic differences due to genetic drift and inbreeding.

It is arguable, however, that environmental influences may have played a role in those issues. Hitherto, it is not possible to assert whether environmental factors acting on development may have contributed to the observed pattern of craniofacial variation. Besides ecological concerns, living conditions (stress markers) might be an object of further studies. Indeed, compared to the Unterwölblig group which has been studied for a long time leading to the discovery of an elevated number of pathologies (Winkler 1985-86; Winkler and Groszschmidt 1987 a,b; Teschler-Nicola, 1987; Teschler-Nicola, 1988; Schultz 1988-89; Schultz and Teschler-Nicola, 1989; Teschler-Nicola and Berner, 1991; Pirsig, Ziemann-Becker and Teschler-Nicola, 1992; Teschler Nicola and Gerold, 2001; Novotny, 2005), the frequencies of pathologies in the Wieselburg group seem to be low instead (Novotny, in preparation). So far, a plausible argument for a sophisticated interpretation of this matter has been not already suggested; from an archaeological point of view, it could be affected by a “more stable political system” (Krenn-Leeb, in preparation).

Inasmuch as the observed pattern of morphological variation is also a consequence of difference in migration rate between sexes, within and between cultural groups, spectrometrical methods (e.g. ICP-SFMS Sr-isotope ratio determination) are also requested to clarify the issue of migration. Indeed, investigations carried out on remains recovered from the south-western Danubian area indicate that not all of them are autochthons (Latkoczy et al., 2001). Therefore, spectrometrical investigations would probably help to shed light on the differences observed between the synchronous Unterwölbliger Gemeinlebarn A and

Franzhausen I sites. Moreover, it is reasonable to expect that this method may help to identify migration of the inhabitants of the Wieselburg area and the Traisen valley (Böheimkirchen group) as well.

To sum up, the analyses carried out here with geometric morphometric methods confirm differences in craniofacial morphology among cultural groups and show considerable allometric variation within sexes that appear to contribute to the group separation among males, which may be also the consequence of a relatively high degree of genetic isolation of the groups resulting from geographical barriers (Wienerwald, river Danube) as well as a patrilocal system leading to more admixture among females than among males. The phenotypical differences of the chronological younger Gemeinlebarn F population are explained by socio-economical changes as indicated by an intensification of metallurgic trading.

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