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Secular trends in the European male facial skull from the Migration Period to the present: a cephalometric study

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SUMMARY Secular trends in the facial skull over three Central European samples spanning more than 13 centuries were examined. Data were 43 conventional cephalometric landmark points for samples dating from 680 to 830 AD (29 male Avars), from the mid-19th century (49 adult Hapsburg Monarchy males), and from the 20th century (54 living Austrian young adult males).

Analyses by standard methods of geometric morphometrics demonstrated shape differences by data and by size, with a strong interaction of these with sample, in that group mean differences were different for small and large individuals (allometry is different from period to period). The oldest sample, from the Migration Period, exhibited allometric features that may possibly be Turkic. There are implications for the orthodontist interested in growth trends or growth predictions in ethnically mixed patient samples.

Introduction

Secular trends in the facial skull have been of considerable interest in orthodontics (Smith *et al.*, 1986). They have been variously ascribed to assumed dietary effects (Kiliaridis *et al.*, 1985; Yom-Tov and Yom-Tov, 2004), to increased malocclusion (Varrela, 1990; Vyslozil and Jonke, 1994; Weiland *et al.*, 1997; Lindsten *et al.*, 2002), or to other environmental factors (Jäger *et al.*, 1998). Many studies have attempted to assess these trends geometrically, but the conclusions have been conflicting or ambiguous (Anderson *et al.*, 1975; Key and Jantz, 1981; Dibbets and Nolte, 2002). Jonke *et al.* (2007) studied secular trends in the light of (putative) environmental effects. The aim of the present investigation was to study secular trends in a more general context: to what extent are the putative environmental effects less pronounced than facial skull shape changes ascribable to differences in ethnicity?

Materials and methods

The sample included three distinct groups. The oldest consisted of 29 skulls of male Avars buried in a Migration Period grave field dated 680–830 AD (in use shortly before the demise of these peoples approximately 870 AD) discovered near Zwölfaxing, Lower Austria (Lippert, 1969; Müller, 2004). The Avars are presumed to be of either Central Asian or Caucasian (but in any case Turkic) origin that invaded Europe in waves from the fifth century onward (Mitscha-Märheim, 1957; Breuer, 2005). After their defeat by Charlemagne, large numbers of Slavs migrated into Central Europe, and the region of the former Avar Khaganate became occupied by Bavarians, Hungarians, and Bulgarians (Pohl, 2002).

The second group consisted of 49 cephalograms of the Weisbach collection of Caucasian soldiers who died in the service of the Hapsburg Empire in the late 19th century (Weisbach, 1892; Vyslozil and Jonke, 1994).

The most recent group comprised the cephalograms of 54 male soldiers conscripted at the end of the 20th century into the Austrian Federal Army. (All individuals who volunteered agreed to a lateral head film being taken and signed an appropriate consent form.)

The cephalograms were digitized and 43 points from the 51-point cephalometric system of the University of Michigan University School Study (Riolo *et al.*, 1974) were registered. Figure 1 shows these on a stereotyped tracing. All landmarks were digitized by one author (MB) from tracings made by the first author (EJ). Paired landmarks were digitized as averages of left- and right-side locations. In a small replication study, the same operator digitized four of the 103 films, selected at random, four times each. The within-case sum of squares was 0.13 per cent of the between-case sum of squares for shape (in Procrustes units), for an intraclass correlation of 0.9987, which is satisfactorily high for the following results to be considered robust against digitizing error. Two different versions of the landmark configuration (all 43 points or all 26 points on the bony anatomy) were analysed by modern Procrustes-based geometric morphometrics (GMM; Marcus *et al.*, 1996). For an introduction to the methodology of GMM, see Halazonetis (2004).

The methods of GMM can be explained from many different points of view, from mathematics (Small, 1996) through to statistics (Dryden and Mardia, 1998), via biomathematics (Bookstein, 1991, 1998) and into clinical orthodontics itself (Halazonetis, 2004). For a clinical

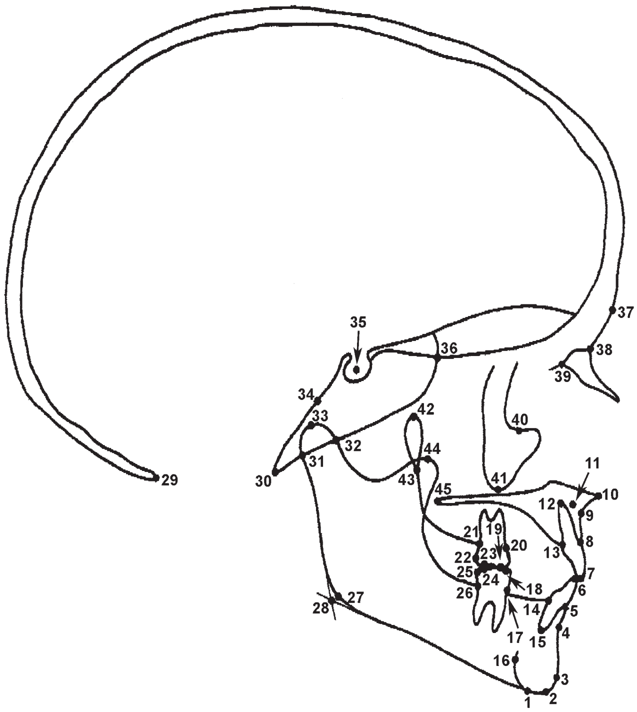

Figure 1 Landmarks used in the study, after Riolo *et al.* (1974). Points 29 and 34 were missing or difficult to visualize in many of the Migration Period and 19th-century specimens and so were omitted from statistical analysis. 1, menton; 2, gnathion; 3, pogonion; 4, point B; 5, infradentale; 6, lower incisor incisal edge; 7, upper incisor incisal edge; 8, supradentale; 9, point A; 10, anterior nasal spine; 11, L point; 12, upper incisor apex; 13, upper incisor lingual bony contact point; 14, lower incisor lingual bony contact point; 15, lower incisor apex; 16, lingual symphyseal point; 17, lower molar mesial cemento-enamel junction (CEJ); 18, lower molar mesial cusp tip; 19, upper molar mesial cusp tip; 20, upper molar mesial CEJ; 21, upper molar distal CEJ; 22, upper molar distal contact point; 23, upper molar distal cusp tip; 24, lower molar distal cusp tip; 25, lower molar distal contact point; 26, lower molar distal to the CEJ; 27, gonion; 28, gonial intersection; 29, opisthion; 30, basion; 31, articulare, posterior; 32, articulare, anterior; 33, condylion; 34, centre of the spheno-occipital synchondrosis; 35, sella turcica; 36, ethmoid registration point; 37, glabella; 38, nasion; 39, frontomaxillonasal suture; 40, orbitale; 41, inferior zygoma; 42, pterygo-maxillary fissure, superior; 43, pterygo-maxillary fissure, inferior; 44, coronoid process; 45, posterior nasal spine.

orthodontist, a good way to construe the basic idea is as a geometric solution to the problem of superimposition of cephalograms. All the landmarks of all the cephalograms of any data are set down on a page simultaneously so that the analysis of the trends that they show is unbiased as regards location and direction of the underlying processes. [Although the data in the present study were two-dimensional, the preceding statement is also true for biplane cephalograms; Dean *et al.* (2000) analysed the Broadbent-Bolton biplane normative standards using these methods.] The square roots of the summed squared distances between corresponding landmarks of two forms after this superposition are called Procrustes distances; they are the smallest possible for any sort of superimposition.

There is a cost to the method: the intentional separation out of size information, to be restored later in the form of correlations of the shape patterns with one particular size measurement (centroid size, the sum of the squared distances of all the landmarks from their common centroid, case by case). In the present research, in addition to that correlation, centroid size was incorporated prior to extracting those principal components, a recent variant technique (Mitterocker *et al.*, 2004). In exchange for this inconvenience, the toolkit encompasses the statistics of all possible ordinary size measurements (such as interpoint distances) and all possible ordinary shape measurements (such as angles or ratios) that can be evaluated on the same cephalograms (Bookstein, 1991).

These sets of optimally superimposed shapes have principal components [relative warps (RWs)], on which some of the figures rely, and they also have regressions on size (usually called 'allometry' in the biometric literature), on grouping variables (here, secular differences), or on both at the same time (the main finding in the present study, the interaction of size allometry with sample). All of these can be drawn as deformation grids by a contemporary version of the cephalometric tool introduced by Moorrees and Lebret (1962). The grids used in the present research, thin plate splines (TPS, Bookstein, 1991), are the smoothest possible warps that deform one set of points exactly into another. Further discussion is supplied by Slice (2005).

Missing landmarks

The present report concerns three separate samples, two of which, as noted in Jonke *et al.* (2007), had essentially no missing data.

However, for the Migration Period sample, landmark 34 (centre of the spheno-occipital synchrondrosis; Figure 1) was always missing, and landmark 29 (opisthion) was missing more than half the time. These points were discarded, leaving 43 for which there were a total of 168 missing points, involving 27 of the 43 landmarks used in the analysis.

Substitution of coordinates of these points proceeded by a variant of the standard estimation/maximization algorithm commonly used for missing data estimation in other multivariate statistical contexts (McLachlan and Krishnan, 1997). For a recent review of this method in morphometrics, see Gunz *et al.* (2005). The six Migration Period forms with complete data were averaged. Then, for each of the 23 forms that had any missing landmarks, the positions for these landmarks were estimated by computing a TPS from the average to the individual skull using only the landmarks that were present for that skull (Yaroch, 1996), then applying the spline to the mean positions of the landmarks that were in fact missing in the specimen. The completed specimens were then averaged to supply a new template for the spline, and the whole loop (a total of 168 points over 23 forms) was iterated until convergence.

This method was preferred to those that involve a regression structure, especially when, as in the following analysis, alternative models of that regression structure are being considered (Mitterocker *et al.*, 2004; Gunz *et al.*, 2005).

With the data thus completed, a total of 132 landmark configurations were available, of which 49 were from the Weisbach collection, 54 of contemporary Austrians, and 29 from the Migration Period grave field. Centroid size and Procrustes shape coordinates were computed for these configurations in the usual way (Jonke *et al.*, 2003, 2007), without any further adjustments for the missing data estimations.

Results

The average centroid sizes for the three samples were 45.06, 47.17, and 47.27 for the Weisbach, modern, and Migration Period, respectively. The mean of the Weisbach sample was significantly different from that of the other two samples. Within-group standard deviations were 1.49, 1.86, and 1.80; the difference of the Weisbach group variance from that of the other two samples was not significant after a Bonferroni correction (Altman, 1997) to compensate for the three separate comparisons. The distribution of Procrustes shape coordinates (Figure 2a) confirmed expectations, with variances that differed by landmark but no outliers of significance to alter the statistical results. The average shapes are shown in Figure 2b for the three groups; all pairs differ significantly beyond the 0.001 level by permutation test of Procrustes distance (Good, 2000) using 2000 permutations. (A permutation test reorders one variable, such as group, and recomputes the relationship with another variable, such as shape, repeatedly; the significance level is the fraction of random permutations having a stronger signal than the signal actually observed.)

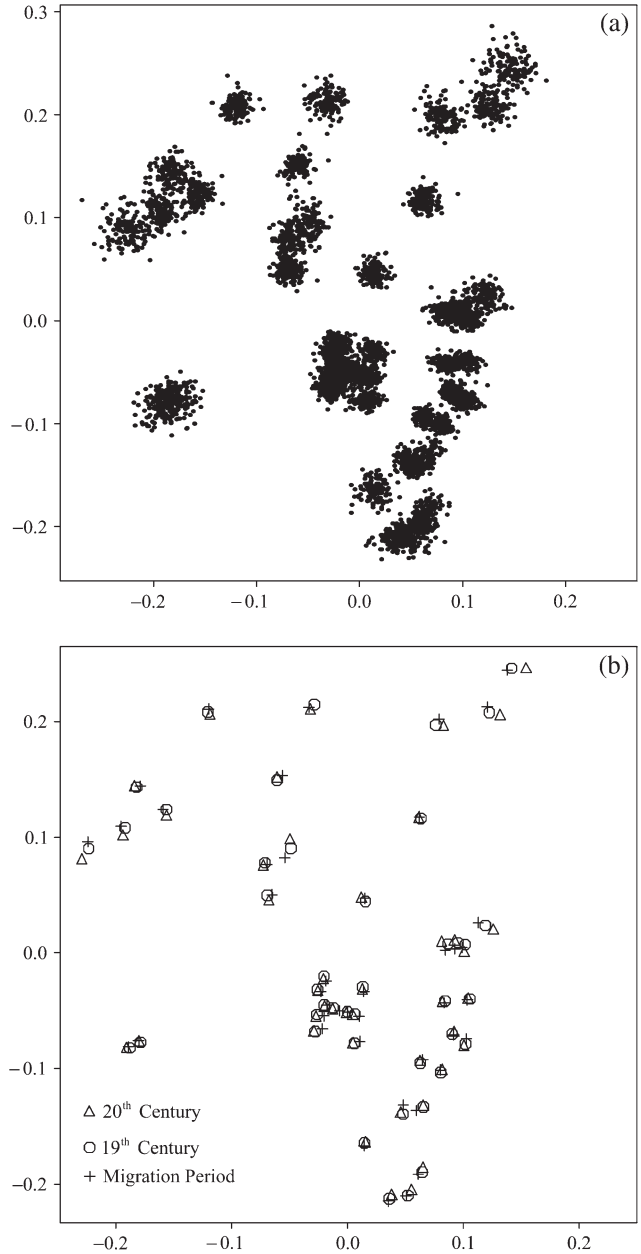

Figure 2 Conventional scatter plots of Procrustes shape coordinates for the full data set of 43 landmarks on 132 forms (a) and the three subsample average shapes (b).

In Figure 2b, those landmarks for which the three plotting symbols of the three group averages are discernibly separately spaced appear in the expected order: the 19th-century sample is intermediate between the Migration Period and 20th century samples. This is confirmed in Figure 3a, the scatter of the first pair of RWs (principal components of shape in the Procrustes metric) for the full sample of 132. The means by group, plotted as oversize symbols, are nearly collinear and in the anticipated (i.e. chronological) order. However, there evidently remains a significant amount of within-group variation around these means, which requires further investigation.

A suitable introit to this further investigation exploits the size–shape RWs (Mitterocker *et al.*, 2004). Size–shape RWs are principal components of the space of Procrustes shape coordinates as augmented by one single additional variable, the (natural) logarithm of centroid size. It can be shown that on a model of pure digitizing noise, the resulting expected statistical structure is spherical, so that the interpretation of principal components as informative dimensions of correlated variation still makes sense, and that all the classic approaches to allometry (the dependence of shape on size) can go forward using various graphic manipulations of this single eigen-extraction. Figure 3b shows the standard introductory plot for this analysis, the scatter of the first two size–shape RWs. Now the group means confirm (by position on the horizontal axis, the first principal component) the larger mean size of the Migration Period group and the modern group with respect to the Weisbach group.

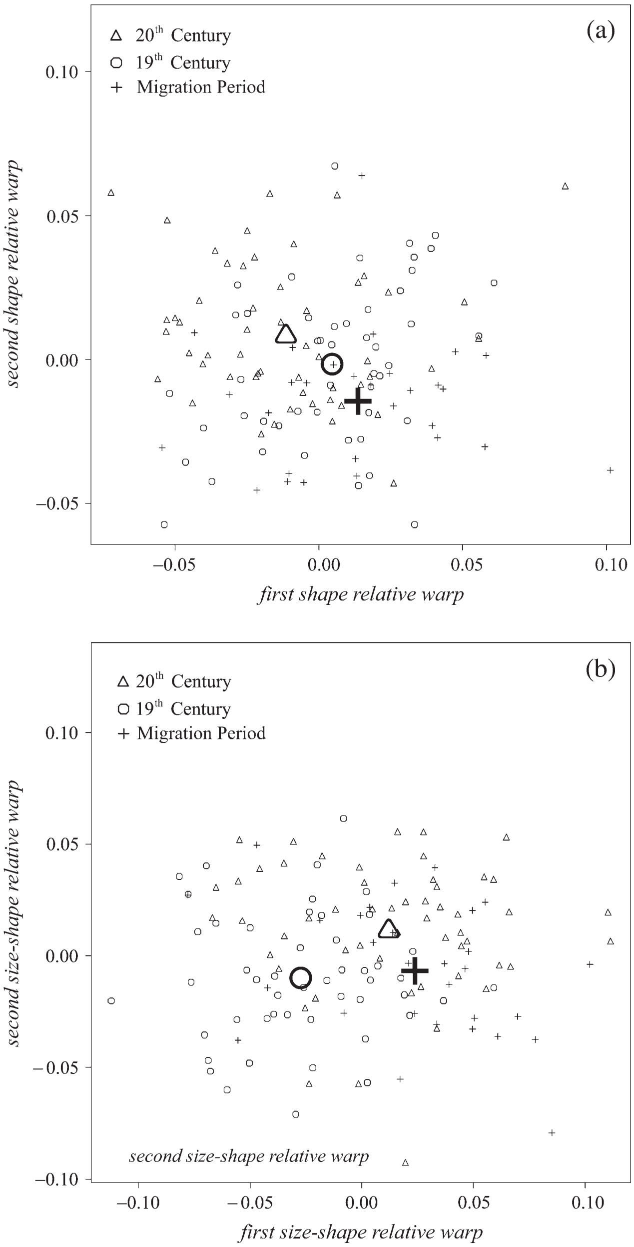

Figure 3 (a) The first pair of relative warps (RWs) for the sample of 132 shapes (cf. Figure 2a). Group means are at the three points plotted with larger symbols. (b) The first two RWs for analysis of size–shape space. Size is aligned mainly with the horizontal axis here; the smallness of the 19th-century sample is thus graphically confirmed.

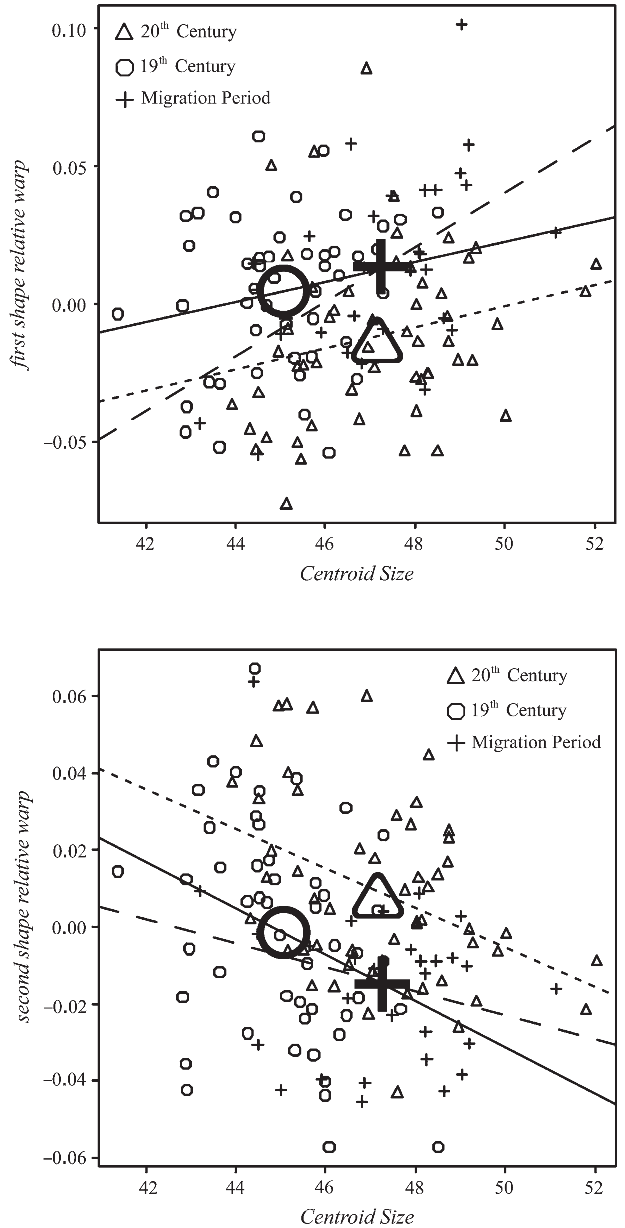

Figure 4 Allometric regression of the first two shape relative warps on size, pooled and by group. The group legend is the same as in Figure 3, and the lines are assigned separately by group. Note that the regressions of the 19th and 20th century samples are parallel, differing only in intercept, whereas those for the Migration Period sample are not. It follows that all shape comparisons need to be carried out at a range of specific sizes (cf. Figure 5).

The easiest way to examine size dependencies is to set centroid size by itself on the horizontal axis and examine the dependency of those first two shape components separately. Figure 4 shows this dependence both in pooled scatter plots that differentiate the samples by plotting symbol and in their separate allometric regressions. The relationship between the 19th and 20th century size allometry is as expected, parallel regressions with different intercepts. However, plots comparing these two groups on subsequent principal components showed a lack of parallelism, and even for RW_1 and RW_2, the size allometry for the Migration Period sample is different, and so pairwise shape comparisons need to be made at a specified size. The differences among these three regression lines are significant in each panel of Figure 4 at $P < 0.002$ by permutation test of Procrustes distance using 1000 permutations. The smallest and largest forms in the pooled data set were selected (the smallest is from the Weisbach sample, the largest from the modern sample) and, for both selected sizes, the expected shape for each group at that size was constructed. Omitting the dental landmarks (for reasons set out in Jonke *et al.*, 2007), the grids shown in Figure 5 for sample mean comparisons at constant size were generated, while the orthogonal set of comparisons, predicted shapes at large size as a transformation of those at small size, by group, are set out in Figure 6.

Figure 6 confirmed the general changes of vertical to horizontal facial proportions with size but also indicated a repositioning of the gonial region toward the posterior in the two more recent samples that is not matched in the Migration Period sample. Apparently, the Migration Period mandible did not participate in the antero-posterior growth that is associated with the larger face height in the 19th and 20th century samples. This can also be seen in the comparisons of Figure 5, showing a relatively less posterior gonion in the Migration Period sample but only at the larger of the two 'standard sizes'.

Discussion

It has been claimed that the Turkic morphological features have been partially retained in the Central European Avar population (Kollautz, 1954). If so, it is suggested that this retaining of Asian morphological features explains why the allometric regressions of RWs on centroid size are not parallel to the same regressions in the 19th and

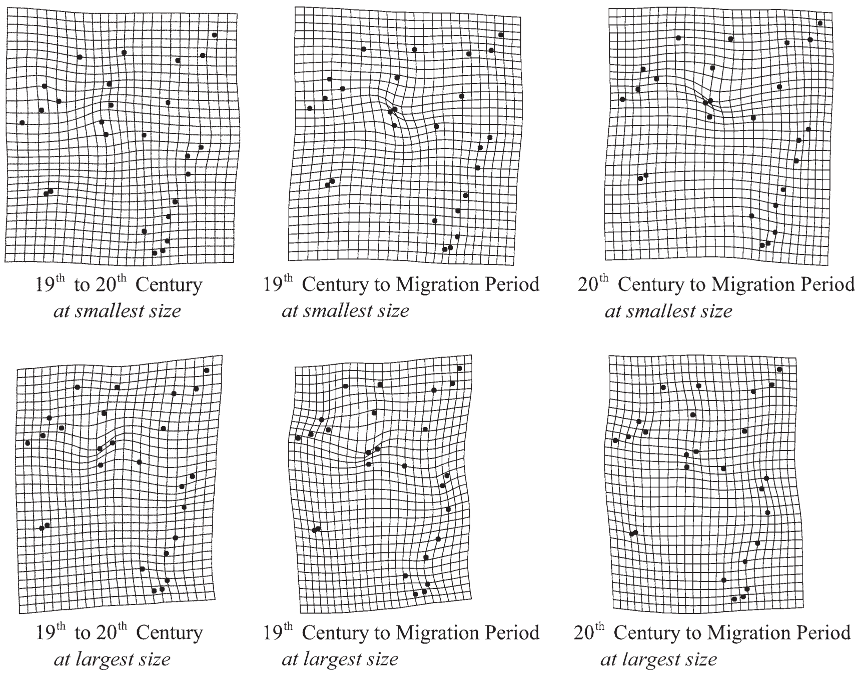

Figure 5 Group mean shape differences adjusted for size allometry. Comparison across the vertical in this figure indicates the effect of choice of a specific size at which to carry out the shape comparisons. The sizes here are the pooled sample minimum and maximum.

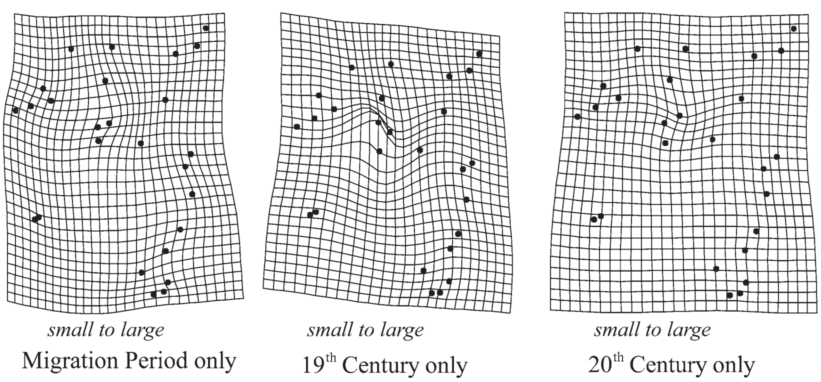

Figure 6 Group shape differences for each age-specific sample. Largest and smallest refer to maximum and minimum in each group.

20th century samples (Figure 4)—all the more so because the grave field had been in use for almost 150 years and probably the antiquity range of the skulls spans a time interval in excess of that separating the 19th and 20th century samples. The specimens of the Avar sample were not all young males. The age-at-death of individuals whose skulls were incorporated in the sample was determined by traditional anthropological methodology (Martin, 1928; Szilvàssy, 1980). Toward the demise of the Avars (approximately 870 AD), it is reasonable to assume that the individuals had, during their lifetimes, interbred with other ethnic groups that ultimately became their masters (Mitscha-Märheim, 1957; Lippert, 1969) with the consequence that the sample studied was probably not ethnically homogeneous. Although both the 19th and 20th century samples were male, due to the multi-ethnicity of the Austro-Hungarian Monarchy, also cannot be considered ethnically homogeneous, the differing allometry during the late Migration Period suggests a craniofacial morphological complex of, to some extent Asian, features integrated slightly differently from that observed in the recent European soldier skulls (Figure 4).

The relative upward shift of the coronoid process reported by Jonke *et al.* (2007) here characterizes the large forms only (Figure 5, lower row). The interaction could well be due to the robustness that characterizes the maxilla of large size in general, combined with the very difficult definition of the points of any fissure such as the pterygo-maxillary. The final diagram, Figure 7, shows how widely scattered were the three points controlling this region of the grid with respect to the scale of the triangle of these three points. It is believed (Moyers and Bookstein, 1979) that the vertical coordinates of the pterygo-maxillary points are far too difficult to locate and far too dependent on local accidents of robust osteogenesis or remodelling to sustain any interpretation at the scale conveyed by the grid lines in Figures 5 and 6.

While the difficulty of digitizing the vertical coordinates of the pterygo-maxillary points may contribute to the wide scatter observed in Figure 7, possibly the partially retained Turkic feature set of the Avars is also a large effect—all the more so since the allometric relations of the recent samples are parallel in Figure 4, yet not in the Migration Period sample.

Because the allometric relations in Figure 4 are not parallel, allometries should be checked in other ethnic groupings so as to match the patient as closely as possible before orthodontic treatment planning. While static allometric analyses of a group of males at one moment in their ontogeny are presented here, there is sufficient coherence between this static allometry and the corresponding growth allometry for this same cautionary note to apply: 'allometries could well be different in different ethnic groups'. To the extent that male growth patterns in the Migration Period arose from the same integration processes as those seen in the 20th century, this conclusion acquires even greater emphasis. Note also that, as these groups differed in mean (centroid) size, a growth prediction would need to be itself constrained by group (as reported here; after all, largest and smallest groups differed by approximately 5 per cent).

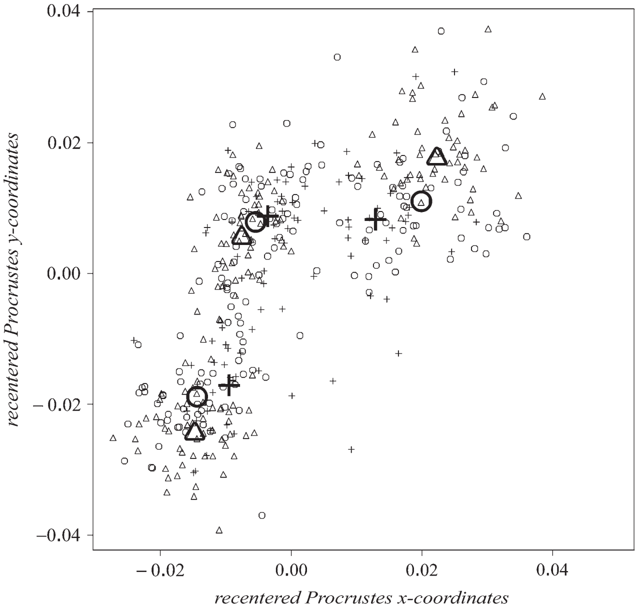

Figure 7 Detail of shape scatter plots in the region between pterygo-maxillary fissure and coronoids. While the group mean positions (large symbols) indicate the local grid features shown in Figures 5 and 6, there is far too much scatter near these points to credit any details of the mean changes locally or any aspect of the difference in dependence of shape on size.

In the present times, when Europeans move from where their ancestors had lived for many centuries to other areas and when immigrants from other regions of the world settle in Europe in large numbers, the mosaic of features derived from many people that constitute the present make-up of this continent stresses the need for the orthodontist to be aware of the wider range of morphological features, especially allometric, that patients now possess.

Conclusions

1. Mean centroid sizes differ significantly between the 19th century and the other two groups. All pairs of average shapes were significantly different at the 0.001 level.
2. The first two RWs of Procrustes shape coordinates show a linear progression of average shapes, in the correct temporal order (Figure 3a).
3. The two recent samples (19th and 20th century) show the same allometric trends, but the Migration Period sample does not. This difference is attributed more to an admixture of Asian (Turkic) facial morphology in the Avars (i.e. the Migration Period sample) and less to dietary change effects.
4. Shape differences are greater in larger faces. Statistically significant differences were not found in the smaller faces.

5. A relative upward shift of the coronoid process can be discerned in the large forms only. The extent to which the inhomogeneous ethnicity contributes to the unclear signal of the smaller forms cannot be determined.

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References

Altman D G 1997 Practical statistics for medical research. Chapman & Hall, London

Anderson D L, Thompson G W, Popovich F 1975 Evolutionary dental changes. American Journal of Physical Anthropology 43: 95–102

Bookstein F L 1991 Morphometric tools for landmark data: geometry and biology. Cambridge University Press, New York

Bookstein F L 1998 A hundred years of morphometrics. Acta Zoologica Academiae Scientiarum Hungaricae 44: 7–59

Breuer E 2005 Chronological studies to early-medieval findings at the Danube region: an introduction to Byzantine art at barbaric cemeteries. Tettnag, Vienna

Dean D, Hans M G, Bookstein F L, Subramanyan K 2000 Three-dimensional Bolton-Brush growth study landmark data: ontogeny and sexual dimorphism of the Bolton standards cohort. Cleft Palate-Craniofacial Journal 37: 145–156

Dibbets J M H, Nolte K 2002 Comparison of linear cephalometric dimensions in Americans of European descent (Ann Arbor, Cleveland and Philadelphia) and Americans of African descent (Nashville). Angle Orthodontist 72: 324–330

Dryden I L, Mardia K V 1998 Statistical shape analysis. Wiley, Chichester

Good P 2000 Permutation tests, 2nd edn. Springer Verlag, Berlin

Gunz P, Mitteroecker P, Bookstein F L 2005 Semilandmarks in three dimensions. In: Slice D E (ed.) Modern morphometrics in physical anthropology. Kluwer, New York, pp. 73–98

Halazonetis D J 2004 Morphometrics for cephalometric diagnosis. American Journal of Orthodontics and Dentofacial Orthopedics 125: 571–581

Jäger U, Bruchhaus H, Finke L, Kronemeyer-Hauschild K, Zellner K 1998 Säkularer Trend bei der Körperhöhe seit dem Neolithikum. Anthropologischer Anzeiger 56: 117–130

Jonke E, Prossinger H, Bookstein F L, Schaefer K, Bernhard M, Freudenthaler J W 2007 Secular trends in the facial skull from the 19th century to the present, analyzed with geometric morphometrics. American Journal of Orthodontics and Dentofacial Orthopedics 132: 63–70

Jonke E, Schaefer K, Freudenthaler J W, Prossinger H, Bookstein F L 2003 A cephalometric comparison of skulls from different time periods—the Bronze age, the 19th century and the present. Collegium Antropologicum 27: 789–801

Key P, Jantz R L 1981 A multivariate analysis of temporal change in Arikara craniometrics: a methodological approach. American Journal of Physical Anthropology 55: 247–259

Kiliaridis S, Engström C, Thilander B 1985 The relationship between masticatory function and craniofacial morphology. Part I: a cephalometric longitudinal analysis in the growing rat fed a soft diet. European Journal of Orthodontics 7: 273–283

Kollautz A 1954 Die Awaren. Saeculum 5: 129–178

Lindsten R, Ögaard B, Larsson E, Bjerklin K 2002 Transverse dental and dental arch depth dimensions in the mixed dentition in a skeletal sample from the 14th to the 19th century and Norwegian children and Norwegian Sami children of today. Angle Orthodontist 72: 439–448

Lippert A 1969 Das Awarenzeitliche Gräberfeld von Zwölfaxing in Niederösterreich. Prähistorische Forschungen 7: 1–159

Marcus L F, Corti M, Loy A, Naylor G, Slice D E 1996 (eds.) Advances in morphometrics. Plenum Press, New York

Martin R 1928 Lehrbuch der Anthropologie in systematischer Darstellung. Gustav Fischer, Jena

McLachlan G J, Krishnan T 1997 The EM algorithm and extensions. Wiley, New York

Mitscha-Märheim H 1957 Dunkler Jahrhunderte goldene Spuren. Wollzeilenverlag, Wien

Mitteroecker P, Gunz P, Bernhard M, Schaefer K, Bookstein F L 2004 Comparison of cranial ontogenetic trajectories among hominoids. Journal of Human Evolution 46: 679–697

Moorrees C F A, Lebret L 1962 The mesh diagram and cephalometrics. Angle Orthodontist 32: 214–231

Moyers R L, Bookstein F L 1979 The inappropriateness of conventional cephalometrics. American Journal of Orthodontics 75: 599–617

Müller S 2004 Das Awarenzeitliche Gräberfeld von Zwölfaxing, NÖ. Thesis, University of Vienna

Pohl W 2002 Die Awaren. Ein Steppenvolk in Mitteleuropa 567–822 n. Chr C H Beck, München

Riolo M L, Moyers R E, McNamara J A, Hunter W S 1974 An atlas of craniofacial growth. Monograph No. 2, Craniofacial Growth Series. Center for Human Growth and Development, University of Michigan, Ann Arbor

Slice D E 2005 (ed.) Modern morphometrics in physical anthropology. Kluwer, New York

Small C G 1996 The statistical theory of shape. Springer, New York

Smith B H, Garn S M, Hunter W S 1986 Secular trends in face size. Angle Orthodontist 56: 196–204

Szilvàssy J 1980 Die Skelette aus dem Awarischen Gräberfeld von Zwölfaxing in Niederösterreich. Anthropologischen Gesellschaft in Wien (Hrsg) Bd 3

Varrela J 1990 Occurrence of malocclusion in attritive environments: a study of a skull sample from southwest Finland. Scandinavian Journal of Dental Research 98: 242–247

Vyslozil O, Jonke E 1994 Kieferorthopädisch-anthropometrische Vergleichsuntersuchung an 100 Jahre alten menschlichen Schädeln und österreichischen Bundesheersoldaten. Informationen 4: 409–436

Weiland F J, Jonke E, Bantleon H P 1997 Secular trends in malocclusion in Austrian men. European Journal of Orthodontics 19: 355–359

Weisbach A 1892 Deutsche Männer aus Niederösterreich. Verlag Hölzl, Wien

Yaroch L A 1996 Shape analysis using the thin-plate spline: Neanderthal cranial shape as an example. American Journal of Physical Anthropology 23 (Supplement) 43–89

Yom-Tov Y, Yom-Tov S 2004 Climatic change and body size in two species of Japanese rodents. Biological Journal of the Linnean Society 82: 263–267