European Journal of Orthodontics 23 (2001) 275–285

Facial growth: separating shape from size

R. J. Hennessy* and J. P. Moss**
*MRC Human Biochemical Genetics Unit and **St Bartholomew's and the Royal School of Medicine and Dentistry, London, UK

SUMMARY Optical surface scanning technologies produce dense three-dimensional (3D) data sets, which allow detailed analysis of surface morphology. This paper describes a method of analysing change in facial shape independently of change in size. The 3D data from three male subjects from the age of 6–21 years were recorded using an optical surface scanner. A series of 22 conventional landmarks were located with the aid of horizontal and vertical profiles across the face, and were analysed using geometric morphometrics. The 3D landmark co-ordinates were scaled and aligned using Generalized Procrustes Analysis (GPA) and analysed by Principal Component Analysis (PCA) to determine the shape change over the growth period for each individual.

The results show that the centroid size reaches a steady value at different times for each of the subjects. When analysing shape versus age, highly significant correlations were found with principal component 1 (PC-1), but not with other principal components. PC-1 encompassed 40 per cent of the total variance for each subject. The movement of facial landmarks with time that is represented by PC-1 in each of the individuals is described. The use of these techniques has enabled the individual characteristics of facial growth to be identified and also has revealed the subtle changes in shape that continue after change in size has ceased.

Introduction

Until recently, the growth of the face and jaws has been monitored using direct clinical measurement (Farkas, 1994) and, more frequently, using lateral skull radiographs (Broadbent *et al*., 1975; Popovich and Thompson, 1977). All these investigations have measured the face and jaws in two dimensions (2D), but the face is a three-dimensional (3D) object and, therefore, needs to be measured in 3D.

There is considerable variation in the timing of growth in different individuals, and this varies with the age, sex, and ethnicity of the individual. The growth of an individual may be followed longitudinally and take many years. Cross-sectional growth studies of the normal population may also be undertaken provided that the numbers of individuals are sufficient. Often there is a benefit in being able to make comparisons between groups, rather than following changes in an individual normal face. There are, however, considerable differences between individuals in any ethnic groups.

The study of 3D facial growth presents two major problems. First, 3D data must be acquired and, second, analytical methods must be developed that allow the major features of the growth vectors to be established in a way that is both mathematically sound and readily interpreted. This paper describes the analysis of growth of the face in 3D using a system of optical surface scanning to obtain the data and a 3D landmark analysis that addresses the following questions: what is variation in size with age, shape with age, shape with size (allometry) and are these the same for each individual?

Materials

Three male Caucasian subjects were studied. All gave informed consent for participation in this study.

In subject A, the face was recorded from the age of 6–22 years. The facial shape was first recorded using conventional plaster casts and these were later digitized using a 3D surface scanner. Figure 1 illustrates scans of this subject at the ages of 6 and 22 years.

Subjects B and C (who are brothers) were recorded by surface scanning from the ages of 10–18 and 9–19, respectively.

Methods

Optical surface scanning

Surface co-ordinates were recorded by a conventional optical surface scanner, a non-contact optical technique which records 40,000 3D co-ordinate points in less than 10 seconds, with an accuracy of ~0.5 mm and a radial resolution of ~0.2 mm. The scanner, which was

(a) (b) (c)

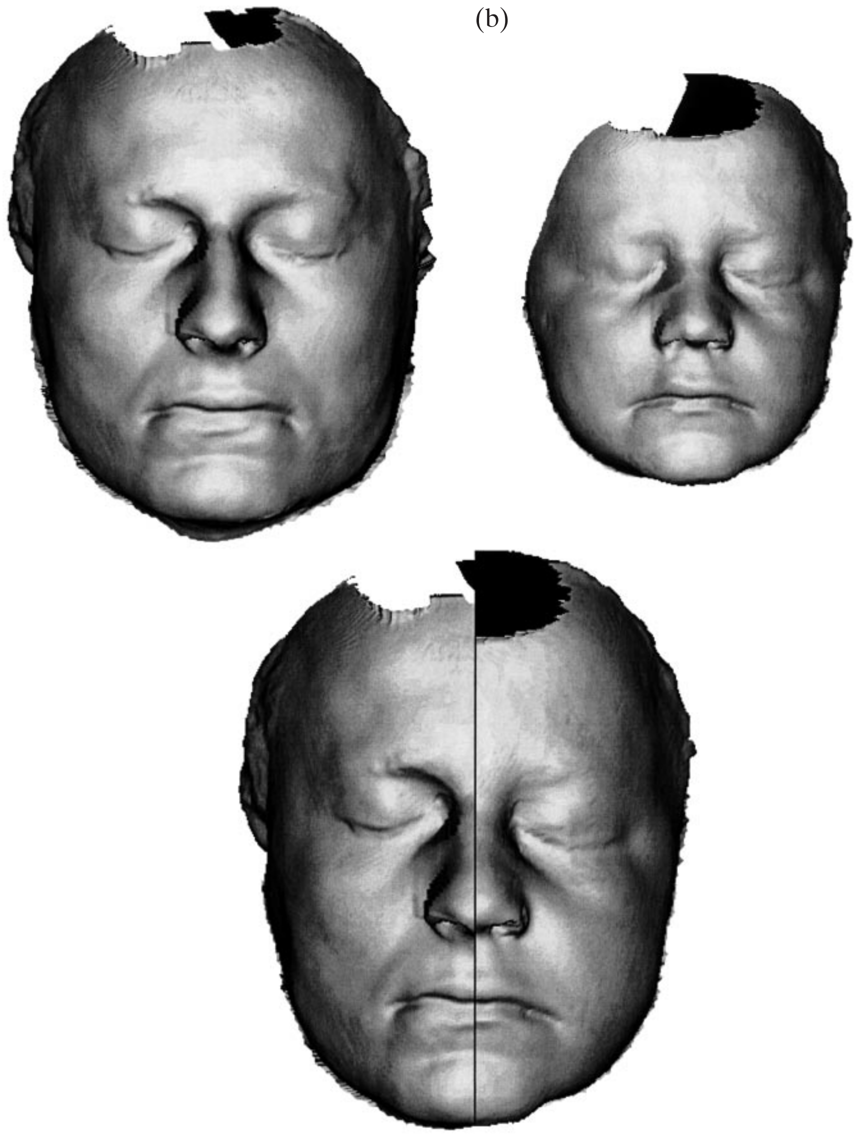

Figure 1 Subject A, aged (a) 22 and (b) 6 years plotted to same scale. (c) Composite image with age 22 (left) and aged 6 years (right) plotted to same size.

developed at University College London, has been extensively applied to the study of facial shape (Moss *et al.*, 1989) and its performance independently evaluated (Aung *et al.*, 1995).

Landmark extraction

Landmarks can be assigned to three categories (Bookstein, 1991). Type 1 landmarks are characterized by the juxtaposition or intersection of tissues, Type 2 landmarks are points of extremity of local curvature, typically points of maximum curvature, and Type 3 landmarks are extremal points, often defined with respect to an external co-ordinate system. In some cases, landmarks can be a mixture of types.

To aid the location of some landmarks, the local surface properties at each recorded point on the face were calculated via a surface fitting method (Coombes *et al.*, 1991; Hennessy *et al.*, 1998; Jackson *et al.*, 1999). The following quantities were used: Gaussian curvature, which measures the internal curvature; curvedness that measures the total curvature; shape index that varies from 0 (spherical cup) through 0.5 (symmetric saddle) to 1 (spherical cap). The variation in these quantities over the facial surface was examined by plotting their values as horizontal and vertical profiles through points of interest.

In this study the landmarks were categorized into three groups.

1. Conventional landmarks, as defined by Farkas (1994), were located with the aid of vertical and horizontal profiles. These landmarks, along with their types in brackets were: alar crest (1), subnasale (1), columella breakpoint (3), alare (3), inner canthus (2), outer canthus (2), cheilion (1), labiale superius (1 and 2), labiale inferius (1 and 2), stomion (1), and crista philtri (1 and 2).
2. One conventional Type 2 landmark, soft tissue nasion, defined as the point of maximum concavity and maximum convexity on the bridge of the nose, was located as the point of minimum shape index, i.e. the point where the local surface most closely approaches the symmetric saddle shape.
3. Some type 3 landmarks as defined by Farkas (1994) were redefined as type 2 landmarks using calculated surface properties. Pronasale was located as the point of maximum total curvature on the tip of the nose. Pogonion was located as the point of maximum Gaussian curvature on the anterior aspect of the chin and sublabiale was located as the extremal point of Gaussian curvature under the lower lip, i.e. the point where the surface is most creased.

These 22 landmarks are shown in Figure 2.

Analysis of size and shape

The approach taken in this investigation, that is geometric morphometrics, follows the method described by O'Higgins and Jones (1998) in their analysis of craniofacial growth of the Old World monkey *Sooty mangabee*. That was based on 31 cranial landmarks which were considered to be developmentally homologous. The distinguishing feature of geometric morphometrics is that the co-ordinates of the landmarks are statistically analysed, after scaling and alignment, rather than inter-landmark distances. This has the advantage that the results of statistical analyses can be visualized as deformations of landmark configurations and the sensitivity is greater since more shape information is analysed.

3D landmark co-ordinates were scaled and aligned via Generalized Procrustes Analysis (GPA). GPA first converts the landmark sets to unit size and produces a size measure (centroid size) for each specimen. The configurations are then superimposed via rotation and translation, and a mean shape (the Procrustes mean) is calculated. The displacements of each landmark from the Procrustes mean (the Procrustes residuals) are calculated and these are the input to statistical analysis.

The GPA was carried out using the program Applied Procrustes Software (APS, Penin 1999) and the Procrustes residuals were checked against the results from the program Generalized Rotational Fit in N dimensions (GRF-ND; Slice 1993).

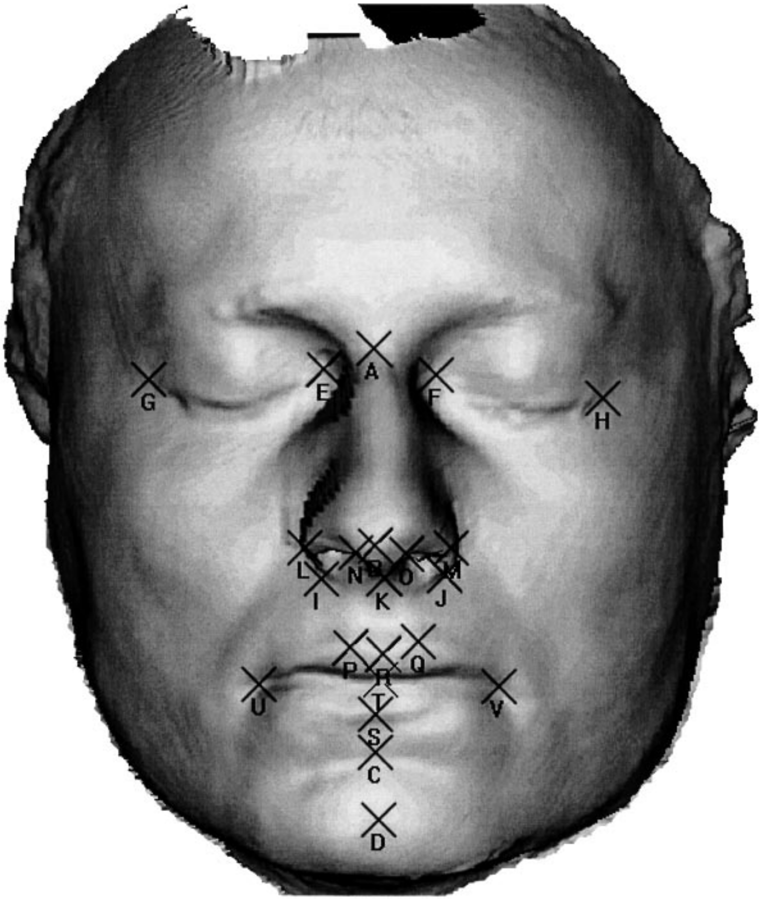

Figure 2 Subject A aged 22 years with 22 landmarks superimposed. Key to landmarks: A, soft tissue nasion; B, pronasale; C, sublabiale; D, pogonion; E, F, inner canthus; G, H, outer canthus; I, J, alar crest; K, subnasale; L, M, alare; N, O, columella breakpoint; P, Q, crista philtrum; R, labiale superius; S, labiale inferius; T, stomion; U, V, cheilion.

The residuals were then analysed by principal component analysis (PCA) to determine the dominant shape change over the growth period for each subject. PCA was carried out by the APS program. The Procrustes residuals were also exported to SPSS (1997), and the PCA was repeated both to check the APS result and to allow further analysis. The APS program was finally used to visualize the shape change associated with the principal components.

The procedure was carried out separately for subject A (11 datasets), subject B (11 datasets), and subject C (5 datasets).

Results

Reproducibility

The effect of landmark imprecision on the plots of principal component 1 (PC-1) versus age was investigated for subject A in a reproducibility study. The landmarks were re-identified and recorded for one scan (aged 20 years) on six additional occasions by the same investigator several months after the original landmark placing. Each new set of landmarks was subsituted for the original data and the PCA was recalculated. Figure 3 shows the PC-1 scores for the original

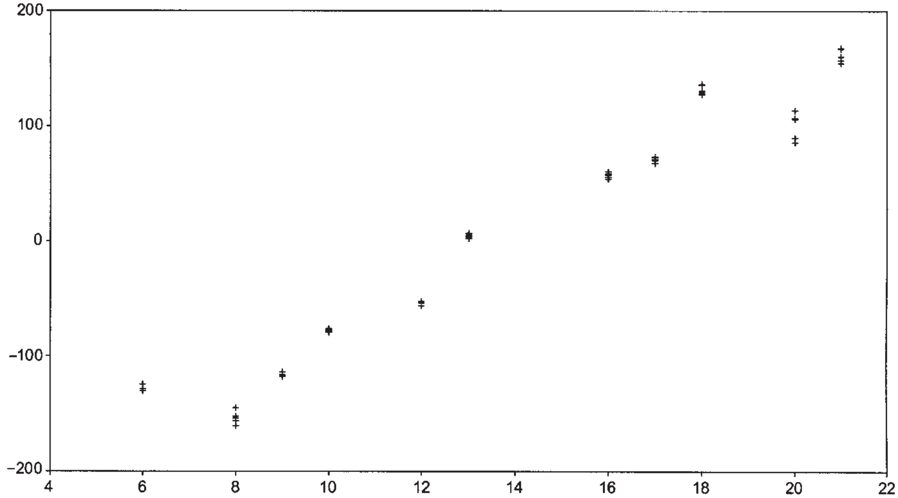

Figure 3 Reproducibility study. Subject A, PC-1 score (vertical axis) plotted against age (years, horizontal axis), original data plus six repeats with remeasured landmark co-ordinates at age 20.

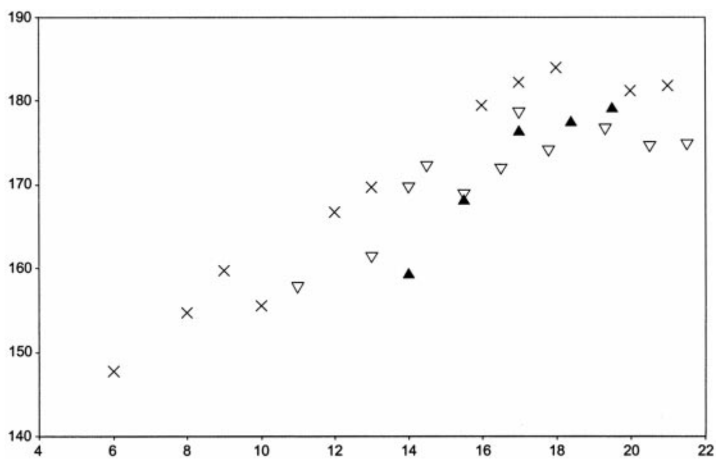

Figure 4 Centroid size (mm, vertical axis) plotted against age (years, horizontal axis). Subject A ×, subject B ▽, subject C ▲.

PCA and the extra 6 PCAs plotted against age. It can be seen that the PC-1 scores at each age were affected by variability in landmark placement at age 20 years. The variation in PC-1 scores at each age was much less than the variation in PC-1 scores with age. The age variation of PC-1 scores was therefore not excessively disturbed by imprecision in landmark location.

Size versus age

Figure 4 shows centroid size plotted against age for all three subjects. For subject A centroid size attained a steady value at approximately 16 years, for subject B size attained a plateau at about 17 years, and for subject C size was still increasing at about 19 years.

Table 1 Pearson correlation coefficients of PC scores.

Subject	Size	Age
PC-1		
A	0.949**	0.980**
B	0.875**	0.941**
C	0.966**	0.978*
PC-2		
A	–0.070 (0.838)	–0.027 (0.937)
B	–0.057 (0.867)	0.294 (0.381)
C	0.064 (0.918)	–0.219 (0.723)
PC-3		
A	–0.067 (0.845)	0.047 (0.890)
B	–0.154 (0.650)	–0.115 (0.737)
C	0.259 (0.674)	0.409 (0.494)

*Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).
Statistical significance level given in brackets, two-tailed.

Table 2 Percentages of variance for the first 5 PCS.

PC	Percentage of total	Cumulative percentage
Subject A		
1	40.0	40.0
2	20.5	60.5
3	8.7	69.2
4	6.7	76.0
5	6.4	82.4
Subject B		
1	39.2	39.2
2	21.4	60.6
3	9.2	69.9
4	7.4	77.3
5	6.7	84.0
Subject C		
1	43.5	43.5
2	26.4	69.9
3	20.1	90.0
4	10.0	100.0

Shape versus age

The correlations of the first three PC scores with age for all subjects were statistically tested by calculating the Pearson correlation coefficient. In all cases, highly significant correlations were found with PC-1 (Table 1), but not with the other PCs. Table 2 shows the percentages of total variance explained by the first 5 PCs. Figures 5, 6, and 7 show plots of PC-1 score versus age. The striking correlation with PC-1 score is immediately evident in each case. Since this is the only PC showing correlation with age and as it encompasses approximately 40 per cent of the total variance, PC-1 provides a good description of age-related shape change in each subject.

Closer examination of the plots of PC-1 versus age reveals that, while all increase smoothly with age, differences are apparent particularly at greater ages. This is most clear when comparing subjects A and B for which there are most data points. Visual inspection of the plot for subject A shows a linear increase over the age range 8–21 years, which is also indicated by the Pearson correlation coefficient of 0.95. For subject B, the plot appears to reach a plateau by the age of approximately 16 and this non-linearity is confirmed by the lower Pearson correlation coefficient value of 0.88. For subject C, both visual inspection and the high Pearson correlation coefficient (0.97) indicate a linear relationship over the age range 14–20 years.

The geometric meaning of PC-1 can be revealed by computer graphic techniques, which show how the configuration of landmarks changes in different regions of principal component space. The program APS plots the Procrustes mean co-ordinates and allows the points to be joined up to enhance the intelligibility of the display. The points are then displaced to represent movement along a PC so that the shape change can be inspected. This facility was used, together with varying the scale and the viewpoint, to gain an understanding of the shape change associated with PC-1. To illustrate the results Figures 5, 6 and 7 show anterior and side views of the Procrustes mean configuration aligned in the standard head position with the configuration representing movement either way along PC-1 superimposed.

Careful inspection of the graphics allowed the main characteristics of the shape change to be distinguished. They are described below and are also discernible from Figures 5–7. The movement of landmarks is described with respect to the Procrustes mean and the landmarks are orientated in the natural head position.

For subject A, Figure 5, the upper facial landmarks all moved backwards, the nasion

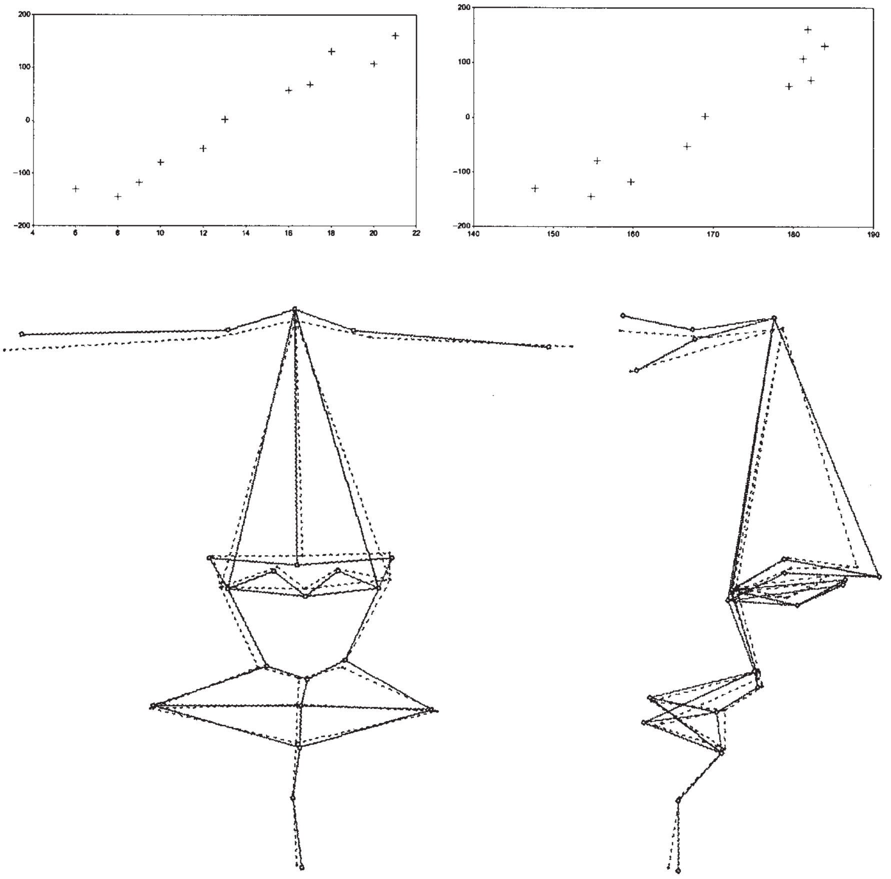

Figure 5 Subject A. Top left: PC-1 score (vertical axis) versus age (years, horizontal axis). Top right: PC-1 (vertical axis) score versus centroid size (mm, horizontal axis). Lower figures: Procrustes mean configuration (dashed lines) and mean configuration displaced to represent positive movement along PC-1, i.e. in direction of greater age. Anterior view (left) and right lateral view (right).

moved upwards, and the inner canthii moved inwards. For the nasal landmarks, the forward landmarks, pronasale, and columella breakpoint all moved strongly forwards, while subnasale moved down, and the alar crests moved together and down. The mouth landmarks and labiomental fold showed little movement. Pogonion moved forward.

For subject B, Figure 6, in the upper face nasion moved strongly upwards, while inner and outer canthii both moved together and backwards. The nasal landmarks were dominated by forward and downward movement of the nose tip. The alar crests moved back and down, alares moved back and laterally, and subnasale down. There was some movement of the mouth landmarks with cheilion moving backwards and the lower lip down. The labiomental fold and pogonion both moved forward.

For subject C, Figure 7, in the upper face, inner and outer canthii moved medially. For the nose, the forward landmarks all moved forward and down, while the alar crests moved back and the alares moved down. There was considerable movement of the mouth landmarks, with the upper lip and corners moving up and back, the lower lip down and strongly forwards. Labiomental fold and pogonion also moved strongly forwards with pogonion also moving down.

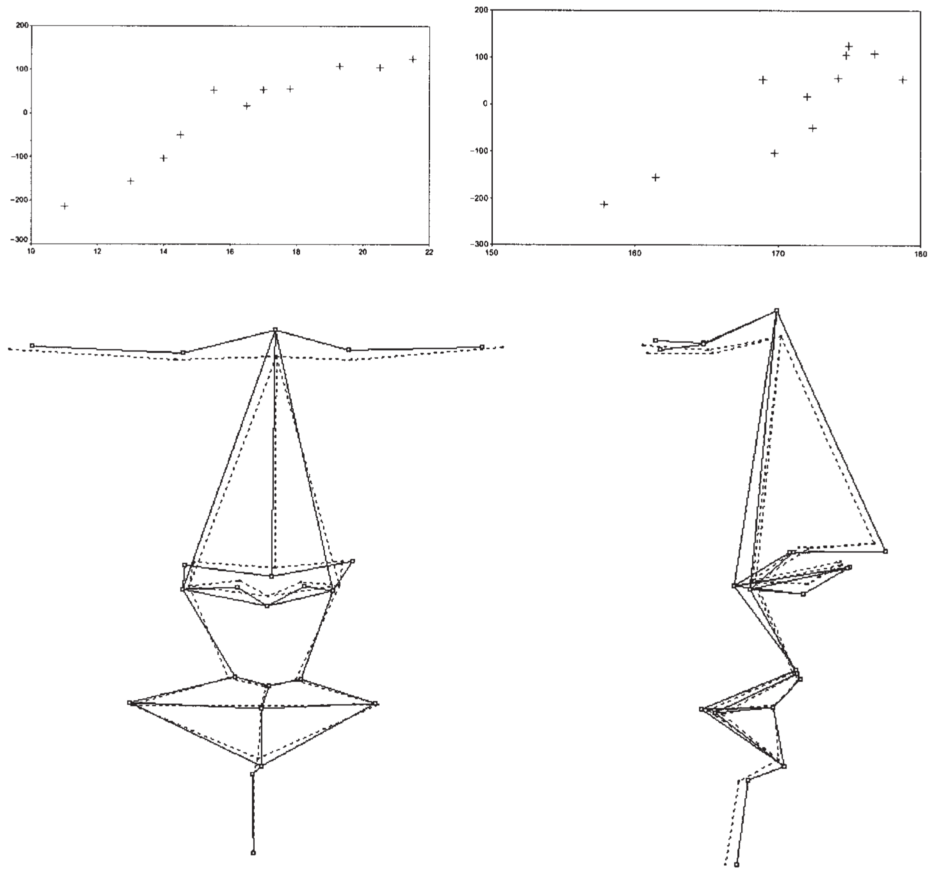

Figure 6 Subject B. Top left: PC-1 score (vertical axis) versus age (years, horizontal axis). Top right: PC-1 (vertical axis) score versus centroid size (mm, horizontal axis). Lower figures: Procrustes mean configuration (dashed lines) and mean configuration displaced to represent positive movement along PC-1, i.e. in direction of greater age. Anterior view (left) and right lateral view (right).

Shape versus size

Figures 5, 6 and 7 shows PC-1 scores plotted against centroid size for each subject. The correlations between PC-1 score and size, shown in Table 1, are high indicating a significant allometric relationship of shape and size. There was no evidence of significant correlations between other PC scores and size, and so PC-1 provides a reasonable description of the allometry in each case. For subject A the change in size had ceased by 17 years of age, but change in shape continued and the resulting allometric plot is almost vertical at a centroid size of ~185mm. For subject B, the plot of PC-1 versus size shows considerably more scatter than for subject A and this is manifested in the lower correlation coefficient (0.88). For subject C, the plot of PC-1 versus size varies smoothly and indicates an approximately linear allometric relation over the size range. The geometric meaning of PC-1 for each subject is described in the previous section.

Discussion

The dense surface datasets recording the faces of these three individuals have had to be reduced to sets of 3D landmarks before the patterns of change in size and shape could be elucidated with statistical shape analytical techniques.

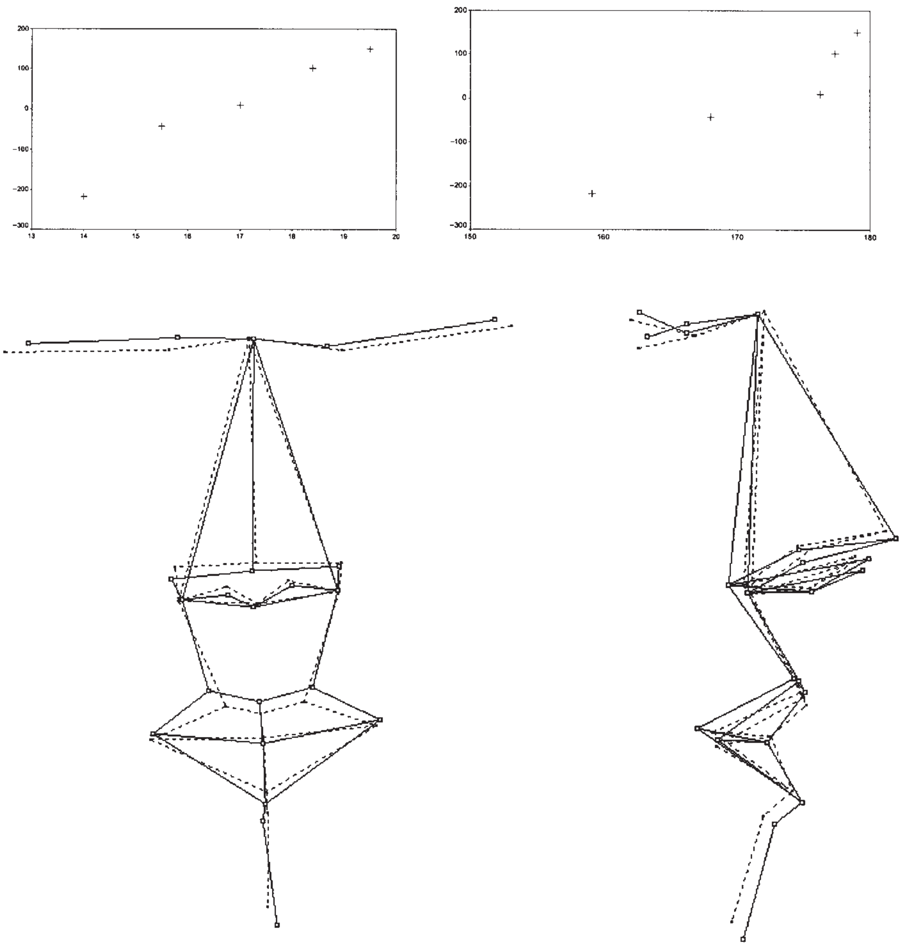

Figure 7 Subject C. Top left: PC-1 score (vertical axis) versus age (years, horizontal axis). Top right: PC-1 (vertical axis) score versus centroid size (mm, horizontal axis). Lower figures: Procrustes mean configuration (dashed lines) and mean configuration displaced to represent positive movement along PC-1 i.e. in direction of greater age. Anterior view (left) and right lateral view (right).

Size versus age

The relationship of centroid size to age is simply studied since it involves neither GPA nor PCA. The results for each subject are different thus illustrating the variation in growth. Both subjects A and B plateau at the age of 18, whereas subject C appears to be still growing.

Shape versus age

The main criticism of geometric morphometrics is the arbitrariness of the choice of alignment procedure (Lele and Richtsmeier, 1991), but O'Higgins and Jones (1998) have demonstrated that, in practice, if the variation in shape variability is small, the choice of registration method is unimportant. Where the growth of individuals is being examined and PC-1 explains approximately 40 per cent of the total variance, it is reasonable to assume that the data are sufficiently concentrated for a registration-based procedure to be used. O'Higgins and Jones (1998) also demonstrated that for concentrated data the Procrustes residuals could be used as a very good approximation to the co-ordinates projected onto the tangent plane.

For each subject the PCA has produced a single PC that correlates closely with age. The percentage variation explained is 40–50, which is somewhat lower than that found by O'Higgins and Jones (1998) for their allometric study of different monkey skulls. One might expect a higher percentage in the present subjects, since individual growth vectors are being studied and the random variation in the data should be less. This may be due to the difficulty in identifying soft tissue facial landmarks, which are generally less well defined than skeletal landmarks. In addition, facial expression will introduce some random variability in the soft tissues in the faces of living subjects. All the scans were taken in the relaxed position with the teeth together in order to minimize this random variation. It is likely that both factors have contributed to this random component, which would reduce the PC-1 percentage. The reproducibility study shows that the imprecision in landmark location is small compared with the shape changes due to facial growth as modelled by PC-1.

The subjects have growth trajectories that share major similarities and have significant differences illustrating how the variation in shape with age differs between individuals. The major similarities, in the upper face are the medial movement of both canthii, especially the outer canthii, and in the midface the forward and downward movement of the tip of the nose. The face thus becomes narrower and the nose relatively larger in each case. The differences in the lower face in shape change with age are apparent. In subject A, there is little change in the mouth and jaw, whilst subject C shows distinct changes and those changes in subject B are intermediary. Thus, while the same shape change pattern continues in the upper face, different patterns are followed in the lower face, demonstrating the power of geometric morphometrics to reveal subtle differences.

For subjects A and B the continuation of change in shape after the change in size has resulted in an interesting finding. Behrents (1984) has shown that some adults, over a period of 40 years, continue to grow at a very slow rate, but the cumulative effect can be as much as 10 mm. However, the data in this study only extends to 21 years and this small incremental growth is not seen. The comparison of the temporal patterns of shape illustrates how subtle information about facial change can be obtained by this method. This could have important implications for the comparison of normal and pathological facial development, and the understanding of facial development after trauma or surgery.

The visualization of the descriptions of shape change due to growth does not involve registration, since it simply consists of displacing the Procrustes mean configuration to reflect movement along PC-1. This description can be also statistically analysed to reveal the subtle variability of facial shape change.

Shape versus size

All three plots of PC-1 versus size could be interpreted as linear allometric relations of shape and size. However, since the ages are known, the relationship of shape to size can be examined as a consequence of that of shape to age and of age to size.

For subject A, the Pearson correlation coefficient of 0.95 gives no indication that, at greater ages, the size is constant, while the shape is still changing. This is seen in the shape versus size plot as an apparent spread of points of greater size. This spread is therefore not due to imprecise data, but the smooth variations of both shape and size with age.

For subject B, the plot of size versus age shows considerably more spread than for subject A, and this is manifested in the scatter in the PC-1 versus size plot and also in the lower correlation coefficient (0.88). This spread, which may be reflected in the lowest percentage explained by PC-1 of the three subjects, means that, although an allometric relationship is clear, fine structure is harder to distinguish. The PC-1 versus age plot, by contrast, varies smoothly indicating that the PCA has been able to distinguish the smooth change in shape with age.

For subject C, the plots of PC-1 versus age and size, and of size versus age all vary smoothly and indicate an approximately linear allometric relationship over the size range.

It is clear that, in each case, the knowledge of age has significantly aided the interpretation of the allometric plots of shape versus size.

Conclusions

1. The statistical shape analysis techniques used, along with knowledge of age, have enabled the individual growth characteristics of the face to be distinguished.
2. The results reveal the subtle changes in shape that continue after change in size has ceased.
3. The methods used would provide a means of analysing normal and pathological craniofacial growth.

Address for correspondence

Dr Robin Hennessy
Department of Clinical Pharmacology
Royal College of Surgeons in Ireland
St Stephen's Green
Dublin 2
Republic of Ireland

Acknowledgements

We wish to acknowledge financial support from the Medical Research Council and the UK Forensic Science Service. We are also grateful to Patricia Goodwin, Dr Alf Linney, Dr Robin Richards, and their colleagues in the UCL Medical Graphics Imaging Group, for their continuous support and advice.

References

Aung S C, Ngim R C K, Lee S T 1995 Evaluation of the laser scanner as a surface measuring tool and its accuracy compared with direct facial anthropometric measurements. British Journal of Plastic Surgery 48: 551–558

Behrents R G 1984 A treatise on the continuum of growth in the aging craniofacial skeleton. PhD thesis, University of Michigan, Ann Arbor

Bookstein F L 1991 Morphometric tools for landmark data. Cambridge University Press, Cambridge

Broadbent B H, Broadbent B J, Golden W H 1975 Bolton standards of dentofacial developmental growth. CV Mosby Co., St Louis

Coombes A M, Moss J P, Linney A D, Richards R 1991 A mathematical method for the comparison of three dimensional changes in the facial surface. European Journal of Orthodontics 13: 95–110

Farkas L G 1994 Anthropometry of the head and face, 2nd edn. Raven Press, New York

Hennessy R J, Moss J P, Linney A D, Goodwin PM 1998 A new method for the analysis of the face in three dimensions using a system of shape analysis. European Journal of Orthodontics 20: 476–477

Jackson S J, Hennessy R J, Moss J P 1999 Shape analysis of the facial soft tissue changes following orthognathic surgery. European Journal of Orthodontics 21: 593 (Abstract)

Lele A, Richtsmeier J T 1991 Euclidean distance matrix analysis: a co-ordinate-free approach for comparing biological shapes using landmark data. American Journal of Physical Anthropology 86: 415–427

Moss J P, Linney A D, Grindrod S R, Mosse C A 1989 A laser scanning system for the measurement of facial surface morphology. Optics and Lasers in Engineering 10: 179–190

O'Higgins P, Jones N 1998 Facial growth in *Cercocebus torquatus*: an application of three-dimensional geometric morphometric techniques to the study of morphological variation. Journal of Anatomy 193: 251–272

Penin X 1999 APS: Applied Procrustes software. Faculte de Chirurgie Dentaire de Paris V, Paris

Popovich F, Thompson G W 1977 Craniofacial templates for orthodontic case analysis. American Journal of Orthodontics 71: 406–420

Slice D E 1993 GRF-ND: generalised rotational fitting of N-dimensional data. Department of Ecology and Evolution, State University of New York, Stony Brook, New York

SPSS 1997 Statistical package for social sciences, Version 8.0.0. SPSS Inc., Chicago