A three-dimensional evaluation of human facial asymmetry

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ABSTRACT

Soft-tissue facial asymmetry was studied in a group of 80 young healthy white Caucasian adults (40 men, 40 women) with no craniofacial, dental or mandibular disorders. For each subject, the 3-dimensional coordinates of 16 standardised soft-tissue facial landmarks (trichion, nasion, pronasale, subnasale, B point, pogonion, eye lateral canthi, nasal alae, labial commissures, tragi, gonia) were measured by infrared photogrammetry by an automated instrument. The form of the right and left hemifaces was assessed by calculating all the possible linear distances between pairs of landmarks within side. Side differences were tested by using euclidean distance matrix analysis. The mean faces of both groups were significantly asymmetric, i.e. the 2 sides of face showed significant differences in shape, but no differences in size.

Key words: Euclidean distance matrix analysis.

INTRODUCTION

A mild degree of asymmetry is common in the face of normal human individuals (Lu, 1965; Vig & Hewitt, 1975; Shah & Joshi, 1978; Alavi et al. 1988; Peck et al. 1991; Pirttiniemi, 1992; Ferrario et al. 1993*c*, *d*). The degree of asymmetry is obviously higher in unhealthy individuals, where irregular development of skeletal, dental and soft tissues can differentially contribute to clinically discernible imbalances (Williamson & Simmons, 1979; Alavi et al. 1988; Pirttiniemi et al. 1990; Schmid et al. 1991; Pirttiniemi, 1992). Indeed, the 2 symmetric halves which characterise the first stages of development of skeletal structures in vertebrates partly modify their basic design during subsequent growth, and different degrees of asymmetry can develop. The soft-tissue cover partly masks the underlying skeletal imbalances (Peck et al. 1991; Ferrario et al. 1993*d*), and skeletal asymmetries of less than 3% are not clinically discernible (Lu, 1965).

Several kinds of measurements have been used for the quantification of craniofacial asymmetry. Metric distances, areas, angles and ratios can be calculated for the left and right sides separately, and the difference between homologous measurements will supply information about the dominant side (Woo, 1931; Vig & Hewitt, 1975; Shah & Joshi, 1978; Williamson & Simmons, 1979; Alavi et al. 1988; Pirttiniemi et al. 1990; Peck et al. 1991; Schmid et al. 1991; Pirttiniemi, 1992; Ferrario et al. 1993*a*, *d*). Unfortunately these methods provide a set of measurements which refer only to local imbalances, and do not allow a full face analysis. Moreover, while providing good information about size differences, they do not reflect the shape differences between the 2 sides. Alternatively the right and left side forms can be assessed separately with a comprehensive form analysis such as Euclidean Distance Matrix Analysis (EDMA) (Corner & Richtsmeier, 1991; Lele, 1991; Lele & Richtsmeier, 1991, 1992; Ferrario et al. 1993*b*, *c*, *e*, *f*, 1994*a*), and then tested for their homogeneity. The latter approach provides not only a good measurement of form difference, separating the contributions of size and shape, but can also supply information about the areas of major variation by suggesting which landmarks contribute most to the form difference (Corner & Richtsmeier, 1991; Lele & Richtsmeier, 1991, 1992). Moreover, it can be applied to both 2-dimensional and 3-dimensional data.

Radiographs and photographs have been employed for the quantitative analysis of craniofacial structures in small groups of selected patients. Two main shortcomings can be recognised: the risks of radiographic analyses, and the poor definition of 3-

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dimensional structures on 2-dimensional films or prints. These methods supply unreal data derived from the 2-dimensional projection of facial landmarks. On the other hand, an infrared instrument developed for the detection of single markers (ELITE) (Ferrigno & Pedotti, 1985; Frigo, 1990; Ferrario et al. 1994*b*), coupled with suitable algorithms, provides the 3-dimensional coordinates of facial landmarks, which can be used both in standard linear and angular measurements (Ferrario et al. 1994*b*) and in more comprehensive form analyses.

A previous 2-dimensional photographic investigation demonstrated sexual dimorphism in the form of the adult human face (Ferrario et al. 1993*f*), and implied the presence of some facial asymmetry. In this study the 3-dimensional coordinates of selected facial landmarks of a new group of young healthy adults have been collected using infrared photography, and EDMA was used to quantify their global facial asymmetry.

MATERIALS AND METHODS

Sample

Forty females and 40 males aged 19–32 y (mean age 21 y) from a group of 128 healthy white Caucasian dental students were screened by a detailed questionnaire and verified through clinical examination. All subjects gave informed consent. The selection criteria employed were published by Ferrario et al. (1993*d–f*). Briefly, all the subjects had sound dentitions, with bilateral Angle Class I first permanent molar relationship, absence of anterior or lateral cross-bite, no previous craniofacial trauma or surgery, no previous or current orthodontic treatment, and no mandibular or craniocervical disorder.

Collection of facial landmarks

The 3-dimensional coordinates of 16 standardised facial landmarks were collected automatically using the ELITE system (BTS, Milan, Italy). The system consists of 2 CCD cameras that photograph the

Table 1. *Definition of points (landmarks) used in the analysis*

Median points (on the midsagittal plane)		
1	Soft-tissue nasion	N′
2	Subnasale	Sn
3	Soft-tissue pogonion	Pg′
4	Trichion	Tri
5	Pronasale	Pn
6	Soft-tissue B′ point	B′
Lateral points (right and left sides)		
7	Eye lateral canthus	Can
8	Tragus	Tr
9	Soft-tissue gonion	Go′
10	Nasal ala	Ala
11	Labial commissure	Com

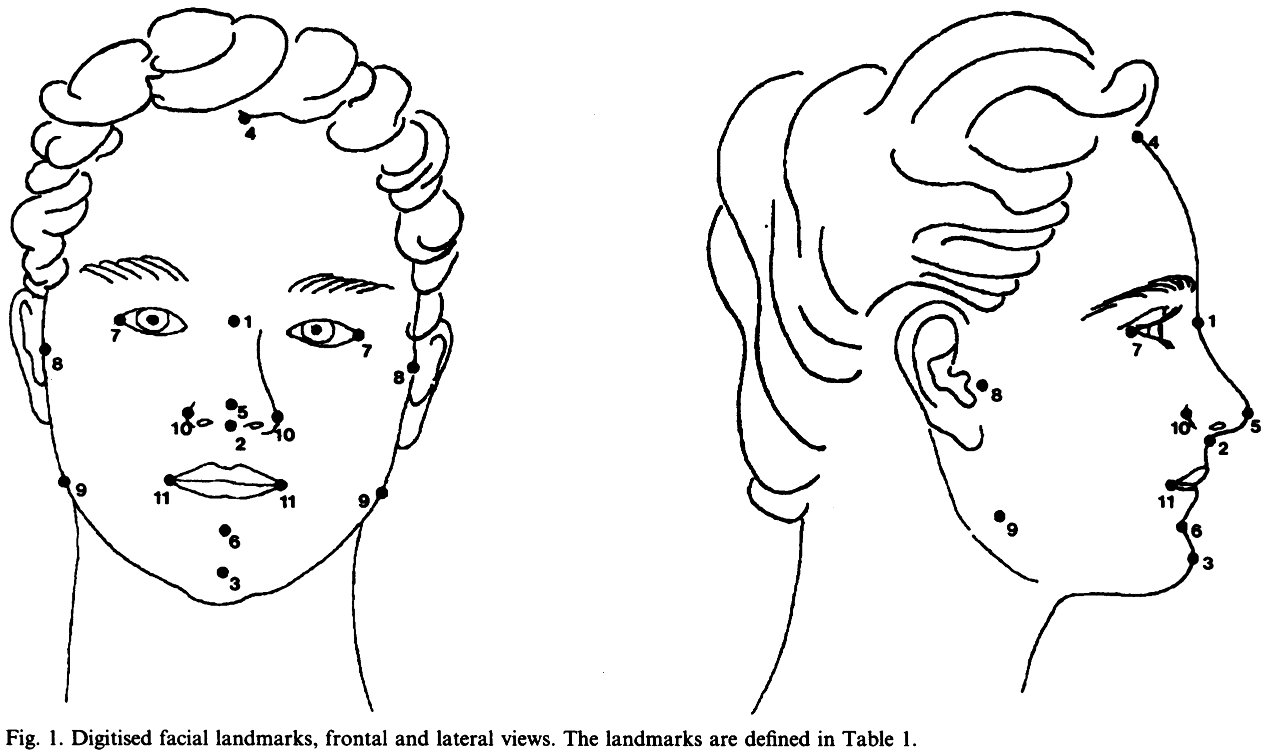

Fig. 1. Digitised facial landmarks, frontal and lateral views. The landmarks are defined in Table 1.

subject, real-time hardware for the recognition of markers, and software for the 3-dimensional reconstruction of landmarks by X, Y and Z coordinates relative to the reference system (Ferrigno & Pedotti, 1985; Frigo, 1990; Ferrario et al. 1994*b*). Before each session, the system is carefully calibrated to correct the optical and electronic distortions of the TV images, and to obtain actual metrical data.

Each subject sat with the head in natural position, and the 16 facial landmarks were located by a careful inspection (i) and/or palpation (p), and traced with a black eye-pencil; all points for all subjects were located and traced by the same operator (Table 1, Fig. 1): (1) median points (on the midsagittal plane): trichion (i); soft-tissue nasion (the innermost point between the forehead and nose) (i/p); pronasale (nasal apex) (i); subnasale (i); soft-tissue B point (i/p); and soft-tissue pogonion (the most prominent point on the chin) (i); (2) lateral (left and right) points: eye lateral canthus (approximating the frontozygomatic suture) (i/p); nasal ala (i); labial commissure (i); tragus (i); and soft tissue gonion (i/p). On the centre of each point a 2 mm hemispheric reflective marker was later fixed using double-sided adhesive plaster.

The subjects were seated in an upright position on a stool in front of the 2 cameras pointed to obtain a stereometric view of the subjects' faces with their jaws in centric occlusion (i.e. natural dental contact without clenching force). The CCD cameras lit up the reflective markers with an infrared stroboscope, and the centres of these points were automatically recognised and recorded by the system; for each subject one right-side and one left-side acquisition of 0.1 s each were collected with a sampling frequency of 50 Hz. The subject rotated on the stool about 90° between each side acquisition (Fig. 2).

Two side (left and right) acquisitions were used because it was not possible to see all 16 points at one time with a single frontal view: in most subjects the soft tissue gonion and tragus markers were hidden by other facial structures. The 2 side acquisitions were obtained with the subject positioned so that the cameras collected only 12 points at a time: the 6 median points, the 5 homolateral points and the controlateral labial commissure. The ELITE system provided the spatial X, Y and Z coordinates of the 12 points from each side acquisition. Seven points were common to both acquisitions, but their coordinates relative to the reference system were different (the subject was moved between the acquisitions). A computer program developed at the Laboratorio di Anatomia Funzionale dell'Apparato Stomatognatico combined the 24 points for each subject, and provided the coordinates of all 16 points of interest referred to a common reference system. These 16 landmarks were later used in the calculations.

The mathematical reconstruction of point coordinates was as follows: first, in both the frames (right and left sides) the coordinates were transformed, setting the soft tissue nasion as the origin of the X, Y and Z axes. In a second step, 2 consecutive rotations of coordinates were performed, the first around the Z axis (anteroposterior), the second around the X axis (right–left), so that in both views the soft tissue nasion–subnasale line coincided with the Y axis (vertical). The last step combined the 2 side views on the Y axis, and controlled the coincidence of the common landmark coordinates. In all cases, the positions of 6 (subnasale, pogonion, trichion, pronasale, B′ point and labial commissure) of the 7 common landmarks were consistent (the nasion coordinates were set at 0, 0 and 0 by the algorithm for both views).

Euclidean Distance Matrix Analysis (EDMA) (form matrix and form difference matrix)

The EDMA compares the form of 2 objects (or of 2 groups of objects) individualised by N homologous landmarks whose cartesian coordinates are known. The method was described in detail by Lele (1991), Lele & Richtsmeier (1991, 1992), and Ferrario et al. (1993*b*, *c*, *e*, *f*, 1994*a*). For each subject and for each hemiface (right side and left side), the 3-dimensional coordinate data collected by the ELITE system were used to generate a form matrix consisting of all possible spatial linear distances between pairs of landmarks. Both matrices included the relevant lateral points (landmarks 7–11) and the median line points (landmarks 1–6). This produced 40 female and 40 male form matrices of 55 distances. Form matrices were then averaged within sex and side, thus obtaining 4 mean form matrices.

Within each sex, homologous linear distances from the right and left-side matrices were paired, and a form difference matrix was obtained by calculating a ratio for each linear distance; linear distances from the right side served as the numerator, while left-side distances appeared in the denominator. The 55 ratios were then sorted from lowest to highest, and the statistics T_1 = maximum ratio/minimum ratio, and T_2 = median ratio, were calculated (Ferrario et al. 1993*c*). These 2 values described the form difference (Corner & Richtsmeier, 1991). The ratio of extreme ratios represented the total range of shape difference

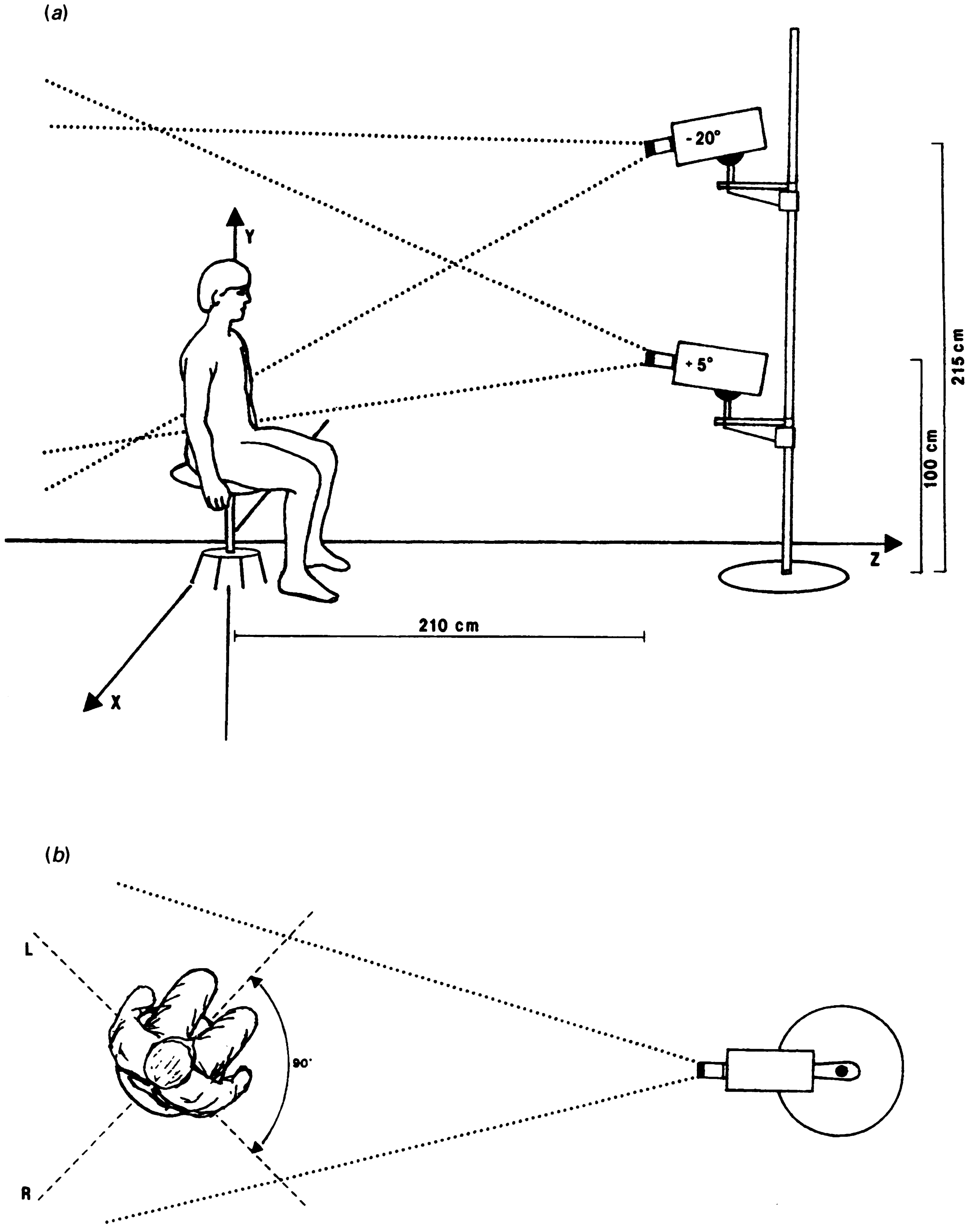

Fig. 2. Experimental set-up, with (*A*) side and (*B*) superior views. Coordinate axes, CCD cameras and position of the subject during right-side (R) and left-side (L) acquisitions.

between the right and left-side hemifaces. The median ratio was a measure of the general size difference represented by the form difference matrix.

The T_1 and T_2 values were used to test the null hypothesis of similarity of forms. If the 2 forms are equal, the form difference matrix is a matrix of constants (if only the shape is similar then the constants are equal to some number different from 1; if the size is also similar then this number should be 1). Therefore, if the null hypothesis is true, the statistic T_1 should be close to 1. The statistical significance of the form difference (i.e. H_0 = similarity of forms, H_a = difference between forms) was tested following a bootstrap procedure (300 repetitions) (Efron, 1979; Corner & Richtsmeier, 1991; Lele & Richtsmeier, 1991; Cheverud et al. 1992).

In each of the 300 bootstrap samples the median ratio T_2 and the maximum ratio/minimum ratio T_1 were computed, and the positions of the observed values of the 2 statistics relative to their null distribution were analysed. The null hypothesis (no differences between right and left sides, i.e. symmetric faces) was rejected if the observed T statistics were in one of the extreme tails of the distribution, being equal to or less than 5% ($P \leqslant 0.05$). This allowed separation of the shape difference from the size difference.

All calculations were performed on a Z-Station 466 Xn (Zenith Data System Co., St Joseph, MI), using original computer programs written by one of the authors (V.F.F.).

Data collection error

The reproducibility of landmark identification and marker positioning has already been tested (Ferrario et al. 1993*d*, 1994*b*). In brief, the same operator marked 5 subjects (2 men, 3 women) once, and then a second time after a 1 wk interval. The facial landmarks of the subjects were collected with ELITE. The within-operator error was estimated to be about 2 mm for all the 3 point coordinates (X, Y and Z). No side-linked differences were found for any lateral points.

To assess the reproducibility of the data collection procedure (ELITE system and mathematical reconstruction of point coordinates), the facial landmarks of the same 5 subjects were identified and collected twice with the same ELITE calibration, and then with 2 different ELITE calibrations. The combined error of ELITE system and computer programs (where differences could arise from the approximation algorithms) was estimated to be about 0.1 mm for all the 3 point coordinates.

RESULTS

The analysis of symmetry was performed within sex by comparing the right and left hemifaces using EDMA. For each sample, the 55 ratios between like distances were sorted from lowest to highest and the relevant matrices are presented in Table 2. Only the upper and lower ends of the matrices are shown because the central ratios are all equal to 1. In fact, the 2 compared forms comprised not only all the 7 lateral points but also the 6 median points in order to control for asymmetries of the profile. Obviously the 15 distances calculated between couples of median points did not vary in the 2 form matrices, and their ratios were always 1.

The mean faces of both groups were significantly asymmetric, i.e. the 2 sides of face had a significant difference in shape: in men, $P_1 = 0.04$ when the ratio of extreme ratios (statistic $T_1 = 1.0440/0.9941$ =

Table 2. *Form difference matrices for the analysis of symmetry in male and female faces sorted from lowest to highest ratio*

	Men		Women	
	Landmarks[1]	Ratio[2]	Landmarks[1]	Ratio[2]
1	10–1	0.9941	4–7	0.9873
2	2–11	0.9941	7–10	0.9909
3	1–11	0.9943	10–11	0.9940
4	8–9	0.9945	2–11	0.9943
5	1–10	0.9956	4–8	0.9945
6	4–11	0.9974	2–7	0.9952
7	4–10	0.9977	7–8	0.9982
8	4–7	0.9982	5–7	0.9991
..	...	......	....	......
..	...	......	....	......
40	4–9	1.0105	1–7	1.0077
41	7–10	1.0106	8–11	1.0081
42	4–8	1.0107	3–8	1.0092
43	1–8	1.0111	6–11	1.0105
44	6–11	1.0125	8–9	1.0108
45	5–8	1.0141	1–9	1.0142
46	1–9	1.0171	9–10	1.0149
47	7–9	1.0182	1–10	1.0153
48	5–7	1.0218	5–10	1.0153
49	3–9	1.0225	5–9	1.0154
50	2–9	1.0255	7–9	1.0159
51	9–10	1.0263	2–9	1.0159
52	6–9	1.0268	3–11	1.0163
53	5–9	1.0272	6–9	1.0209
54	5–10	1.0311	3–9	1.0241
55	9–11	1.0440	9–11	1.0331
	T_1obs = 1.0502		T_1obs = 1.0464	
	P_1 = 0.040		P_1 = 0.023	
	T_2obs = 1.0043		T_2obs = 1.0008	
	P_2 = 0.233		P_2 = 0.483	

Only the upper and lower ends of the matrices are shown. [1]Landmarks are defined in Table 1 and are the endpoints of each linear distance. [2]Mean distance between the landmarks in the right-side sample divided by the corresponding distance in the left-side sample. P_1: T_1obs = maximum ratio/minimum ratio compared to a T null distribution estimated using a bootstrap procedure. P_2: T_2obs = median ratio compared to a null distribution estimated using a bootstrap procedure.

1.0502) was compared to a null distribution estimated by a bootstrap procedure, in women $P_1 = 0.023$, $T_1 = 1.0331/0.9873 = 1.0464$. Conversely, no differences in size were demonstrated: statistic T_2 or median ratio = 1.0043, $P_2 = 0.233$ in men, and $T_2 = 1.0008$, $P_2 = 0.483$ in women.

Most of the ratios listed in both form difference matrices were higher than 1, indicating that, on average, the right side of face was larger than the left regardless of sex. Nevertheless, size differences among individuals were minimal, ranging in women from −1.3% (left side larger, landmarks 4–7, trichion–eye lateral canthus distance) to 3.3% (right side larger, landmarks 9–11, soft tissue gonion–labial commissure distance), and in men from −0.6% (left side larger, landmarks 10–11, nasal ala–labial commissure distance) to 4.4% (right side larger, landmarks 9–11).

The form difference matrices were further analysed to identify the areas where right and left sides could have some specific features. In both groups the distances between the landmarks 8 (tragus) and 9 (soft-tissue gonion) and the other facial landmarks were larger on the right than on the left side, and the highest ratio (soft-tissue gonion–labial commissure distance) was the same.

DISCUSSION

To our knowledge, no other studies have assessed the facial asymmetries of normal adults in a narrow age range using a whole face analysis performed on 3-dimensional data. Previous investigations dealt with the 2-dimensional projections of landmarks, and calculated individual linear measurements and ratios which did not take the whole structure into account, and thus could not offer an evaluation of the comprehensive form differences (Vig & Hewitt, 1975; Shah & Joshi, 1978; Williamson & Simmons, 1979; Peck et al. 1991; Pirttiniemi, 1992; Ferrario et al. 1993*d*).

An analysis of facial asymmetry should take into account both the arrangement of structures (shape) and the relative dimensions of the left and right hemifaces (size) (Ferrario et al. 1993*e*). In this study shape differences were evaluated by using the ratio of the extreme ratios, while size differences were evaluated using the median ratios. In both men and women, the 2 hemifaces were of similar size but were significantly different in shape. Most of the differences were localised in the lower third of the lateral facial surface (tragus and soft-tissue gonion), which was slightly larger on the right.

In our previous 2-dimensional photographic investigation (Ferrario et al. 1993*f*) we found a significant sexual dimorphism in the form of the adult human face, and supposed that some of the results could be explained by a sex-specific facial asymmetry. The present 3-dimensional study found a significant facial asymmetry, but no apparent sex differences. However, the data collected in the 2 studies are not directly comparable, even though similar landmarks were employed. The difference does not derive from the samples because the same selection criteria were used, and sex, race and age were not different. The difference stems from the fact that while the previous study was performed only in the frontal plane, and landmark coordinates (2-dimensional projections of 3-dimensional points) were collected using conventional photographic equipment, the present study analysed real spatial points.

The addition of more landmarks could improve understanding of the form characteristics of the face, but the landmarks should have a biological significance and a unique definition in all subjects, i.e. landmarks should unequivocally correspond to definable anatomical structures (such as bones, nerves or muscles) (Bookstein, 1984; Lele & Richtsmeier, 1991, 1992; Ferrario et al. 1993*b*), and this obviously limits the number of possible points.

The soft-tissue facial asymmetry found in these 80 normal adult subjects is in accord with the dentoalveolar asymmetry of healthy dentitions that has been reported on the basis of the shape of dental arches interpolated by mathematical functions, using linear measurements taken from photographs of dental casts, and in more comprehensive analyses of size and shape arch characteristics (Alavi et al. 1988; Ferrario et al. 1993*a*, *e*). Asymmetry seems to be an intrinsic characteristic of the human face, and because the individuals included in the present study were selected according to widely recognised criteria of dental and craniofacial normality, the relative degree of asymmetry in the general population is probably higher.

There is no consensus in the literature on the degree, side and spatial localisation of facial asymmetry. In all investigations a significant facial asymmetry has been demonstrated even in aesthetically pleasing faces, but no agreement exists about the side of dominance (Woo, 1931; Lu, 1965; Vig & Hewitt, 1975; Shah & Joshi, 1978; Williamson & Simmons, 1979; Alavi et al. 1988; Pirttiniemi et al. 1990; Peck et al. 1991; Schmid et al. 1991; Melnik, 1992; Pirttiniemi, 1992; Ferrario et al. 1993*d*). Although Vig & Hewitt (1975) found in their radiographic investigation that the cranial base and maxillary regions were significantly larger on the left side, Shah & Joshi (1978) stated that the total facial structure was larger on the right side. Woo (1931), working on skulls, found that the right frontal and parietal bones were larger than the left, but that the left malar bone was predominant. In the photographic study by Ferrario et al. (1993*d*) the lower part of the face was dominant on the right side in both men and women, while Peck et al. (1991) found larger right-side structures but the difference was not statistically significant. Melnik (1992) showed that the side of facial dominance was a function of age: while at 6 y of age the left side was the larger, at 16 y the right side was dominant.

It is difficult to compare these studies, since the methods, the measurements and the sample characteristics (age, sex, race) are very different. We believe that most of the differences are methodological in nature, and depend upon the use of 2-dimensional projections for the quantification of 3-dimensional structures. Indeed, when separate lateral, postero-anterior and submental-vertex radiographic or photographic 2-dimensional projections are used, 2 kinds of error can result: errors of projection and errors of landmark identification. Different head orientations (especially in anteroposterior radiographic views) will result in different linear and angular dimensions (El Mangoury et al. 1987; Schmid et al. 1991; Pirttiniemi, 1992; Tng et al. 1993). Moreover, some landmarks may be hidden by other structures, or their definition may depend on head position. Many of these problems are avoided in the 3-dimensional technique adopted in this investigation which allowed the direct identification of the landmarks on the subject's face, and the calculation of undistorted measurements that were also directly computed in 3-dimensional space.

In conclusion, the investigation demonstrated that the measurement protocol adopted (data collection by the ELITE system, mathematical reconstruction of 3-dimensional facial coordinates) was suitable for the quantitative analysis of normal adults and for the detection of their asymmetry. Moreover, the method of 3-dimensional analysis of the human face has some advantages over other systems. It does not expose the patient to potentially harmful procedures, and may provide better evaluation of the harmonic relationships among craniofacial structures, including the contribution of muscles and adipose tissue (Peck et al. 1991; Ferrario et al. 1993*e*, 1994*b*). Independently of its application as a research tool for the definition of normative data, it could be usefully applied in clinics as a supplement to classic cephalometric analysis, especially on young subjects, in order to locate potential growth imbalances, to follow their spontaneous compensation, or to plan treatment strategies for their elimination.

REFERENCES

Alavi DG, BeGole EA, Schneider BJ (1988) Facial and dental arch asymmetries in Class II subdivision malocclusion. *American Journal of Orthodontics and Dentofacial Orthopedics* **93**, 38–46.

Bookstein FL (1984) A statistical method for biological shape comparisons. *Journal of Theoretical Biology* **170**, 475–520.

Cheverud JM, Kohn LAP, Konigsberg LW, Leigh SR (1992) Effects of fronto-occipital artificial cranial vault modification on the cranial base and face. *American Journal of Physical Anthropology* **88**, 323–345.

Corner BD, Richtsmeier JT (1991) Morphometric analysis of craniofacial growth in Cebus appella. *American Journal of Physical Anthropology* **84**, 323–342.

Efron B (1979) Bootstrap methods: another look at the jackknife. *Annals of Statistics* **7**, 1–26.

El Mangoury NH, Shaheen S, Mostafa YA (1987) Landmark identification in computerized posteroanterior cephalometrics. *American Journal of Orthodontics and Dentofacial Orthopedics* **91**, 57–61.

Ferrario VF, Sforza C, Colombo A, Miani A Jr, D'Addona A (1993*a*) Position and asymmetry of teeth in untreated dental arches. *International Journal of Adult Orthodontics and Orthognathic Surgery* **8**, 277–285.

Ferrario VF, Sforza C, D'Addona A, Miani A Jr, Poggio CE (1993*b*) ANB skeletal types correlated to facial morphology: Euclidean distance matrix analysis. *International Journal of Adult Orthodontics and Orthognathic Surgery* **8**, 181–190.

Ferrario VF, Sforza C, Miani A Jr, Serrao G (1993*c*) Dental arch asymmetry in young non-patient subjects evaluated by Euclidean distance matrix analysis. *Archives of Oral Biology* **38**, 189–194.

Ferrario VF, Sforza C, Miani A Jr, Tartaglia G (1993*d*) Craniofacial morphometry by photographic evaluations. *American Journal of Orthodontics and Dentofacial Orthopedics* **103**, 327–337.

Ferrario VF, Sforza C, Miani A Jr, Tartaglia G (1993*e*) Human dental arch shape evaluated by Euclidean-distance matrix analysis. *American Journal of Physical Anthropology* **90**, 445–453.

Ferrario VF, Sforza C, Pizzini G, Vogel G, Miani A (1993*f*) Sexual dimorphism in the human face assessed by euclidean distance matrix analysis. *Journal of Anatomy* **183**, 593–600.

Ferrario VF, Sforza C, Miani A Jr, Tartaglia G (1994*a*) Maxillary versus mandibular arch form differences in human permanent dentition assessed by Euclidean distance matrix analysis. *Archives of Oral Biology* **39**, 135–139.

Ferrario VF, Sforza C, Poggio CE, Serrao G (1994*b*) Facial three-dimensional morphometry. *American Journal of Orthodontics and Dentofacial Orthopedics* (in press)

Ferrigno G, Pedotti A (1985) Elite: a digital dedicated hardware system for movement analysis via real-time TV signal processing. *IEEE Transactions on Biomedical Engineering* **32**, 943–949.

Frigo C (1990) Three-dimensional model for studying the dynamic loads on the spine during lifting. *Clinical Biomechanics* **5**, 143–152.

Lele S (1991) Some comments on coordinate-free and scale invariant methods in morphometry. *American Journal of Physical Anthropology* **85**, 407–417.

Lele S, Richtsmeier JT (1991) Euclidean distance matrix analysis: a coordinate-free approach for comparing biological shapes using landmark data. *American Journal of Physical Anthropology* **86**, 415–427.

Lele S, Richtsmeier JT (1992) On comparing biological shapes: detection of influential landmarks. *American Journal of Physical Anthropology* **87**, 49–95.

Lu KH (1965) Harmonic analysis of the human face. *Biometrics* **21**, 491–505.

Melnik AK (1992) A cephalometric study of mandibular asymmetry in a longitudinally followed sample of growing children. *American Journal of Orthodontics and Dentofacial Orthopedics* **101**, 355–366.

Peck S, Peck L, Kataia M (1991) Skeletal asymmetry in esthetically pleasing faces. *The Angle Orthodontist* **61**, 43–48.

Pirttiniemi P (1992) *Associations of Mandibulofacial Asymmetries, with Special Reference to Glenoid Fossa Remodelling*. Oulu, Finland: University of Oulu.

Pirttiniemi P, Kantomaa T, Lahtela P (1990) Relationship between craniofacial and condyle path asymmetry in unilateral cross-bite patients. *European Journal of Orthodontics* **12**, 408–413.

Schmid W, Mongini F, Felisio A (1991) A computer-based assessment of structural and displacement asymmetries of the mandible. *American Journal of Orthodontics and Dentofacial Orthopedics* **100**, 19–34.

Shah SM, Joshi MR (1978) An assessment of asymmetry in the normal craniofacial complex. *The Angle Orthodontist* **48**, 141–148.

Tng TTH, Chan TCK, Cooke MS, Hagg U (1993) Effect of head posture on cephalometric sagittal angular measures. *American Journal of Orthodontics and Dentofacial Orthopedics* **104**, 337–341.

Vig PS, Hewitt AB (1975) Asymmetry of the human facial skeleton. *The Angle Orthodontist* **45**, 125–129.

Williamson EH, Simmons MD (1979) Mandibular asymmetry and its relation to pain dysfunction. *American Journal of Orthodontics* **76**, 612–617.

Woo TL (1931) On the asymmetry of the human skull. *Biometrika* **22**, 324–352.