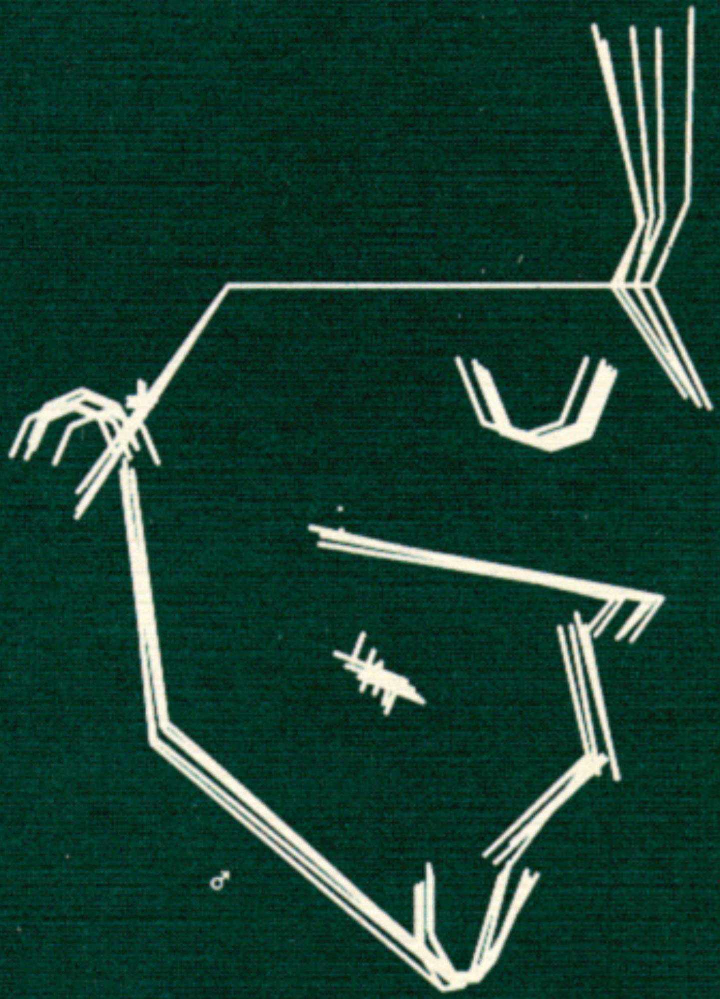
DIETMAR SEGNER

Stability of the craniofacial pattern during growth



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1. Introduction

1.1 Statement of the problem

Since the introduction of cephalometrics it has been used for two main purposes. One has been research into the relationship of the morphology of the different tissues that make up the facial skeleton. The other has been the furthering of clinical work - especially diagnosis, treatment planning, and re-evaluation of treatment related changes. Cephalometrics has also been used in research and in clinical applications to describe and predict growth, which is synonymous for change in morphology.

In order to make the evaluation of cephalometric x-rays more reliable and reproducible, orthodontists early introduced a large variety of measurements. These linear and angular measurements made it possible to describe the morphology of a facial skeleton with a set of numbers. Although this set of numbers should be reproducible even if another person evaluates the same x-ray, the numbers themselves don't mean anything without a frame of reference. Only in conjunction with a concept of a *NORM* can anybody derive any information from a set of cephalometric measurements. A norm in this context can be derived from the mean of a reference population, from values that are considered ideal for some reason, or from past experiences of the operator.

This fact not only holds true for a numerical representation of facial morphology but also for the contours on the x-ray film itself. If an unexperienced operator views a cephalometric x-ray he won't be able to detect pathological situations. Only after he has seen a range of cephalograms that can be associated with normal and abnormal clinical situations and behaviors he will have developed a sense of what might be considered normal. The sum of the cephalograms he has looked at together with the clinical situations they were related to make up his frame of reference.

When cephalograms are evaluated using a certain number of measurements the operator has to know which values for these measurements he can consider acceptable and which of them are abnormal. Orthodontists have set up "ideal values" for each kind of measurement. Sometimes these values were just postulated and sometimes they were derived from analyzing a reference population. From experiences with the cases he treated successfully Tweed (1954) for example required a value of 65° for the angle between the lower incisor long axis and the Frankfort horizontal (FMIA). Because Tweed was a well-known and accepted clinician this value has served as a norm for a long time. In many studies a value of 2° resulted as the population average for the angle ANB. This value has hence been widely used as a norm for sagittal jaw relationship. Either way these "ideal values" or "norm values" were fixed values.

This approach surely has deficiencies. A population norm will be the same for every patient. Consequently the treatment goals for every patient will be alike. This fact in itself doesn't conform with most people's striving for individuality. Another major drawback of this approach is that only part of the available information is used while another part -probably the larger one- isn't used at all. If each variable is looked at individually all information regarding the interrelationship of the measured values is forfeit. These relationships between the different variables and how they show up in an individual seem to contain the more important part of the information that can be drawn from the cephalograms.

One problem that arises when an analysis of the interrelationships between the measured variables is attempted is the more complicated statistics that has to be employed. Means and standard deviations have to give way to correlations, regressions, factor analyses, or covariance selection methods (Rehpenning 1983) to name only a few of the available techniques.

In the quest to derive more and more sophisticated information from the cephalograms two different lines can be followed. One is to attempt to understand and analyze the relationship or association between the different individual measurements. The result will be something that Solow (1966) called "a pattern of craniofacial associations". The other line is to look into the changes over time. For this purpose x-rays that are taken at different ages have to be compared. The possible changes in size and/or morphology can then be attributed to growth, treatment effect, or a combination of both. Usually growth studies result in tables or graphs that list the population mean for different ages. This approach, therefore, does not incorporate the concept of craniofacial associations.

A combination of both approaches is likely to describe the growth related changes more accurately and with greater benefit to clinicians and researchers.

1.2. Review of the literature

Since the invention of radio-cephalometry by Broadbent (1931) in the United States and Hofrath (1931) in Germany a great number of papers have been published regarding cephalometrics. As the method of cephalometric radiography proved to be rather reliable only a relatively small number or papers dealt with the x-ray method itself. Most papers described methods to analyze the cephalograms (Krogman and Sassouni 1957, Requet and Martin-Lacombe 1965) or gave "norm"-values for a certain population.

In his paper Broadbent (1931) discusses the advantage of an adjusted head holder and a standardized technique for the reproducibility of the x-ray measurements. One of the classic studies was carried out by Björk (1947). He studied young male adults (Swedish conscripts) and boys of around 12 years of age, of whom he took cephalograms in a cephalostat developed by himself. He measured 65 angles and linear measurements. Later he and Palling (1954) analyzed the growing subjects again to observe growth changes. Björk's observations and mean values have been widely used not only in Scandinavia but in a number of analyses worldwide (i.e. Hasund et al. 1974).

Studies with large materials were carried out among others by Ricketts (1960, 1961; "1000 cases"). He used the patients that applied for treatment and calculated averages from their facial morphology. Work like that by Steiner (1953) emphasized the importance of cephalometry for clinical diagnosis and planning.

From northern Europe a study using 56 boys and girls from Oslo, Norway, was conducted by Hummerfelt (1970). It listed means of the 10 to 12 year old children separately for both sexes and compared them between sexes and with other studies such as Björk's (1947). It appeared that significant differences to the established standards of these other analyses were common. Only a few of these differences, such as the angle ML-NSL in Björk's study could be attributed to different methods of measuring the variables. Regional and ethnic differences or differences in sample selection had to be responsible for the remainder. These region-based differences between normative data were also underlined in studies by Thilander et al. (1982) and Solow and Sarnäs (1982).

Serial studies are very difficult to implement. A longitudinal sample, where each subject is radio-graphed several times with intervals of between 1 and 5 years in between takes a long time and a great deal of organizational effort to accumulate. Furthermore in the developed countries the use of radiography in the study of healthy individuals is either prohibited or strongly regulated. Increased patient and operator awareness to the potential dangers of x-ray radiation create further problems. Often longitudinal studies cover only relatively short intervals during the growth period. If several of such shorter intervals from different patients are put together a mixed-longitudinal study results. This method makes growth studies more feasible but introduces some disadvantage such as inter-individual variation masking intra-individual, growth related changes.

Two well-known studies of this kind are those by Broadbent et al. (1975) and that of the Michigan Growth Center (Riolo 1974). They listed mean values for every age bracket and separately for male and female subjects. From these numbers and curves it is not only possible to determine what is "normal" at a certain age, but also what changes occur during growth. These changes are actually only the change in population mean. There is no proof available that every patient follows the same trend. This was shown by Ødegaard (1970) who studied the growth of young Norwegian children with the aid of implants. He developed methods to control such errors and obtain quasi-serial information from a set of shorter observation periods in different subjects (mixed longitudinal data).

Studies employing truly longitudinal materials without the use of implants have been published by Björk (1947, 1963), Björk and Palling (1954), van der Linden F P G M (1959), Hummerfelt and Slagsvold (1972), Bishara (1981), and Berg (1983). Through the use of implants in his material Björk was able to not only give data on the development of cephalometric variables over time but also to determine where growth occurred and what changes in morphology resulted. He showed that upwards and backwards growth in the condyle region of the mandible resulted in a forward and downward displacement of the mandibular body. He also proved that the jaws could display considerable rotation during growth. This change in inclination of the mandibular inferior border or nasal floor resulted in marked different configurations of the facial skeleton and also affected the dentition and occlusion.

Hummerfelt and Slagsvold only gave skeletal x-ray measurements of the prognathism of the jaws and sagittal interbase relationship for their material of 50 male and female subjects. These were registered at 11 and at 25 years of age. They found an increase in prognathism of both jaws and a decrease of the ANB-angle in the male subjects. However, the female subjects showed a slight increase of the ANB-angle.

Bishara used 20 male and 15 female untreated subjects with an acceptable occlusion. He took 10 cephalograms between the ages of 4 and 17. Unfortunately he tried to reduce the number of norms and only gave 5 different standards for all ages and both sexes.

Berg studied the cephalometric records and plaster models of 113 Norwegian children between 6 and 12 years of age. He divided his sample into subgroups representing different malocclusion types. He found that the changes due to growth within each subgroup did not alter the differences between the groups that were present already at the age of 6.

While all previous works put the main emphasis on population means and sometimes standard deviations the following papers looked into the relationship between the different variables and thereby tried to produce more sophisticated analyses.

In his classic study *The pattern of the craniofacial associations* published in 1966 Solow pointed out that there is a certain pattern of associations between the components of the craniofacial complex. On a material of 102 male dental students of between 20 and 30 years who had not received any orthodontic treatment he used the mathematical/statistical techniques of correlation and factor analysis to describe relationships between linear and angular measurements in the cranium and also measurements of body dimensions. In a theoretical analysis he showed that any two variables that share common reference points display a correlation. This correlation that would be expected was called *topographical correlation*. Solow called only the remaining amount of correlation the real, biological correlation. The correlation and factor analysis showed a general association between size measurements in the head and body. Associations of variables within a certain region of the craniofacial complex, such as the nasopharynx or the cranial base and maxilla were also found. Dental compensation of skeletal anomalies could also be detected although Solow also found a correlation between severe skeletal discrepancies and resulting dental malocclusions.

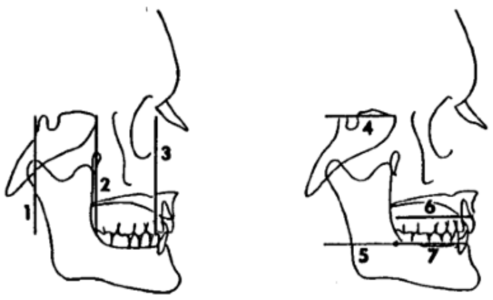

Fig. 1.1 Linear measurements to determine if *form balance* of the craniofacial complex exists. From: Enlow et al. (1969)

Enlow et al. (1969) presented a cephalometric analysis that is based on an individual's own morphology rather than population standards. They tried to analyze the *anatomic fit* among the different bones of the craniofacial complex. The reference was to be the individual itself and not a population standard. For this means they defined 3 vertical and 4 horizontal length measurements on the cephalogram (Fig. 1.1). Depending on whether these length measurements would have a certain ratio to each other Enlow et al. called this *form balance* or *imbalance*. They took this concept further in that they also looked at the length increments of these linear measurements resulting from growth. If these growth increments again showed the proper ratios the form balance persisted throughout growth and they spoke of *growth balance*.

SNA	NL-NSL	NSBa	ML-NSL	SNB		ML-NL
74	16.5	146	48	72	I	31.5
75	15.5	144	46	73	I	30.5
76	14.5	142	44	74	I	29.5
77	13.5	140	42	75	I	28.5
78	12.5	138	40	76	I	27.5
79	11.5	136	38	77	I	26.5
80	10.5	134	36	78	I	25.5
81	9.5	132	34	79	I	24.5
82	**8.5**	**130**	**32**	**80**	I	**23.5**
83	7.5	128	30	81	I	22.5
84	6.5	126	28	82	I	21.5
85	5.5	124	26	83	I	20.5
86	4.5	122	24	84	I	19.5
87	3.5	120	22	85	I	18.5
88	2.5	118	20	86	I	17.5
89	1.5	116	18	87	I	16.5
90	0.5	114	16	88	I	15.5

Fig. 1.2 *Harmony box* according to Hasund. Any set of values on a horizontal line are assumed to represent harmonious combinations of values.

Hasund et al. (1974) demonstrated that the relation between prognathism and inclination of both mandible and maxilla showed a certain association. There was also a consistent pattern between these four measurements and the cranial base flexion. With more retrognathic positions of the maxilla and mandible the jaws tended to show a more posterior inclination (steeper maxillary and mandibular planes). At the same time the angle between the anterior cranial base and the clivus was larger (less flexion). If a patient under analysis reflected these associations the face was called *harmonious*, if not it was called *disharmonic*. The actual measurements of a patient were not compared to a population mean but the combination of these measurements was analyzed. Patients with completely different facial types could all display a harmonious association of the parts of the facial skeleton. A reference population was necessary only to describe the harmonious associations. Hasund et al. presented these desirable combinations of maxillary and mandibular prognathism and inclination as well as cranial base flexion in the form of a graphical table called *harmony box* (Fig. 1.2). Segner (1987) and Segner and Hasund (1991) improved and refined this concept and developed a harmony box that was based on regressions rather than the standard deviations of the variables.

Moorrees (1953) and Moorrees and Kent (1986) avoided the use of cephalometric variables by the use of a biorthogonal analysis, more commonly called *mesh analysis*. A rectangular mesh was projected onto the cephalometric drawing in a standardized way. From a reference population average locations of the landmarks <u>in relation to the mesh</u> were studied and listed. Then the actual landmarks of a patient in relation to the standard mesh are compared to these standards. The difference can then be used to distort the mesh on a proportional basis (Fig. 1.3). Deviations of the patient's facial skeleton reflect in a distortion of the originally rectangular grid and thus become more visible. Another advantage is that differences in absolute dimensions like body

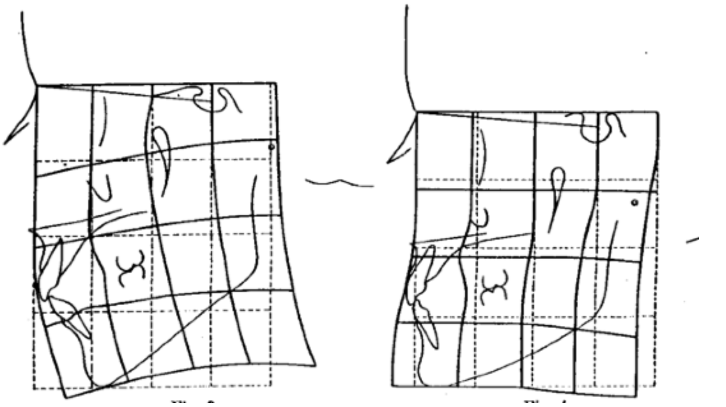

Fig. 1.3 Mesh diagram analysis. The unbroken lines reflect the deviation of a patient's craniofacial pattern from the standard. From: Moorees (1953)

size are eliminated since the mesh is applied in a standardized way.

Bookstein (1983) followed another approach. He drew sets of triangles between the landmarks on the cephalogram. Then he compared the triangles with the same triangles after some growth had occurred. For each triangle he could find *growth invariants*, that is geometric properties of the triangles that did not change although the shape of the triangle itself was modified by growth. As a result every change in morphology could be described by the change in length ("dilatation") along two axes in each triangle that were perpendicular to each other. If only a change in size took place, the dilatations along the two axes were of equal amount. Different dilatations for each axis also resulted in a change of shape. Bookstein found that no universal "center of growth" existed and that the principle axes of dilatation could vary considerably between the different triangles. The advantage of the method was that no external coordinate system needed to be defined.

Järvinen (1986) took that concept further and compared an individual's facial pattern with that of a reference population by setting up 18 triangles between the cephalometric landmarks. Then he calculated the dilatation axes and coefficients by which triangles in the reference profile could be transformed to the corresponding triangles of the subject under analysis. For each triangle the direction of the major axis and the dilatation coefficients for both axes resulted (Fig. 1.4). From these data conclusions about the deviations of the patient could be drawn. In the shown example the lower two triangles show similar, homologous dilatation vectors. The upper triangle shows a different transformation. Here the major axis is more downwards. In orthodontic terms the maxilla in the case under survey is positioned too much downwards and forward in comparison to the reference profile resulting in a deep and distal configuration.

The problem of the errors inherent in the method of radio-cephalometry was studied by Björk (1947) and Slagsvold and Petersen (1977). Richardson (1966), Kvam and Krogstad (1969) and Baumrind and Frantz (1971[a]) looked into the reproducibility of landmarks on cephalometric radiographs. They found that the accuracy with which a landmark can be located depends on which landmark is used and on the experience of the operator. Furthermore the accuracy of landmark location varies between the vertical and horizontal direction.

Ødegaard (1970), Baumrind and Frantz (1971[b]) and later Houston (1983), described different measures to describe the accuracy of certain variable measurements and how these

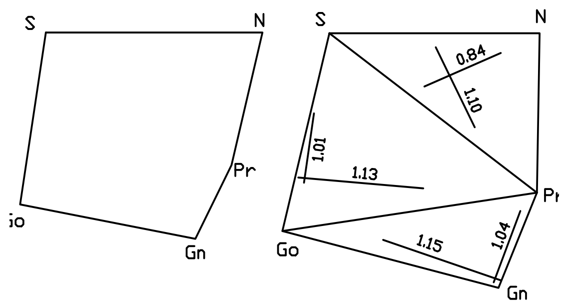

Fig. 1.4 Biorthogonal analysis: The left polygon shows the average population pattern, the right shows an individual's pattern and the dilatation axes and coefficients. See text.

measures can be calculated and compared. The effect of double or multiple registrations of the same x-ray on the accuracy of conventional measurements was discussed by Baumrind and Frantz (1971[b]) and Houston (1983). Double registration seemed to reduce the measurement error and at the same time allowed to detect gross errors in landmark identification.

Buschang et al. (1985, 1987) estimate the influence of inaccuracies in the cephalometric method on craniofacial correlations and suggest the use of correction factors.

1.3. Purpose of the investigation

As known to the author so far no study has looked into the change in the associations of the craniofacial parts. Several studies listed tables that gave population means for different ages (Fig. 1.5) and some presented superimposed drawings (Fig. 1.6). These means of presentation, however, cannot produce the full amount of information that are contained in the basic data. They merely represent singular bits of information that need to be put together to fit into a comprehensive description of the changes. Unfortunately such a comprehensive description is not readily available and requires complicated methods and mathematical models.

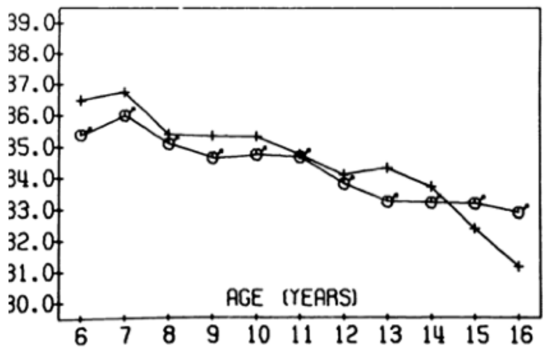

Fig. 1.5 Representation of the change of one variable (ML-NSL) over time. From: Riolo et al. (1974)

Following the numerous studies listed above the present investigation has the following purposes:

1. It is attempted to find patterns in the association of the bony and dental parts of the facial skeleton. The basis for this is the morphology of the craniofacial complex at different ages.
2. If such associations can be ascertained methods to describe these patterns shall be presented.
3. The main objective is to study the influence of growth on the relationships between the sets of measurements. For this purpose it is necessary to distinguish between pure increase in size and change in

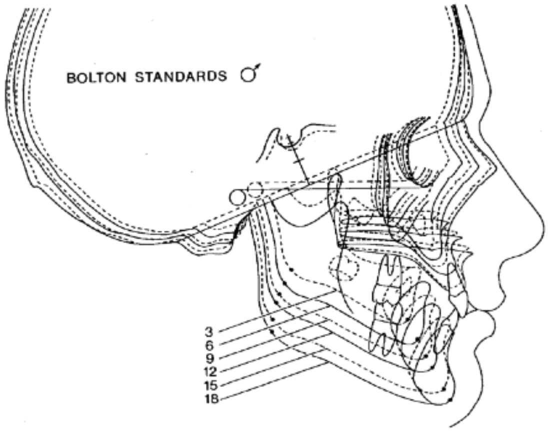

Fig. 1.6 Representation of the change by superimpositions of averaged drawings. From: Broadbent et al. (1975)

shape. A method to eliminate size related differences needs to be developed. Then it will be tested whether differences between the morphological patterns at the different age groups exist and also if the growth related changes themselves display a consistent pattern.

4. Finally the problem of intra-individual variation in relation to inter-individual variation will be addressed. It will be tested whether the pattern of change within an individual is consistent or whether this pattern varies itself. This problem immediately leads to the question whether an individual's growth related changes can be prognosed.
5. As the detection of minuscule changes requires a high quality of the basic serial data a thorough analysis of landmark and variable errors needs to be conducted. This analysis shall result in the selection of appropriate variables and the estimation of error variance in relation to true variable variance.

2. Material and Method

2.1 Material for investigation

To study the growth effects a serial material from the community of Nittedal in Norway was used. The community of Nittedal is located about 30 km north of Oslo. During the last 3 decades it has changed from rural to suburban character (Berg 1983). Starting in 1966 children in the public school system were asked to come to dental/orthodontic examinations that included the taking of lateral X-Rays, orthopantomograms, impressions, and photographs. These records were taken every three years starting at age 6 and up to the age of 18 years.

Of 1269 children in the community within the right age bracket about 30% did not respond at all while many more either moved away or required orthodontic treatment and were excluded for that reason (Berg 1983).

Of the available children 80 met the criteria of an Angle class I occlusion at the age of 12 years and onwards with no major crowding or spacing, no open bite, no deep bite with gingival contact, no agenesis of any permanent teeth with the exception of wisdom teeth, and no orthodontic treatment prior or during the observation period. An Angle class II or III of up to ¼ of a premolar width on one or both sides was considered acceptable.

Table 2.1 Age distribution of serial material

Registration	mean age	S.D.	n
A	5.96	0.37	60
B	8.94	0.37	80
C	11.92	0.38	80
D	14.92	0.39	79
E	18.20	0.38	55

The distribution of the material regarding the age at the time of the registrations is shown in Table 2.1.

It can be seen that the standard deviation of the age is very low, meaning that the x-rays were taken rather accurately at the planned ages (6, 9, 12, 15, and 18 years of age).

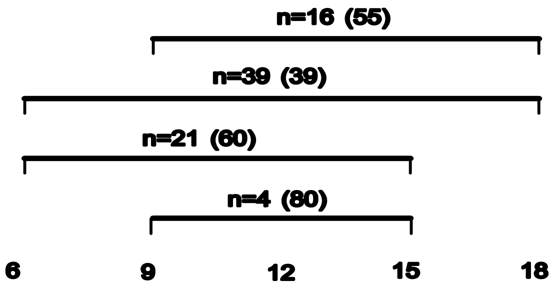

Fig. 2.1 Frequencies of different observation periods. Figures in brackets show total number of patients availble for that period due to overlapping group affiliation.

Figure 2.1 shows the frequencies of the different possible observation periods. All except for 4 subjects in the study were available for at least 4 out of the 5 possible registrations. It can be seen that 39 patients had the whole set of 5 recordings. 60 had records from 6 to 15 years of age while 55 had records from 9 to 18 years of age. The latter two groups included the 39 patients for whom the whole set of recordings was available. Due to illness records of one subject out of the group of 39 that had been under observation from 6 to 18 years could not be obtained at 15 years of age. This exception is not shown in Fig. 2.1.

The material therefore has to be called mixed-longitudinal although it has a strong serial component because half of the subjects are fully longitudinal and the remainder have all been under observation for 80% of the maximum observation period.

Table 2.2 Sex distribution by age group

Regis-	♂		♀		∑
tration	n	%	n	%	n
A	25	41.7	35	58.3	60
B	32	40.0	48	60.0	80
C	32	40.0	48	60.0	80
D	32	40.5	47	59.5	79
E	16	29.1	39	70.9	55
total	137	38.7	217	61.3	354

Table 2.2 shows the sex distribution for each of the age groups. A slight bias towards a higher percentage of female subjects is present at the younger age groups. For the 18-year group this shift increases to a ratio of 7:3. The reason for this bias is unknown; it might be speculated that the cooperation of female patients during puberty is better. A chi^2-test showed that the slight differences in sex distribution between the age groups were not significant.

2.2. X-ray method

All x-rays of a group were taken using the same x-ray equipment. The head was positioned in a LUMEX cephalostat. To make the soft tissue structures visible on the same headfilm an aluminum wedge was used to reduce the intensity in the area of the soft tissue profile.

The focus-film distance was 1.97 m. The distance of the median plane of the head to the film in the cassette was 0.13 m.

The enlargement factor V was calculated using the formula

$$V = \frac{d_1}{d - d_1} \cdot 100\%$$

where d is the focus-film distance and d_1 gives the film-median plane distance (Fig. 2.2).

The geometry described above gives an enlargement factor of 7.06%. As this magnification factor influences all linear measurements it was mathematically eliminated by dividing a correction factor of (V/100)+1 into all linear measurements.

The subjects were oriented with the Frankfort horizontal roughly parallel to the floor. No attempt was made to record natural head position. The patients were asked to close their mouth until the teeth were in contact. The lips were to remain relaxed.

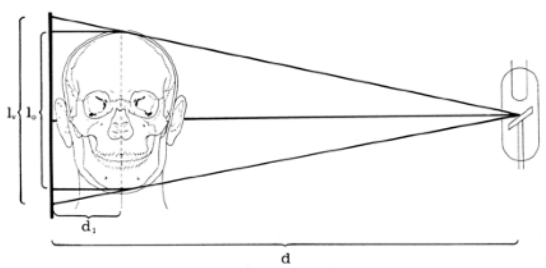

Fig. 2.2 Calculation of X-ray enlargement

2.3. Method of analyzing the x-rays

General set-up, digitizing process

The x-rays were analyzed in a two-step procedure. In a first step sheets of acetate were taped to the x-rays. In a dark room the landmarks were identified and marked on the acetate sheet. For orientation purposes a few structures were also sketched. In a second step the tracings were taped to the surface of a digitizer and entered into a computer.

In a preliminary study it was found that this two-step approach led to better accuracy. Especially the landmarks in dark regions of the x-rays were very difficult to locate when it was attempted to digitize them directly on the x-ray. The x-ray, the (translucent) digitizer and the digitizer's pointing device absorb too much light for accurate landmark localization.

All x-rays were analyzed individually, even in the serial material. No effort was made to superimpose the serial pictures whatsoever.

As the purpose of the study included an investigation into the reliability of the different landmarks and reference lines each x-ray was analyzed twice through a special process of double recordings. One month after the first tracing on the first acetate sheet had been made a second acetate sheet was taped to the same x-ray without removing the first one. The first acetate sheet was taped to the film at the right edge while the second sheet was taped to the film at the left edge (Fig. 2.3). Thereby it was possible to lift the first sheet from the headfilm without giving up its position relative to the film. After the second acetate sheet had been marked in the same manner both sheets could be flapped back so that they lay on top of each other in the correct relation to the x-ray film. Then two more strips of adhesive were used to secure the position of the sheets relative to each other so that later they could both be removed from the headfilm as one set without loosing the relation of the two markings for each landmark. Figure 2.3 shows how the two tracings were arranged on the headfilms.

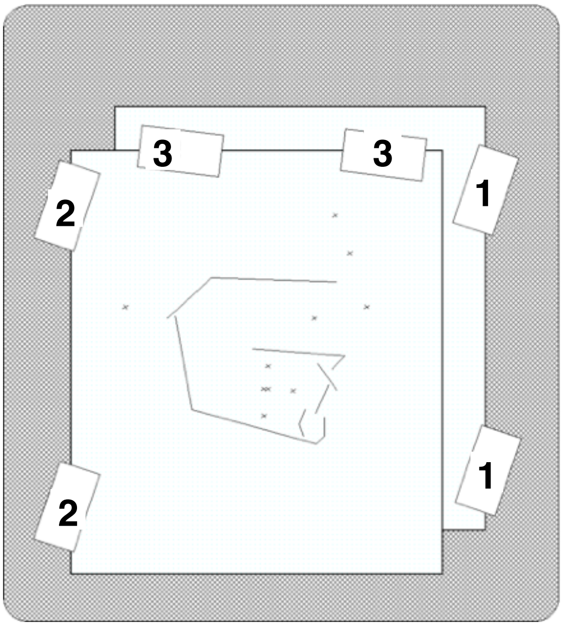

Fig. 2.3 The set of two tracing sheets attached to each X-ray on the right („1“) and left („2“) edges. The position towards each other was later secured at the top edge („3“).

For the digitizing process the the set of two connected tracing sheets were taped to the digitizing surface in a way that only one of the two tracings could be seen at a time while the position relative to the digitizer was secured (Fig. 2.4). The digitizer used was a HIPAD EDT11A[1]. It was connected to a portable IBM compatible computer. The program for recording, analyzing, storing and evaluating the data was written in Turbo Pascal 5.0 by the author.

Later the desired variables were calculated from the stored landmark coordinates and the results transferred to an ASCII file. From these raw data error analyses and the arithmetic means between the two measurements were calculated. If the difference between the values of a variable on the two tracings of a single x-ray exceeded the Dahlberg error for that specific variable by a factor of 4 one of these two measurements was considered an outlier

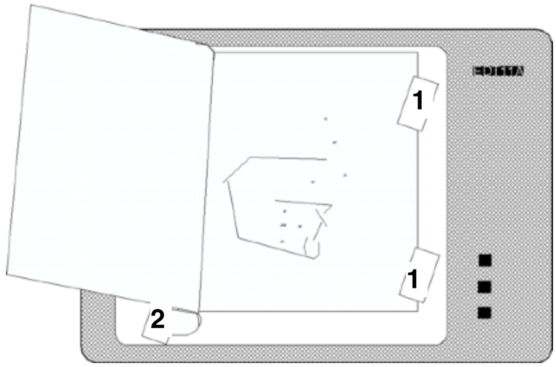

Fig. 2.4 Two tracings secured to the digitizer. One is flapped up so that the landmarks on the other can be entered unhindered from the other.

and the x-ray was traced a third or -if necessary- a fourth time. As a result two sets of measurements for each x-ray without outliers were available. Of these two measurements the arithmetic mean was calculated and used for the statistical analyses with the SPSS–PC+[2] package.

To obtain scattergrams for the individual landmarks the middle of the line connecting the two markings ("A" and "B" in Fig. 2.5) for that landmark was calculated for each headfilm. This midpoint represented an "assumed correct localization" for that landmark. Then these sets of 3 points (markings from the two tracings and the midpoint) were superimposed on the midpoints (Fig. 2.5 bottom). While all midpoints fell on top of each other and represented the center of the coordinate system the markings of the tracings resulted in scattergrams that were symmetric with regard to the origin (Fig. 2.5, bottom). Through computational rotations the axes in theses scattergrams corresponded to the NSL and a perpendicular to it.

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1 Houston Instruments Division of Bausch & Lomb, Austin, Texas, USA

2 SPSS Inc., Chicago, Illinois, USA

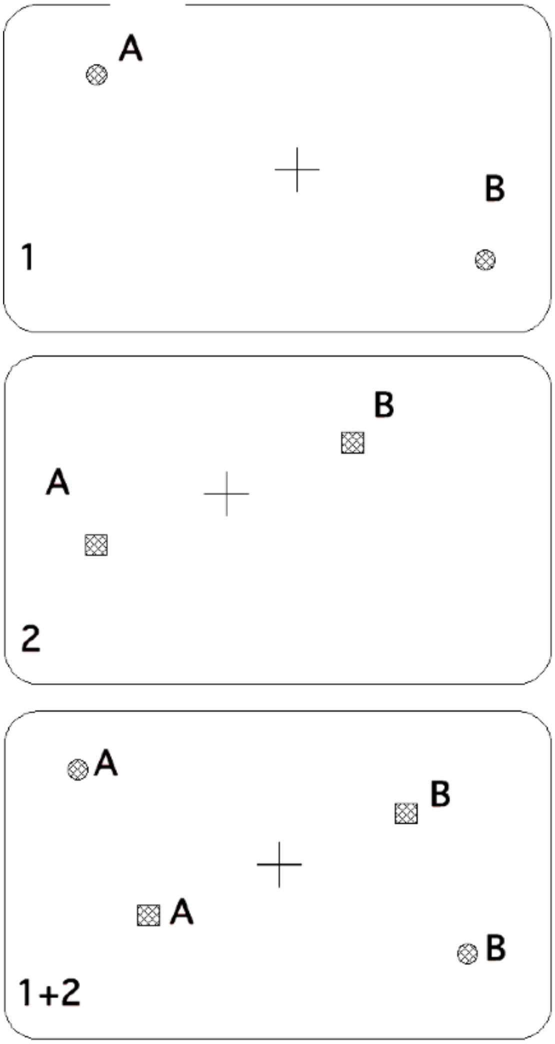

Fig. 2.5 Creation of the scattergrams. The two figures at the top show two X-rays with two markings each for a landmark. The lower figure shows the superimposition on the „assumed correct landmark localizations".

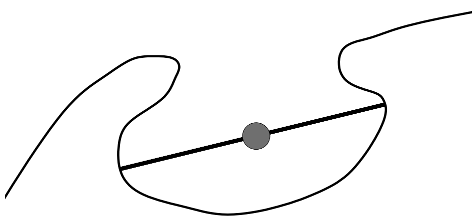

Fig. 2.6 Largest diameter of the bony crypt of sella turcica

Landmark definitions for lateral x-ray

The landmarks used for this study are shown in Table 2.3. It was attempted to use only landmarks that can be found directly on the x-rays with as little geometric constructions as possible.

Table 2.3 Landmarks used in the investigation. The numbers correspond to Figure 2.9

Cranial Base		
S	Sella	1
N	Nasion	2
Ba	Basion	3
Ar	Articulare	4
Po	Porion	5
Glab	Glabella	6
Fore	Forehead point	7
Maxilla		
A	A-point (Subspinale)	8
Sp	Anterior nasal spine	9
Pm	Pterygomaxillare	10
Orb	Orbitale	11
Mandibula		
B	B-point (Supramentale)	12
Pg	Pogonion	13
Progn	Prognathion	14
Gn	Gnathion (Menton)	15
Sy	Symphysis lingual	16
tgh	Gonion horizontal ramus tangent	17
tga	Gonion ascending S ramus tangent	18
tgo	Tangent point gonion	19
Dental		
Ui	Maxillary incisal edge	20
Ua	Maxillary incisor apex	21
Li	Mandibular incisal edge	22
La	Mandibular incisor apex	23
Mu	Maxillary 1st molar occl. surface	24
Ml	Mandibular 1st molar occl. surface	25

The individual definitions used in the present study for these landmarks were as listed below:

Sella

Sella is defined as the center of the bony crypt of the sella turcica. It is a constructed point in the median plane. The landmark is found at the center of the largest diameter of sella turcica (Fig. 2.6).

Nasion

The most anterior point of the naso-frontal suture. If the anterior end of the suture leads into a "V" between frontal and nasal bone the most posterior point of this V is used. The landmark is located in the median plane.

Basion

The most posterior and inferior point of the clivus in the median plane; at the same time the most anterior point of the large foramen. In some cases the inner cortical layer was used instead of the outer.

Articulare

The intersection of the collum of the mandible with the lower border of the external cranial base. If two such intersections appear on the x-ray they were averaged. It is a constructed landmark that is not in the median plane.

Porion

The highest point of the external auditory meatus (anatomic porion). Again averaging was often necessary.

Glabella

The most anterior point on the anterior contour of the forehead above *nasion*. This landmark lies underneath the eyebrows. In the youngest group the glabella protuberance was often all but undetectable, so that in these cases the definition had to be modified. Here the point where the flat surface of the forehead changes into a convexity that leads to the concavity above the nose.

Forehead point

A point where the flat surface of the forehead changes into a more curved convexity that leads towards the top of the skull.

A-point

The deepest point of the anterior concavity of the upper alveolar process. It is determined by finding the point on the contour that has the largest perpendicular distance from a line between anterior nasal spine and limbus alveolaris.

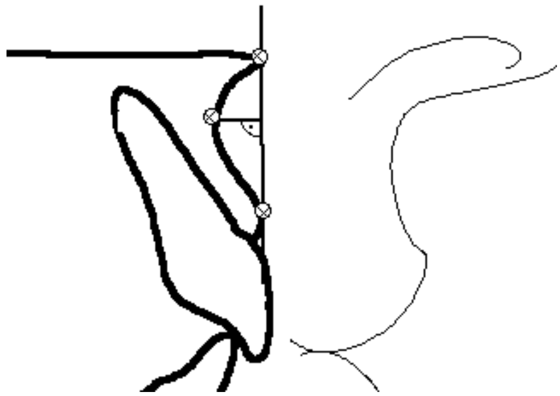

Fig. 2.7 Constructioin to determine A-point

Anterior nasal spine (Sp)

The most anterior point of the bony part of the anatomic anterior nasal spine.

Pterygomaxillare (Pm)

On the lateral x-ray the intersection of the dorsal contour of the maxilla with the soft or hard palate. In cases were the actual intersection is not visible due to molars on their path of eruption these lines are interpolated to find the intersection. The landmark posterior nasal spine can be either more anteriorly or more posteriorly than Pm.

Orbitale

The most inferior point of the orbital rim. If two contours were present the midpoint of a line connecting the two most inferior points was used.

B-point

The deepest point of the anterior concavity of the lower alveolar process. It is determined by finding the point on the contour that has the largest perpendicular distance from a line between the landmark pogonion and limbus alveolaris.

Pogonion

Pogonion is the most anterior point of the bony chin determined relative to the mandibular line (Fig. 2.8).

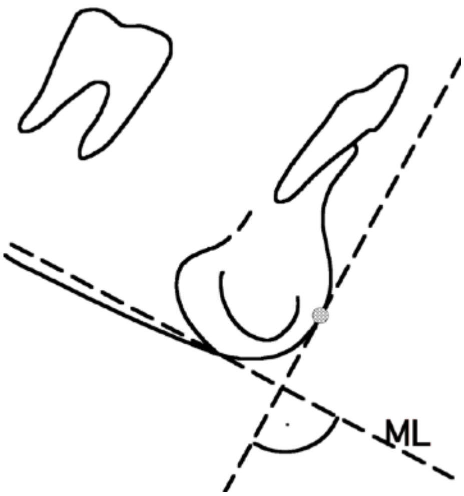

Fig. 2.8 Construction to determine *pogonion*

In cases with a receding chin that do not show a convexity at Pogonion and a concavity at B-point different definitions were utilized. B-point was located by finding a point on the anterior contour of the alveolus that is closest to a line that divides the apical and the middle part of the lower incisor. Pogonion was then located on the anterior contour of the chin with a perpendicular distance from the mandibular line that is half of that of B-point.

Prognathion

A point on the ventro-caudal contour of the mandibular symphysis that is most distant from the condyle. It is located between the landmarks *pogonion* and *gnathion*. Some investigators call this landmark gnathion and the name menton is then used for the landmark called *gnathion* in the present study.

Gnathion (Gn)

The most inferior point of the bony chin relative to the mandibular line. This landmark is often called *menton*. Some investigators have defined this landmark as most inferior relative to Frankfort Horizontal.

Symphysis lingual

The most dorsal point on the mandibular symphysis relative to *ML*.

Gonion horizontal ramus tangent (tgh)

A point on the caudal contour of the mandible in the gonion region that is used as a tangent point in the construction of the mandibular line. Double contours were averaged.

Gonion ascending ramus tangent (tga)

A point on the posterior contour of the mandibular gonion region that is found by laying a tangent to the convexity at gonion from Articulare. Double contours were averaged.

Tangent point Gonion (tgo)

A point outside the bone where a tangent from landmark gnathion to the lower edge of the gonion region (Gntgh) and from articulare to the posterior edge of the gonion (Artga) intersect. This landmark is not identical with the landmark *gonion* on the bone surface that is sometimes used.

Maxillary incisal edge

The incisal point of the most prominent central maxillary incisor

Maxillary incisor apex

The apex point of the most prominent central maxillary incisor

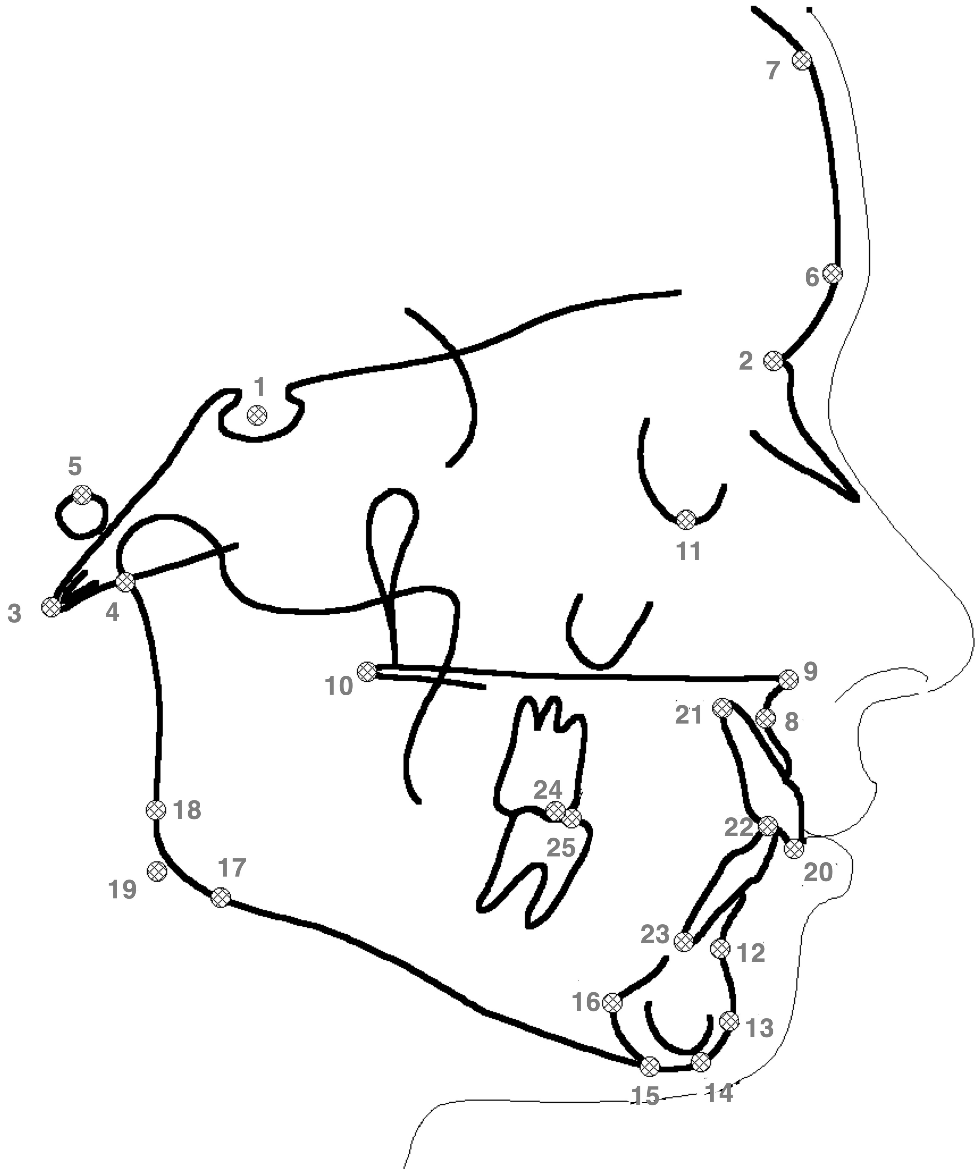

Fig. 2.9 Landmarks on lateral X-ray

Mandibular incisal edge
The incisal point of the most prominent central mandibular incisor

Mandibular incisor apex
The apex point of the most prominent central mandibular incisor

Maxillary 1st molar occlusal surface
The intersection of the mesial approximal contour of the maxillary first permanent molar with the contour of the lower first molar. If the first molars were not in occlusion the mesial cusp was used.

Mandibular 1st molar occlusal surface
The intersection of the mesial approximal contour of the mandibular first permanent molar with the contour of the upper first molar or the second bicuspid/deciduous molar. If the mandibular first molar was not in occlusion the mesial cusp was used.

Reference lines

From the landmarks defined above a number of main reference lines were defined. As the main reference line in the anterior cranial base the Nasion-Sella-Line (*NSL*) was used. All superimpositions as well as most angular measurements of inclinations and prognathism were done relative to this line. In the following this line is used synonymous with anterior cranial base.

As further horizontal reference lines the nasal line (*NL*, sometimes also called palatal plane) and the mandibular line (*ML*) were used. *NL* was defined by the landmarks *pterygomaxillare* and *anterior nasal spine* and *ML* by point *tgh* and *gnathion*.

Vertical reference lines from *nasion* to *A-point (NA)*, *B-point (NB)*, and *pogonion (NPg)* were used. In addition to these reference lines a number of lines were used for the calculation of the variables used in this study (Section 2.4). These include

- an occlusal plane that was constructed between the midpoint of a line connecting the maxillary and mandibular incisal edges and the midpoint of a line connecting the mesial cusps of the first upper and lower molars. If the teeth involved had not erupted at the time the x-ray had been taken this line could not be constructed.
- the ascending ramus line from landmarks *articulare* to *tga*. The line is therefore tangent to the posterior contour of the gonion region. In case of double contours these were averaged.
- the connecting line from *basion* to *sella*.
- the *Frankfort horizontal*, a line from landmarks *porion* to *orbitale*.
- a line representing the inclination of the forehead from *glabella point* to the landmark *forehead*.
- a line from *nasion* to *gnathion*.
- the long axes of the maxillary and mandibular incisors.
- a perpendicular to *ML* through *pogonion*.
- the *Y-axis*, a line from *sella* to *prognathion*.

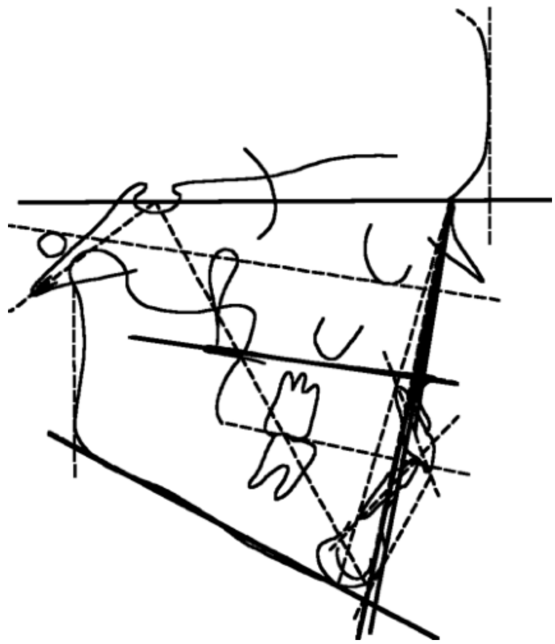

Fig. 2.10 Main reference lines (unbroken) and auxilliary lines (broken)

2.4. Variables used

Out of the shear unlimited number of variables that can be constructed from the landmarks listed in the previous section 31 were selected for further analysis. The criteria were

- good reproducibility
- readily obtainable from the cephalograms without complicated construction
- giving meaningful information.

The first item is discussed in the chapter on error analysis (section 2.5). Certain landmarks should only be used for sagittal measurements while others are better for vertical measurements. Variables were considered to be readily obtainable, if they were made up of angles, distances between landmarks, or distances from reference lines. In two cases (Index of anterior face heights and variable cross) the value was computed by the simple addition of two distances or by dividing one distance into another. More complex calculation would lead to increased measurement error and do not give more meaningful information.

Variables that are based on complicated constructions often violate the third criteria for variable selection in that the information they provide is not easily interpretable. It was considered advantageous if each variable could be attributed to a certain dimension in describing the facial skeleton, such as sagittal position of a jaw or the inclination of a jaw. Variables that combine sagittal and vertical information were avoided with the exception of the angle between the Y-axis and nasion-sella-line. This measurement was used to check whether such a variable might contribute additional information.

For all linear measurements it is important to state whether they have been corrected for X-ray enlargement. In the present study the enlargement has been eliminated mathematically for all linear variables.

A list of the variables used in the present study is given in Table 2.4.

Table 2.4 Variables used in the investigation.

<u>Sagittal position of jaws</u>
SNA
SNB
SNPg
<u>Sagittal relation of jaws</u>
ANB
ANPg
Wits
<u>Inclinations of jaws</u>
ML-NSL
NL-NSL
ML-NL
GntgoAr
<u>Cranial base</u>
NSBa
FH-NSL
OrbNA
ForeHead
<u>Linear dimensions</u>
S-N
N-Gn
Cross
Ar-Progn
$PgNB_{mm}$
Chin
Symph
NSp'
Sp'Gn
Index
<u>Tooth positions/inclinations</u>
$\underline{1}$-NA°
$\underline{1}$-NA_{mm}
$\overline{1}$-NB°
$\overline{1}$-NB_{mm}
$\overline{1}$-APg_{mm}
$Pg\perp ML_{mm}$
<u>Other</u>
Y-axis

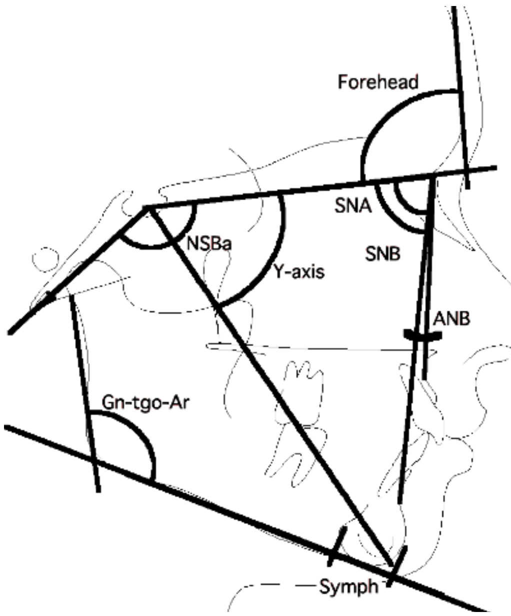

Fig. 2.11 Variables used in the investigation

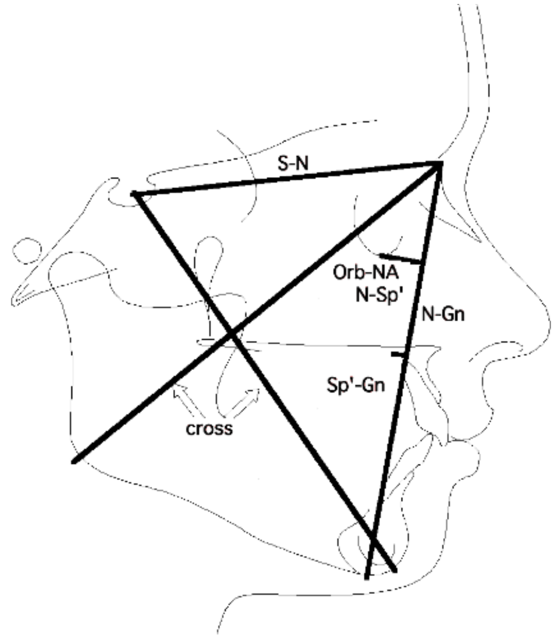

Fig. 2.12 Variables used in the investigation, continued

SNA

SNA is the angle between the anterior cranial base (*NSL*) and the line from *nasion* to *A-point* (Fig. 2.11). It is a measure of the degree of prognathism of the maxilla.

SNB

SNB is the angle between the anterior cranial base (*NSL*) and the line from *nasion* to *B-point* (Fig. 2.11). It represents the prognathism of the mandible as measured at the alveolar process.

SNPg

SNPg is the angle between *NSL* and the line from *nasion* to *pogonion* (Fig. 2.13). It is also an indicator of mandibular prognathism, but as opposed to *SNB* it is measured at the skeletal part instead of the alveolar process.

ANB

The angle between *A-point, nasion*, and *B-point* (Fig. 2.11). If A-point is dorsal of the NB-line the angle is negative. This angle is a measure of the sagittal position of the maxillary and mandibular alveolar processes relative to each other.

ANPg

The angle between *A-point, nasion*, and *pogonion* (Fig. 2.13). If A-point is dorsal of the NPg-line the angle is negative. Similar to *ANB* this angle is a measure of the sagittal position of the maxillary alveolar process in relation to the skeletal mandible.

Wits value

The Wits value is a linear measure of the sagittal relation of the alveolar processes. *A-point* and *B-point* are projected onto the occlusal plane. The linear distance between the projected points along the occlusal plane represents the *Wits value* (Fig. 2.14). In a neutral relationship of the jaws the value is expected at between 0 and 1 mm (Jacobson 1975).

ML-NSL

The angle between the *ML* and the *NSL*. This variable represents the inclination of the lower mandibular border relative to the anterior cranial base (Fig. 2.13).

NL-NSL

The angle between the *NL* and the *NSL*. This variable represents the inclination of the nasal or palatal plane relative to the anterior cranial base (Fig. 2.13).

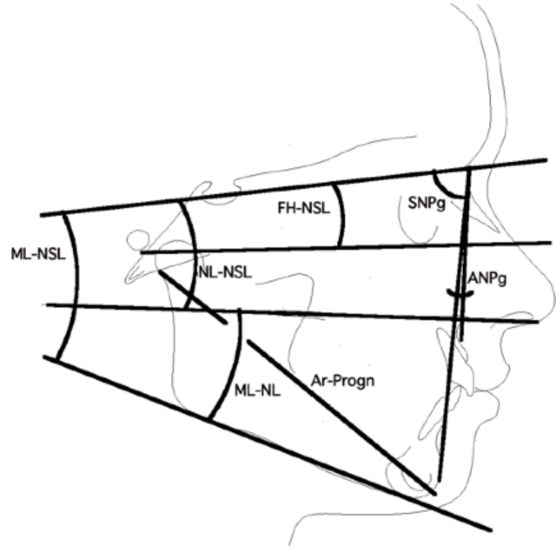

Fig. 2.13 Variables used in the investigation, continued

ML-NL

This measurement is the angle between the lines *NL* and *ML* or the difference between the variables *ML-NSL* and *NL-NSL* (Fig. 2.13). It epitomizes the divergence of the maxillary and mandibular planes.

Gn-tgo-Ar

This angle represents the acuteness of the gonial angle of the mandible. It is measured between *ML* and the *ascending ramus tangent* (Fig. 2.11).

NSBa

This value gives the angle between the anterior cranial base (*NSL*) and the clivus line (*S-Ba*) (Fig. 2.11). The angel reflects cranial base flexure.

FH-NSL

The angle between the *Frankfort Horizontal* and the anterior cranial base as depicted by *NSL* (Fig. 2.13).

Orb-NA

The shortest distance of the point *orbitale* from the vertical reference line *NA* measured in mm (Fig. 2.12).

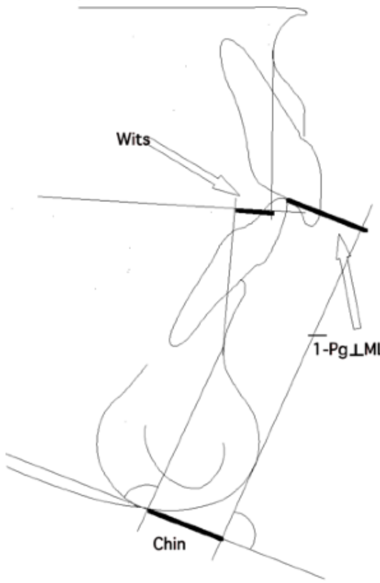

Fig. 2.14 Variables used in the investigation, continued

ForeHead inclination

The angle between the line from *glabella* to the landmark *forehead*. Measured is the cranial-dorsal angle (Fig. 2.11). An angle below 90° characterizes a receeding forehead.

S-N

The linear distance between the landmarks *sella* and *nasion* (Fig. 2.12).

N-Gn

The linear distance between the landmarks *nasion* and *gnathion* (Fig. 2.12). It gives the vertical height of the lower two thirds of the face.

Cross

The sum of the distances between *sella* and *prognathion* and between *nasion* and *tgo* (Fig. 2.12). This variable is used to describe the size of the facial skeleton.

Ar-Progn

The linear distance between the landmarks *articulare* and *prognathion* (Fig. 2.13). It represents the length of the mandible.

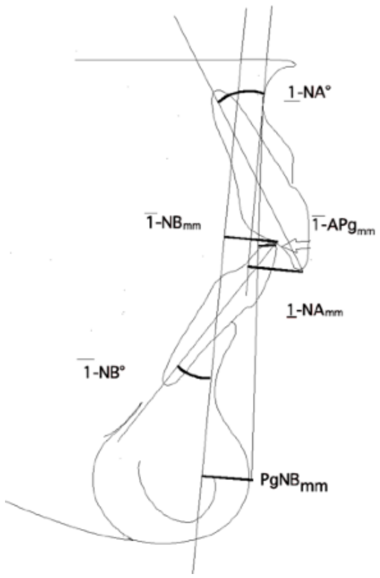

Fig. 2.15 Variables used in the investigation, continued

$PgNB_{mm}$

The chin prominence measured as the shortest distance from *pogonion* to the vertical reference line *NB* (Fig. 2.15).

Chin

The chin prominence measured as the distance between the landmarks *pogonion* and *B-point* when projected on *ML* (Fig. 2.14).

Symph

Sagittal width of the mandibular symphysis measured as the distance between the projections of the landmarks *pogonion* and *symphysis lingual* on the mandibular line (Fig. 2.11).

N-Sp'

Midfacial height measured as the distance from *nasion* to *Sp'* (intersection of N-Gn with NL). (Fig. 2.12)

Sp'-Gn

Lower facial height measured as the distance from *Sp'* to *gnathion* (Fig. 2.12).

Index

Ratio of *N-Sp'* to *Sp'-Gn* expressed as a percentage:

$$Index = \frac{N\text{-}Sp'}{Sp'\text{-}Gn} \cdot 100\%$$

$\underline{1}$-NA°

Inclination of the long axis of the maxillary incisor relative to line *NA* (Fig. 2.15).

$\underline{1}$-NA_{mm}

Shortest distance of the incisal edge of the maxillary incisor from the line *NA* (Fig. 2.15). When the incisal edge is ventrally of the line the value is positive.

$\bar{1}$-NB°

Inclination of the long axis of the mandibular incisor relative to line *NB* (Fig. 2.15).

$\bar{1}$-NB_{mm}

Shortest distance of the incisal edge of the mandibular incisor from the line *NB* (Fig. 2.15). When the incisal edge is ventrally of the line the value is positive.

$\bar{1}$-APg_{mm}

Shortest distance of the incisal edge of the mandibular incisor from the line *APg*. When the incisal edge is ventrally of the line the value is positive (Fig. 2.15).

1-$Pg \perp ML_{mm}$

Shortest distance of the incisal edge of the mandibular incisor from a vertical to *ML* through *pogonion* (Fig. 2.15).

Y-axis

The angle between a line from *sella* to *prognathion* and the *NSL* (Fig. 2.11).

2.5. Error analysis

To control the method error of the investigation the different sources of errors have to be looked into separately.

Localization of landmarks on lateral cephalograms

The process of digitizing landmarks in the way described above involves a number of possible sources of errors:

1. The discrepancy between what the operator considers to be the correct localization of the landmark and the correct localization of the landmark according to the definition.
2. Errors in positioning the cross hair of the digitizing device in the desired position.
3. Errors in the electronic digitizing process due to inaccuracies and instabilities of the equipment and rounding errors in the digital representation of the (analogous) landmark localization.

Item 1 is influenced mainly by the quality of the x-ray, by efficacy of the light box and the intensity of the surrounding light, by the experience of the investigator, and by clear and unambiguous landmark definitions.

The second item depends on the thickness of both cross hair of the digitizing device and pencil marks, on the steady hand and skill of the investigator, and on the correct angle of view. If the line of view isn't perpendicular to the digitizing surface parallax errors will occur (Fig. 2.15). The size of this parallax error will depend on the vertical distance between x-ray film/digitizing surface and crosshair of the digitizing device as well as the angle of view. By tilting the digitizing surface towards the operator this error was minimized.

The last point depends almost completely on the quality and correct operation of the digitizing equipment. The process of calculating and storing the digitized values in the computer can usually be carried out with neglectable error. While the resolution of the digitizing equipment used is 0.1 mm the actual accuracy is not as high. According to the manufacturer's specifications (Bausch & Lomb 1983) the absolute accuracy is 0.381 mm. This value gives the absolute error, that is the accuracy in the digitizing of any point on the digitizing surface. For cephalometric measurements only the distances of angles between landmarks that are relatively close together are of interest. The digitizing of these landmarks is usually influenced by the same absolute error. Only the difference between the absolute errors for each of the landmarks are of interest for the purpose of cephalometric measurements. This difference is the relative error and it is of considerably smaller size. If all y-coordinates were -for example- 1 mm too large, the absolute error would be 1 mm but the relevant relative error would still be zero. All cephalometric measurements would be correct. According to Wingberg (1984), who used the same digitizing equipment, the error induced by the digitizing equipment is not larger than 0.1 mm in either x- or y-direction.

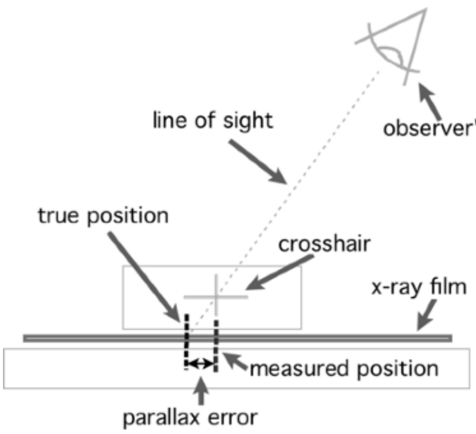

Fig. 2.15 Parallax error in digitizing process

To study the part of the variation in landmark identification that is introduced by the perception of the investigator and by the pencil markings a modification of the method used by Baumrind and Frantz (1971[a]) was employed.

All x-rays were evaluated twice. Two tracing sheets were taped to the x-ray in a way that each could be marked individually while assuring that their relation towards each other was fixed. During the process of marking and digitizing only one of the sheets was visible at a time. At this point there were two sets of coordinates for each landmark stored in the computer. The mean of these two x- and y-values was then calculated and used as the assumed true location of the landmark.

The difference between this assumed true position and the actual digitized position in x- and y-direction was calculated. As there were only two measurements this difference was always half the difference between the two actual measurements. In the next step all actually recorded positions of a landmark were mathematically superimposed on the assumed true location of that landmark. The result is a scattergram with the assumed true position of the landmark at the origin of the coordinate system. These scattergrams consist of originally 708 points (354 X-rays with 2 recordings each) of which due to program limitations only the first 220 pairs were selected to draw the scattergrams in Figures 2.16 to 2.38.

In addition the distribution of the scattergrams was evaluated by calculating the standard deviation in the direction of the x- and y-coordinates for all coordinate pairs. For this study the x-axis was defined to be the Nasion-Sella-Line while the y-axis was perpendicular to it through Sella. The standard deviation of the landmark localization was calculated using the formula

$$S.D._x = \sqrt{\frac{\sum (X_1 - X_2)^2}{2n}}$$

where X_1 represents the x-coordinate of the first recording and X_2 that of the second recording. "n" is the number of x-rays, in this case 292. The standard deviation in the y-direction was calculated correspondingly.

It has to be kept in mind that the values calculated in this manner not only reflect the errors listed under number 1. above, but also the errors under number 2. and 3. The size of these will be estimated further down. Table 2.5 shows the standard deviations for the landmark localization in x- and y-direction.

It can clearly be seen that for many landmarks the variance in x-and y-direction differs considerably. The error that is introduced into a measurement by using a certain landmark depends a lot on the orientation of the reference line. The landmark Pogonion for example is the landmark with the highest accuracy of all sagittal measurements. For vertical measurements, on the other hand, its accuracy is average at most.

Because of the importance of the orientation of the landmark scatter for the kind of measurement a landmark might accurately be used for Figures 2.16 to 2.38 show the scattergrams of the landmarks used in this investigation.

Table 2.5 Standard deviation of x- and y-coordinates of landmarks determined through double registrations

Landmark	$S.D._X$	$S.D._Y$
Sella	0.30	0.31
Nasion	0.29	0.34
Basion	0.80	0.87
Articulare	0.37	0.40
Porion	0.91	1.10
Glabella	0.40	1.85
Forehead point	0.60	1.99
A-point	0.31	0.85
Ant. nasal spine	0.64	0.32
Pterygomaxillare	0.52	0.43
Orbitale	0.99	0.72
B-point	0.31	0.87
Pogonion	0.30	0.78
Prognathion	0.46	0.47
Gnathion (Menton)	0.86	0.33
Symphysis lingual	0.41	0.89
Gonion horiz. tang.	1.05	0.47
Gonion asc. ramus tang.	0.48	1.39
Tangent point gonion	0.50	0.48
Maxillary incisal edge	0.32	0.29
Maxillary incisor apex	0.71	0.96
Mandibular incisal edge	0.32	0.35
Mandibular incisor apex	0.71	0.91

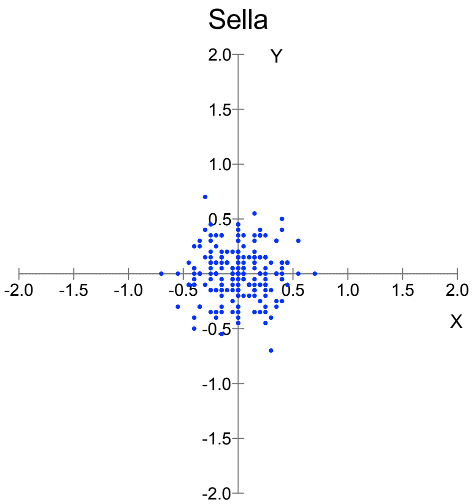

Fig. 2.16 Scattergram for Sella

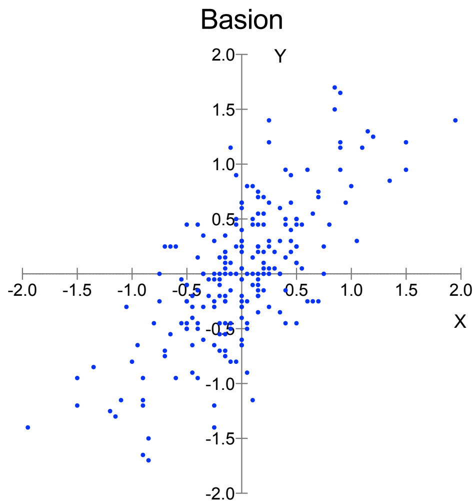

Fig. 2.18 Scattergram for Basion

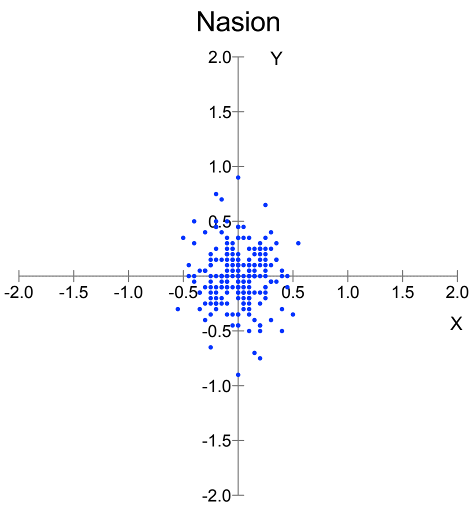

Fig. 2.17 Scattergram for Nasion

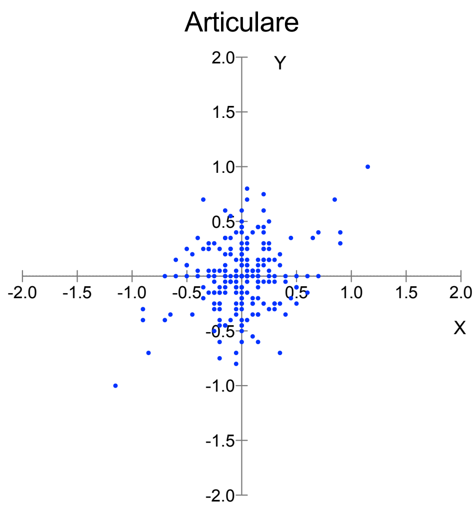

Fig. 2.19 Scattergram for Articulare

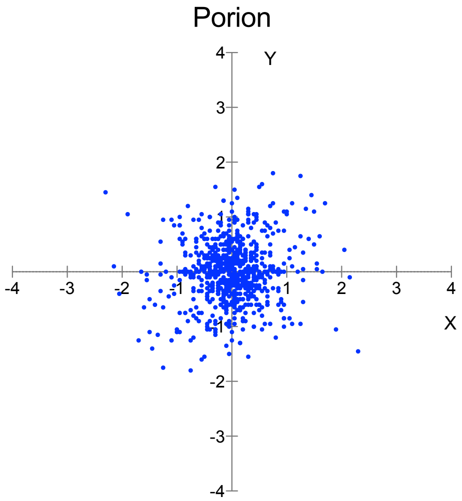

Fig. 2.20 Scattergram for Porion

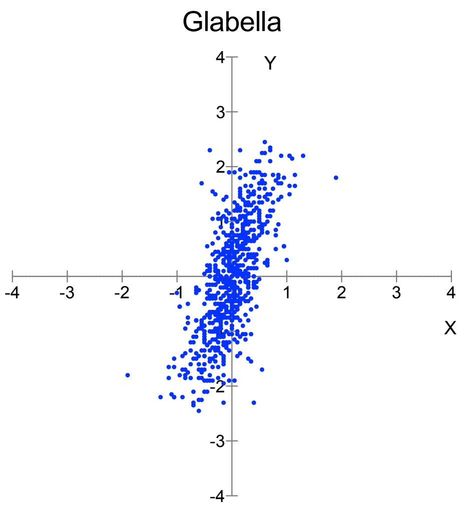

Fig. 2.21 Scattergram for Glabella

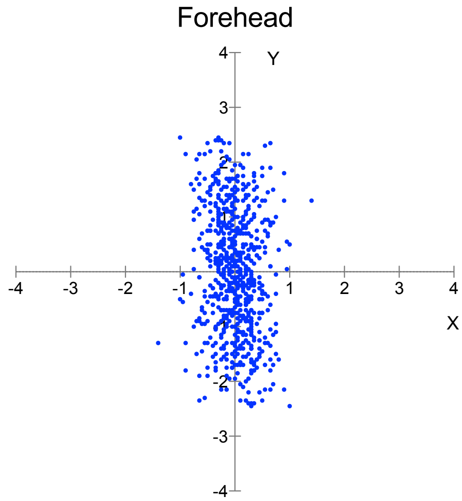

Fig. 2.22 Scattergram for ForeHead

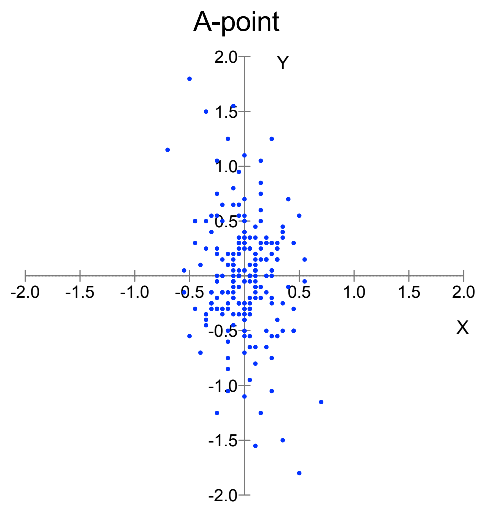

Fig. 2.23 Scattergram for A-point

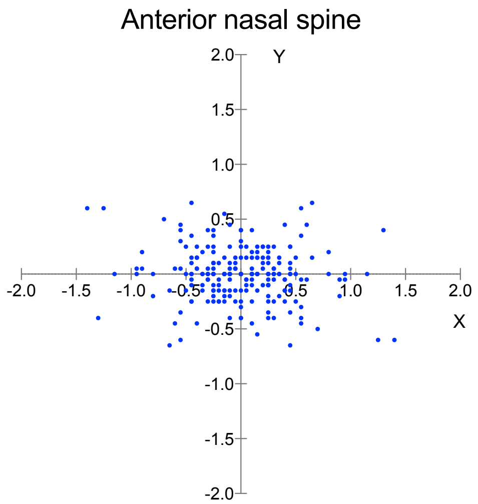

Fig. 2.24 Scattergram for Anterior nasal spine

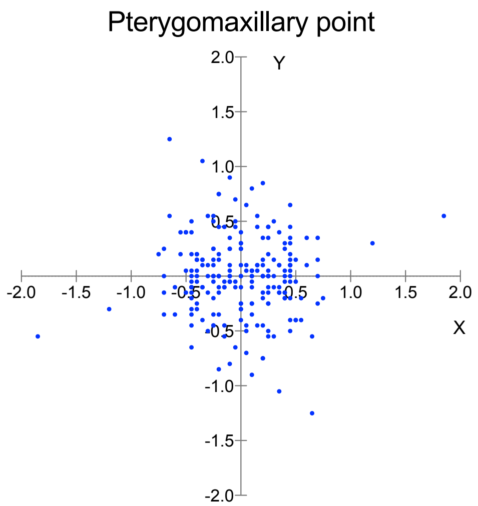

Fig. 2.25 Scattergram for Pterygomaxillary point

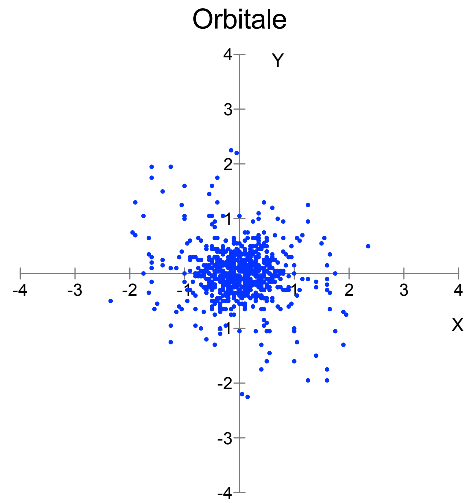

Fig. 2.26 Scattergram for Orbitale

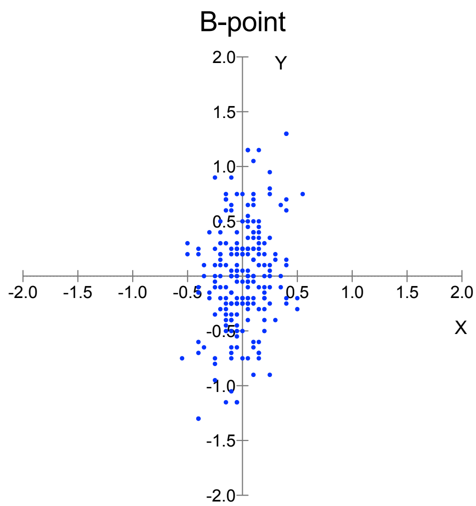

Fig. 2.27 Scattergram for B-point

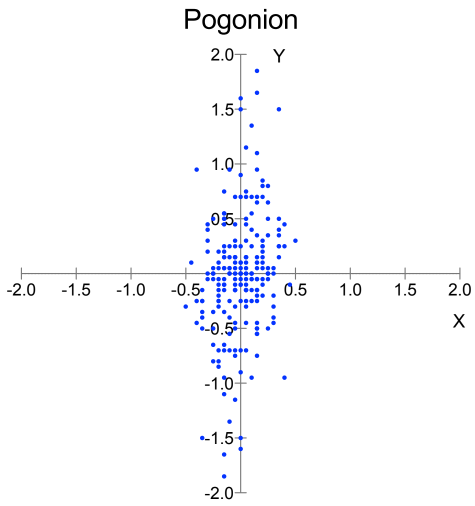

Fig. 2.28 Scattergram for Pogonion

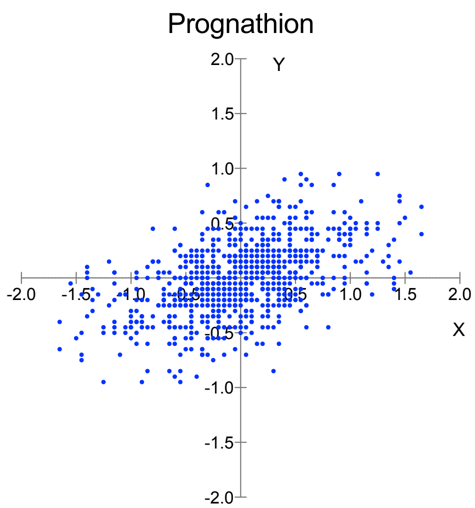

Fig. 2.29 Scattergram for Prognathion

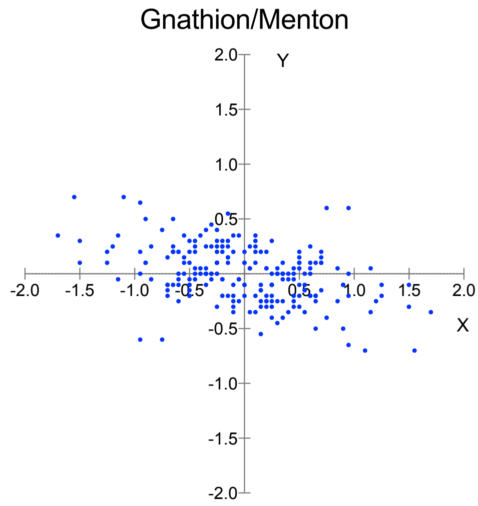

Fig. 2.30 Scattergram for Gnathion

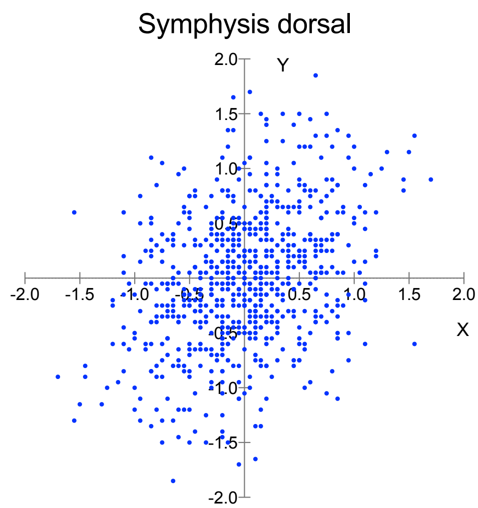

Fig. 2.31 Scattergram for Symphysis dorsal

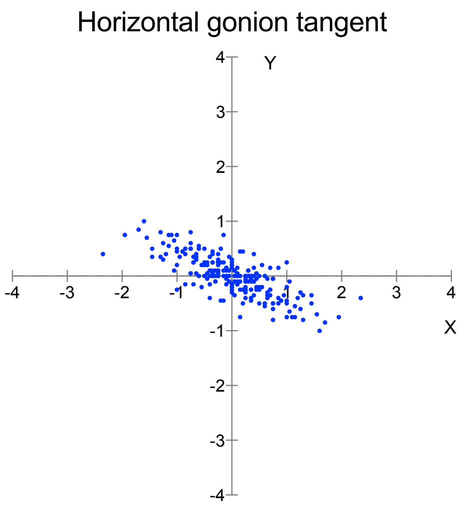

Fig. 2.32 Scattergram for Horizontal gonion tangent

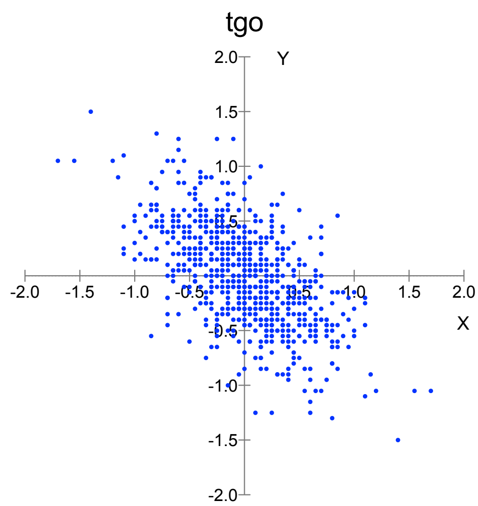

Fig. 2.34 Scattergram for tgo

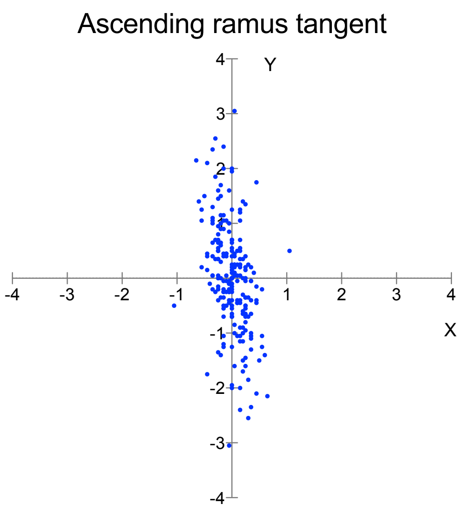

Fig. 2.33 Scattergram for Ascending ramus tangent

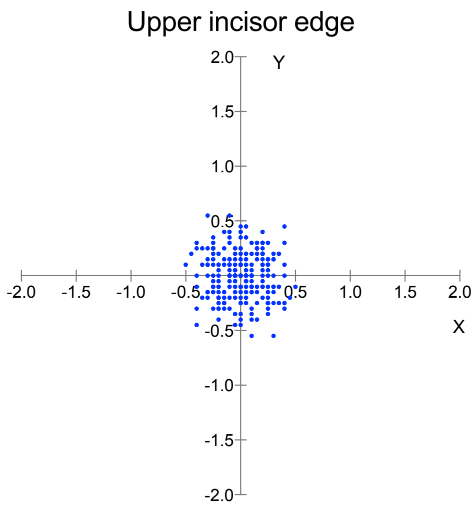

Fig. 2.35 Scattergram for Upper incisor edge

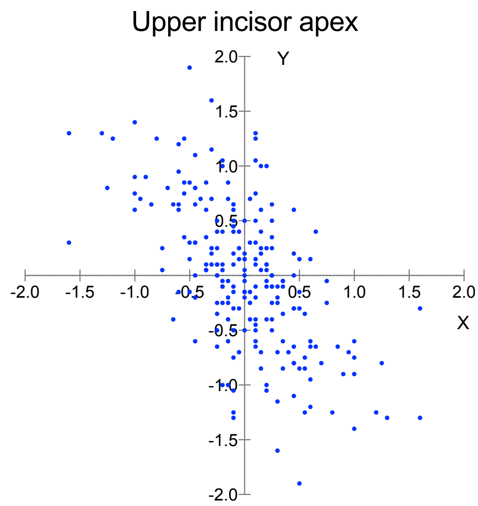

Fig. 2.36 Scattergram for Upper incisor apex

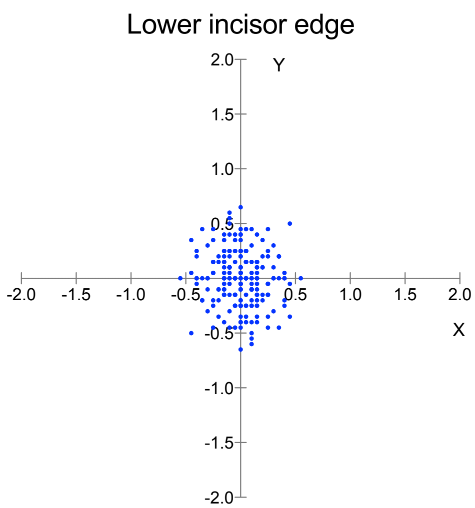

Fig. 2.37 Scattergram for Lower incisor edge

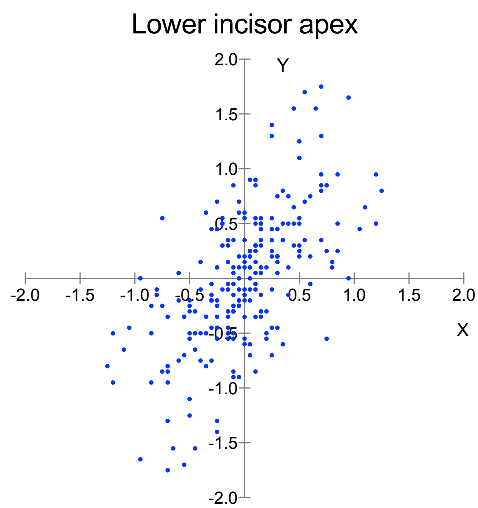

Fig. 2.38 Scattergram for Lower incisor apex

The scattergrams for Sella and Nasion were nearly round and rather compact. There were a number of outliers for Nasion in the vertical direction. These led to the higher standard deviation in y-direction as compared to the x-direction.

The landmarks A-point, B-point, and Pogonion all showed long-drawn scattergrams in the vertical direction. Especially for A-point outliers of up to 2 mm were not uncommon. The long axis of the scattergrams was slanted slightly from dorso-cranial to caudo-ventral for A-point and vice versa for both B-point and Pogonion.

Markings of Anterior nasal spine were distributed horizontally with a slight downward slope resembling the average inclination of the nasal line.

The scattergram of Pterygomaxillare was not very compact, but it lacked a clear longitudinal axis.

With the exception of a few outliers along the bottom of the cranial base the scattergram for Articulare was quite compact and round. These outliers had to be attributed to incorrect evaluation of double contours.

Basion showed widely scattered markings, but they adhered strictly to the main axis of the occipital part of the cranial base (clivus). When the standard deviation was calculated perpendicular to the average Sella-Basion-line it was reduced to 0.52 while the standard deviation along the Sella-Basion-axis was increased to 1.22. If Basion is only used to describe the flexion of the cranial base the accuracy of localization seemed similar to that of other hard tissue landmarks of average accuracy.

The markings of the mandibular landmarks Gonion ascending ramus tangent, Gonion horizontal tangent and Gnathion were all very much spread along the contour of the bone which didn't surprise when their nature as tangent points was considered.

The incisal points of the maxillary and mandibular central incisors both displayed very compact and round scattergrams while the apex points were spread out considerably along the average long axis of these teeth.

Aside from the difference in the dispersion measures of the different landmarks the fact that some of the landmarks could not be determined on a number of radiographs severely limits the usefulness of variables based on such reference points.

For the present study the landmarks *porion* and *orbitale* induced problems. In about 10% of the cases they could not be determined without doubt. None of the dental measurements and the "Wits" value could be calculated for the 6-year group as the incisors and the first molars usually had not erupted fully. As the reason for this finding was the biological timing rather than cephalometric procedure these cases were not included in Table 2.6. In addition a few cases showed missing landmarks for incisor apex points.

Tab. 2.6 Percentage of X-rays on which landmarks could not be determined (n = 708 radiographs)

Landmark	Not determinable in % of cases
Porion	9.6%
Orbitale	8.7%
Maxillary incisor apex	0.3%
Mandibular incisor apex	0.6%
Occlusal plane at 1st molar	0.6%

The shape of the scattergrams is very similar to those found by Baumrind and Frantz (1971[a]) although their error variances in X and Y direction are somewhat larger for all landmarks with the exception of *porion*. The reason might be that they employed 5 different judges with four tracings each for locating the landmarks.

The relation between landmark error and variable error

Variables for cephalometric measurement are usually made up of distances and angles. If indices are used they are again based on ratios of linear or angular measurements. It is therefore sufficient to look into the influence of landmark error on linear and angular measurements.

For linear measurements the influence of landmark error on the measurement is quite simple. The standard error of the linear measurement s_e is merely the square root of the sum of the error variance of the two landmarks in the direction of the connecting line (Fig. 2.39):

$$s_e = \sqrt{s_1^2 + s_2^2}$$

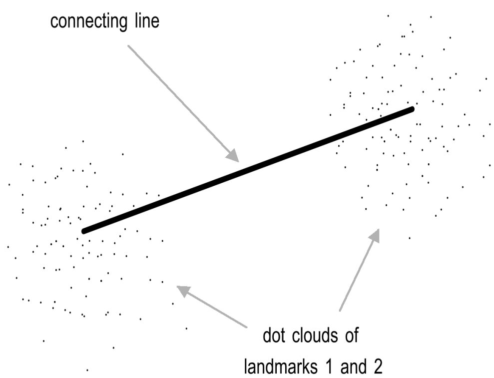

Fig. 2.39 Influence of landmark scatter on distance measurements

To get an accurate measurement it should be ensured that the error in landmark localization for both landmarks is lowest in the direction of the connecting line.

Angular measurements are somewhat more complicated. The standard error of an angular measurement is the square root of the sum of the squares of the standard errors of the angular orientation of the two reference lines that make up the angle under investigation. The standard error of the angular orientation of a line then depends on the error of locating the two landmarks defining the line in a direction *perpendicular* to the line and the distance between the two landmarks (Fig. 2.40).

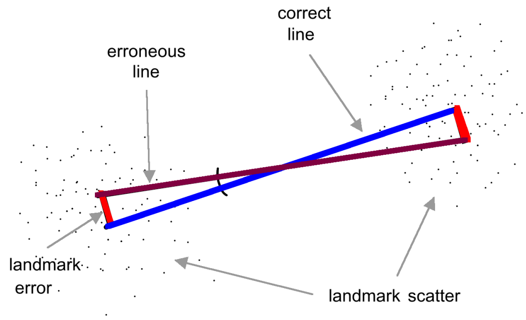

Fig. 2.40 Influence of landmark scatter on angular measurements

The angular error ε can be calculated as

$$\tan \epsilon = \sqrt{\frac{s_{e_1}{}^2 + s_{e_2}{}^2}{d}}$$

where s_{e1} and s_{e2} are the standard errors of the two landmarks perpendicular to the line and d is the distance between the two landmarks. If the standard error $se_{\perp}$ perpendicular to the reference line is not known it can be estimated assuming an elliptical error distribution from the standard errors in x- and y-direction by using

$$se_{\perp} = \frac{se_x \cdot se_y \cdot \sqrt{se_x^2 \cdot (1 + \tan^2\alpha) + se_y^2 \cdot (1 + \frac{1}{\tan^2\alpha})}}{\tan^2\alpha \cdot se_x^2 + \frac{1}{\tan^2\alpha} \cdot se_y^2}$$

where α is the angle between a vertical line and the reference line under survey.

As the angular error ε should be below 5° the tangents function will be almost linear. Therefore the angular error is inversely proportional to the square root of the distance between the landmarks:

$$\epsilon \approx \frac{1}{\sqrt{d}} \times \sqrt{s_{e_1}{}^2 + s_{e_2}{}^2}$$

For accurate angular measurements it is therefore not sufficient if the error of landmark localization perpendicular to the connecting line is low. In addition the distance between the two landmarks should be maximal. If neither of these requirements is fulfilled that variable can be expected to be rather unstable and unreliable. An example for this would be the Norderval line, a line through B-point that is tangent to the chin prominence.

The line N-Pg can be used as a positive example. Although pogonion has a quite high standard error of localization in y-direction, the standard error in x-direction is rather low. This together with the fact that the distance from nasion to pogonion is one of the largest in the facial skeleton makes the N-Pg line one of the most stable reference lines in any analysis. This can also be seen from the low Dahlberg error for the measurement SNPg (Chapter 2.5.6 below).

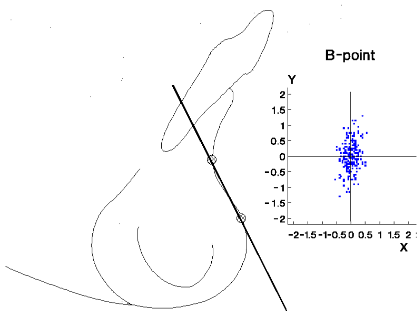

Fig. 2.41 Example for unfavorable definition of a cephalometric variable: undesirable orientation of landmark scatter at B-point in combination with a very short distance between landmarks

Method error of variables on lateral x-ray

The accuracy of a method of measuring biological data can be established by performing repeated measurements. Ideally the whole measurements would have to be repeated. Due to ethical reasons this is not possible in cephalometric analyses. Repeated measurements have to be limited to double evaluation of x-rays.

Among the measures used in the literature to describe the accuracy of measurements are the method error according to Dahlberg (1940), the measure ω^2 (Ødegaard et Bøe 1972), the reliability coefficient according to Houston (1983) and the correlation coefficient between the two measurements. All these describe the random error. A possible systematic error between the two measurements can be detected using a test for differences between means in a paired material such as the paired t-test or the non-parametric Wilcoxon test.

The Dahlberg method error gives the standard deviation of the measurement error. It is calculated by the formula:

$$s_e = \sqrt{\frac{\sum d^2}{2n}}$$

where d is the difference between the two measurements and n is the number of measurements. This measure is useful to compare the accuracy of a study with other studies that use the same cephalometric variables. A comparison of reliability between different variables within one study is not possible since the Dahlberg method error is influenced by the units used. If a distance was measured in metres instead of millimeters, the method error would be 1000 times smaller and thus could not be compared to other measurements that use units of millimeters or inches. In addition it is not possible to compare the reproducibility of an angular variable with a linear one due to the different units.

To compare the reproducibility between different variables within one study the reliability coefficient according to Houston (1983) is of better value. It gives the error variance as a percentage of the variable variance. The formula to calculate it is

$$Rel = 1 - \frac{s_e^2}{s_t^2}$$

where s_e is the Dahlberg error and s_t is the total observed variance $s_v^2 + s_e^2$ with s_v as the standard deviation of the variable itself which cannot be measured directly. If there was no error variance (Dahlberg method error of zero) the value of the reliability coefficient would be 1. Houston states that the coefficient should be above 0.97 or 97% if expressed as a percentage, but he admits that for some variables this might not always be achieved.

Ødegaard's ω^2 differs in that it calculates the ratio between error variance and *true* variable variance instead of *measured* (total) variance.

$$\omega^2 = \frac{s_e^2}{s_v^2} = \frac{s_e^2}{s_t^2 - s_e^2}$$

As the error variance should be below 5% of the total variance this value can be compared to the reliability coefficient described by Houston if subtracted from 1. The resulting values will be slightly smaller (difference < 0.25%). Only when the error variance forms a larger part of the total variance will these two measures give different values.

Since the reliability coefficient is a measure without a unit, the values for different variables can be compared without problem. If two variables describe the same morphologic feature the one with the higher coefficient should be used.

The importance of the reliability coefficient is also stressed by Buschang et al. (1985) who show that existing craniofacial correlations are masked by technical error. They state that the true correlation can be calculated by dividing the square root of the product of the reliabilities of the two variables into the observed correlation.

A disadvantage of the reliability coefficient is the fact that its value depends on the standard deviation of the population. The same accuracy of the measurements as described by the Dahlberg method error will lead to lower reliability coefficients if the standard deviation of the variable under survey is lower for the material under study than for a comparable material. This effect has to be taken into account when comparing population cross-sectional materials with ideal occlusion materials. Since the latter show a lower variable variance the reliability coefficient for such materials tends to be higher.

When using the correlation coefficient to describe the reliability of the measurements it should be as close to +1.0 as possible.

The values for this study are shown in Table 2.7. Most values for method error were around or lower than 0.5 degrees or mm. Merely incisor inclinations, *NSBa, GntgoAr, Forehead inclination*, and *Index* showed values around 1. All variables showed reliability coefficients of above 97% with the exception of *Wits*, *NL-NSL*, *NSBa*, *OrbNA*, ForeHead inclination, all incisor inclinations, all chin measurements including $PgNB_{mm}$, and the angle of Frankfort horizontal to NSL.

Table 2.7 Dahlberg method error, reliability coefficient and correlation coefficient of variables under survey

Variable	Method error	Reliab. coeff.	r	n
SNA	0.45	98.30	0.984	354
SNB	0.38	98.77	0.988	354
SNPg	0.35	99.12	0.992	354
ANB	0.30	97.62	0.978	354
ANPg	0.32	98.45	0.985	354
Wits	0.53	90.72	0.917	299
ML-NSL	0.55	98.96	0.990	354
NL-NSL	0.65	92.21	0.927	354
ML-NL	0.72	98.12	0.982	354
Gn-tgo-Ar	0.92	98.58	0.987	354
NSBa	0.97	95.31	0.957	354
FH-NSL	0.62	93.61	0.884	320
OrbNA	0.54	90.56	0.776	318
ForeHead	1.30	96.56	0.969	354
S-N	0.35	98.98	0.990	354
N-Gn	0.41	99.76	0.998	354
Cross	0.55	99.89	0.999	354
ArProgn	0.40	99.77	0.998	354
PgNBmm	0.35	95.41	0.958	354
Chin	0.43	94.70	0.951	354
Symph	0.47	93.21	0.941	354
N-Sp'	0.37	99.14	0.992	354
Sp'-Gn	0.36	99.51	0.995	354
Index	0.99	97.61	0.977	354
1-NA°	1.48	93.26	0.947	299
1-NAmm	0.42	95.49	0.963	301
$\bar{\bar{1}}$-NB°	1.37	92.96	0.934	306
$\bar{\bar{1}}$-NBmm	0.33	96.79	0.970	312
$\bar{1}$-APgmm	0.34	96.38	0.967	312
1-Pg⊥MLmm	0.46	97.17	0.976	312
Y-axis	0.44	98.45	0.985	354

All correlation coefficients between first and second tracing were above 0.925 except for the distance *orbitale* to NA, Frankfort horizontal inclination to NSL (r = 0.884) and Wits value (r = 0.917).

The results for the inclination of the Frankfort horizontal are actually worse than can be seen

Table 2.8 Method error compared to studies by other authors. For present study the 18 year age group was used.

Variable	Investigator				
	Segner	Ødegaard	Berg	Baumrind	Solow
	1992	1970	1983	1971	1966
	18y	410y	9y	?	adult
SNA	0.45	0.39	0.51	1.18	0.63
SNB	0.38	0.26	0.39	0.96	0.52
SNPg	0.35	0.36	0.40		0.62
ANB	0.30	0.34		0.62	0.41
ANPg	0.32				0.43
Wits	0.53				
ML-NSL	0.55	0.53	0.73	1.74	0.54
NL-NSL	0.65	0.56	0.93		1.00
ML-NL	0.72		2.05		0.84
Gn-tgo-Ar	0.92	0.74	1.12		0.95
NSBa	0.97	0.69	0.60		0.90
FH-NSL	0.62				
OrbNA	0.54				
ForeHead	1.30				
S-N	0.35	0.34	0.30		0.44
N-Gn	0.41		0.46		0.47
Cross	0.55				
ArProgn	0.40				
$PgNB_{mm}$	0.35				
Chin	0.43				
Symph	0.47				
N-Sp'	0.37	0.33			
Sp'-Gn	0.36	0.31			
Index	0.99				
$\underline{1}$-NA°	1.48			1.85	
$\underline{1}$-NA_{mm}	0.42		0.52	0.86	
$\bar{1}$-NB°	1.37			3.00	
$\bar{1}$-NB_{mm}	0.33		0.34	0.51	
$\bar{1}$-APg_{mm}	0.34		0.32	0.56	
1-Pg⊥ML_{mm}	0.46				
Y-axis	0.44			1.17	

from the values for reliability coefficient and correlation coefficient because in only 320 out of the 354 x-rays was it possible to determine the line without guess work. On the other 34 x-rays at least one of the points porion or orbitale could not be located or were established very differently on the two evaluations and had to be rejected as described in section 2.3. As the Frankfort horizontal is neither well reproducible nor determinable in every case it seemed unsuitable as a main reference line and was thus not used for further analysis.

Table 2.8 compares the method errors of this study with those of some other cephalometric studies (Ødegaard 1970, Berg 1983, Baumrind and Frantz 1971[b], Solow 1966). When comparing these studies it has to be kept in mind that the methods of data selection and the patient material differed between the five studies listed. In the present study, in Berg's, which used the same material, in Baumrind and Frantz' and in Janson's (1982), only one headfilm of each subject at a time was available. The error of the method therefore only included errors induced by landmark identification and the actual measuring of distances and angles. In Ødegaard's and Solow's studies two headfilms were taken of every patient. These figures consequently include errors induced by the x-ray procedure and patient positioning in the cephalostat.

Ødegaard, Solow and Janson measured the cephalometric variables without the aid of electronic devices while Berg used an early kind of electronic system for measuring distances and angles.

In the investigation by Baumrind and Frantz (1971[b]) 5 different judges evaluated the x-rays and hence the listed method error reflects inter-operator variability rather than intra-operator variability. As different operators might have slightly different concepts of the exact location of a landmark this inter-operator variability can be expected to exceed intra-operator variability.

In addition they used the formula

$$s = \sqrt{\frac{\sum d^2}{N\,(K-1)}}$$

where K gives the number of tracings, in this case 5. By using *(K-1)* instead of *K* they allowed for incomplete independence of the tracings. To compare their figures with those by the other authors they should be multiplied by 0.64, which is (5-1) over 5 squared.

Ødegaard's values were similar to the ones found in the present investigation. Solow's were higher than Ødegaard's and the ones in the present study. The differences between these studies and the present study might represent the error variability introduced by taking two x-rays instead of one. Berg's values were lower than Solow's but higher than Ødegaard's and higher than in the present study.

Baumrind and Frantz' values were the highest of the five. Even after multiplication with 0.64 they were still slightly higher than Berg's and Solow's. Given the fact that 5 different persons might have had different concepts of how and where to locate certain landmarks this finding had to be expected.

Table 2.9 Correlation coefficients between double registrations compared to other studies. For present study the 18-year age group was used.

Variable	Segner 1992	Janson 1982
SNA	0.984	0.979
SNB	0.988	0.991
SNPg	0.992	0.990
ANB	0.978	0.949
ANPg	0.985	
Wits	0.917	
ML-NSL	0.990	0.866
NL-NSL	0.927	0.938
ML-NL	0.982	0.950
Gn-tgo-Ar	0.987	0.969
NSBa	0.957	0.983
FH-NSL	0.884	
OrbNA	0.776	
ForeHead	0.969	
S-N	0.990	
N-Gn	0.998	
Cross	0.999	
ArProgn	0.998	
PgNB$_{mm}$	0.958	0.907
Chin	0.951	
Symph	0.941	
N-Sp'	0.992	0.992
Sp'-Gn	0.995	0.996
Index	0.977	
$\underline{1}$-NA°	0.947	0.935
$\underline{1}$-NA$_{mm}$	0.963	0.936
$\bar{1}$-NB°	0.934	0.931
$\bar{1}$-NB$_{mm}$	0.970	0.989
$\bar{1}$-APg$_{mm}$	0.967	
1-Pg⊥ML$_{mm}$	0.976	
Y-axis	0.985	

Table 2.11 Reliability coefficients by age group (n=60, 80, 80, 79, 55 for the groups). Values below 0.95 in **bold print**.

Variable	Age				
	6	9.	12.	15.	18.
SNA	97.48	99.00	97.49	98.67	98.44
SNB	97.77	98.96	98.30	98.89	98.91
SNPg	98.52	99.06	98.64	99.10	99.19
ANB	95.96	97.74	96.76	97.79	97.78
ANPg	96.51	98.41	97.62	98.34	99.00
Wits		**91.81**	**87.93**	**93.41**	**88.73**
ML-NSL	98.18	98.57	98.69	98.95	99.10
NL-NSL	**86.98**	**90.53**	**94.23**	**92.79**	**94.37**
ML-NL	95.55	97.77	98.00	97.78	98.67
Gn-tgo-Ar	97.16	98.20	98.30	98.26	99.00
NSBa	**92.33**	96.44	96.30	95.16	95.11
FH-NSL	**90.92**	**92.50**	95.23	**94.21**	**93.66**
OrbNA	**87.09**	**87.24**	**87.76**	**92.01**	**90.92**
ForeHead	**91.72**	**92.71**	**93.74**	**94.46**	96.23
S-N	96.17	97.83	98.18	98.28	98.25
N-Gn	99.09	99.28	99.14	99.41	99.68
Cross	99.12	99.17	99.37	99.62	99.58
ArProgn	98.54	98.94	99.09	99.15	99.48
PgNB$_{mm}$	**92.01**	**91.93**	**92.78**	**93.13**	96.71
Chin	**83.82**	**87.61**	**92.26**	**93.26**	**94.58**
Symph	**78.96**	**89.83**	**94.04**	**94.73**	**93.36**
N-Sp'	97.77	97.67	97.68	97.75	97.57
Sp'-Gn	98.45	98.69	99.05	99.29	99.58
Index	96.02	96.90	97.79	97.93	97.86
1-NA°		91.87	92.43	95.65	92.96
1-NAmm		93.73	93.81	95.90	96.61
$\bar{1}$-NB°		90.79	91.38	90.79	96.98
$\bar{1}$-NBmm		94.79	97.01	97.09	98.02
$\bar{1}$-APgmm		95.35	95.52	97.03	97.55
1-Pg⊥MLmm		96.39	96.01	97.71	98.02
Y-axis	97.52	98.18	98.48	98.77	98.79

As some authors use the correlation coefficients between the first and second measurement of the same x-ray to account for the error of the method Table 2.9 compares values listed by another investigator with those found in the present study. The values found by Janson (1982) compared very well with the ones in the present study with only slight differences. The only marked difference was found for *ML-NSL* where Janson found unexpectedly low values.

Table 2.10 Method error by age group (n=60, 80, 80, 79, 55 for the groups)

Variable	Age				
	6	9	12	15	18
SNA	0.58	0.35	0.51	0.40	0.40
SNB	0.46	0.33	0.41	0.36	0.35
SNPg	0.39	0.32	0.38	0.33	0.32
ANB	0.38	0.27	0.31	0.28	0.27
ANPg	0.43	0.27	0.34	0.30	0.24
Wits		0.43	0.61	0.47	0.62
ML-NSL	0.59	0.54	0.56	0.53	0.53
NL-NSL	0.73	0.67	0.56	0.70	0.58
ML-NL	0.91	0.65	0.68	0.74	0.61
Gn-tgo-Ar	1.03	0.87	0.92	0.97	0.78
NSBa	1.20	0.85	0.86	1.02	0.91
FH-NSL	0.62	0.69	0.55	0.62	0.61
OrbNA	0.51	0.53	0.55	0.52	0.60
ForeHead	1.48	1.43	1.25	1.17	1.10
S-N	0.35	0.33	0.34	0.36	0.40
N-Gn	0.37	0.36	0.45	0.45	0.38
Cross	0.56	0.57	0.53	0.51	0.62
ArProgn	0.39	0.37	0.40	0.43	0.40
PgNBmm	0.34	0.36	0.37	0.37	0.30
Chin	0.49	0.46	0.38	0.40	0.42
Symph	0.53	0.49	0.43	0.42	0.49
N-Sp'	0.30	0.35	0.37	0.40	0.42
Sp'-Gn	0.33	0.36	0.36	0.38	0.34
Index	0.91	1.06	0.96	0.99	0.99
1-NA°	-	1.56	1.52	1.18	1.68
1-NAmm	-	0.41	0.46	0.41	0.41
$\bar{1}$-NB°	-	1.35	1.42	1.51	1.09
$\bar{1}$-NBmm	-	0.34	0.29	0.34	0.32
$\bar{1}$-APgmm	-	0.31	0.34	0.32	0.36
1-Pg⊥MLmm		0.42	0.49	0.44	0.46
Y-axis	0.50	0.43	0.42	0.39	0.44

To find out if the reliability of measurements changes with the age of the subjects the method error was calculated separately for the different age groups. The results are listed in Table 2.10 and 2.11.

In the 6-year age group too few incisors were erupted to give meaningful results. It can be seen that in general the values of the youngest group are not as good as those of the other age groups. The other age groups display fairly similar values.

The largest differences for the young group appear in values representing the sagittal situation, while the measures of anterior face height show no difference as compared to the other age groups. Cranial base angle NSBa and the inclinations of maxilla and mandible occupy an intermediate position.

Although lower quality of the x-rays in the years 1966 to 1969 cannot be ruled out it seems that the higher method errors stem from the fact that the alveolar process of the mandible is much more inclined in this group. The bony chin is receding rather than protruding. Usually the measurement accuracy of the angles SNB and SNPg benefit from the low horizontal error variance (see Figs. 2.27 and 2.28). When the lower alveolar process is inclined the longer axis of the scattergram of landmark error will also be inclined in a clockwise direction. The measurement error of variable SNB will then be influenced to a higher extent by the unfavorable, usually vertical, long axis of the landmark error.

The repeatability of the measurement SNA in the youngest age group is impaired by the erupting central upper incisors. Often they produce a bulky prominence on the labial contour of the alveolar process.

When looking at the reliability coefficients for the different age groups it should be kept in mind that the subgroups each represent a relatively homogeneous group with a rather low variable standard deviation as compared to a cross-sectional material that might include subjects of different age groups and with a variety of malocclusions. Therefore the reliability coefficients for the present study tend to be lower than those of studies with less selective materials.

The selection of variables should be influenced by two main factors. The first is the accuracy and stability of the measurement and the second is the importance of the variable and the feasibility of substituting it with another (better) variable. The former criterion can be addressed by looking at the reliability coefficient and at occurrences where it is not possible to determine the variable.

Houston (1983) recommended that the reliability coefficients for cephalometric variables should not fall below 97% which would keep the error variance below 3% of total variance. He allowed, however, that this won't always be possible.

Because of the effects of the special selection criteria outlined above a limit of 95% was selected in Table 2.11. All values that fell below this limit are shown in bold print. It appears that again the younger groups show less reliability.

Of the variables under survey *Wits value*, the measurement *OrbNA*, Frankfort Horizontal to NSL, and *ForeHead* in the younger groups clearly displayed problems with regard to reliability. In 34 or 9.6% of all x-rays it was impossible to determine the variable *FH-NSL* and the remaining 90.4% still had reliability coefficients below 95%. As many measurements that use the NSL as a reference showed very high reliability it could be concluded that it was the Frankfort Horizontal that introduced the instability. For *Orb-NA* these numbers were 36 or 10.2% undeterminable and a reliability coefficient of only 95.3%.

As the Frankfort Horizontal was not the only horizontal reference line available these results led to the decision not to use variables based on it in further analyses. The large error variability of the variable *Orb-NA* similarly disqualified it for any analyses. For information purposes the descriptive statistics for these variables will nevertheless be listed further down.

The *wits value* also was not available in a number of cases although the reasons were somewhat different. In the young subjects the incisors and/or the first molars had not erupted so that it was not possible to determine the occlusal plane. In some of the older subjects extensive fillings and sometimes prosthodontic crowns on the first molars made designating the occlusal plane difficult. As the angle *ANB* contains very similar information its use seemed preferable.

Values below 95% occurred also for the variables *NL-NSL*, $PgNB_{mm}$, *Chin*, *Symph*, the incisor inclinations $\underline{1}$*-NA°* and $\overline{1}$-NB°, and even the incisal edge positions in the younger groups. For the maxillary inclination *NL-NSL* and the variables describing the chin region a noticeable improvement occurred in the older groups. This might have been due to improved x-ray contrast of the more mature bone but the main reason was an increase of the variable variance. With more growth that had already taken place the skeletal morphology was more differentiated.

Regarding the incisor inclinations the difficulties in locating the apex points in combination with the relatively short distance from incisor point to apex point made it difficult to obtain reliable measurements. If possible the linear measurements with the incisal edges should be given preference over the inclination variables.

2.6. Statistical method

Geometric associations between the variables

Many cephalometric angles and linear measurements share the same landmarks. If such a landmark is moved the value of more than one variable is changed. If, for example, the landmark Pogonion in Fig. 2.42 is moved in a ventral direction the angle SNPg as well as ANPg will be effected. While SNPg will increase ANPg will decrease. Therefore, there is a certain negative correlation between these two variables that stems from the variation in the sagittal position of landmark Pogonion. For this effect it does not matter whether the variation is due to biological variation in the position of pogonion or variation in the process of locating it. Even the landmark scatter leads to a certain correlation between the variables (Houston 1983).

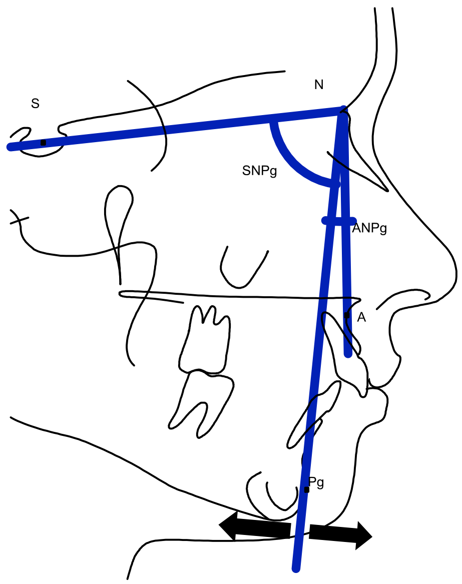

Fig. 2.42 Example for a *topographic correlation*: the angles ANPg and SNPg do not change independently of each other when *pogonion* is moved sagittally

This effect has been called *topographic correlation* by Solow (1966). Johansen (1966) developed formulas to estimate these topographic correlations. Solow could then demonstrate that these topographic correlations really did appear in cephalometric measurements. If there was a significant descrepancy between the calculated (topographic) correlations and the observed correlations for a variable he concluded that here a non-topographical and thus "biological" correlations must also exist.

Such geometric associations are not limited to variables sharing landmarks. Often two landmarks are close to each other and their relationship towards each other leaves only room for minor variation as compared to the total variation of their position in space. An example would be the landmarks pogonion and gnathion. Due to the proximity of these two landmarks their position relative to each other does not change very much between different individuals. The position of the mandibular symphysis as a whole in relation to the anterior cranial base is subject to large variations in the vertical and sagittal dimension.

As a result there is a geometric association between for example the angles SNPg and ML-NSL. When the mandibular symphysis is situated more anteriorly or more cranially, the angle SNPg will increase while ML-NSL will decrease. This effect probably explains part of the well known strong correlation between these two angles.

It has been stated that correlations that stem partly from geometric correlations do not represent real correlations. However, for clinical purposes it seems that the reason for a correlation does not make a difference. If the expected association of the skeletal parts is lacking in a patient the operator will encounter more problems no matter whether it was a topographic or a "real" biological correlation. For this purpose all relevant correlations have been entered in this study.

Basic statistics

All statistical calculations were carried out on a PC-compatible desktop computer using the program SPSS/PC+ by SPSS Inc., Chicago, USA. Descriptive statistics of all variables under survey were calculated.

To test for the normality of the distributions of each variable the Kolmogorov-Smirnov one-sample test was used with a level of significance of 0.05. If the resulting value does not exceed 0.05 there is reason to believe that the distribution of the tested variable differs from a normal distribution.

From the set-up of the study it is clear that the variable age cannot be normally distributed. As records were taken every three years at the ages 6, 9, 12, 15, and 18 with a rather low variance the age variable is multi-modally distributed. Especially when interpreting the results of the correlation and factor analyses this fact has to be kept in mind.

Presentation of serial data

As the material was not purely longitudinal but mixed longitudinal some problems with sub-group selection had to be dealt with. That part of the material that was available for the registration at the age of 18 years might (and did) show slightly different mean values at one or more of the recordings. Even though these differences were slight they might have led to unexplainable changes between the different registrations.

Table 2.12 gives an example of this effect employing 48 subjects of which only 39 were available for the 18-year registration. While ANB decreases continuously the value for 18 years contradicts this trend in that it shows an increase of 0.11° from 15 to 18 years (Tab. 2.12, first column). When looking at the mean value only for those subjects who could be registered also at 18 years of age it can be seen that they display a mean that is 0.2° higher at 9, 12, and 15 years of age. With a 95% confidence interval of ±0.59 for a subgroup of n=39 such slight differences in the mean are to be expected. The apparent increase from 15 to 18 years of age is therefore not due to growth changes but rather due variations in the mean of the selected subgroups.

Tab. 2.12 shows effect of deviating mean for a sub-group. The subjects who are available at 18 y show a mean *ANB* that is 0.2° higher than that for the whole group. See text for explanation.

age	whole group n = 48 (39)	only patients who were available at 18 y n = 39	calculated mean values
9	2.46	2.66	2.46
12	2.31	2.51	2.31
15	1.45	1.65	1.45
18	1.56	1.56	1.36

To list meaningful data anyway, a method similar to that employed by Ødegaard (1970) was used. As all subjects were available at the 12 year registration the means for that age group were assumed to be the most reliable ones (best representation of the population mean). Now the growth related changes before and after that registration were added or subtracted to this 12-year base value. Since only the changes for the 3-year intervalls were used the effect of deviating sub-group means was eliminated.

The right column in Table 2.12 explains this method. At 12 (and 15) years the means of the angle stem from the whole group (n = 48). The value for 18 years is calculated by subtracting the change between 15 and 18 years in the sub-group of 39 that are available at 18 years (0.09°) from the mean at 15 years for the complete sample (1.45°). Under the assumption that all 48 subjects develop alike the group mean at 18 years of age should be 1.36°.

The data presented in Table 3.1 was treated using this method. Using only the 39 patients that were available for all 5 registrations would have avoided this problem since the material had been a purely serial one. But the increase in group size was considered worth the extra problems that arise with a mixed longitudinal material. However, a mixed longitudinal material is still much superior to a cross-sectional one.

Tests for normality of the distribution

To verify that the distribution of the values for the variables under survey closely resemble a normal distribution a one-sample Kolmogorov-Smirnov (K-S) test was used. This test compares the actual distribution of a tested variable with a normal distribution of the same mean and standard deviation as the variable. The result is a Kolmogorov-Smirnov Z value for which a probability can be calculated. If this probability is smaller than 0.05 the tested distribution is among the 5% of distributions that deviate most from normality.

Some statistical tests require that the variables they operate on are normally distributed. If according to the K-S test they do not meet this requirement the results of the statistical test have to be interpreted with care or disregarded, depending on how sensitive the test is to departure from normality.

Test for differences between age-groups

As the material is a mixed-longitudinal one a non-parametric Friedman test for differences between related samples was used to test for significant differences between registrations at the 5 different age periods.

Correlations and regressions

Correlations coefficient between the variables were calculated according to Pearson.

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{(n-1)\, s_x s_y}$$

Significance levels are calcualted for a two-tailed test. The minimum level of significance for this study ($p < 0.01$) is shown as ** in the tables and a level of $p < 0.001$ is denoted as *** to conform with customary standards.

Assumptions have to be made about the distributions of the two or more variables used in correlation or regression analyses. Usually the dependent variable is expected to display normality and equality of variance for all values of the independent variables, independence of the observation, and linearity of the association (Norusis 1988). However, it is not essential that the independent variables conform to these requirements. It is, therefore, possible to use dichotomous variables such as sex or ordinal variables as independent variables in such models. As the variable age is distributed multi-modally in this study (Section 3.2) this point is of great importance.

Partial correlation coefficients between two variables *x* and *y*, that eliminate the joint influence of a third variable *z* are calculated as

$$r_{xy.z} = \frac{r_{xy} - r_{xz} \cdot r_{yz}}{\sqrt{(1 - r_{xz}^2) \cdot (1 - r_{yz}^2)}}$$

(Sachs 1984).

Test for differences between correlation coefficients

To test for such differences both correlation coefficients were z-transformed according to R.A. Fisher using

$$\dot{z} = \frac{1}{2} \ln \frac{1+r}{1-r}$$

The two transformed coefficients were then compared using

$$\hat{z} = \frac{|\dot{z}_1 - \dot{z}_2|}{\sqrt{\frac{1}{n_1 - 3} + \frac{1}{n_2 - 3}}}$$

If this standardized z-value was above 1.96 the hypothesis that the two coefficients do not differ could be rejected with an error probability of $p<0.01$.

Multible Analysis of Variance (MANOVA)

The multiple analysis of variance is a method to test the hypothesis that a set of variable means does not differ between two or more groups, for example between male and female subjects.

If one or more variables are believed to have an influence on the outcome of that test, they can be made covariates and their effect nullified. In the above example the larger size of male subjects might falsely lead to rejection of the null hypothesis that no shape differences exist. If age was made covariate the influence of somatic size can be eliminated for the test.

Additional tests used in conjunction with MANOVA will be named in the results section.

Factor analysis

Factor analysis is a statistical technique used to identify a limited number of hypothetical variables or *factors* that can describe the pattern of correlations between a larger number of variables. These hypothetical variables do not necessarily exist or might not be directly measurable but they can often be attributed to well-known concepts. The degree of prognathism of the face could be used as an example for such an hypothetical variable. Although it is a well-known term there is no single variable that can be used to measure it. There are, however, a number of directly measureable variables that together can be used to determine the degree of prognathism.

Out of the huge number of variables that can be measured on a cephalogram factor analysis helps to identify these underlying, not directly observable, constructs. Although these *factors* are hypothetical because they cannot be measured directly on the x-rays they usually contain more information than any single directly measured variable (Solow 1966). This is due to the fact that a good factor model can describe a high percentage of the variation of a data set using only a much smaller number of factors instead of the full set of variables. Consequently each factor has a higher expressivity than any one variable.

In addition the method identifies those cephalometric variables that seem to represent unique information, that is a bit of information that is not represented by any other variable.

The basic assumption of factor analysis is that a limited number of underlying constructs or factors can explain complex phenomena. All the information is derived from the correlation matrix of all measured variables. The correlation between two of these variables might be real, but they might also be due to correlation with a third variable that has not been measured. This underlying third variable is the one that is of interest to explain the association of the other variables. A brief example might make this fact clearer: The decrease in the population of storks in central Europe and the declining birth rate show a highly significant correlation. The reason is not a "real" correlation but rather a correlation of both variables with a third variable such as time or a higher level of industrialization. The goal of the factor analysis is to identify such not directly observable factors.

To do this the factor analysis uses a mathematical model that is similar to that of a multiple regression equation. Each actual variable V_x is expressed as a linear combination of the underlying factors:

$$V_x = a_1F_1 + a_2F_2 + a_3F_3 + U_x$$

where F_1, F_2, and F_3 represent the *common factors* and a_1 to a_3 the factor coefficients. These coefficients are called *factor loadings*. U_x is a *unique factor*. It explains that part of the variation in V_x that cannot be explained by the common factors. The quality of the factor model increases with a decreasing value for this U_x.

A factor analysis carried out in several steps:

- The first step is to set up the correlation matrix for all variables. From this matrix those variables that do not correlate with any others can be identified. These are likely to represent individual factors.

- In the next step a number of factors are extracted. It has to be decided, how many factors are necessary to represent the data sufficiently accurately. Several methods to perform this factor extraction have been described: Principal component analysis (Harman 1967), principal axis factoring, alpha factoring, and maximum likelihood among others.
- The third step involves the rotation or transformation of the factors. This process doesn't improve the factor model with regard to overall explained variance, but by accumulating high loadings on either a few variables or a few factors it makes the model more interpretable. Again, different algorithms for the rotation process have been described. These methods split into two main groups, those that use orthogonal rotations and those that use oblique rotations. In the orthogonal rotation the axes remain at right angles toward each other during the rotation process. The advantage is that the resulting transformed factors remain fully uncorrelated. The oblique methods, on the other hand, allow for an even simpler factor pattern matrix at the expense of the factors not being uncorrelated any more.
- Among the orthogonal algorithms are varimax, equamax and quartimax; the oblimin rotation is an example for an oblique algorithm.
- The last step involves the interpretation of the matrix of factor loadings. From the set of variables that have a high loading on a certain factor it can often be deducted, what quality this factor represents.

For the present study the principle component analysis as the most commonly used method of variable extraction was used. The rotation was performed using the oblimin algorithm. No effort was made to pre-select the variables to be used in the analysis.

Variation in the craniofacial pattern of individual subjects

All the previous methods of analysis had the aim to define any changes of the average craniofacial pattern during growth as well as any sex related differences in these changes. To find out how individual subjects change during growth these individuals' deviations from the average trend need to be separated from the average modification of the craniofacial association.

To do this the individuals' sets of 10 most important variables (PC's) were related to the means and standard deviations of these variables for the respective age and sex group. If these normalized distances did not change from one examination to the next, it could be said that the craniofacial pattern did not change in that individual. If the normalized distances from the group means did change from one examination to another a change of the pattern occurred.

The set of 10 values for each patient can be represented by a vector

$$X = \begin{vmatrix} x_1 \\ x_2 \\ .. \\ x_{10} \end{vmatrix}$$

To standardize this vector each value has to be z-transformed

$$x_{1_n} = \frac{x_1 - \bar{x}}{s}$$

The standard normalized vector defines a point in 10-dimensional space that represents the subject's craniofacial pattern in relation to the average pattern for that sex and age-group. If that point lay close to the origin of the 10-dimensional coordinate system, the patient would display an average craniofacial pattern. If for the next examination the point lay at or near the previous location no change in the pattern would have occured that is based on individual variation from the average development of the population. Nevertheless, the actual values of the patient's vector at the next examination might differ from the previous ones because that represents the common trend of the population. The method is used to describe growth related development in relation to the population average.

An example with a 2-dimensional vector might clarify this. The two dimensions shall be represented by the variables SNB and Gn-tgo-Ar. The means and standard deviations for these variables in boys at the ages of 9 and 15 are

	9 years	15 years
SNB	77.91	80.37
	(2.61)	(2.63)
Gn-tgo-Ar	127.27	123.05
	(5.61)	(6.25)

A hypothetical patient A might have an SNB of 75.3° and a Gn-tgo-Ar of 132.9° at the age of 9 years. At the age of 15 the values changed considerably to 77.7° and 129.3° respectively. When looking at the z-transformed vectors or at the location of patient A in the 2-dimensional space (Fig. 2.43) it becomes clear that he did not change relative to what is normal for boys between 9 and 15 years of age:

original values

$$\begin{vmatrix} 75.3 \\ 132.9 \end{vmatrix} \Rightarrow \begin{vmatrix} 77.7 \\ 129.3 \end{vmatrix}$$

z-normalized values

$$\begin{vmatrix} -1.0 \\ 1.0 \end{vmatrix} \rightarrow \begin{vmatrix} -1.0 \\ 1.0 \end{vmatrix}$$

A second patient B shows another development. Here the values for SNB and Gn-tgo-Ar change from 78.0° to 81.5° and from 125.0° to 118.0° respectively:

original values

$$\begin{vmatrix} 78.0 \\ 125.0 \end{vmatrix} \rightarrow \begin{vmatrix} 81.5 \\ 118.0 \end{vmatrix}$$

z-normalized values

$$\begin{vmatrix} 0.0 \\ -0.4 \end{vmatrix} \rightarrow \begin{vmatrix} 0.4 \\ -0.8 \end{vmatrix}$$

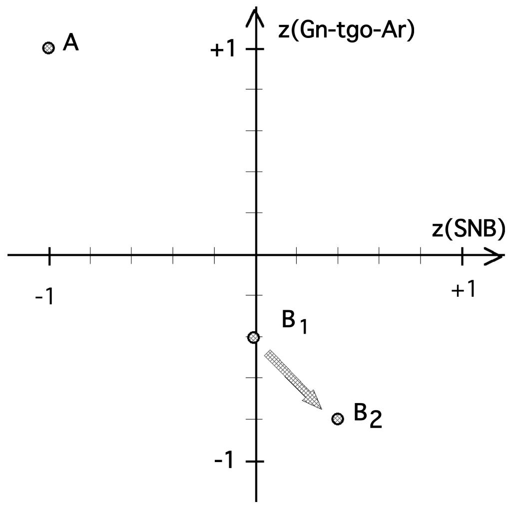

Fig. 2.43 2-dimensional coordinate system with the z-transformed variables *SNB* and *Gn-tgo-Ar* on the axes. The vectors of the two registrations of the example patients A and B are shown

The distance between the two vectors is a measure of the change that took place during the time span between the two recordings. In the simplified example this distance can either be measured in the graph of Figure 2.43 or it can easily be calculated by

$$d = \sqrt{(z(SNB_{t1}) - z(SNB_{t2}))^2 + (z(GntgoAr_{t1}) - z(GntgoAr_{t2}))^2}$$

$z(SNB_{t1})$ is the z-score of SNB at the first examination (t1).

In the more general form with 10 dimensions a graphical representation is not possible any more and the distance has to be calculated by

$$d = \sqrt{\sum_{i=1}^{p} (v_{t1_i} - v_{t2_i})^2}$$

with p=10. v_{t1} and v_{t2} are the values of each of the ten variables at the two examinations. As a comparison of these vectors requires that all 10 variables have valid values a problem arose due to the fact that *FH-NSL* could not be determined in a number of cases (see p. 37). These cases would have had to be droped entirely for further analyses. Therefore the variable *FH-NSL* was excluded from this analysis and vectors with only 9 remaining dimensions were used.

3. Results

3.1 Descriptive Statistics

Means for each age group

Table 3.1 lists the means and standard deviations for each age group and separately for male and female subjects. The definition of the variables are explained in section 2.4 (p. 20). No values are listed for the dental variables in the 6-year group as only a small number of these teeth were fully erupted. For the same reason it was neither possible to determine an occlusal plane nor the Wits ratio.

All variables describing the degree of prognathism of the jaws (SNA, SNB, and SNPg) increased with age resulting in more prognathic faces in the older age groups. An exception was a slight decrease in angle SNA from 6 years to 9 years. The reason for this was the eruption of the upper incisors around the age of 6 years. During the eruption the labial contour of the alveolar bone showed a bulge that brought the Apoint to a more labial position which resulted in a larger SNA angle. At 9 years of age this phenomenon had disappeared.

The angular variables characterizing the sagittal base relationship (ANB, ANPg) showed a development from a distal relationship towards smaller values and thereby a more mesial relationship (Fig. 3.1). Wits ratio remained similar over the whole observation period.

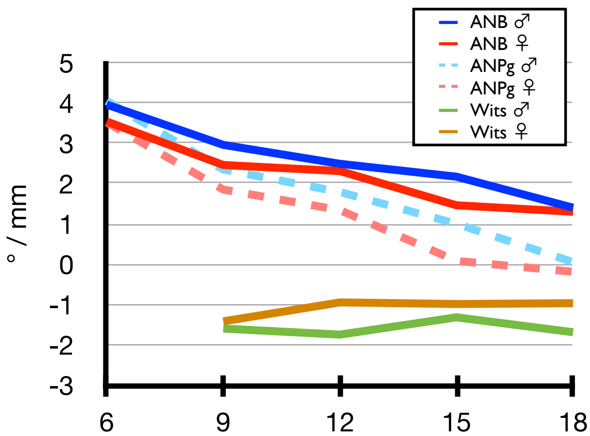

Fig. 3.1 Development of the sagittal base relationship

Table 3.1 Means and standard deviations for all variables by sex and age group

Variable	Age-group	♂ x̄	♂ s	♀ x̄	♀ s
SNA	6	81.18	3.57	80.89	3.68
	9	80.87	3.48	80.07	3.58
	12	81.60	2.70	80.82	3.52
	15	82.54	3.02	80.96	3.66
	18	82.53	2.72	81.14	3.29
SNB	6	77.22	2.43	77.35	3.47
	9	77.91	2.61	77.61	3.61
	12	79.11	2.30	78.51	3.67
	15	80.37	2.63	79.50	3.85
	18	81.13	3.00	79.85	3.56
SNPg	6	77.13	2.54	77.38	3.67
	9	78.52	2.67	78.23	3.69
	12	79.80	2.47	79.49	3.77
	15	81.53	2.77	80.89	3.95
	18	82.52	3.25	81.34	3.75
ANB	6	3.96	2.19	3.54	1.70
	9	2.96	1.95	2.46	1.64
	12	2.49	1.84	2.31	1.71
	15	2.17	1.77	1.46	1.89
	18	1.40	1.69	1.30	1.88
ANPg	6	4.05	2.74	3.52	1.98
	9	2.35	2.55	1.85	1.89
	12	1.79	2.47	1.34	2.05
	15	1.00	2.40	0.08	2.23
	18	0.05	2.32	-0.19	2.35
Wits	6	-	-	-	
	9	-1.60	1.42	-1.42	1.56
	12	-1.75	1.69	-0.95	1.74
	15	-1.32	1.50	-0.99	2.06
	18	-1.69	1.49	-0.97	1.97
ML-NSL	6	34.93	4.27	33.82	4.61
	9	33.56	4.49	32.67	4.53
	12	32.27	4.77	31.17	5.03
	15	30.10	4.97	28.97	5.41
	18	28.13	5.61	28.04	5.62

Table 3.1 continued

Variable	Age-group	♂ x̄	♂ s	♀ x̄	♀ s
NL-NSL	6	8.46	2.14	7.92	1.96
	9	8.29	2.28	8.39	2.17
	12	8.42	2.48	8.50	2.25
	15	8.20	2.50	8.47	2.70
	18	8.01	2.61	8.30	2.44
ML-NL	6	26.47	4.36	25.89	4.39
	9	25.28	4.61	24.28	4.26
	12	23.85	5.07	22.67	4.62
	15	21.90	5.15	20.49	4.89
	18	20.12	4.99	19.74	5.39
Gn-tgo-Ar	6	131.06	6.05	129.14	6.13
	9	127.27	5.61	125.22	7.04
	12	125.86	6.05	123.10	7.64
	15	123.05	6.25	120.17	7.96
	18	120.51	6.83	119.01	8.01
NSBa	6	133.49	4.03	134.49	4.40
	9	133.13	4.47	134.05	4.57
	12	132.73	4.40	133.67	4.59
	15	132.03	4.21	133.61	4.90
	18	131.22	3.24	133.57	4.29
FH-NSL	6	8.51	2.08	8.23	2.03
	9	8.85	2.78	8.97	2.41
	12	8.72	2.36	9.10	2.68
	15	8.32	2.47	9.27	2.64
	18	7.78	2.30	9.21	2.46
OrbNA	6	12.12	1.58	11.17	1.26
	9	11.81	1.41	11.39	1.54
	12	12.14	1.62	12.19	1.55
	15	13.04	1.84	12.34	1.83
	18	13.99	1.88	12.54	1.93
ForeHead incl.	6	103.16	5.50	103.09	5.01
	9	99.55	5.58	99.92	5.19
	12	95.09	5.62	95.67	4.65
	15	90.66	5.34	92.74	4.61
	18	86.47	5.14	91.54	4.99

Table 3.1 continued

Variable	Age-group	♂ x̄	♂ s	♀ x̄	♀ s
S-N	6	60.71	1.56	59.79	1.95
	9	63.06	2.17	62.35	2.24
	12	64.94	2.26	64.53	2.66
	15	67.66	2.57	66.18	2.77
	18	68.83	2.90	66.38	2.59
N-Gn	6	92.41	3.79	90.57	3.79
	9	99.12	4.36	97.02	3.95
	12	104.13	4.95	102.40	4.67
	15	111.14	6.26	106.81	4.90
	18	113.79	6.52	107.70	5.42
Cross	6	188.29	6.77	185.67	5.30
	9	203.00	6.65	200.00	5.78
	12	214.42	6.59	212.44	6.62
	15	230.53	8.83	223.65	6.52
	18	238.06	10.03	226.68	6.84
ArProgn	6	85.47	3.10	84.21	3.36
	9	92.13	5.31	90.42	3.86
	12	97.72	3.29	96.31	4.74
	15	105.44	4.22	101.72	4.52
	18	108.81	4.82	103.33	4.82
$PgNB_{mm}$	6	-0.15	1.51	0.02	0.94
	9	0.96	1.65	0.97	0.97
	12	1.16	1.59	1.63	1.19
	15	2.07	1.60	2.42	1.25
	18	2.45	1.82	2.61	1.58
Chin	6	3.69	1.35	3.28	1.16
	9	5.07	1.46	4.97	1.24
	12	5.62	1.36	5.72	1.38
	15	6.89	1.62	6.58	1.52
	18	7.26	1.71	6.72	1.86
Symph width	6	12.74	1.18	13.18	1.16
	9	13.85	1.36	13.75	1.66
	12	14.22	1.54	14.37	1.91
	15	14.92	1.62	14.77	1.99
	18	15.13	1.56	14.86	2.07

Table 3.1 continued

Variable	Age-group	♂ $\bar{x}$	♂ s	♀ $\bar{x}$	♀ s
N-Sp'	6	40.73	2.20	40.21	1.91
	9	44.27	2.29	43.90	2.28
	12	46.86	2.59	46.68	2.32
	15	49.75	2.87	48.40	2.47
	18	50.70	2.18	48.54	2.45
Sp'-Gn	6	51.69	2.63	50.34	2.72
	9	54.86	3.17	53.11	3.06
	12	57.27	3.72	55.72	3.70
	15	61.39	4.80	58.42	4.00
	18	63.09	5.15	59.16	4.54
Index	6	78.96	4.85	80.12	4.49
	9	80.91	5.67	82.91	6.24
	12	82.12	6.52	84.10	6.41
	15	81.45	7.17	83.19	6.72
	18	80.85	5.90	82.43	7.15
$\underline{1}$-NA°	6	-	-	-	-
	9	22.93	5.31	23.25	5.68
	12	23.05	4.65	22.14	6.13
	15	21.29	4.43	22.22	6.43
	18	21.73	5.48	22.19	6.81
$\underline{1}$-NA_{mm}	6	-	-	-	-
	9	3.15	1.63	3.26	1.70
	12	3.93	1.83	3.63	1.86
	15	4.05	1.73	4.23	2.22
	18	4.41	2.43	4.33	2.18
$\overline{1}$-NB°	6	-	-	-	-
	9	25.51	4.74	25.92	4.31
	12	26.06	4.76	25.66	4.97
	15	25.19	4.61	23.33	5.16
	18	23.87	6.17	22.62	6.33
$\overline{1}$-NB_{mm}	6	-	-	-	-
	9	3.69	1.66	3.37	1.36
	12	4.15	1.84	3.66	1.56
	15	4.22	2.07	3.37	1.87
	18	3.99	2.78	3.26	1.96

Table 3.1 continued

Variable	Age-group	♂ $\bar{x}$	♂ s	♀ $\bar{x}$	♀ s
1-Pg_{mm}	6	-	-	-	-
	9	1.70	1.57	1.66	1.36
	12	2.25	1.74	1.71	1.54
	15	2.08	1.86	1.57	1.86
	18	2.20	2.79	1.52	2.07
1-Pg⊥ML	6	-	-	-	-
	9	7.60	2.14	7.08	2.31
	12	7.96	2.39	7.74	2.56
	15	9.06	2.93	8.58	2.90
	18	9.31	3.60	8.74	3.22
Y-axis	6	66.46	2.91	66.15	3.79
	9	66.37	2.82	66.43	3.53
	12	65.95	2.81	66.06	3.86
	15	65.33	3.02	65.44	3.91
	18	64.71	3.93	65.26	4.08

The female subjects did not show much change in the period from 15 to 18 while this period involved substantial changes in the male subjects.

The inclination of the nasal plane (NL-NSL) did not display major changes during growth. All values were around or slightly above 8°. The mandibular plane inclination showed a different picture. It decreased continuously and markedly by 7° among the male subjects and 6° among the female subjects. This resulted in an average closing rotation of the mandibular inferior border of 0.6° and 0.5° respectively. The standard deviation of ML-NSL was more than twice as large as NL-NSL.

As the inter-base angle ML-NL represents the difference between ML-NSL and NL-NSL a similar development could be observed for it. The mandibular angle Gn-tgo-Ar also showed a large decrease of 10° for both sexes during that period. The large standard deviation of close to 8° denoted a large inter-individual variability.

The flexure of the cranial base as described by angle NSBa displayed only minor changes towards a smaller angle. In the male group a decrease of 2.3° occurred between the 6 and 18-year groups with a decrease of 0.9° in the female group. The angle between the Frankfort horizontal and the NSL demonstrated no systematic changes and remained between 7.8° and 9.3°. The distance between orbitale and the reference line NA showed slightly increased values for the older groups. The slight decrease in the male group from age 6 to 9 and the stagnation in the females of that age again seems to be a result of the eruption of the upper incisors. The inclination of the frontal bone (ForeHead incl.) displayed a marked and continuous decrease, that is a protrusion of the glabella region relative to the frontal bone. Both sexes started at the same value of 103.1° and the changes were similar for both sexes with the exception of the 18-year group where the male subjects showed values below 90° which denoted even an opposite inclination. For this group the frontal bone was retrusive in relation to the glabella.

All linear measurements increased substantially during growth and were larger for the male subjects. The only exception was the variable $PgNB_{mm}$ where the female subjects exhibited larger values for all age groups. They had, therefore, a more prominent chin.

The ratio *Index* showed an increase from 6 to 12 years of age for both sexes. After the age of 12 this trend was reversed and the values decreased again. Relative to the inter-individual variation as described by the standard deviation of 6% to 7% the age related changes of ± 2% were small.

The dental variables showed a very slight retrusion of upper and lower incisor inclination relative to the reference lines NA and NB. The positions of the incisal edges displayed a more complicated behavior. The upper incisal edge continuously moved labially relative to the NA-line by about 0.15 mm annually..

The lower incisal edges also shifted labially relative to the reference line NB in the early observation periods (♂ up to 15 yrs, ♀ up to 12 yrs). After that age $\bar{1}$-NB_{mm} not only returned to the value at 9 years of age but decreased even more (Fig. 3.2). If the reference line APg was used instead of NB the incisal edges moved labially from 9 to 12 years of age. From 12 to 15 they moved lingually. From 15 to 18 they continued the lingual movement in the female group while in the male group they displayed a labial movement again (Fig. 3.2). Relative to a mandibular reference system (Pg in relation to ML) the lower incisal edges continuously moved labially by a total of 1.7 mm or 0.1 mm annually.

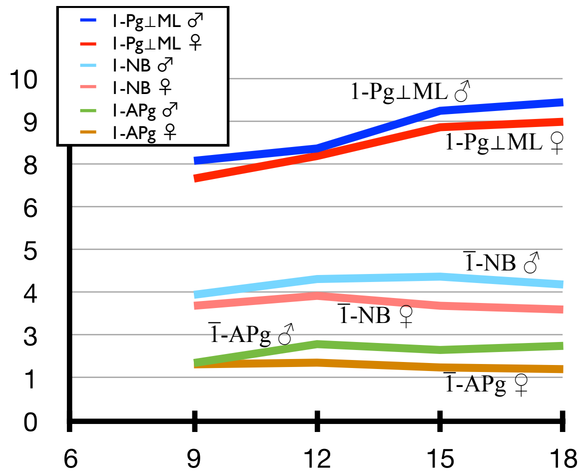

Fig. 3.2 Position of the lower incisal edge in relation to different reference lines (NB-line, APg-line, and a perpendicular to ML through pogonion)

The means for the variable Y-axis were rather constant and similar between the male and female subjects. A very small but consistent decrease of around 1° over the whole period from 6 to 18 years could be observed for both sexes.

Regarding the standard deviation of the variables there is generally a trend towards larger values in the older groups for both sexes. This was true especially for the linear and vertical variables. Inter-individual differences therefore seem to become more pronounced during growth. Opposed to this trend were the sagittal variables that use the landmark A-point. In the 6-year group these variables display a higher standard deviation which seems to stem from the fact that the antero-posterior position of A-point not only represents variation in the sagittal position of the maxilla but -at this age- also the variability in the time of eruption and eruption path of the upper central incisors.

Sex differences

To check for differences between male and female subjects the results of the non-parametric Mann-Whitney U-test are summarized in Table 3.2. As can be seen none of the variables at 12 years showed any significant difference. At 6 years only *Orb-NA* and *S-N* showed differences and merely 3 variables displayed differences at the 5%-level at the age of 9 years. At 15 years of age significant differences appeared for most of the linear measurements and for ANB and ANPg. At 18 years of age all major linear measurements with the exception of chin measurements and incisal edge positions clearly exhibited differences. The most distinct differences could be found for the variable *cross*. For the 18-year group the Z-score from the Mann-Whitney U is 4.74.

In summary it could be said that differences between male and female subjects were slight and insignificant at the beginning of the observation period. Through growth they became more and more pronounced until all linear measurements displayed highly significant differences at the age of 18. None of the angles reached the level of significance at 18. The lack of differences at the age of 12 might be explained by the fact that the girls at that age have gone through part of their puberty while the boys still haven't entered it. Thus the female subjects might have temporarily "caught up" with the males. Angular and ratio measurements seemed to be almost unrelated to the patients' sex.

Table 3.2 Significant differences between male and female subjects by age group.
Test: Mann-Whitney U-test

Variable	Age				
	6	9	12	15	18
SNA					
SNB					
SNPg					
ANB				*	
ANPg				*	
Wits					
ML-NSL					
NL-NSL					
ML-NL					
Gn-tgo-Ar					
NSBa					
FH-NSL					
Orb-NA	*				*
ForeHead incl					*
S-N	*			*	**
N-Gn				**	**
Cross				***	***
ArProgn				***	***
PgNB$_{mm}$					
Chin					
Symph width					
N-Sp'				*	**
Sp'-Gn		*		**	*
Index					
1-NA°					
1-NA$_{mm}$					
$\bar{1}$-NB°					
$\bar{1}$-NB$_{mm}$					
$\bar{1}$-APg$_{mm}$					
1-Pg$\perp$ML$_{mm}$					
Y-axis					

* $p<0.05$ ** $p<0.01$ *** $p<0.001$

Normality of the distribution

When looking at the distribution of the measured values it has to be decided, whether to look at the distribution of a variable for each age group individually or for the whole observation period. In the former case 5 distribution curves would be obtained, in the latter only one.

All variables were tested separately for every age group for deviation from a normal distribution using a one-sample Kolmogorov-Smirnov goodness of fit test. All variables used in the present study did not show any significant departures from normality. The variable that showed the least conformity with a normal distribution was ANPg at the age of 9 years. Here the KS Z-value was 1.181 which translates into a two-tailed probability of 0.123.

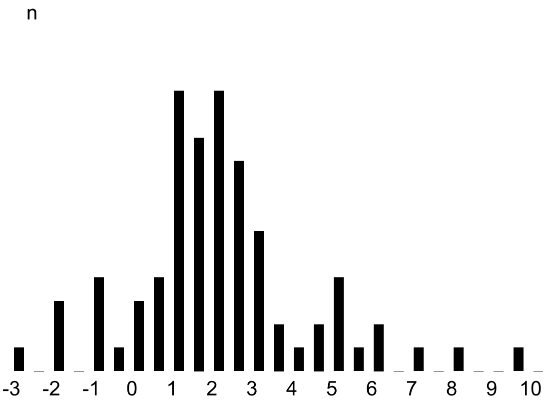

Figure 3.3 Distribution of the variable ANPg at the age of 9 that showed the largest departure from normality. This deviation, however, is statistically not significant ($p > 0.10$).

All other variables had KS Z-values of 1.000 or less. Thus none of the variable distributions displayed a significant deviation from a normal distribution.

When looking at all age groups simultaneously a problem arose from the set-up of the study. The x-rays were taken at fixed ages and always 3 years apart. As can be seen from Table 2.2 these recordings were carried out quite precisely which resulted in a low standard deviation of the age at each recording. When all recordings were joined to form one sample, the variable

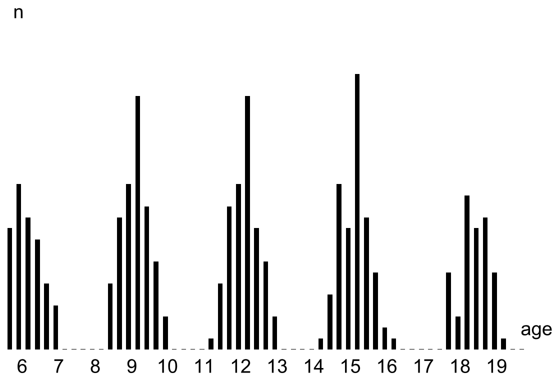

Figure 3.4 Multi-modal distribution of the variable age when looking at all age groups simultaneously. Each of the 5 distributions is normally distributed when looked at separately

age had to exhibit a multi-modal distribution (Fig. 3.4).

This distribution obviously showed a significant aberration from normality ($p<0.001$). Of the measured variables only the measurement *Index* (Fig. 3.5) showed a significant deviation from normality ($p<0.05$). The variable ANPg nearly reached significance while all others did not show anomalies.

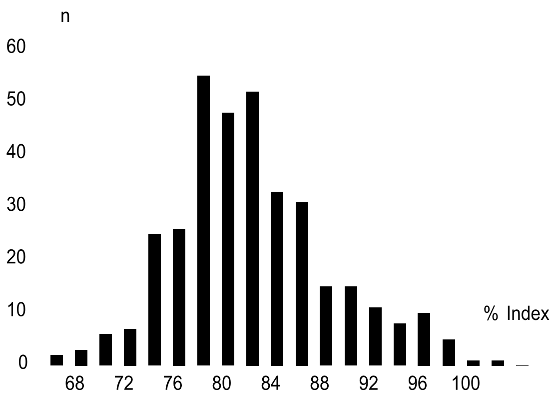

Figure 3.5 Distribution of the variable *Index*. With a KS Z-value of 1.424 (p=0.035) it deviated from a normal distribution.

3.2 Influence of age on variables

As could be seen from Table 3.1 the mean values of many measurements changed in the growing subjects used for this study. It appears that growth directly influences all linear size measurements, but it can also influence angles, ratios and proportions if growth does not affect all parts of the facial skeleton simultaneously and with the same velocity.

Linear variables

First the influence of growth on the linear size measurements shall be looked at. Table 3.3 shows linear correlation coefficients between these variables and the age of the subjects separately for both sexes.

Table 3.3 Linear correlation coefficients between linear size measurements and age

Variable	Sex ♂	Sex ♀
S-N	0.780	0.639
N-Gn	0.848	0.761
Cross	0.916	0.898
ArProgn	0.912	0.838
$PgNB_{mm}$	0.409	0.603
Chin	0.641	0.611
Symph width	0.423	0.351
N-Sp'	0.840	0.729
Sp'-Gn	0.741	0.625

$p<0.001$ for all correlations

All correlation coefficients were highly significant but nevertheless considerably different. The highest coefficient could be found for the variable *cross* with 0.916 for the male subjects and 0.898 for the female subjects. The lowest correlations were found for the measurements *Symph* in both sexes and $PgNB_{mm}$ in the male subjects. With the exception of $PgNB_{mm}$ all correlations were smaller for the female subjects.

Length measurements reflect a combination of the amount of growth itself and the direction of this growth. In Figure 3.6 this influence of growth direction on the linear measurement is demonstrated. The figure shows an angular body similar to the mandible. If growth takes place at point A the result on the total length measurement AP depends on the direction of the growth. If the growth occurs towards A' the gain in length will be less as compared to the case were growth develops towards A"

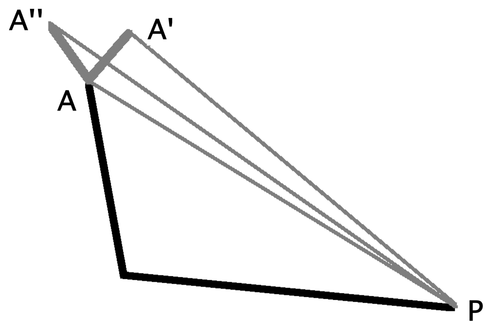

Fig. 3.6 Influence of growth direction on linear measurements. Length A"P is longer then A'P although growth amounts AA' and AA" are equal.

.Such effects do not occur if the direction of growth coincides with the length measurement itself as would be the case in measuring the length of a straight tubular bone. Such measurements hardly exist in the facial skeleton, but the distance measurement *S-N* should behave in a similar way. There shouldn't be any exogenous factors influencing growth in this area. Therefore it is quite surprising that this variable does not show very high correlations. For other linear measures functional stimuli and exogenous factors are likely to have an influence and thus lower the association between age and size. Such variables would be $PgNB_{mm}$, *Chin*, *Symph*, and *Sp'-Gn*, which are all influenced by mandibular inclination, tooth eruption, and head posture. The variables *cross* and facial height *N-Gn* reflect the sum of the size of several bony parts and it might be assumed that variations in growth direction as well as exogenous factors somewhat level each other out. This might explain the high correlation factors observed for these variables.

A correlation coefficient of 0.916 in the male subjects between the variable *cross* and age can explain 84.0% of this variable's variation. Interindividual variations in the timing of the developmental stages and non-linearities in growth speed account for the remaining 16.0% unexplained variance.

For some analyses it was considered interesting to compare variables and patterns with the relative stage of actual somatic growth rather than the chronological age. For these analyses the variable *cross* was therefore used as a measure of absolute growth.

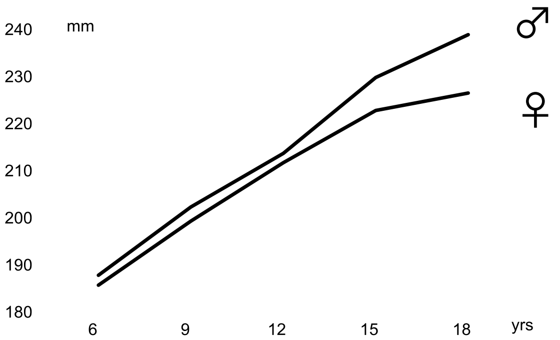

Figure 3.7 Incremental growth curves for the

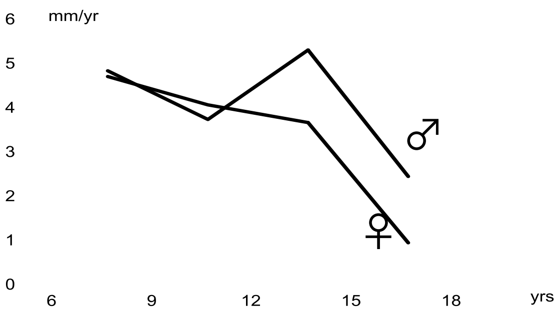

Figure 3.8 Average growth velocities for the variable *cross* for the 3-year intervals between observations. Values are displayed in the middle of the 3year periods.

Figures 3.7 shows the mean growth curves for the variable *cross* over time for boys and girls. Shown are the values for the 5 recordings Figure 3.8 shows the average growth speed in millimeters per year for the 4 intervals between observations. While a pubertal growth peak could be observed for the male group during the interval from 12 to 15 years of age no such peak was detectable for the female subjects. If a similar peak existed for the girls, too, it would fall into the interval from 9 to 12 as well as from 12 to 15 due to the earlier puberty in girls. Accordingly that growth peak would not be detectable with the set-up of this study.

Nonlinear variables

Angular variables, ratios, and linear variables that represent a position more than a size may also be influenced by age. To check this these variables were also correlated with age. The results can be found in Table 3.4. It can be seen that a number of these variables also showed significant correlations with age.

Mandibular prognathism as expressed by *SNB* and *SNPg* displayed significant positive correlations with age. The association was stronger in the male subjects and for the variable *SNPg*. Sagittal base relationship also showed correlations when measured as angles (*ANB*, *ANPg*) but not when delineated by the "Wits" value. Here the correlations coefficients were similar for both sexes.

The inclination of the mandibular plane (*ML-NSL*) as well as the gonial angle showed a negative correlation (closing rotation) with age. While the maxillary plane inclination *NL-NSL* did not show any association with age the interbase angle *ML-NL* showed a negative correlation coefficient similar to that of *ML-NSL*.

The cranial base angles *NSBa* and Frankfort horizontal to NSL did not show an association with the variable age. The inclination of the forehead showed a high correlation with age for both sexes. These were with between 0.59 to 0.66 the highest coefficients for this set of variables. The distance of orbitale to the NA-line was age correlated but the coefficients were lower than any of the linear measurements in Table 3.3.

Among the dental variables only slight correlations could be found for the position of the upper incisal edge relative to the NA-line and for the position of the lower incisal edge relative to

Table 3.4 Linear correlation coefficients between angular, ratio, and position measurements and age

Variable	♂	♀	♂+♀
	Correlations with *age*:		
SNA	0.130	0.044	0.0614
SNB	0.309**	0.163	0.1943**
SNPg	0.419***	0.243**	0.2869***
ANB	0.278**	0.256***	0.2655***
ANPg	0.327***	0.355***	0.3449***
Wits	0.050	0.130	0.1096
ML-NSL	0.338***	0.290***	0.3079***
NL-NSL	0.011	0.033	0.0199
ML-NL	0.327***	0.311***	0.3188***
GntgoAr	0.347***	0.321***	0.3327***
NSBa	0.148	0.050	0.0759
FHNSL	0.134	0.072	0.0068
OrbNA	0.383***	0.279***	0.3066***
ForeHead incl	0.657***	0.586***	0.5996***
Index	0.039	0.019	0.0311
$\underline{1}$-NA°	0.050	0.098	0.0834
$\underline{1}$-NA_{mm}	0.276**	0.211**	0.2314***
$\bar{1}$-NB°	0.112	0.243**	0.2008***
$\bar{1}$-NB_{mm}	0.088	0.026	0.0139
$\bar{1}$-APg_{mm}	0.095	0.045	0.0045
Pg⊥ML	0.241**	0.242**	0.2399***
Y-axis	0.141	0.049	0.0719

** $p < 0.01$ *** $p < 0.001$

pogonion. For the female subjects a correlation between lower incisor axis inclination and age proved significant.

Surprising were the differences between the correlation coefficients in male and female subjects for the variables SNB and $\bar{1}$-NB_{mm}. None of these differences was statistically significant at $p<0.05$, however.

Although a number of these variables displayed highly significant correlations with age all correlation coefficients were smaller than the ones for the linear variables in Table 3.3 with the exception of forehead inclination.

3.3 Bivariate associations

A comprehensive table of all correlation coefficients between the variables under investigation can be found in appendix A. That table contains 961 coefficients and is thus quite complex. For better clarity only subsets of variables will be analyzed in the course of the following text.

The associations between the linear measurements are listed in Table 3.6. It appeared that the 4 variables *cross*, N-Gn, Ar-Progn, and N-Sp' were closely correlated (r between 0.723 and 0.932). The distance S-N also showed high coefficients although they were clearly smaller than the ones for the 4 variables mentioned above.

The lowest correlation among this group of variables occurred between the maxillary measurement NSp' and the mandibular measurement Ar-Progn (r = 0.723). On the other hand Ar-Progn showed moderately high, but above average, associations with other mandibular variables like *chin* and *symph width*.

Table 3.7 shows correlations among the angular skeletal variables and the ratios *Wits* and *Index*. Nearly all combinations of any two variables showed significant correlations. The presence of a significant relationship in itself is interesting, but the intensity of the association is also of interest.

The variables describing the prognathism of the jaws (SNA, SNB, and SNPg) displayed very high coefficients between them from 0.745 to 0.967. The measurements describing sagittal base relationship (ANB, ANPg, and Wits) showed considerable differences. While ANB and ANPg were very closely related with a coefficient of 0.945 Wits value exhibited much lower affiliations with the other two variables (r=0.616 and r=0.485). The close association between ANB and ANPg is surprising since the variability of $PgNB_{mm}$ should reduce the correlation.

Only a low correlation appeared between the variables describing the inclinations of the maxilla and mandible. ML-NL correlated closely with ML-NSL (r = 0.90) but only slightly with NL-NSL (r = 0.16). The gonial angle was associated mainly with ML-NSL and ML-NL but not with NL-NSL. *Index* showed moderate correlations with maxillary inclination NL-NSL and interbase angle ML-NL. These variables and gonial angle Gn-tgo-Ar were the only correlations with *Index* that showed coefficients of more than 0.26.

The inclination of the frontal bone (*ForeHead*) displayed moderate negative correlations (r=0.321..0.471) with the variables representing prognathism. This stands for a more retrusive frontal bone in cases with prognathic jaws. The

Table 3.6 Correlations between the variables representing linear measurements (♂+♀ combined, n=354)

	S-N	N-Gn	cross	ArProgn	$PgNB_{mm}$	chin	symph	NSp'	Sp'Gn
S-N		**0.663**	**0.776**	**0.781**	**0.449**	**0.540**	**0.446**	**0.657**	**0.554**
N-Gn	**0.663**		**0.899**	**0.810**	**0.303**	**0.632**	**0.376**	**0.873**	**0.926**
cross	**0.776**	**0.899**		**0.932**	**0.514**	**0.655**	**0.517**	**0.845**	**0.786**
ArProgn	**0.781**	**0.810**	**0.932**		**0.557**	**0.747**	**0.522**	**0.723**	**0.737**
$PgNB_{mm}$	**0.449**	**0.303**	**0.514**	**0.557**		**0.771**	**0.503**	**0.389**	**0.185**
chin	**0.540**	**0.632**	**0.655**	**0.747**	**0.771**		**0.481**	**0.563**	**0.577**
symph	**0.446**	**0.376**	**0.517**	**0.522**	**0.503**	**0.481**		**0.307**	**0.364**
NSp'	**0.657**	**0.873**	**0.845**	**0.723**	**0.389**	**0.563**	**0.307**		**0.624**
Sp'Gn	**0.554**	**0.926**	**0.786**	**0.737**	**0.185**	**0.577**	**0.364**	**0.624**	

2-tailed probabilities, all coefficients $p < 0.001$

Table 3.7 Significant correlations among angular skeletal variables

	SNA	SNB	SNPg	ANB	ANPg	Wits	ML–NSL	NL–NSL	ML-NL	Gn-tgo -Ar	NSBa	FH-NSL	Fore-head	Index	Yaxis
SNA	**1.000**	**0.839**	**0.745**	**0.287**	**0.258**		**0.339**	**0.336**	**0.199**		**0.505**	**0.611**	**0.321**	**0.266**	**0.569**
SNB	**0.839**	**1.000**	**0.967**	**0.281**	**0.280**	**0.455**	**0.577**	**0.429**	**0.402**		**0.564**	**0.630**	**0.408**	0.137	**0.814**
SNPg	**0.745**	**0.967**	**1.000**	**0.389**	**0.453**	**0.432**	**0.672**	**0.424**	**0.502**	**0.213**	**0.510**	**0.556**	**0.471**		**0.846**
ANB	**0.287**	**0.281**	**0.389**	**1.000**	**0.947**	**0.616**	**0.419**	0.163	**0.358**	**0.193**			0.153	**0.227**	**0.431**
ANPg	**0.258**	**0.280**	**0.453**	**0.947**	**1.000**	**0.485**	**0.520**	0.164	**0.461**	**0.290**			**0.253**	**0.259**	**0.466**
Wits		**0.455**	**0.432**	**0.616**	**0.485**	**1.000**				**0.224**	**0.349**	**0.290**			**0.395**
ML-NSL	**0.339**	**0.577**	**0.672**	**0.419**	**0.520**		**1.000**	**0.276**	**0.904**	**0.678**	0.139	**0.294**	**0.270**	**0.298**	**0.719**
NL-NSL	**0.336**	**0.429**	**0.424**	0.163	0.164		**0.276**	**1.000**	0.161		**0.319**	**0.359**		**0.468**	**0.420**
ML-NL	**0.199**	**0.402**	**0.502**	**0.358**	**0.461**		**0.904**	0.161	**1.000**	**0.686**			**0.246**	**0.513**	**0.552**
Gn-tgo-Ar			**0.213**	**0.193**	**0.290**	**0.224**	**0.678**		**0.686**	**1.000**	0.144		0.166	**0.331**	
NSBa	**0.505**	**0.564**	**0.510**			**0.349**	0.139	**0.319**		0.144	**1.000**	**0.607**	**0.419**	0.151	**0.369**
FH-NSL	**0.611**	**0.630**	**0.556**			**0.290**	**0.294**	**0.359**			**0.607**	**1.000**	**0.234**	**0.218**	**0.479**
ForeHead	**0.321**	**0.408**	**0.471**	0.153	**0.253**		**0.270**		**0.246**	0.166	**0.419**	**0.234**	**1.000**		**0.185**
Index	**0.266**	0.137		**0.227**	**0.259**		**0.298**	**0.468**	**0.513**	**0.331**	0.151	**0.218**		**1.000**	
Yaxis	**0.569**	**0.814**	**0.846**	**0.431**	**0.466**	**0.395**	**0.719**	**0.420**	**0.552**		**0.369**	**0.479**	**0.185**		**1.000**

2-tailed probabilities: all listed coefficients $p < 0.01$, **coefficients in bold print** $p < 0.001$

variable also showed a moderately high correlation with the flexure of the cranial base (r=0.419). This observation fitted into the general trend with a large NSBa-angle in retrognathic faces. The forehead would be prominent in these cases.

The angle NSBa showed moderate associations that were highly significant with all variables except ANB, ANPg, and ML-NL. The correlations with ML-NSL, Gn-tgo-Ar, and *Index* were significant, but low. Very similar associations on a slightly higher level were found for the variable Frankfort horizontal.

The variable Y-axis showed a good correlation with the sagittal variables SNB (r=0.81) and SNPg (r=0.856) and the vertical variable ML-NSL (r=0.729). It displayed also moderate associations with all other variables except for Gn-tgo-Ar, Index, and *ForeHead*.

The association between prognathism variables and inclination variables were moderate, as were the associations between the mandibular inclination and the sagittal skeletal relationship variables. The strongest association could be observed between the sagittal mandibular measure SNPg and the mandibular inclination ML-NSL (r=0.67). The angles SNB and SNPg (mandibular prognathism) correlated moderately with the sagittal inter-base relationship measures ANB, ANPg, and Wits. Interestingly, the strongest association with ANB could be found for SNPg (r=0.39) and not SNB or SNA as would be expected according to the topographic correlation concept. SNA was connected with ANB and ANPg but not Wits.

Associations between the dental variables and the variables describing the size and shape of the chin are shown in Table 3.8. The variable ANB has been added to check which of the dental measurements shows the strongest dependency on the sagittal skeletal relationship and the variable *cross* to check if the linear measurements are growth- and size-related.

Table 3.8 Significant correlations among dental and chin variables (ANB and *cross* also included)

	$PgNB_{mm}$	Chin	Symph	1-NA°	1-NA_{mm}	1̄-NB°	1̄-NB_{mm}	1̄-APg_{mm}	1-Pg⊥ML	ANB	cross
$PgNB_{mm}$	**1.000**	**0.771**	**0.503**			**0.543**	**0.473**	**0.505**	**0.501**	**0.505**	**0.514**
Chin	**0.771**	**1.000**	**0.481**			**0.337**		**0.190**	**0.822**	**0.360**	**0.655**
Symph	**0.503**	**0.481**	**1.000**						0.178		**0.517**
1NA°				**1.000**	**0.851**	0.170		**0.469**		**0.575**	
1NA_{mm}				**0.851**	**1.000**	0.172	**0.238**	**0.607**		**0.632**	**0.218**
1̄-NB°	**0.543**	**0.337**		0.170	0.172	**1.000**	**0.857**	**0.772**	**0.565**	**0.443**	
1̄-NB_{mm}	**0.473**				**0.238**	**0.857**	**1.000**	**0.852**	**0.352**	**0.480**	**0.233**
1̄-APg_{mm}	**0.505**	**0.190**		**0.469**	**0.607**	**0.772**	**0.852**	**1.000**	**0.364**		0.167
1-Pg⊥ML_{mm}	**0.501**	**0.822**	0.178			**0.565**	**0.352**	**0.364**	**1.000**	**0.271**	**0.260**
ANB	**0.505**	**0.360**	**0.079**	**0.575**	**0.632**	**0.443**	**0.480**		**0.271**	**1.000**	**0.262**
Cross	**0.514**	**0.655**	**0.517**		**0.218**		**0.233**	0.167	**0.260**	**0.262**	**1.000**

2-tailed probabilities: all listed coefficients $p < 0.01$, **coefficients in bold print** $p < 0.001$

Table 3.8 shows that the incisal edge position and long axis inclination measurements for both the maxillary and mandibular incisors were strongly correlated as long as the same reference line was used for both measurements. Substituting the APg-line for the NB-line as a reference for the lower incisal edge did not lower the coefficient very much. If, however, the lower incisor position was measured relative to the mandible (1-Pg⊥ML_{mm}) only moderate correlations with the other variables describing the lower incisors were found.

The association between upper and lower incisors was low. Merely the variable APg_{mm} was correlated moderately with upper incisor inclination and strongly with upper incisor position.

The incisor inclinations did not show any association with the variable *cross* which was to represent the size of the subject. The incisor position measurements displayed only low correlations with *cross*. The highest coefficient with 0.260 was found between 1-Pg⊥ML_{mm} and *cross*. In Table 3.4 it can be seen that this variable also showed the highest correlation with age. With the exception of this variable all coefficients were much lower than the ones between cross and the linear measurements in Table 3.4. It could therefore be confirmed that the linear measurements of the incisal edges represent positions rather than sizes.

The sagittal skeletal relationship as depicted by ANB showed moderate correlations (r=0.443 .. 0.632) with incisor position and inclinations relative to the NA and NBline. No correlation was found if the incisor position was measured relative to the APg-line and only low coefficients when the mandibular reference was used. The direction of these association was such that a compensatory pattern was observed. In cases with a large ANBangle the upper incisors were more retruded while the lower incisors were in a more protruded position and vice versa.

The width of the mandibular symphysis did not have an effect on incisor position or inclination. $PgNB_{mm}$ didn't correlate with the upper incisor variables either. If the reference line NB was used for the lower incisors the value $PgNB_{mm}$ showed the highest correlation coefficients of all non-dental variables (r=0.47 for position and 0.54 for inclination). The variable *chin*, which employs the same landmarks as $PgNB_{mm}$ but with the mandible as a reference system, showed a very high correlation with lower incisor position only if it was also measured relative to the mandibular reference system. Merely slight or no correlations to the dental variables showed if they were measured relative to the NA- or NB-line.

The 3 variables describing the mandibular symphysis (*PgNB$_{mm}$*, *Chin*, and *Symph width*) displayed only moderate to high associations with each other although they measure the contour of the chin/symphysis region in a rather similar way. PgNB$_{mm}$ and *Symph* displayed moderate associations with *cross* while *Chin* showed with 0.72 the highest coefficient. PgNB$_{mm}$ and *Symph* thus seem to be influenced less by somatic growth than by other factors.

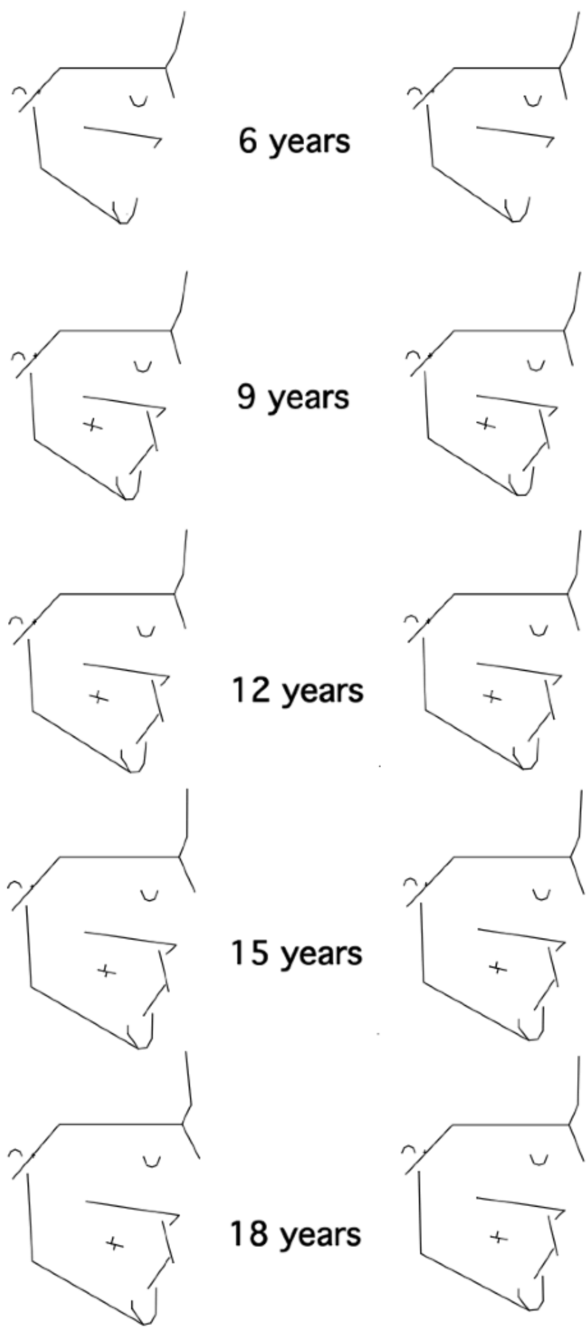

Fig. 3.9 Averaged polygon drawings of male and female subjects for each of the age groups

3.4 Craniofacial pattern / multivariate associations

In the previous chapters it was described how the variables under survey show both inter-individual variation and growth related changes. Further it was shown that the variation of each individual variable is not independent of that of other variables. On the following pages it will be shown if and in which way several variables show an inter-dependence a so called pattern.

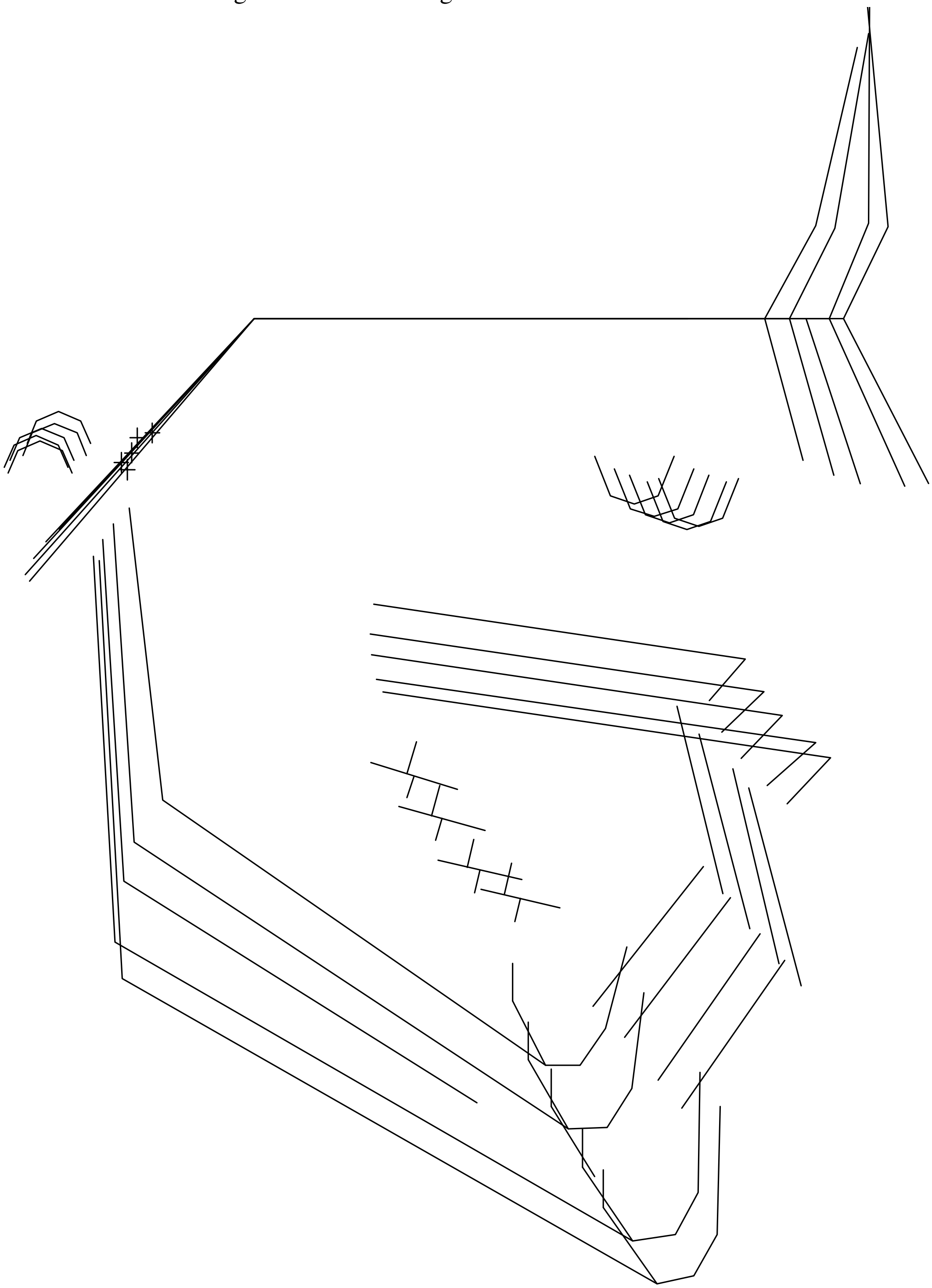

Fig. 3.10 Superimposition of average polygon drawings of male subjects for each of the 5 age groups

Graphical representation

The association of the parts of the cranio-facial bones at each of the survey ages can be seen in the averaged polygon plots of Figure 3.9. These polygon plots were constructed by averaging the X- and Y-coordinates of every landmark within each age group. Then a number of lines were drawn between the average landmark locations. All drawings were oriented so that the *NSL* showed horizontally. Because only few of the subjects had their first molars and incisors fully erupted at the first examination the lines representing these teeth were omitted in that group.

Aside from the expected increase in all linear dimensions the most notable observation was a forward development of the lower part of the face relative to the cranial base. The nasal bone duplicated this trend and tilted more ventrally. The frontal bone on the other hand tilted back-

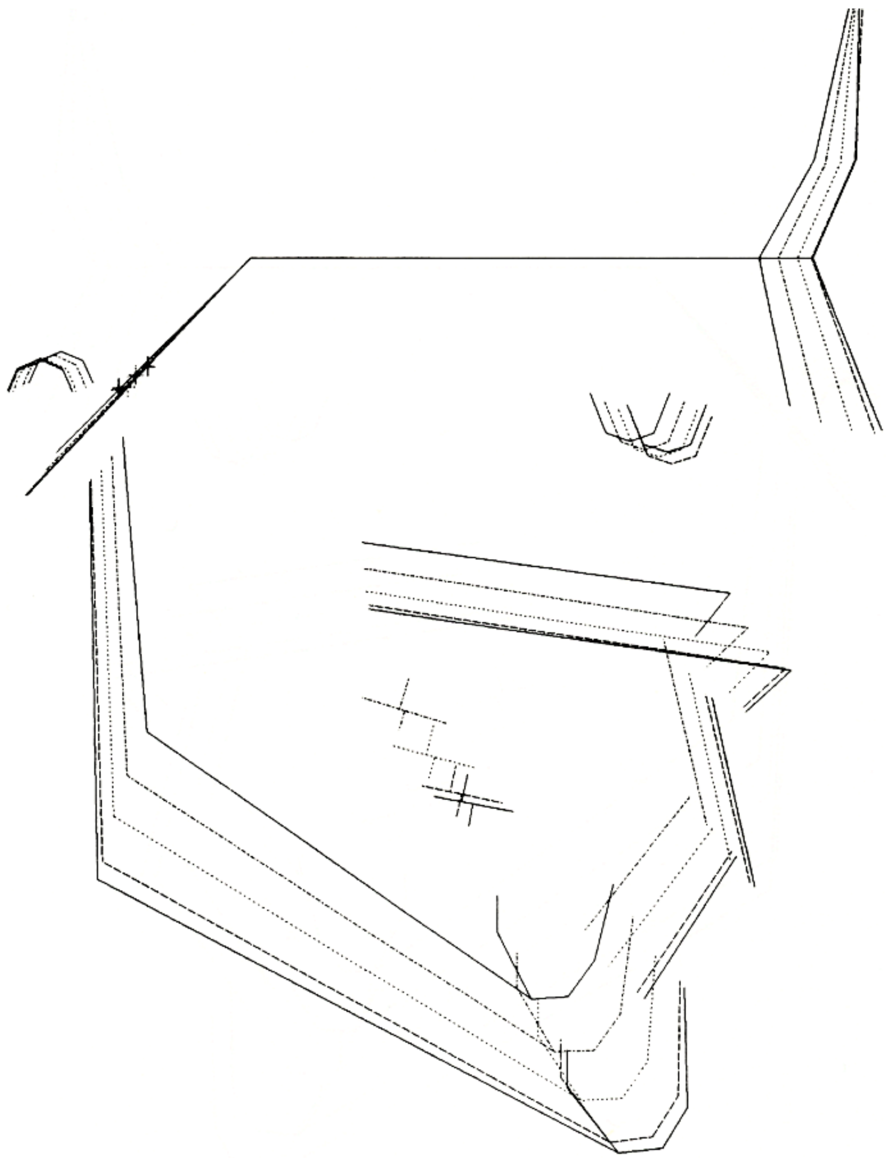

Fig. 3.11 Superimposition of average polygon drawings of female subjects for each of the 5 age groups.

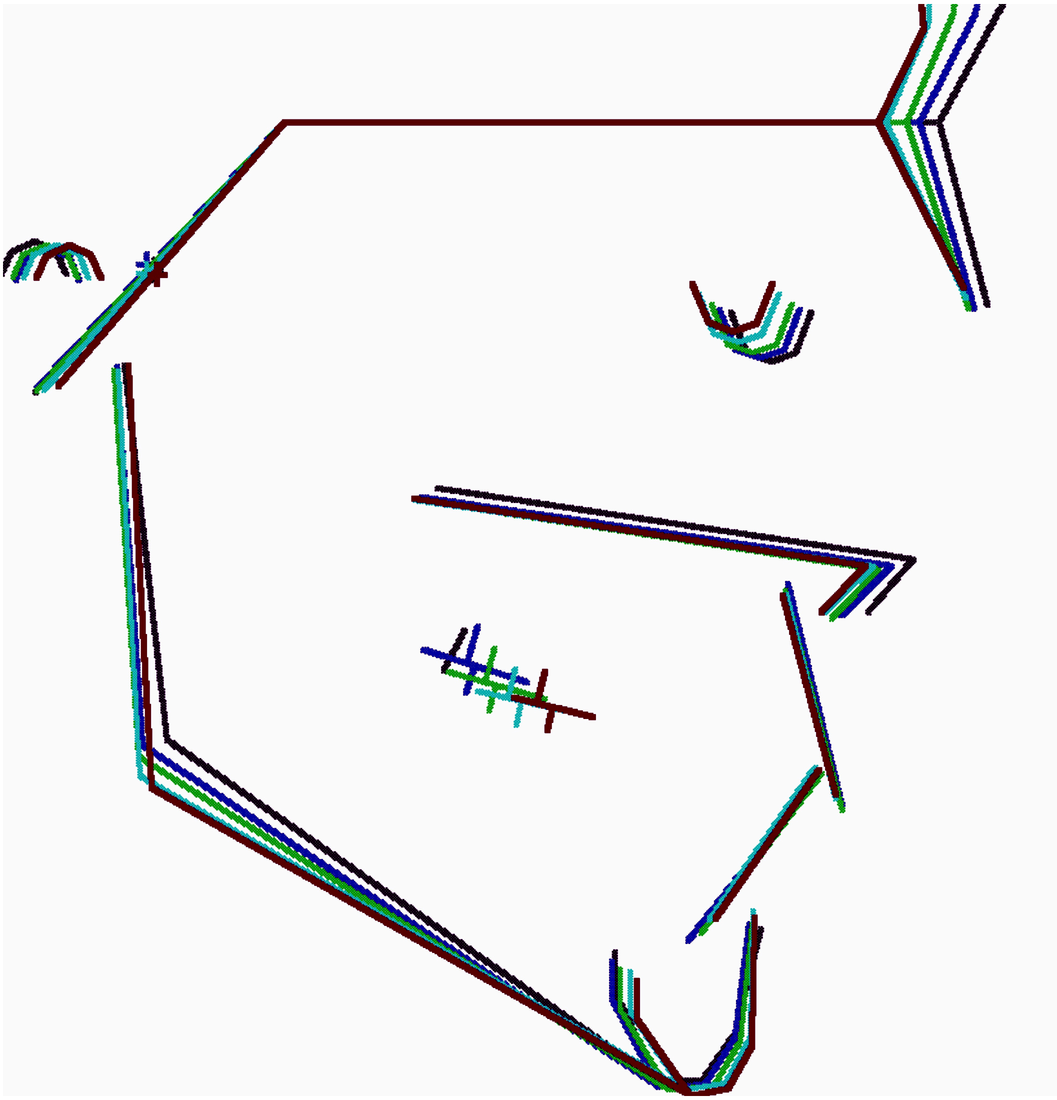

Fig. 3.12 Superimposition of average polygon drawings of male subjects for each of the 5 age groups. Before superimposition the drawings were adjusted for size according to the variable *cross*

wards. The chin was roughly on the caudal extension of the tangent to the frontal bone. This axis displayed a counter-clockwise rotation when the faces were oriented with the noses to the right. These observations were similar for both sexes.

More subtle changes in the pattern could be found when the polygon drawings were superimposed on *sella* and the *nasion-sella-line* (Fig. 3.10 and 3.11). The inclination of the forehead tilted backwards because glabella moved forward considerably, especially in the male subjects. The upper end of the forehead, at the junction of the neuro-cranium and the face, showed hardly any movement at all. The landmark *nasion* and the nasal bone exhibited a ventral movement and the nasal bone also a ventral tilting of its end.

The maxillary complex displayed an increase in length and a parallel translation in a downward and anterior direction. The infraorbital rim did not move downward as much as the

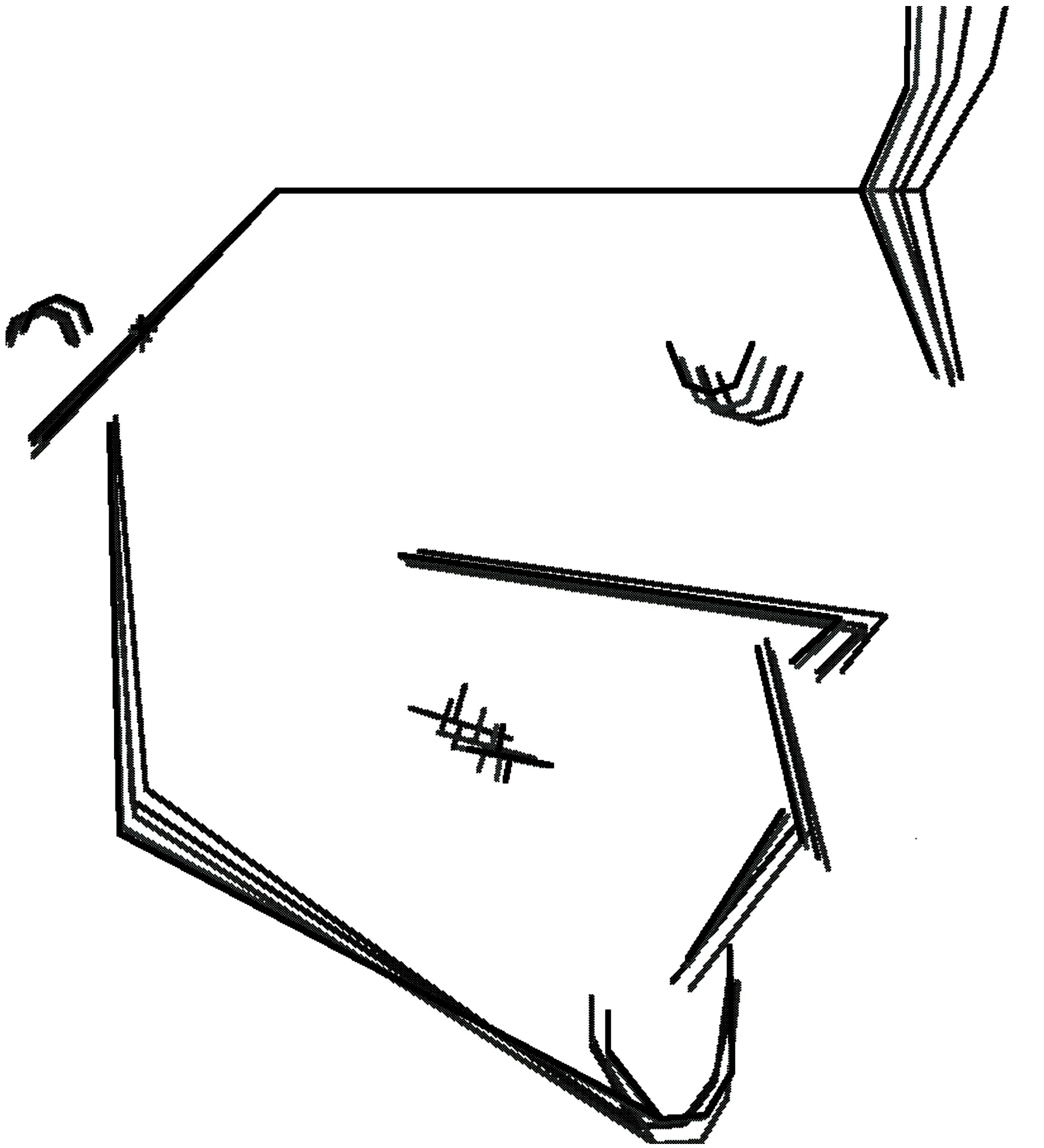

Fig. 3.13 Superimposition of average polygon drawings of female subjects for each of the 5 age groups. Before superimposition the drawings were adjusted for size according to the variable *cross*

remainder of the maxilla. The mandible also showed an increase in length, but here the displacement was not a simple parallel translation. It also included a marked anterior rotation of the mandibular base. The gonion region moved caudally faster than the mandibular symphysis. The theoretical centre of rotation was located about 5 cm ventrally of the glabella region. In addition to the effects of the anterior rotation of the mandible the chin also became more prominent through remodelation processes.

The teeth seemed to follow the displacements of the basal bones with only slight alterations in inclinations, overjet, and overbite. The molar relation developed slightly mesially.

In order to better distinguish between pure changes in size and changes in shape the average polygon drawings were again superimposed, but this time they were size-adjusted prior to the superimposition. For this purposes the 18-year polygons were not changed in size while the polygon drawings for each of the younger groups were enlarged by a factor calculated for each age group from the variable *cross* as

$$m = \frac{cross_{18}}{cross_{age}}$$

As such proportionate enlargements do not change angles, ratios, and relative positions and assuming that the variable *cross* truly represents the state of somatic growth any variation in the shape of the individual parts or their pattern of association should be easily detectable. Figures 3.12 and 3.13 display these size-adjusted superimpositions.

The similarities of the superimposed polygon drawings were astonishing. Especially for the male subjects the line drawings proved almost congruent. Merely the frontal bone inclination and the gonial angle region displayed major differences in shape. The cranial edge of the frontal bone grew forward much less than the reference variable *cross* and the anterior cranial base represented by the line SN increased its length still considerably less than *cross*. In Fig. 3.12 the shortest line belongs to the 18-year drawing. Maxilla displayed slighltly less than average growth in the sagittal direction while its vertical growth was rather similar to the change of the reference measure *cross*. The growth of the mandible was also synchronized with *cross* with the exception of the gonial angle region. The anterior region and symphysis followed the general trend very closely in the sagittal and vertical plane.

The gonial region displayed above average lengthening of the ascending ramus resulting in a relative downward growth of gonion and an anterior rotation of the inferior border and in a slight advancement of pogonion in relation to the average amount of growth.

The superimposition of the female subjects displayed the same pattern though the changes in the forehead region and on the mandibular inferior border were not as pronounced as those in the males. The 12-year group displayed an above average lower face height that showed in a caudal displacement of the mandibular symphysis. In the older age groups the mandibular symphysis had returned to its average growth position.

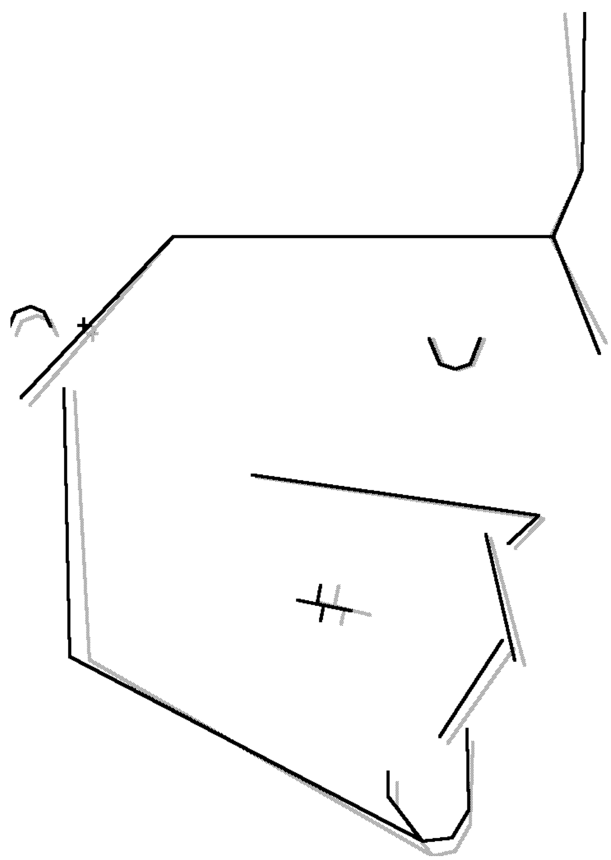

Fig. 3.14 Superimposition of size-adjusted average polygon drawings of 18 year old female (black line) and male (grey line) subjects.

Table 3.9 Correlations between 10 varimax rotated principal components and 16 skeletal angular, ratio, and position variables. Major correlations and variables best explaining the 10 principle components are in bold print.

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
SNA	0.894	0.317	0.050	0.163	0.119	0.086	0.063	0.125	0.151	0.072
SNB	**0.928**	0.211	0.061	0.060	0.066	0.057	0.127	0.156	0.161	0.006
SNPg	0.907	0.260	0.090	0.176	0.048	0.072	0.131	0.132	0.140	0.019
ANB	0.046	**0.946**	0.018	0.185	0.096	0.053	0.113	0.053	0.015	0.141
ANPg	0.066	0.837	0.062	0.493	0.099	0.016	0.104	0.017	0.009	0.132
Wits	0.314	0.857	0.116	0.128	0.078	0.028	0.130	0.084	0.076	0.228
ML-NSL	0.592	0.161	0.553	0.234	0.178	0.041	0.087	0.031	0.091	0.443
NL-NSL	0.352	0.097	0.010	0.095	0.305	0.046	**0.851**	0.135	0.084	0.010
ML-NL	0.433	0.118	0.562	0.193	0.334	0.020	0.334	0.035	0.052	**0.460**
GntgoAr	0.029	0.076	**0.983**	0.052	0.111	0.037	0.028	0.033	0.010	0.016
NSBa	0.358	0.112	0.047	0.076	0.037	0.191	0.125	**0.868**	0.210	0.001
FHNSL	0.480	0.057	0.018	0.077	0.086	0.124	0.087	0.260	**0.813**	0.026
ForeHead	0.117	0.038	0.025	0.055	0.042	**0.977**	0.030	0.135	0.075	0.007
Index	0.084	0.081	0.190	0.065	**0.943**	0.048	0.215	0.029	0.061	0.053
Yaxis	0.830	0.317	0.039	0.233	0.080	0.047	0.110	0.127	0.064	0.264
PgNBmm	0.058	0.237	0.115	0.951	0.056	0.063	0.050	0.067	0.055	0.046

The last superimposition (Figure 3.14) compares the 18-year male and female drawings, again corrected for size. Differences showed in a relatively more retrusive upper forehead and a more ventral position of clivus/glenoid fossa and ascending ramus in the male subjects. The nasal bone was also slightly less steep and the lower face height in relation slightly larger in the male group. Anterior cranial base, glabella region, maxillary and mandibular inclinations, and the prognathism of the jaws were strikingly similar.

Principle component analysis

As the amount of statistical calculations increases immensely with the number of variables analyzed at the same time it is imperative to limit the number of variables. A restriction in the number of variables also reduces the error probability because the degrees of freedom depend among other things on the number of independent variables.

As a first step those variables that show the least mutual redundancy need to be isolated. Each of these variables will contain a great deal of unique information that cannot be obtained from other variables. A method that achieves this selection process is called a *principle component analysis (PC)*.

As it was the association of the parts of the facial skeleton rather than the growth related dimensions that was of interest only the skeletal angular, index, and position variables were entered into the PC. Thus 16 variables fell under this category.

The PC extraction mechanism resulted in 10 principal components with an eigenvalue of above 0.20. These 10 components accounted for 98.76% cumulated variance. The remaining 1.24% variance was accounted for by the remaining 6 components. None of them reached the level of 0.20 and therefore they did not contribute a great deal of unique information. The loadings of the 16 variables under survey on these 10 main components was then calculated and rotated using the varimax algorithm. The results are shown in Table 3.9. The complete output of the PC analysis can be found in appendix B.

The 6 variables that contributed least to explained variance were SNA, *Wits*, SNPg, ANPg, ML-NSL, and Y-axis. The somewhat surprising appearance of SNA among these variables required closer investigation. Although SNA had a very high correlation with principle component #1 (r = 0.894) the variables SNB and SNPg showed with 0.928 and 0.907 even higher loadings and were therefore used. In the mandible the variable representing the alveolar sagittal position SNB appeared to be slightly more relevant than the variable representing the sagittal position as measured at the chin (SNPg) which was hence disregarded.

Among the variables representing the sagittal base relationship ANB clearly showed the highest values with *Wits* and ANPg displaying similar but lower values. Taking the variables for inclination into consideration only NL-NSL displayed unique information (r = 0.851 with PC #7). ML-NSL and ML-NL showed rather similar loadings. However, ML-NL showed the highest correlation with PC #10 and was consequently given preference over ML-NSL.

The variables NSBa, GntgoAr, FHNSL, *Index*, *ForeHead incl.*, and $PgNB_{mm}$ all represented unique information and showed high and singular correlations with the PC's #8, #3, #9, #5, #6, and #4.

The variable Y-axis showed only moderate loadings on the PC's #2, #4, and #10. A relatively high loading on PC #1 was nevertheless considerably lower than the ones by SNB, SNPg, and SNA. The variable could not provide information that was not already available from other measurements.

In trying to interpret the factors that originated from the PC analysis the following explanations were attributed:

#1 degree of prognathism of the jaws
#2 sagittal base relationship
#3 gonial angle
#4 chin prominence
#5 anterior vertical proportions
#6 inclination of forehead
#7 inclination of palatal/nasal plane
#8 cranial base flexion
#9 angle between Frankfort horizontal and NSL
#10 divergence of jaw bases

It has to be stressed that the fact that a certain measure appears among these principle components doesn't necessarily imply clinical relevance. The fact that *ForeHead inclination* appears as factor #6 merely indicates that none of the other variables entered into the PC could provide information redundant to that included in the variable *ForeHead*. The same is true for the variable FH-NSL (factor #9).

Influence of sex and age on craniofacial pattern (MANOVA)

In the next step it was tested if the associations between the 10 principle components that describe the craniofacial pattern are influenced by gender and agegroup. This analysis was carried out using a multivariate analysis of variance with sex and age-group as dependent and the 10 principle components as independent variables. As all PC's with the exception of $PgNB_{mm}$ were based on angular and ratio measurements the use of a covariate to eliminated somatic size differences was considered disadvantageous. The variable $PgNB_{mm}$ did not show a relationship with the linear dimension variable *cross* (0.453) as close as some of the linear size measurements did.

As a test of multivariate difference *Pillai's Trace* was used as it is said to be the most robust criterion of the most commonly used tests *Wilks' Lambda*, *Hotelling's Trace*, *Roy's Largest Root*, and *Pillai's Trace* (Morrison 1990, Norusis 1988). Therefore, possible mild violations of the homogeneity of covariance matrices or multivariate normality would not have biased the test results.

Nevertheless, the assumptions of homogeneity of the covariance matrices and the absence of identity in the correlation matrix was tested. The homogeneity of the variance was tested univariately using *Cochrans C* and multivariately using *Box's M test*. Both tests did not show any hints for inhomogeneities. *Box's M* value was 542.5 which corresponds to an F value of 0.930 with 495,41625 degrees of freedom ($p \approx 0.864$).

The determinant of the correlation matrix was 0.017. Transformed according to *Bartlett's test of sphericity* an F-value of 1244.63 with 45 degrees of freedom was calculated. The tested hypothesis that the correlation matrix represented an identity matrix was thus rejected at a significance level of $p < 0.001$. The assumptions in conducting the MANOVA procedure itself were therefore not violated.

Table 3.10 Results of MANOVA with 10 principle components of craniofacial pattern

Effect of age-group		
Pillais Trace	0.730	
approx. Fvalue	6.787	
Significance of F	0.000	***
Effect of sex		
Pillais Trace	0.099	
approx. Fvalue	3.309	
Significance of F	0.000	***
Interaction sex/age-group		
Pillais Trace	0.097	
approx. Fvalue	0.761	
Significance of F	0.860	n.s.

The results (Table 3.10) showed that both dependent variables sex and age-group had a highly significant ($p < 0.001$) effect on the set of variables as an entirety. A univariate F-test showed, which of the 10 variables had the major impact on this result. For the sex differences it were mainly the variables *Gn-tgo-Ar*, *NSBa*, *ForeHead*, and $PgNB_{mm}$ and to a lesser degree the variables *Index*, *FH-NSL*, and *ANB*. The only variables that didn't seem to have an influence on the differences between the age-groups were *NL-NSL*, *NSBa*, and *FH-NSL*.

No interactions between the dependent variables *sex* and *age-group* could be found. Therefore the pattern of change between the age-groups did not differ between the male and female subjects. Only the variable *ForeHead* showed a significant deviation from this trend in the univariate F-test. This might be attributed to the peculiarly large decrease of this angle between the age-groups 15 and 18 in the male subjects (Table 3.1). During all other observation periods and in the male and female groups this angle displayed a rather homogeneous decrease.

When interpreting the results it has to be kept in mind that the MANOVA procedure employed treats the data as if it was a set of independent vectors. This would mean that every set of values is thought of being independent of all others. However, since the material is mixed-longitudinal there is more than one set of values from each patient. As the sample isn't fully longitudinal a procedure for repeated measurements would have been possible only on part of the material. As repeated measurement procedures usually are more apt to reject the null-hypothesis and as the procedure employed already rejected the null-hypothesis at a high level of significance for the effects of sex and age it was considered unlikely that any different results would emerge.

3.5 Pattern of change in the craniofacial configuration

From sections 3.1 and 3.2 it is evident that many variables in the facial skeleton change during growth. It is now of interest if these changes are strictly coordinated, meaning that the changes also display a certain pattern. If such a pattern exists, it is of interest whether it will lead to a different craniofacial association and whether such a pattern displays inter-individual and intra-individual stability. If all individuals adhere to the same pattern of change and if an individual's pattern does not change during the years of growth the adult craniofacial morphology should be predictable accurately.

Associations between the growth related changes of the variables

Table 3.11 shows the linear correlation coefficients between the changes of the variables. These changes were calculated as

$$\Delta_V = V_{18yr} - V_{6yr}$$

Because only very few dental measurements were available at 6 years of age no differences could be calculated for these variables either. This also includes the *Wits*-ratio.

Generally speaking associations existed between the changes of angular variables describing the shape of the facial skeleton as well as between the increase in the linear measurements. Quite high coefficients appeared between the change in prognathism between maxilla and mandible ($r_{SNA/SNB} = 0.845$). This value is rather similar to that between the measured angles themselves (0.839; Table 3.7). A strong association existed between the sagittal changes and the changes in inclination NL-NSL, ML-NSL, FH-NSL and cranial base flexion NSBa (0.453..0.697). The more posteriorly the jaws rotated the less did maxilla grow forward. If, however, the jaws showed an anterior rotation and the cranial base flexure increased the prognathism of the face tended to increase.

No association between ΔANB and any other variable with the exception of the related variable ΔANPg could be observed. The coefficient between the change in SNA and ΔANPg was significant but with ΔANB it barely missed significance. The coefficients between the change in sagittal base relationship and the change in SNB and SNPg were close to zero, however. This difference between the influences of ΔSNA and ΔSNB was unexpected as both angles share an arm with the angle ANB.

For the vertical angular variables the change in ML-NSL was the only one that significantly accounted for changes in the interbase angle ML-NL (r=0.748). Changes in gonial angle GntgoAr accounted for changes in ML-NSL. An unexpected finding was an association with a coefficient of 0.441 between the change in anterior cranial base length *S-N* and the change in ML-NL.

The change in the angle between NSL and the Y-axis correlated with the variations of all angular variables that describe prognathism of the jaws and inclination. The highest coefficients were found for SNPg (r=-0.811) and ML-NSL (r=+0.812).

Correlations appeared between changes in forehead inclination, changes in Frankfort horizontal inclination, and cranial base flexion NSBa. A receding forehead (small angle *Fore-Head incl.*) tended to be accompanied by a small NSBa angle and a small angle between Frankfort horizontal and NSL, all signs of a more prognathic facial type. The correlations between variation of forehead inclination and the increase in the linear measurements N-Gn, *cross*, Ar-Progn, and Sp'-Gn needed to be looked into more closely. All of these correlation seemed to result from a joint correlation with the sex of the subjects. In male persons the forehead inclination decreased more and the linear variables increased more than in female subjects. To check this partial correlation coefficients that eliminated the influence of the variable sex were calculated. This resulted in the elimination of any significant correlations between the change in linear length measurements and changes in the variable *ForeHead*

Tabelle 3.11 Correlations between changes of variables

	ΔSNA	ΔSNB	ΔSNPg	ΔANB	ΔANPg	ΔML NSL	ΔNL NSL	ΔML NL	Δ Gn-tgo-Ar	ΔNSBa	ΔFH-NSL	ΔOrb-NA	ΔFore Head	ΔS-N	ΔN-Gn	ΔCross	Δ Ar-Progn	ΔPgNB	ΔChin	ΔSymph	Δ N-Sp'	Δ Sp'-Gn	ΔIndex	ΔYaxis
ΔS-NA	.	**0.845**	**0.829**		0.491	0.453	**0.562**			**0.543**	0.461													**0.610**
ΔS-NB	**0.845**	.	**0.944**			**0.592**	**0.524**			**0.640**	**0.628**													**0.748**
ΔSNPg	**0.829**	**0.944**	.			**0.669**	**0.570**			**0.697**	**0.644**													**0.811**
ΔANB				.	**0.844**																			
ΔANPg	0.491			**0.844**	.																			
ΔML-NSL	0.453	**0.592**	**0.669**			.	**0.542**	**0.748**	**0.663**	0.433														**0.812**
ΔNL-NSL	**0.562**	**0.524**	**0.570**			**0.542**	.			**0.668**	0.501										0.442		0.454	**0.550**
ΔML-NL						**0.748**		.	**0.700**					0.429									0.425	**0.521**
ΔGntgoAr						**0.663**		**0.700**	.															
ΔNSBa	**0.543**	**0.640**	**0.697**			0.433	**0.668**			.	0.548		0.510											0.427
ΔFHNSL	0.461	**0.628**	**0.644**				0.501			0.548	.		0.483			**0.590**	**0.571**							
ΔOrbNAmm												.												
ΔForeHead										0.510	0.483		.		0.489	**0.518**	0.480				0.404	0.431		
ΔSN								0.429						.		**0.604**	**0.649**							
ΔN-Gn													0.489		.	**0.829**	**0.758**				**0.792**	**0.905**		0.455
ΔCross											**0.590**		**0.518**	**0.604**	**0.829**	.	**0.911**				**0.705**	**0.715**		
ΔAr-Progn											**0.571**		0.480	**0.649**	**0.758**	**0.911**	.				**0.639**	**0.659**		
ΔPgNBmm																		.	**0.675**					
ΔChin																		**0.675**	.					
ΔSymph width																				.				
ΔNSp'							0.442								**0.792**	**0.705**	**0.639**				.	0.457	0.443	0.421
ΔSp'Gn													0.431		**0.905**	**0.715**	**0.659**				0.457	.	**0.579**	
ΔIndex							0.454	0.425													0.443	**0.579**	.	
ΔYaxis	**0.610**	**0.748**	**0.811**			**0.812**	**0.550**	**0.521**		0.427					0.455						0.421			.

n = 39; all listed correlations $p < 0.01$, those shown in **bold** $p < 0.001$

incl. The matrix of partial correlation coefficients can be found in appendix C.

All increases in size measurements displayed moderate to strong correlations with the change in variable *cross*. The increase in anterior cranial base length ΔS-N did not show significant correlations with the lower, middle, or total face height increase. This finding was even more unexpected since there was a correlation ($p<0.001$) with the growth in mandibular length ΔAr-Progn. These two distance measurements were quite far apart and also not in the same direction. When eliminating the influence of the variable sex there wasn't even an association between the growth in S-N and *cross*. S-N seemed to behave quite differently from the other length measurements.

Midfacial vertical growth as well as growth in the lower face height are more closely related to the change in variable *cross* than to that of the mandibular variable Ar-Progn. While midfacial growth and a posterior rotation of maxilla (increase in NL-NSL) were positively correlated no such association could be found for lower facial height growth and either ML-NSL or ML-NL.

The change in anterior facial *index* could be associated with maxillary and mandibular rotation and midfacial and lower facial height development.

A highly significant correlation coefficient between the increase in length measurements Δ*cross* and ΔAr-Progn with an anterior rotation of the Frankfort plane relative to NSL was evident. The size of these coefficients decreased only slightly when controlling for the effect of the subjects sex. The coefficients were with 0.498 and 0.467 still significant at $p<0.01$. No mechanism or explanation could be found for this observation.

The two different methods to measure chin prominence $PgNB_{mm}$ and *chin* showed related changes. These were not related to changes in any of the other skeletal variables. Also the changes in symphysal width did not correlate with any of the other growth effects. This was somewhat surprising as the actual chin prominence did show highly significant correlations with -for example- ANB, ANPg, ML-NSL, and *cross*.

It was also checked whether the morphology at the beginning of the observation period (at the age of 6) could lead to assumptions about the future changes that would occur during growth. In Table 3.12 the changes of the variables (to the right) are correlated with the variables themselves as they were at the first examination (downwards). Through the use of partial correlations the effects of sex differences was eliminated.

The highest coefficient ($r=0.601$) was found between the angle SNA and the change of SNA during growth. If SNA was large in the beginning only a small increase or even a decrease was to be expected. This represented some kind of self-correction mechanism. Similarly SNA tended to decrease more if ANB was large in the beginning. It was surprising to also find that mandibular prognathism (SNB and SNPG) increased less and flexion of the cranial base decreased in cases with a large SNA. This represented a development towards a more retrognathic face in cases with maxillary prognathism, which would be opposed to self-correction.

With a large NSBa-angle (little flexion of cranial base) this angle tended to decrease (self-correction; $p<0.001$) and maxillary inclination showed a trend towards an anterior rotation. A retrusive forehead (small angle *ForeHead incl*.) was associated with less forward growth of the mandible (ΔSNB, ΔSNPg) and a decrease of NSBa. However, cases with a retrusive forehead did have more prognathic mandibles in the first place (Table 3.7).

Subjects with a large total face height ("long face") showed above-average increases in lower face height and a decrease in *Index* towards a more open configuration. A large midfacial height in the beginning also resulted in decreasing values of *Index* as did a large Y-axis angle. A large lower facial height led to even more vertical growth in the lower face and thereby

Table 3.12 Correlation coefficients between the variables at the first examination (6 years) and the change of these variables during the following 12 years, controlled for the variable sex.

Changes ➜ Variable at 6 yrs ⬇	ΔSNA	ΔSNB	ΔSNPg	ΔNL-NSL	ΔNSBa	ΔN-Gn	ΔN-Sp'	ΔSp'-Gn	ΔIndex
SNA	**0.601**	0.443	0.450		0.421				
SNB									
SNPg									
ANB	0.451								
ANPg									
ML-NSL									
NL-NSL									
ML-NL									
Gn-tgo-Ar									
NSBa				0.434	**0.562**				
FH-NSL									
OrbNA									
ForeHead incl.		0.493	0.428		**0.533**				
S-N									
N-Gn								0.497	0.498
Cross									
ArProgn									
$PgNB_{mm}$									
Chin									
Symph width									
N-Sp'									0.440
Sp'-Gn						0.419		**0.540**	
Index									
Y-axis									0.461

n = 39; all correlations listed $p < 0.01$, those in **bold** $p < 0.001$; 2-tailed test

also in total face height. For all of these vertical measurements no self-correction but rather a worsening of the situation could be observed.

None of the changes in other variables displayed significant correlations with the initial measurements. This included the variables ANB and ML-NSL that would be of special interest in orthodontic treatment planning.

Changes of individual craniofacial pattern in relation to average growth

For each subject and registration the ten principle components found in section 3.4 without the variable *FH-NSL* (leaving 9) were treated as a vector. These values were standard normalized (z-transformed) using the means and standard deviations for each age group separately for boys and girls. After this procedure every transformed variable showed a mean of zero and a standard deviation of 1.0. Then it was checked which distance lay between each subjects vectors from registration to registra-

Table 3.13 Mean distances between 9-dimensional vectors between different registrations

	$\bar{x}$	S.D.	median
6–9 yrs	1.383	0.416	1.345
9–12 yrs	1.069	0.362	1.071
12–15 yrs	0.995	0.346	0.931
15–18 yrs	1.016	0.453	0.903
9–15 yrs	1.416	0.487	1.374
6–18 yrs	2.087	0.505	1.979

tion. Table 3.13 gives these distances for all 3-year periods as well as the periods from 9 to 15 and 6 to 18 years of age.

For all 3-year periods the distances lay around 1.0 with the exception of the period 6 to 9 years where it was 1.38. A distance of 1.0 could result if -for example- all 9 variables changed each by ⅓ of the corresponding standard deviation of that variable relative to the population mean. This would be, for example, about 0.9° for *SNB* or 2.2° for *Gn-tgo-Ar*. If certain variables showed less change, other must have varied in relation to the group mean more than average.

Table 3.14 Mean positive changes between diffe-rent registrations for each of the 9 PC variables. FH-NSL also shown for this univariate listing

period: variable:	6-9	9-12	12-15	15-18	9-15	6-18
SNB	0.33	0.27	0.23	0.23	0.37	0.54
ANB	0.38	0.32	0.29	0.33	0.40	0.51
NL-NSL	0.47	0.43	0.39	0.41	0.57	0.74
ML-NL	0.33	0.25	0.24	0.22	0.36	0.51
Gn-tgo-Ar	0.25	0.18	0.21	0.24	0.26	0.39
NSBa	0.37	0.29	0.29	0.26	0.36	0.56
ForeHead	0.36	0.26	0.23	0.31	0.38	0.57
$PgNB_{mm}$	0.48	0.30	0.27	0.30	0.40	0.73
Index	0.41	0.29	0.30	0.24	0.40	0.57
(FH-NSL	0.56	0.46	0.37	0.44	0.57	0.75)

To find out if there were difference between the constancy of the variables the changes in the z-normalized variables were also analyzed individually for each variable (Table 3.14). The variable *Gn-tgo-Ar* was clearly the one with the least relative change. This variable had a relatively high standard deviation (between 5.61 and 8.01 depending on the age group; Table 3.1). Relative to this considerable inter-individual variation this angle proved rather stable intra-individually. While *Gn-tgo-Ar* showed a steady and significant decrease during growth (Tables 3.1 and 3.4) only small intra-individual variations in this trend could be observed. Thus a relatively large gonial angle in a young individual remained large and a smaller one tended to remain small. The variables *NL-NSL*, *FH-NSL*, and to a degree $PgNB_{mm}$ showed the highest average intra-individual variation.

In the next step it was tested whether there was a relationship between a subject being far away from the group mean and the amount of change in craniofacial pattern. A meaningful self-correction mechanism should show as negative correlation coefficients, a further unfavorable development of the status quo as a positive correlation coefficient. The correlation coefficients in Table 3.15 showed that no such associations existed. None of the coefficients reached significance.

In Table 3.16 it was tested if there was a correlation among the amounts of pattern changes between the different observation periods. Again no significant correlations could be found. Therefore it could neither be shown that subjects who showed a great deal of change when they were young also displayed large changes when they were older nor that young subjects who showed large pattern changes became very stable when they were older. The amount of pattern change during the different age periods appeared uncorrelated.

Table 3.15 Correlation coefficients between distance of patient vector from group mean (top of table) and change in pattern during different periods (left).

	Distance from group mean at age				
Change:	6	9	12	15	18
6-9	0.006	-0.005	0.096	0.171	0.201
9-12	-0.221	0.047	0.045	0.124	0.150
12-15	-0.114	-0.070	-0.067	0.005	-0.103
15-18	-0.217	-0.223	-0.214	-0.232	-0.187
9-15	-0.144	0.048	0.042	0.219	0.114
6-18	0.022	-0.195	-0.149	-0.163	-0.122

no significances at $p < 0.01$, two-tailed test

Table 3.16 Correlations between the amounts of pattern change during the different age periods.

Periods:	6-9	9-12	12-15	15-18
6-9	1.000	0.205	-0.051	-0.162
9-12		1.000	0.011	0.123
12-15			1.000	0.294
15-18				1.000

no significances at $p < 0.01$, two-tailed test

The last test looked into the mode by which the pattern changes came about. It was checked whether a variable showed a monotonous change in one direction or whether the changes were unsystematic with varying directions. In Table 3.17 the direct distances between the 6- and 18-year vectors were compared to the sum of the four distances between 6 and 9, 9 and 12, 12 and 15, and 15 and 18. Also shown is the ratio between these two figures. If the change occurred in a uniform direction there should be no difference between these two measures and the ratio should be close to 1.0. If the direction of pattern change shifted very much a large difference between the two measures should be detectable. Here the ratio would show a larger figure because the straight line is shorter than the dogleg or even zigzag path.

No big differences appeared between the variables. For all of them the sum of the 3-year differences was about twice as large as the direct difference between the 6- and 18-year value. The values for *PgNB*$_{mm}$, *SNB*, and *ForeHead* showed a slightly more consistent behavior while the variable *ANB* displayed a more varied development. The development of the sagittal base relationship was therefore more apt to be influenced by intra-individual variation.

Table 3.17 Distance between 6- and 18-year z-transformed variables compared to the sum of the 4 observation intervals between 6 and 18 years.

	Δ_{6-18}		$\Sigma_{3\text{-yr diffs}}$		ratio
	$\bar{x}$	s	$\bar{x}$	s	
SNB	0.54	0.44	1.06	0.52	1.96
ANB	0.51	0.36	1.28	0.45	2.51
NL-NSL	0.74	0.53	1.63	0.68	2.20
ML-NL	0.51	0.33	1.03	0.33	2.02
Gn-tgo-Ar	0.39	0.35	0.85	0.35	2.18
NSBa	0.56	0.40	1.14	0.51	2.04
FH-NSL	0.75	0.44	1.60	0.61	2.13
ForeHead	0.57	0.39	1.12	0.41	1.96
PgNB$_{mm}$	0.73	0.56	1.40	0.63	1.92
Index	0.57	0.41	1.22	0.47	2.14

Individual line drawings

As a next step all sets of X-Ray data for each patient were superimposed after being corrected for different sizes at each registration. Again, changes in shape and pattern became apparent because they were not masked by the changes in size.

The two patients in Figure 3.15 displayed a craniofacial pattern that remained almost completely unchanged from 6 to 18 years of age. The same proportionate growth changes occurred in all parts of the facial skeleton and thus a mere congruent increase in size took place. The only exception to this observation is the frontal bone which showed the relative retroclination of the upper end of the frontal bone. This could be found for every patient in the sample.

It has to be kept in mind that in reality the different bones of the facial skeleton do not expand as could be deducted from the drawings. As Bjørk (1947) has shown growth in the face results from surface remodeling, condylar

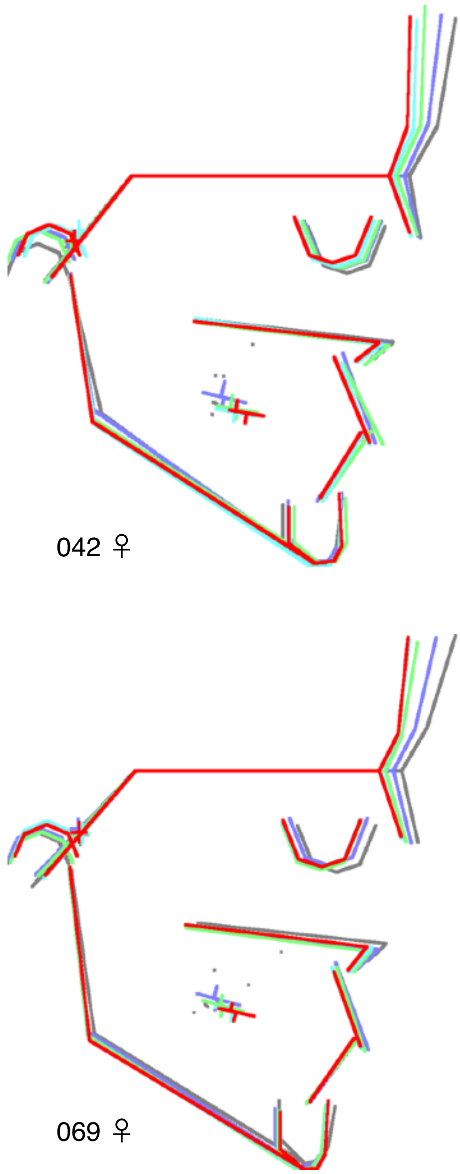

Fig. 3.15 Example for two subjects that did not display significant changes in skeletal morphology during growth. Size-adjusted superimpositions at ages 6, 9, 12, 15, and 18 years.

growth, and sutural growth. However, in the patients that did not show a change in pattern these different growth in these different regions and modes must have occurred in a very well coordinated manner.

Figure 3.16 shows four examples that displayed changes in their craniofacial pattern during growth. Subject *015* showed a parallel anterior rotation of both the maxilla and the mandible. The anterior rotation of the mandible resulted from average vertical growth in the posterior region (ascending ramus/condyle) and less than average vertical growth in the anterior region. Actually the reason seemed to lie partly in a slow vertical growth of the anterior maxilla and not only in a hindered tooth eruption. Through the occlusal contacts of the teeth this was transferred to the mandible.

Subject *008* also exhibited a clear anterior rotation of the mandible. But here the maxilla followed an average growth path without marked rotation and the origin of the mandibular rotation was different. Vertical growth in the posterior region was above average and resulted in a strong downward thrust of the gonion region. Alveolar growth was only average and therefore the mandible rotated anteriorly with an axis further anteriorly than in subject *015*.

Subject *027* did not show differences in the vertical growth between the anterior and posterior region. He demonstrated a discrepancy between sagittal and vertical growth. The downward displacement of the mandible and maxilla in the size adjusted line plot shows that vertical growth was above average, especially from 6 to 12 years. At the same time horizontal growth was clearly less than could be expected as can be seen from the dorsal movement of both jaws.

Differences in the sagittal development can be seen when comparing the size adjusted superimpositions of subjects *015* and *081*. *015* revealed a strong, above average horizontal growth of the mandible, while the maxilla shows an average sagittal growth. In the size adjusted plots A-point does not move horizontally until 15 years of age. Then it increased its horizontal growth velocity slightly. Unusual in this patient is the nearly proportionate increase of the distance between *sella* and *nasion*. Almost all subjects showed a less than proportionate increase of this distance.

Subject *081* displayed quite a different behavior. Here horizontal growth of the mandible was below what could be expected. In the size adjusted superimposition *B-point* and *pogonion* moved dorsally. The reason in this case was not

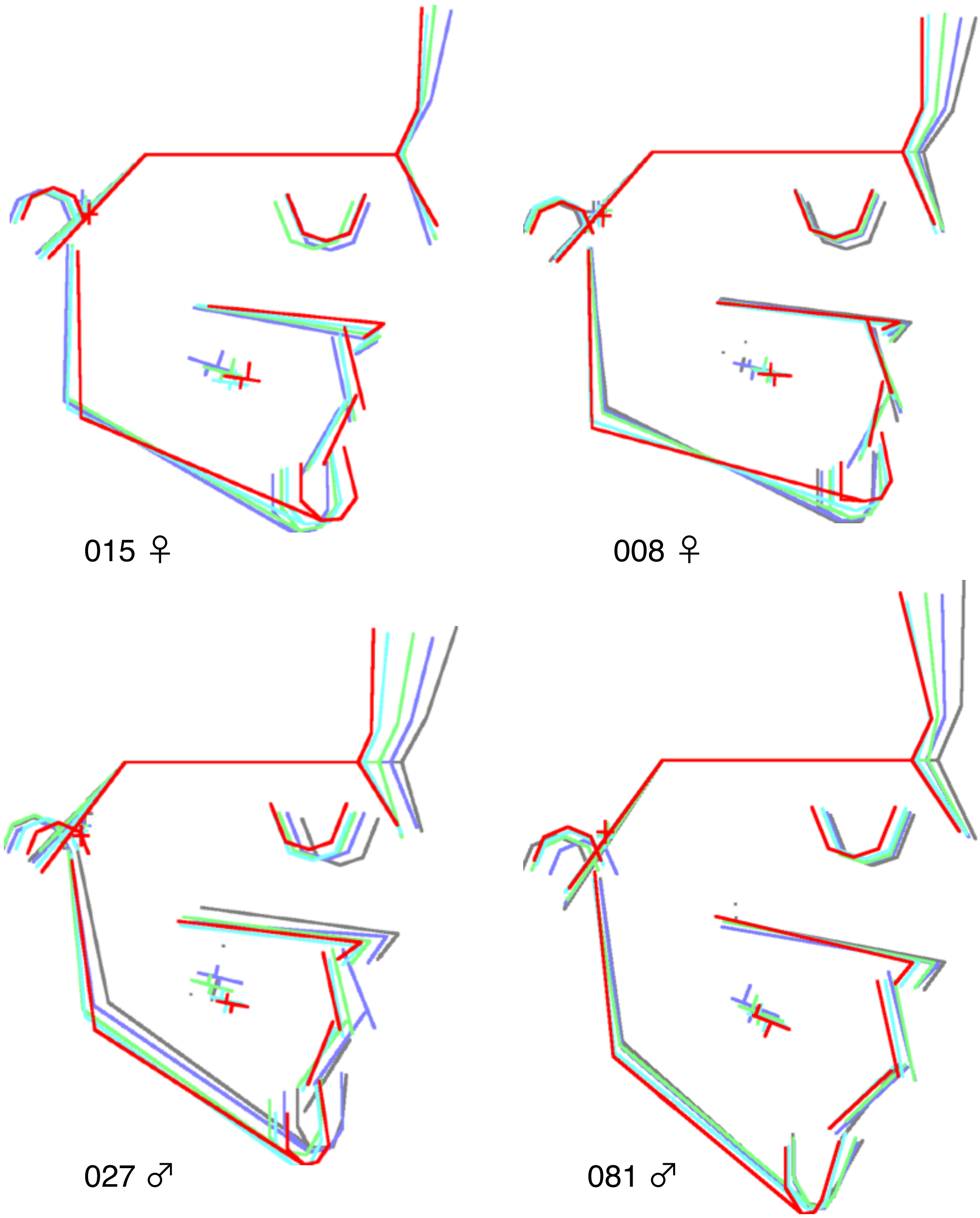

Fig. 3.16 Four subjects that displayed changes in skeletal morphology during growth. Size-adjusted superimpositions at ages 6, 9, 12, 15, and 18 years.

a posterior rotation of the mandible (actually it rotated slightly anteriorly) but a below average horizontal translation. Had the maxilla not shown a similar decreased sagittal growth the patient would have developed a more severe distal skeletal relationship. Actually the sagittal skeletal relationship remained rather distal. The development of *ANB*-angle was

$$8.0° \rightarrow 7.9° \rightarrow 7.7° \rightarrow 6.9° \rightarrow 6.4°.$$

4. Discussion

Setup of study

Two factors provoke disagreement among researchers with regard to serial cephalometric studies. One is selection of the material and the other is whether to use a purely longitudinal, a mixed-longitudinal, or a cross-sectional material.

Criteria for selection of the material can be either an "ideal" or acceptable occlusion or it is attempted to draw an unbiased population sample. It is rather difficult to achieve the latter as most selection methods induce some kind of bias. If, for example, all patients who stray into a clinic are used such a sample will lack subjects that have an ideal occlusion and thus no problems. All kinds of selection criteria that are based on school attendance tend to induce a socio-economic bias. Today not even the formerly popular method to use army conscripts (Björk 1947) leads to acceptable results as certain groups of the population tend to be more successful in avoiding the service than others.

In a longitudinal set-up more problems arise because the sample will include patients that require orthodontic treatment and for ethical reasons such treatment cannot be denied. If a group of subjects has to be excluded because of orthodontic treatment or dentofacial orthopedics the sample cannot be called representative any more.

Lastly for any such study the cooperation of the patients is indispensible. Lack of cooperation can stem either from passive sluggishness (not showing up) or from active disapproval (fear of radiation exposure). Either reason has again a selective effect.

If it is decided that selection shall be according to certain criteria these have to be set. If very strict criteria are selected it will be hard to collect a sufficiently large material. Most researchers using this approach are therefore more lenient in their criteria. Hummerfelt and Slagsvold (1972) accepted a "normal occlusion, although slight irregularities in tooth positioning" were allowed. Bishara's (1981) material all had "clinically acceptable occlusion with no apparent facial disharmony". For the present study similar criteria were set up. The requirement for inclusion into the study group was sagitally not more than ¼ of a premolar width deviation from an Angle class I relationship on both sides or ½ premolar width on one side if the other was in neutral occlusion. Vertically neither open nor deep bite was tolerated and only a moderate amount of crowding.

In the present study no attempt was made to use the facial impression as a criteria. Such a criterion would require objective standards and in addition it was considered unappropriate for the study. Had the study dealt on the esthetic appearance during growth such a selection criterion might have been necessary.

Table 4.1 Comparison of standard deviation of angle ANPg in male young adults between different studies

Author	$\bar{x}$	s
Björk & Palling 1953		
unselected	1.3	3.0
Solow 1966	0.41	3.10
unselected		
Solow/Sarnäs 1982		
Swedes, unselected	0.91	3.13
Danes, unselected	0.23	3.01
Segner 1992	0.05	2.32
only Class I		
Segner 1991	2.38	2.11
only Class II		

What will be the effects of using an Angle class I occlusion as a selection criterion compared to not using any criterion? As severe skeletal malocclusions tend to be accompanied by dental malocclusions these are more likely to not be included in the sample. This will usually not show in the mean values that tend to be rather similar. It seems that the extreme cases that are excluded by the selection process lie on both sides of the neutral spectrum and therefore don't show any net effect. However, the selection method does have an influence on the standard deviation. If the extremes of a distribution are clipped the standard deviation will be small. Table 4.1 compares the standard deviations of the variable ANPg in 6 different investigations. In those studies that did not use a selection criterion the standard deviation is very close to 3° while in those that use Angle class as a selection criterion it is closer to 2° even if the selection criterion is Angle class II.

As one of the goals in orthodontic therapy is the establishment of an acceptable occlusion it is of prime interest for clinical purposes to use such craniofacial situations as a reference or norm where such an occlusion has been achieved. The theory behind this way of thought is that if occlusal guidance mechanisms in nature and/or compensatory mechanisms are able to arrive at an acceptable occlusion it should also be possible to attain this goal through mechanotherapy. Such associations of cephalometric measurements thus seem to be appropriate as normative values.

There are, therefore, two reasons for using a selection criterion for the present study, no uncontrolled bias and better usefulness as a reference basis for clinical application.

The advantages of a purely longitudinal material are obvious. Ødegaard (1970) and Bishara (1981) emphasized this fact. With the finite size of patient samples the standard error of the estimate is often as large or even larger than the changes between two observations due to growth. For the angles SNA and SNB annual changes are usually below 0.4° and the confidence intervals for the mean will be around $\overline{x} \pm 0.8°$ for a group size of 50. Even with a sample ten times larger (n=500) it would still be $\overline{x} \pm 0.3$. It is therefore not at all improbable that the growth related changes of a variable, that are present in the population, do not show because two different samples of the population are compared.

Longitudinal studies do bring about a number of more practical problems. It takes a long time to accumulate a material. In the case of the material used for the present study collection was started in 1971 and still continues. It is difficult to ensure the necessary continuity in the staff of the institution and in the X-Ray equipment (no change in enlargement factor) and problems also arise in tracking the patients when they have moved. Most of these problems could be circumvented because the material used in the present study is only part of the whole material collected from Nittedal. Only cases that fulfilled the requirements were selected after the material was available. However, due to a limited number of class I subjects that were available for all of the registrations some compromises had to be accepted. It is for this reason that the study was not limited to the purely longitudinal subgroup of the sample (n=39). Through the inclusion of another 41 subjects the number could be brought up to 80. Since every patient in the sample was followed for at least 9 years out of the maximum of 12 years the the longitudinal character of the material predominates.

Selection of landmarks, reference lines and variables and method of superimposition

The landmarks used in this study were selected with regard to easy and direct localization. No complicated constructions should be necessary to find a landmark. The landmark error had to be within acceptable limits. For this study the specific directionality of the landmark error of the individual landmarks was considered.

While it is possible to measure a sheer limitless number of variables on a lateral headplate, the selection of variables should be restricted to those that give the necessary information about the skeletal morphology. For orthodontic purposes this would mean the anteroposterior position of maxilla and mandible in relation to each other and in relation to the cranial base, the vertical position of maxilla and mandible in relation to each other and in relation to the cranial base, and the inclinations of maxilla and mandible in relation to each other and in relation to the cranial base. It seems advantageous if a variable measures only one single of these morphological criteria rather than a mixture of two or more of them. In this way interpretation of the data is easier.

It also seems to be beneficial if the variables are easily understandable; that is if the operator can estimate how a variable would change if the morphology is changed. Especially the arithmetic combination of several measurements is likely to disguise the real nature of the problem.

Most important the variables should be accurately and reproducibly measureable. Low reproducibility leads to unstable and sometimes even wrong results of a clinical analysis. In addition it is more difficult to test hypotheses with the necessary accuracy. Many significant results will go undetected in general noise.

The finding that the landmark scatter isn't of circular shape and that some landmarks are better suited for vertical measurements and others for sagittal measurements supports the findings of Richardson (1966), Baumrind and Frantz (1971[a]).

The landmarks *sella* and *nasion* evolved as the ones with the smallest landmark variance with the exception of the dental landmarks maxillary and mandibular incisal edge. This high accuracy was valid for horizontal and vertical measurements. The other two investigations ranked the landmarks similarly although there the standard deviation was somewhat larger. The good accuracy of the landmark *porion* in Baumrind and Frantz' study could not be confirmed for the present data. Especially the fact that *porion* was not always unambigously determinable impaired its usefulnes severly. Similarly *orbitale* was not as reliable as would be desirable.

These findings directly led to the selection of reference lines. The most stable line proved to be the *NSL* because both landmarks were very acurately locatable and also quite far apart. All other reference lines were selected with the orientation of the landmark scatter in mind. Measurements like the angle SNSp and the distance SpPm should be avoided if at all possible. The line NBa isn't optimal either since *basion* shows the least landmark error perpendicular to the long axis of clivus.

The method of superimposition of a sequential series of X-rays taken of the same patient is of major importance. Houston and Lee (1985) compared different methods and found the superimposition on the nasion-sella-line in point *sella* to be the most accurately reproducible one. This reproducibility doesn't necessarily mean it is the best method. It has to be kept in mind that there is no "naturally correct" structure for superimposition. The cephalometric landmark *nasion* does change its position during growth not only in the sagittal plane but also in the vertical direction. Slight differences might therefore arise between superimpositions on the osseous structures of the anterior cranial base (Fig. 4.1) and superimpositions on the *NSL*. For the present study the NSL was chosen as this is the reference line that is most widely used in clinical cephalometrics.

Superimpositions on osseous structures are only possible if the radiographs have exactly

Fig. 4.1 Superimposition on the osseous structures of the anterior cranial base (Houston and Lee 1985)

the same enlargement factor and are of good quality. Overexposure or the lack of contrast make it almost impossible to adjust the X-rays in the correct position. In clinical analyses and also for most scientific studies a superimposition on the NSL is considered more reliable. Following these thoughts this method was also used for the present study.

Means and standard deviations

The data resembles general trends that have been published by other authors who have employed a similar methodology. Differences show up in the absolute values and some details of the changes. Table 4.2 compares the results of the present study with those of Berg (1983). He selected his material from the same base material (Nittedal). His norm-occlusion group consisted of 30 subjects with a strong bias toward females. As he did not list separate values for boys and girls for the norm-occlusion group the data of the present study had to be adjusted to reflect the same sexual bias. This was achieved using

$$\bar{x}_{adj} = \frac{9}{30}\bar{x}_{♂} + \frac{21}{30}\bar{x}_{♀}$$

It is surprising to find substantial differences. The measurements describing prognathism deviated by 1° to 2° consistently for all age groups. Inclinations of the jaws deviated by -0.5° to -2.0° and the angle *NSBa* by -3.5°. Two reason could explain these difference. One is the fact that Berg used a smaller group. By selecting his 30 cases from the whole material he might have inadvertently picket a group that displayed mean values that somewhat deviate from the population mean. Similar effects on a smaller scale might be true for the present material. The other reason might be systematic differences in the perception of landmarks or in the measurement technique. Berg measured the cephalograms using a digital read out system while the present study employed a digitizer coupled directly to the data processing equipment.

The differences in the linear measurements result mainly from the radiographic enlargement. Berg's values for *S-N* are between 7.11% and 7.35% larger and for *N-Gn* these numbers are between 8.23% and 8.80%. The calculated enlargement factor that was used to mathematically correct linear measurements in the present study was 7.06% (Section 2.2) and thus lies close to these differences.

The comparison again emphasizes the difficulties in comparing mean values from different studies. For an accurate and reliable comparison it seems necessary to have all radiographs evaluated by the same author as Solow and Sarnäs (1982) have done. Growth differences found in longitudinal studies are easier to compare as methodological differences are almost eliminated when calculating the differences between two measurements of the same subject.

The values found in the present investigation were compared to those of some others investigations in Table 4.3. The comparison with Hummerfelt and Slagsvold's (1972) data shows nearly perfect agreement when looking at the changes during the growth after 12 years of age. None of the variables showed differences of more than 0.2° when looking at the changes. The means were also very similar. Only the mandibular prognathism (SNB, SNPg) was about 1° smaller in Hummerfelt and Slagsvold's group. This material was different from the present but collected from the same region (Oslo).

Björk and Palling's (1953) data didn't differ very much either.

Table 4.2 Comparison of means in present study with those of Berg (1983). Present study adjusted for Berg's ratio of male to female (21 ♀ / 9 ♂).

	present study sex ratio adjusted			Berg 1983 21 ♀ / 9 ♂		
	6	9	12	6	9	12y
SNA	81.0	80.3	81.0	82.8	81.9	83.1
SNB	77.3	77.7	78.7	78.2	78.4	80.1
SNPg	77.3	78.3	79.8	78.1	79.0	80.8
ML-NSL	34.1	33.0	31.5	33.8	33.5	30.7
NL-NSL	8.1	8.4	8.5	6.0	6.9	6.4
ML-NL	26.1	24.6	23.0	27.9	26.4	24.6
Gn-tgo-Ar	129.7	125.8	123.9	128.2	125.4	123.7
NSBa	134.2	133.8	133.4	131.2	130.9	129.8
S-N	60.1	62.6	64.7	64.4	67.2	69.3
N-Gn	91.1	97.7	102.9	98.6	106.3	111.4

However, their values for prognathism were smaller, especially in the lower jaw. The increase in prognathism was also less, again especially in the lower jaw. As a result SNB and SNPg were about 1° smaller in the adult group.

Studies by Riolo et al. (1974), Solow and Sarnäs (1982), and Solow (1966) were included to check for regional differences and the applicability of the data. It seemed that the subjects in the present investigation were slightly more prognathic than those in the Danish and Swedish samples. This was true for the Hummerfelt/ Slagsvold sample as well. Regarding the inclinations the present material compares well with the Danish samples. The Swedish material displays a more posterior inclination of the mandible and a larger gonial angle. None of these differences are large or of clinical significance.

Regarding the linear measurements differences appeared due to the lack of any correction for radiographic enlargement in the other studies. All Scandinavian studies claim an enlargement factor of 5.6%. The differences between the studies for the linear measurement *S-N* lie between 6.7% and 9.9%, both Solow and Sarnäs (1982). For the vertical measurement *N-Gn* the values were 13.3% (Lindegård 1953) and 11.2% (Solow 1966). With these results it seems questionable if the enlargement factor was calculated correctly in these studies. It seems probable that it should be larger than 5.6% and closer to 7.06% as calculated in the present study.

Riolo et al.'s data for the 12 year old boys differs substantially from the data by Björk and Palling, Hummerfelt and Slagsvold, and the present study. All inclination angles and the

Table 4.3 Comparison of means in present study with those of other studies for male subjects at the age of 12 years and adulthood/18 years

♂	present study		Björk/ Palling		Hummerfelt/ Slagsvold		Riolo et al.	Solow & Sarnäs DK	Solow & Sarnäs S	Solow
	12	18	12	20	12	25	12	adult	adult	adult
SNA	81.6	82.5	81.3	82.0	81.5	82.6	81.2	81.4	82.4	82.0
SNB	79.1	81.1	77.8	79.3	78.2	80.3	77.3			79.4
SNPg	79.8	82.5	78.8	80.7	79.1	81.8	77.9	81.0	81.5	81.2
ANB	2.5	1.4	3.4	2.7	3.3	2.4	3.9			2.4
ANPg	1.8	0.1	2.5	1.3	2.3	0.8		0.2	0.9	0.4
ML-NSL	32.3	28.1					33.8	28.0	29.4	28.2
NL-NSL	8.4	8.0		7.6[a]			6.5	7.6	6.7	7.7
ML-NL	23.9	20.1					27.3	20.3	22.7	21.0
Gn-tgo-Ar	125.9	120.5					126.5	120.1	123.0	120.4
NSBa	132.7	131.2		131.6[b]			129.3	130.5	129.3	129.6
FH-NSL	8.7	7.8					(4.5)			
S-N	64.9	68.8		73.7[b]			78.3[c]	73.4	75.6	73.6
N-Gn	104.1	113.8		128.9[a]			123.3[c]			126.6
ArProgn	97.7	108.8					113.0[c]			
PgNB$_{mm}$	1.2	2.5					1.3[c]			
1-NA°	23.1	21.7					22.8			
1-NA$_{mm}$	3.9	4.4					4.3[c]			
$\bar{1}$-NB°	26.1	23.9					26.1			
$\bar{1}$-NB$_{mm}$	4.2	4.0					5.2[c]			
$\bar{1}$-APg$_{mm}$	2.3	2.2					2.2[c]			
Y-axis	66.0	64.7					67.1			

[a] Lindegård 1953
[b] Björk 1955
[c] 12.7% radiographic enlargement according to Riolo et al.

angle between the *Y-axis* and *NSL* are larger for the Michigan material. Their mandibular prognathism is substantially smaller and maxillary prognathism slightly smaller than in the European materials. The incisor inclinations and positions relative to the NA- and NB-line coincide well with the present study. The linear measurements show a quite different picture.

Even when accounting for the radiographic enlargement given by the authors their linear measurements are larger than in any other study. The corrected *S-N* is with 69.5 mm almost 5 mm larger than the value for the present material at 12 years of age. The values for *N-Gn* and *Ar-Progn* are also 5.3 and 2.6 mm larger than in the present study. These findings underline the importance of paying due attention to the radiographic enlargement in comparative studies as well as in the application of "standards" in clinical diagnosis. The use of angles or ratios eliminates this problem and leaves only discrepancies due to regional differences. From Table 4.3 it seems that even these can be substantial and in comparative studies the selection of a control material should include careful consideration if the region the control material comes from really represents the same morphology as the region from which the study material comes.

Figure 4.2 shows the development of the most important variables graphically. It is apparent, that differences do exist between the investigations. These differences can be found for the absolute values more than for the changes. The material that deviates most is that by Riolo et al. It shows notably more retrognathic mandibles and larger ANB angles. The ML-NSL angle starts at about the same value, but decreases less during growth. At 16 years of age it is more than 3° higher. It is surprising that the material from Michigan shows such substantial differences as the population in that region is mainly of European if not northern European ancestry. These differences included not only the absolute mean values but also the changes over time. This finding implies that standard values from American studies might not be adequate as control data for Northern European studies.

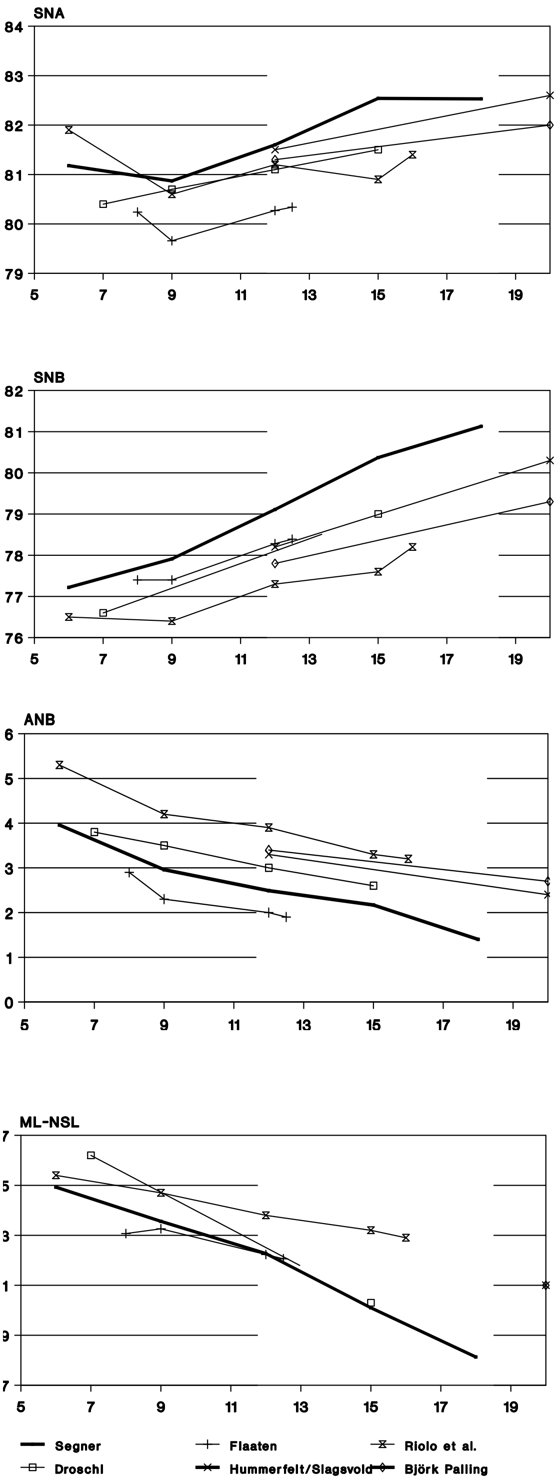

Fig. 4.2 Development of SNA, SNB, ANB, and ML-NSL for male subjects in different investigations

The data by Droschl differs in that it was assembled using a rather different method. Droschl used the average values for a 7-year old group and a 15-year old group and interpolated all other values. No values are listed for adult persons.

The present material shows highest degree of prognathism and the lowest mean ANB angle in the final years of growth. When comparing the curves from Hummerfeld/Slagsvold and Björk/ Palling it is difficult to determine the slope of these lines as both studies used an age for the second registration that was well past the end of growth (25 and 20 years respectively). In the present investigation it is well possible that not all subjects have finished their growth period. Some of the male subjects might continue to grow after the age of 18, especially in the lower jaw. However, the small amount of such growth wouldn't change the mean of the whole group substantially.

The differences between male and female subjects regarding the linear measurements were not surprising. Rather the absence of such differences at the younger ages requires some explanation. While the mean values for the boys were always higher, the difference up to the 12-year examination was small (Fig. 3.7). At the very early ages there is not a large difference between the size of boys and girls in the first place. Later the girls enter the pubertal growth spurt earlier and nearly catch up with the boys. Only after the boys enter their pubertal growth spurt do they separate from the females. For the same reason Bishara (1981) set up identical standards for boys and girls from 5 to 7 and for 8 to 10/12 years of age.

The differences in the angular variables representing sagittal base relationship at 15 years can be explained by the fact that the girls almost reached their final adulthood values at that age while the boys were still close to their pre-pubertal values.

Although Hummerfeld and Slagsvold (1972) didn't test for differences between male and female subjects, they nevertheless listed mean values separately. In contrast to the present study they found prognthism angles that were some 0.5° larger in the females at 12 years of age. At 25 years the angle SNA remained 1° larger in the females while the mandibular angles were 0.5° and 0.7° respectively smaller. The sagittal base relationship was similar in boys and girls at 12 years for both studies. Unexpectedly the SNA-angle increased in Hummerfelt and Slagsvold's study for the females from 12 to 25 years by 0.1°. This behaviour differed from the present study were the angle decreased by 1.0° from 12 to 18 years.

Bivariate associations

Few studies have looked into correlations between cephalometric variables. Solow (1966) and Segner (1989) listed correlations only for adult patients, while in the present investigation the sample consists of subjects of 5 different age groups. Solow used the linear cephalometric variables *S-N*, *N-Gn*, and *Pgn-Cd* in his study. *Pgn-Cd* wasn't used in the present study. However, it represents mandibular length similarly to *Ar-Progn*. The ranking of the correlation coefficients in Solow's study was the same

Table 4.4 Comparison of correlation coefficients among angular skeletal variables between Solow's (1966) data and present study (only adult ♂)

	SNA	SNB	SNPg	ANB	ANPg	ML-NSL	NL-NSL	ML-NL	Gn-tgo -Ar	NSBa
		0.84	**0.75**	0.29	0.26	0.34	0.34	0.20	-0.01	<u>0.51</u>
SNA		0.83	0.71	0.14	0.17	-0.41	0.01	-0.46	0.04	-0.41
		0.70	*0.52*	*0.39*	*0.44*	*-0.17*	*-0.21*	*-0.10*	*0.04*	*-0.30*
	0.84		**0.97**	0.28	0.28	0.58	0.43	0.40	-0.12	**0.56**
SNB	0.83		0.96	-0.44	-0.37	-0.64	-0.45	-0.48	-0.02	-0.35
	0.70		*0.90*	*-0.35*	*-0.26*	*-0.48*	*-0.30*	*-0.36*	*-0.10*	*-0.26*
	0.75	**0.97**		0.39	0.45	0.67	0.42	0.50	0.21	<u>0.51</u>
SNPg	0.71	0.96		-0.55	-0.57	-0.72	-0.50	-0.55	-0.09	-0.24
	0.52	*0.90*		*-0.49*	*-0.51*	*-0.64*	*-0.32*	*-0.49*	*-0.20*	*-0.29*
	0.29	0.28	0.39		0.95	0.42	0.16	0.36	0.19	0.10
ANB	0.14	-0.44	-0.55		0.93	0.48	**0.82**	0.11	0.10	-0.03
	0.39	*-0.35*	*-0.49*		*0.93*	*0.42*	*0.13*	*0.35*	*0.22*	*-0.05*
	0.26	0.28	0.45	0.95		0.52	0.16	0.46	0.29	0.06
ANPg	0.17	-0.37	-0.57	0.93		0.54	**0.72**	0.23	0.18	-0.14
	0.44	*-0.26*	*-0.51*	*0.93*		*0.48*	*0.13*	*0.41*	*0.24*	*-0.01*
	0.34	0.58	0.67	0.42	0.52		0.28	0.90	0.68	0.14
ML-NSL	-0.41	-0.64	-0.72	0.48	0.54		0.46	0.89	0.64	-0.05
	-0.17	*-0.48*	*-0.64*	*0.42*	*0.48*		*0.23*	*0.86*	*0.74*	*0.07*
	0.34	0.43	0.42	0.16	0.16	0.28		0.16	0.02	0.32
NL-NSL	0.01	-0.46	-0.50	**0.82**	**0.72**	0.45		-0.01	0.12	0.12
	-0.21	*-0.30*	*-0.32*	*0.13*	*0.13*	*0.23*		*-0.26*	*0.02*	*0.26*
	0.20	0.40	0.50	0.36	0.46	0.90	0.16		0.69	0.00
ML-NL	-0.46	-0.48	-0.55	0.11	0.23	0.89	-0.01		0.66	-0.11
	-0.10	*-0.36*	*-0.49*	*0.35*	*0.41*	*0.86*	*-0.26*		*0.71*	*-0.06*
	-0.01	-0.12	0.21	0.19	0.29	0.68	0.02	0.69		0.14
Gn-tgo-Ar	0.04	-0.02	-0.09	0.10	0.18	0.64	0.12	0.66		-0.24
	0.04	*-0.10*	*-0.20*	*0.22*	*0.24*	*0.71*	*0.02*	*0.71*		*-0.11*
	<u>0.51</u>	**0.56**	<u>0.51</u>	0.10	0.06	0.14	0.32	0.00	0.14	
NSBa	-0.41	-0.35	-0.24	-0.03	-0.14	-0.05	0.12	-0.11	-0.24	
	-0.30	*-0.26*	*-0.29*	*-0.05*	*-0.01*	*0.07*	*0.26*	*-0.06*	*-0.11*	

top line: present study, whole material (♂ + ♀, 6 to 18 years, n=354 x-rays)
middle line: present study, only 18-year ♂ (n=16)
bottom line: Solow 1966 only young adult ♂ (n=102)

Test for difference between correlation coefficients Segner/Solow: <u>$p < 0.05$</u> **$p < 0.01$**

as in the present one with the lowest coefficient between the horizontal and vertical measurements *S-N* and *N-Gn* and the highest between *N-Gn* and *Pgn-Cd*. The coefficients in Solow's study were much smaller than in the present study. This resulted from the fact that in the present study both variables under survey have a strong association with the variable age (Fig. 3.3). The high correlation coefficients are thus indicative of an indirect correlation through the variable age.

Table 4.4 shows the correlation coefficients between some angular skeletal variables from Solow's material (1966) and from the present study. For the present study the data is listed separately for total sample (in the top line of each 3-line stack) and for the 18-year male group only (middle line). Solow's data is shown in the bottom line of each stack. The coefficients for the whole sample should -analogous to the linear measures- be influenced by joint associations with age. As none of these variables was correlated with age very strongly ($r < 0.42$ for all variables) this effect couldn't be found in Table 4.4. Since the male only 18-year group is rather small (n=16) the confidence interval for the correlation coefficient is quite large, the listed coefficients can only show a trend. A calculated ***r*** of 0.5 has a confidence interval of -0.05 to 0.79 for n=16 (Sachs 1984). Table 4.4 also lists the results of a test for differences between the correlation coefficients of Solow's study and the present investigation.

Most coefficients are quite similar but a little higher than those found by Solow. The correlations between the prognathism of the jaws and the sagittal base relationship and between the cranial base flexion and the prognathism of the jaws were higher in the present investigation. Unexpected high coefficients were found in the present investigation for the association between *NL-NSL* and sagittal base relationship. No explanation could be found other than random error. For many combinations the coefficients between the two studies were actually very close together.

In a study with 275 young adult subjects from Northern and Central Europe Segner (1989) found coefficients that were also very similar to the values found in the present investigation and usually slightly larger than the ones found by Solow (Tab. 4.5)

Tab. 4.5 Correlation coefficients between skeletal angular variables (Segner 1989). Young ♂+♀ adults

	SNA	NL-NSL	NSBa	ML-NSL	SNB
SNA		-0.37	-0.36	-0.42	0.82
NL-NSL	-0.37		0.46	0.32	-0.44
NSBa	-0.36	0.46		0.31	-0.45
ML-NSL	-0.42	0.32	0.31		-0.61
SNB	0.82	-0.44	-0.45	-0.61	

n=275; all correlations $p < 0.001$

.In summary it can be said that highly significant correlations exist between most craniofacial angular measurements. The reason for these associations is a combination of topographic correlation and biological variation. Although the associations are highly significant the coefficients themselves are frequently not high. Only few coefficients exceed a value of 0.7. An **r** of 0.7 would result in $r^2=0.49$ and therefore 49% of explained variance. Even with an r of 0.5 half of the variance of the variable under survey cannot be explained by the correlative association and must therefore have other (unknown) reasons.

Principle components, MANOVA, and Pattern changes

It was interesting that one principal component (PC) or factor accounted for 37.3% of total variance. Through the varimax rotation this most important factor could be closely attributed to variables representing the prognathism of the upper and lower jaw. The variables SNA, SNB, and SNPg all had very high loadings of between 0.894 and 0.928. This factor also had considerable loadings from other variables such as ML-NSL, NL-NSL, ML-NL, FH-NSL, and Y-axis.

The importance that has been placed on the prognathism of the facial type (Hasund et al.

1974, Segner 1989, Segner and Hasund 1991) seems to be justified. The *harmony box* introduced by Segner (1989) lists the variables SNA, NL-NSL, NSBa, ML-NSL, SNB, and ML-NL as a function of prognathism. The prognathism is represented by the vertical position of the values in that box.

Somewhat surprising was the fact that the variable ML-NSL did not show as a principle component. The reason was the close association of ML-NSL with the gonial angle and the degree of prognathism. The loadings were split between factors #1 and #3 and to a lesser extent #10 (Tab. 3.9).

Solow (1966) included variables regarding body height and size as well as measurements on plaster casts and linear cephalometric measurements in his principle component analysis. He excluded variables that showed a high correlation between each other. Even with these differences in methodology he found similar PC's among the angular cephalometric measurements. He found factors for cranial base flexion, maxillary prognathism, and mandibular inclination. He did not find a PC for sagittal base relationship or mandibular prognathism, but he found a linear length measurement in the mandible instead. His statement that the evolving of principle components is strongly dependent on the previous selection of the variables that are used in the study and those that are entered into the PC analysis can be underlined.

It seems reasonable to assume that the shape of the facial skeleton can be described by different sets of variables in a similar way that the position of a point in space can be described by rectangular coordinates (x- and y-values) or by a polar coordinate system (direction and distance from the origin) as in Fig. 4.3.

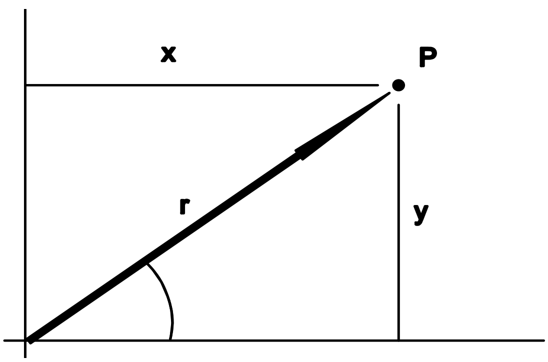

Fig. 4.3 Representation of the position of a point (or the vector from the origin to that point) by either rectangular or polar coordinates

It is therefore not unlikely that a completely different set of variables might result in a completely different set of principle components. It is merely important that care is taken in selecting the variables to ensure that they make up a meaningful and consistent set. In analogy to Figure 4.3 the position of the chin in relation to the anterior cranial base can be described either by a combination of sagittal and vertical measures, for example *SNPg* and *N-Gn* or *ML-NSL*, or by the angle between the NSL and the landmark *prognathion* (*Y-axis*) in combination with a distance measurement (*S-Progn*). The latter method necessitates the use of age, sex, and size related norms to classify the distance measurement. The former method, instead, gives a direct impression of pattern if only the angles are used. In selecting the variables for analyzing lateral radiographs the particularities about landmark error (Section 2.5) should also be observed.

While it is easier to assess the simultaneous growth related changes in size and shape by looking at superimposed line drawings it is much more difficult to perform statistical tests to prove that such changes actually exist. For the MANOVA procedure of which the results are listed in Table 3.10 only angular variables that were selected by the principle component analysis were used. The results showed very clearly that the subjects' sex as well as their age had highly significant influences on the craniofacial pattern. This finding is not surprising since Tables 3.2 and 3.4 showed a significant influence of these two factors on a number of the variables that were selected as principle components. Particularly the variable *Fore-Head incl*. showed a high dependency for age and sex.

The MANOVA procedure did not reveal any interaction between sex and age. Thus it could not be shown that male and female subjects develop significantly different during growth.

The differences that were present between the male and female subjects at the younger ages remained qualitatively unchanged and quantitatively only slightly changed up to adulthood. This result can be supported by looking at the size adjusted superimpositions in Fig. 4.4. The same differences can be found at 6 years of age that become more pronounced during growth and show clearly at 18 years of age. The cranial base flexion is stronger, the ascending ramus of the mandible is more anteriorly positioned, and the mandibular plane is steeper in the male subjects at both ages.

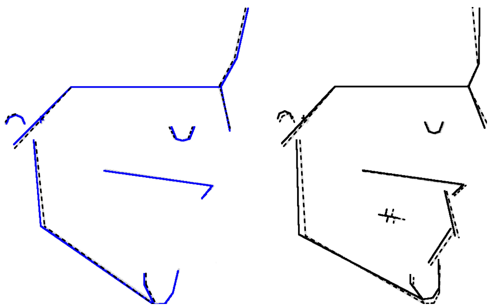

Fig. 4.4 Size adjusted superimpositions of male (broken line) and female (continuous line) averaged scatterplots at 6 (left) and 18 (right) years of age.

Most cephalometric research and statistics are based on groups of patients and the resulting means. Above only the behaviour of the mean values have been discussed, whether univaritely, multivariately, or by averaged polygon drawings. These findings might not represent every individual's behaviour. The consistent decrease of ANB-angle found in this and other studies does not exclude the possibility that ⅓ of the population displays a steady increase in ANB-angle while the remaining ⅔ display a steady decrease. For the clinical situation such individual changes and developments are most interesting. Conventional statistics lacks tools for an easy analysis of such investigations.

Figure 3.16 shows 4 individuals from the present study who did not show the average pattern of growth related changes but rather some very individual patterns. Application of the averaged group data on these individuals will obviously lead to false results. If the average data on pattern change is not always applicable on the individual the question remains *what* data on the pattern changes is applicable. It would be very useful to be able to predict an individual's pattern change from some data derived from measurements of that individual.

Table 3.11 list the associations between the **changes** of craniofacial skeletal variables between the ages of 6 and 18. Thereby it can be seen if, for example, an increase in variable **A** is likely to be associated with an increase in variable **B** or a decrease in variable **C**. If such associations exist the changes do not happen independent of each other and form a *pattern of change*. As it appeared the associations between the changes were rather similar to the associations between the measured variables themselves. The correlation between SNA and SNB was 0.84 (Table 3.7) while the correlation between ∆SNA and ∆SNB was 0.85. The analysis of changes also showed no significant association between the increase in the sagittal measurement *S-N* and the vertical measurement *N-Gn*.

For variables that show a marked age dependency, such as the linear measurements, this behaviour does not surprise. For the morphological measurements the correlations stem from the joint correlation with age or elapsed growth. The correlations between the changes stem from the joint correlation with the time between observations or the amount of growth between these observations. There are, however, a number of variables that do not show a significant correlation with growth or age, for example *SNA* and *NL-NSL*. These also show similar correlation coefficients for the morphological measurements and for the changes. It has to be concluded that certain regulatory mechanisms control the growth changes and lead to the typical pattern that can be observed. Had the subjects displayed the different patterns already before the age of 6 and had there been the same growth changes for all subjects no correlations would have shown.

This theory needed further investigation by correlating the growth changes with the measurements at the first examination (Table 3.12).

If no significant correlation exists no assumptions about growth related changes can be made based on the morphology at younger ages. This is true for the majority of the variables including such important variables as *△ANB*, *△ML-NSL*, and *△ML-NL*. Predictions of the development of these variables are therefore not possible on an individual basis. An individual prediction is not more likely to be accurate than one based on the average changes of the population. This surprising finding supports results published by Björk and Palling (1955). They correlated the change of certain variables between 12 and 20 years of age with the initial values at 12 years. For the angles *ANPg* and *ANB* they found correlation coefficients of 0.01 and -0.08 and conclude that the development of the sagittal jaw relationship during puberty is independent of the skeletal relation before puberty.

For the maxillary and mandibular prognathism they again found no significant correlations. For *SNB* this corresponds with the findings of the present study. However, for maxillary prognathism a highly significant association was found in the present study. Since the coefficient was negative this association represented a self-correcting mechanism. An initially large SNA angle would either decrease or increase less than average and a more retrognathic maxilla would tend to become more orthognathic. As the material was selected with the criterion of not more than ¼ premolar width class II (or ½ premolar width on one side) the occlusal contacts of the cusps might have had an retrusive effect on the maxilla in cases with a slight distal sagittal base relationship and a mild dental class II. Similarly cases with a slight class III might "slide" into a class I, thereby developing a tendency of normalization.

Such an effect could, however, not be observed for the mandible. The reason might be that maxilla is more susceptible to exogenous influences than the mandible. This would support to the observation in orthodontic therapy that it is much more difficult if not impossible to change the growth path of the mandible as compared to the maxilla.

For the vertical measurements a different tendency evolved. Here a tendency towards a worsening of the situation could be observed. Six year old children with a large total face height tended to develop above average increases in lower face height and a decrease in the variable *Index* (towards an open configuration). Similarly a large lower face height at young ages was accompanied by a relatively strong increase in total and lower face heights. A large middle facial height was associated with a decreasing *Index* and thus a more open skeletal configuration. This finding doesn't conform with what could be expected from the topographic association where a large *index* could be expected from a large middle face height.

There was, therefore, no tendency towards a self-correction of the vertical relationship, rather an accentuation of the trend that was already detectable at the young age. Unfortunately these observation were only true for the facial heights and the ratios thereof. There was no association between the change in *ML-NSL* and any of the morphological variables at 6 years. A prediction of mandibular rotation, interbase angle, and of sagittal base relationship (*ANB*) was therefore not possible from the morphology at six years as described by the variables used in the present study.

This finding supports a model that assumes all subjects at a very young age start at some little differentiated average pattern. Through the pattern of growth over time a more differentiated morphological pattern is created.

Individual pattern changes

The evaluation of the amount of change between two patterns (before and after a certain growth interval) is a rather difficult procedure. While it is easy to make some assumptions from looking at the line drawings (Figs. 3.15, 3.16), a numerical evaluation is complicated and not easily comprehensible. For the present study an approach was used where 9 variables that evolved from the principle component analysis as representing unique information were used as a 9-dimensional vector. Through the standardization of these vectors for each age-group the effects of average growth changes as described in Table 3.1 and Figs. 3.10 to 3.13 were eliminated. Only the remainder, that is the deviation of the individual from these group averages was used.

These "deviation vectors" showed constant change. No subject's vector of 9 variables remained unchanged. For each 3-year period the distance between vectors at the beginning and at the end was about 1.0. This figure is without a unit as the variables were Z-transformed. As these distances cannot lie below zero a strong skewness could be expected. The comparison between the means and medians showed however, that this was not the case. The standard deviation was between 0.346 and 0.453 for all periods.

The comparison of the sum of the changes in the four 3-year periods with the change between 6 and 18 years revealed, how consistent the change was. One extreme would be a change in only one direction. Here the sum of the distances for the 3-year intervals should be equal to the total distance between 6 and 18 years. Here the trend of a deviation from the population mean would be straight and without temporary detours. If, however, the total distance between 6 and 18 years is much smaller than the sum of the distances for the 3-year intervals it must be assumed that the pattern of growth changes constantly and some growth changes will be eliminated at a later age by further growth in a different direction. No consistent trend could be observed in this case.

In the present investigation the distance between 6 and 18 years was a little less than half as large as the sum of the four 3-year intervals. Half of the growth related changes in morphological pattern were thus later nullified by further growth. The individual pattern of change therefore did not seem to be very consistent. This fact makes growth predictions rather difficult and unreliable. This observation also proved true for the individual variables (Table 3.17). Here the changes for the variable *ANB* proved to be the least consistent while *SNB*, *ForeHead*, and $PgNB_{mm}$ changed more consistently.

It was then checked whether any connection between the deviation from the population mean at 6 years of age (relative abnormality) and the amount of change in pattern (distance between vectors) existed. As opposed to the results in the previous section no significant tendency towards a self-correction or a worsening of the pattern could be observed. In addition no association between the amount of change in the different observation periods could be observed.

Whatever the causes for a change in craniofacial pattern are, either these causes are not constant over time or the effect they have on the morphology of the facial skeleton changes. No consistent trend of this pattern change can be detected for individual subjects. Typical trends appear only when these individuals are fused to a group. These average trends, however, do not necessarily represent an individual's development. Unfortunately neither the morphology of the craniofacial bones nor the pattern of association between these bones can give reliable information about future growth related changes in the craniofacial pattern. These changes are neither very consistent nor associated to the original morphology. While a complete change of the craniofacial pattern isn't common there are a number of cases that show a considerable degree of change during growth (i.e. #008 and #015 in Figure 3.16).

To exemplify the finding that the morphology at a younger age doesn't necessarily give any clues at the future development Figures 4.5 and 4.6 show the polygon drawing of the two subjects in the present investigation whose craniofacial patterns displayed the least differences. They were found by comparing the distances between the 9-dimensional vectors of all patients pairwise. It is apparent that the morphology at 6 years of age is quite similar (Fig. 4.5). At a later age (15 years) the polygon drawings show that the two subjects have developed notably different (Fig. 4.6). If the craniofacial morphology at the young age could be used to indicate growth related changes the two subjects shouldn't have developed so differently.

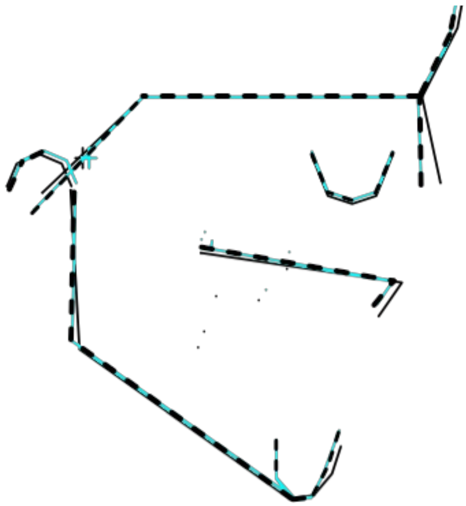

Fig. 4.5 Size adjusted superimpositions of subjects #047 (blue line) and #041 (black line) at 6 years of age. Note the similar morphology.

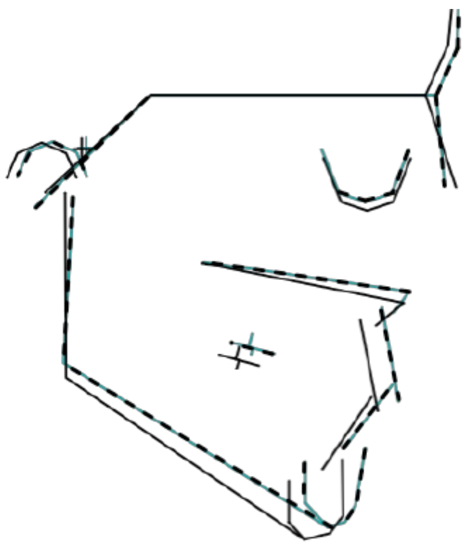

Fig. 4.6 Size adjusted superimpositions of subjects #047 (blue line) and #041 (black line) at 15 years of age. Note the dissimilarities in morphology.

Conclusions

From the results of the present investigation the following conclusions can be drawn:

1. Cephalometric measurements can be considered reliable and reproducible if the landmarks and reference lines are selected with consideration for the size and direction of the landmark scatter.

   Angular measurements ar to be avoided if a reference line is defined by two landmarks located close together. In addition reference lines should be oriented in a way that they are in line with the long axis of the usually elliptical area of uncertainty around the landmarks rather than perpendicular to it.

   In this investigation the reference line *Frankfort Horizontal* proved to be rather unreliable. The reliability coefficients were not very favorable and additionally it could not be determined in all cases.

   In longitudinal studies the growth related changes will be small and even smaller when the intervals between registrations are small. Without a careful error analysis the actual changes will be smaller than the measurement error and therefore not reliably detectable.

2. The mean values for the sample used in the present investigation (Table 3.1) are similar to those found in other Norwegian and Danish investigations. There are, however, differences between the present material and materials from other regions such as Sweden and Michigan, USA. These differences appear predominately for mandibular inclination and mandibular prognathism. If listed normative data are used as a control or reference material it is imperative to match the regional backgrounds of the study and control materials. For Norwegian and Danish studies the normative data from Michigan, USA, have to be regarded unsuitable.

3. Highly significant correlations between the angular skeletal variables are evident. The inclination of the jaws is inversely correlated to the degree of prognathism. This finding supports similar results from other investigations.

   The inclination of the forehead in relation to the anterior cranial base (*NSL*) is also related to the degree of prognathism. If the jaws are positioned more anteriorly the forehead is more retrusive and vice versa.

   Though the linear measurements are correlated to each other the closeness of the association varies considerably. Especially the association between vertical and sagittal linear measurements and between middle and lower facial height is loose.

4. In addition to a proportional increase in the size of the facial cranium the craniofacial pattern displayed the following average changes during growth:

   - a relative shortening of the anterior cranial base due to slow growth in this area.
   - a slight posterior positioning of the maxilla relative to the other structures due to less than average sagittal growth. The relative vertical position of the maxilla remained stable.
   - a relative downward displacement of the gonial region resulting in an anterior rotation of the mandible.
   - a slight ventral movement of the pogonion region.

   The *changes* of the skeletal variables are correlated in a way similar to the variables themselves. The pattern of the change is therefore similar to the craniofacial pattern itself. When growth results in more prognathic jaws it tends to also decrease the inclination of the jaws.

   Slight differences in the craniofacial pattern between male and female subjects became more pronounced during growth. Male subjects had a more anterior position of the ascending ramus and clivus and a more retrusive frontal bone.

5. Inter-individually the changes in craniofacial pattern show considerable differences and even within an individual the pattern of change is not constant over time. Therefore prediction of future changes based on the morphology at an early age are very difficult if not impossible. Only the following trends evolved:

   - sagittally a certain amount of self-correction is evident. A large *SNA* or *ANB* angle at a young age leads to a relatively smaller than average increase in *SNA* during growth.
   - vertically no self-correction but rather a worsening of the situation is to be expected. A large total facial height and particularly a large lower facial height at a young age tends to result in an even longer face and a more open vertical skeletal configuration.

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Appendix A

Correlation matrix of all investigated variables. Missing values were excluded pair-wise

	SNA	SNB	SNPg	ANB	ANPg	Wits	ML-NSL	NL-NSL	ML-NL	GntgoAr	NSBa	FH-NSL	OrbNA	ForeHead	S-N	N-Gn
SNA	1.000	0.839	0.745	0.287	0.258	0.105	0.339	0.336	0.199	0.014	0.505	0.611	0.228	0.321	0.036	0.071
SNB	0.839	1.000	0.967	0.281	0.280	0.455	0.577	0.429	0.402	0.123	0.564	0.630	0.199	0.408	0.230	0.111
SNPg	0.745	0.967	1.000	0.389	0.453	0.432	0.672	0.424	0.502	0.213	0.510	0.556	0.232	0.471	0.320	0.168
ANB	0.287	0.281	0.389	1.000	0.947	0.616	0.419	0.163	0.358	0.193	0.102	0.045	0.065	0.153	0.343	0.070
ANPg	0.258	0.280	0.453	0.947	1.000	0.485	0.520	0.164	0.461	0.290	0.063	0.001	0.021	0.253	0.417	0.149
Wits	0.105	0.455	0.432	0.616	0.485	1.000	0.069	0.120	0.018	0.224	0.349	0.290	0.148	0.105	0.086	0.007
ML-NSL	0.339	0.577	0.672	0.419	0.520	0.069	1.000	0.276	0.904	0.678	0.139	0.294	0.246	0.270	0.292	0.042
NL-NSL	0.336	0.429	0.424	0.163	0.164	0.120	0.276	1.000	0.161	0.023	0.319	0.359	0.195	0.069	0.017	0.128
ML-NL	0.199	0.402	0.502	0.358	0.461	0.018	0.904	0.161	1.000	0.686	0.002	0.142	0.161	0.246	0.307	0.014
GntgoAr	0.014	0.123	0.213	0.193	0.290	0.224	0.678	0.023	0.686	1.000	0.144	0.050	0.132	0.166	0.113	0.128
NSBa	0.505	0.564	0.510	0.102	0.063	0.349	0.139	0.319	0.002	0.144	1.000	0.607	0.227	0.419	0.179	0.184
FH-NSL	0.611	0.630	0.556	0.045	0.001	0.290	0.294	0.359	0.142	0.050	0.607	1.000	0.084	0.234	0.037	0.077
OrbNA	0.228	0.199	0.232	0.065	0.021	0.148	0.246	0.195	0.161	0.132	0.227	0.084	1.000	0.308	0.489	0.310
ForeHead	0.321	0.408	0.471	0.153	0.253	0.105	0.270	0.069	0.246	0.166	0.419	0.234	0.308	1.000	0.540	0.658
S-N	0.036	0.230	0.320	0.343	0.417	0.086	0.292	0.017	0.307	0.113	0.179	0.037	0.489	0.540	1.000	0.663
N-Gn	0.071	0.111	0.168	0.070	0.149	0.007	0.042	0.128	0.014	0.128	0.184	0.077	0.310	0.658	0.663	1.000
Cross	0.216	0.365	0.459	0.262	0.376	0.062	0.388	-0.005	0.396	0.406	0.223	0.050	0.405	0.726	0.776	0.899
Ar-Progn	0.336	0.525	0.619	0.333	0.447	0.188	0.393	0.065	0.375	0.231	0.186	0.102	0.374	0.691	0.781	0.810
PgNB$_{mm}$	0.104	0.183	0.425	0.505	0.754	0.049	0.524	0.108	0.491	0.373	0.024	0.089	0.199	0.393	0.449	0.303
Chin	0.090	0.295	0.463	0.360	0.550	0.201	0.136	0.062	0.112	0.006	0.203	0.013	0.238	0.555	0.540	0.632
Symph	0.196	0.241	0.349	0.079	0.243	0.060	0.381	0.138	0.330	0.239	0.068	0.002	0.268	0.401	0.446	0.376
NSp'	0.070	0.030	0.118	0.175	0.264	0.036	0.104	0.350	0.262	0.277	0.093	0.184	0.269	0.590	0.657	0.873
Sp'Gn	0.168	0.155	0.178	0.024	0.033	0.018	0.147	0.067	0.181	0.009	0.222	0.020	0.288	0.597	0.554	0.926
Index	0.266	0.137	0.067	0.227	0.259	0.062	0.298	0.468	0.513	0.331	0.151	0.218	0.028	0.028	0.092	0.091
$\underline{1}$NA°	0.173	0.139	0.133	0.575	0.447	0.361	0.083	0.158	0.013	0.113	0.000	0.098	0.176	0.171	0.113	0.175
$\underline{1}$NA$_{mm}$	0.104	0.240	0.233	0.632	0.499	0.410	0.134	0.181	0.055	0.007	0.056	0.136	0.140	0.041	0.271	0.134
NB°	0.326	0.074	0.068	0.443	0.538	0.110	0.183	0.044	0.171	0.124	0.007	0.182	0.119	0.056	0.102	0.091
NB$_{mm}$	0.304	0.033	0.093	0.480	0.546	0.164	0.323	0.070	0.305	0.166	0.052	0.143	0.024	0.129	0.054	0.419
APg$_{mm}$	0.195	0.176	0.034	0.032	0.214	0.207	0.211	0.026	0.232	0.171	0.115	0.219	0.138	0.029	0.085	0.283
Pg⊥ML	0.017	0.169	0.277	0.271	0.380	0.332	0.226	0.072	0.269	0.369	0.235	0.029	0.132	0.335	0.237	0.368
Y-axis	0.569	0.814	0.846	0.431	0.466	0.395	0.719	0.420	0.552	0.134	0.369	0.479	0.196	0.185	0.273	0.247

	Cross	ArProgn	PgNB$_{mm}$	Chin	Symph	NSp'	Sp'Gn	Index	$\underline{1}$NA°	$\underline{1}$NA$_{mm}$	$\overline{1}$-NB°	$\overline{1}$-NB$_{mm}$	APg$_{mm}$	Pg⊥ML	Y-axis
SNA	0.216	0.336	0.104	0.090	0.196	0.070	0.168	0.266	0.173	0.104	0.326	0.304	0.195	0.017	0.569
SNB	0.365	0.525	0.183	0.295	0.241	0.030	0.155	0.137	0.139	0.240	0.074	0.033	0.176	0.169	0.814
SNPg	0.459	0.619	0.425	0.463	0.349	0.118	0.178	0.067	0.133	0.233	0.068	0.093	0.034	0.277	0.846
ANB	0.262	0.333	0.505	0.360	0.079	0.175	0.024	0.227	0.575	0.632	0.443	0.480	0.032	0.271	0.431
ANPg	0.376	0.447	0.754	0.550	0.243	0.264	0.033	0.259	0.447	0.499	0.538	0.546	0.214	0.380	0.466
Wits	0.062	0.188	0.049	0.201	0.060	0.036	0.018	0.062	0.361	0.410	0.110	0.164	0.207	0.332	0.395
ML-NSL	0.388	0.393	0.524	0.136	0.381	0.104	0.147	0.298	0.083	0.134	0.183	0.323	0.211	0.226	0.719
NL-NSL	-0.054	0.065	0.108	0.062	0.138	0.350	0.067	0.468	0.158	0.181	0.044	0.070	0.026	0.072	0.420
ML-NL	0.396	0.375	0.491	0.112	0.330	0.262	0.181	0.513	0.013	0.055	0.171	0.305	0.232	0.269	0.552
GntgoAr	0.406	0.231	0.373	0.006	0.239	0.277	0.009	0.331	0.113	0.007	0.124	0.166	0.171	0.369	0.134
NSBa	0.223	0.186	0.024	0.203	0.068	0.093	0.222	0.151	0.000	0.056	0.007	0.052	0.115	0.235	0.369
FH-NSL	0.050	0.102	0.089	0.013	0.002	0.184	0.020	0.218	0.098	0.136	0.182	0.143	0.219	0.029	0.479
OrbNA	0.405	0.374	0.199	0.238	0.268	0.269	0.288	0.028	0.176	0.140	0.119	0.024	0.138	0.132	0.196
ForeHead	0.726	0.691	0.393	0.555	0.401	0.590	0.597	0.028	0.171	0.041	0.056	0.129	0.029	0.335	0.185
S-N	0.776	0.781	0.449	0.540	0.446	0.657	0.554	0.092	0.113	0.271	0.102	0.054	0.085	0.237	0.273
N-Gn	0.899	0.810	0.303	0.632	0.376	0.873	0.926	0.091	0.175	0.134	0.091	0.419	0.283	0.368	0.247
Cross	1.000	0.932	0.514	0.655	0.517	0.845	0.786	0.043	0.104	0.218	-0.016	0.233	0.167	0.260	0.113
Ar-Progn	0.932	1.000	0.557	0.747	0.521	0.723	0.737	0.038	0.003	0.282	0.039	0.184	0.170	0.420	0.311
PgNB$_{mm}$	0.514	0.557	1.000	0.771	0.503	0.389	0.185	0.218	0.007	0.032	0.543	0.473	0.505	0.501	0.355
Chin	0.655	0.747	0.771	1.000	0.481	0.563	0.577	0.042	0.053	0.067	0.337	0.118	0.190	0.822	0.193
Symph	0.517	0.521	0.503	0.481	1.000	0.307	0.364	0.086	0.103	0.043	0.050	0.015	0.127	0.178	0.229
NSp'	0.845	0.723	0.389	0.563	0.307	1.000	0.624	0.405	0.155	0.081	0.052	0.182	0.085	0.249	0.204
Sp'Gn	0.786	0.737	0.185	0.577	0.364	0.624	1.000	0.459	0.152	0.142	0.172	0.502	0.367	0.378	0.238
Index	0.043	0.038	0.218	0.042	0.086	0.405	0.459	1.000	0.040	0.064	0.219	0.362	0.303	0.194	0.051
$\underline{1}$-NA°	0.104	0.003	0.007	0.053	0.103	0.155	0.152	0.040	1.000	0.851	0.170	0.114	0.469	0.141	0.252
$\underline{1}$-NA$_{mm}$	0.218	0.282	0.032	0.067	0.043	0.081	0.142	0.064	0.851	1.000	0.172	0.238	0.607	0.079	0.212
$\overline{1}$-NB°	-0.016	0.039	0.543	0.337	0.050	0.052	0.172	0.219	0.170	0.172	1.000	0.857	0.772	0.565	0.159
$\overline{1}$-NB$_{mm}$	0.233	0.184	0.473	0.118	0.015	0.182	0.502	0.362	0.114	0.238	0.857	1.000	0.852	0.352	0.315
APg$_{mm}$	0.167	0.170	0.505	0.190	0.127	0.085	0.367	0.303	0.469	0.607	0.772	0.852	1.000	0.364	0.119
Pg⊥ML	0.260	0.420	0.501	0.822	0.178	0.249	0.378	0.194	0.141	0.079	0.565	0.352	0.364	1.000	0.102
Y-axis	0.113	0.311	0.355	0.193	0.229	0.204	0.238	0.051	0.252	0.212	0.159	0.315	0.119	0.102	1.000

Appendix B

Full principle component analysis for angular, ratio, and position variables:

Eigenvalues of WITHIN CELLS correlation matrix

	Eigenvalue	Pct of Var	Cum Pct
1	5.96280	37.26752	37.26752
2	3.07788	19.23672	56.50424
3	2.31202	14.45013	70.95437
4	1.19169	7.44803	78.40240
5	1.03366	6.46037	84.86277
6	.72509	4.53183	89.39460
7	.53126	3.32036	92.71495
8	.41151	2.57195	95.28690
9	.30370	1.89813	97.18503
10	.25228	1.57678	98.76181
11	.13485	.84280	99.60462
12	.06252	.39075	99.99537
13	.00074	.00461	99.99997
14	.00000	.00001	99.99998
15	.00000	.00001	100.00000
16	.00000	.00000	100.00000

Normalized principal components

	Components										
Variables	1	2	3	4	5	6	7	8	9	10	11
SNA	.64325	.62730	.33146	.04660	.13584	.20192	.05163	.05469	.03174	.11462	.01601
SNB	.91639	.28480	.02632	.11477	.16164	.10531	.07811	.07881	.00558	.05941	.09453
ANB	.47585	.62075	.54923	.12094	.04377	.17549	.04627	.04214	.06679	.10046	.13975
WITS	.51234	.19123	.58668	.42655	.09080	.07629	.29592	.00402	.05024	.14861	.21873
SNPg	.96050	.12305	.00672	.02070	.10250	.16842	.03756	.03079	.02693	.10540	.07506
ANPg	.50337	.71335	.46338	.09709	.04207	.03865	.01819	.03250	.00510	.00794	.08839
PgNB	.32425	.60154	.09486	.53586	.20685	.27023	.16057	.18483	.12797	.20132	.06393
NSBa	.58273	.39134	.16040	.19716	.31926	.31573	.35193	.09902	.32565	.03260	.01387
GntgoAr	.17886	.31621	.66846	.21731	.08363	.51902	.21279	.02473	.07665	.19153	.07361
ML_NSL	.78994	.29214	.46077	.13469	.03509	.06579	.01193	.00969	.04007	.18785	.12326
NL_NSL	.51670	.33945	.29839	.56943	.16030	.22865	.12629	.23098	.20982	.01592	.11321
ML_NL	.55432	.46878	.62158	.14477	.04372	.04597	.07496	.10480	.06325	.18491	.07018
FH_NSL	.65745	.42517	.00254	.17818	.11544	.21440	.15506	.45928	.24083	.04976	.00792
INDEX	.03417	.60793	.41344	.43350	.18011	.05387	.30504	.24869	.22128	.17484	.02446
ForeHead	.25418	.26046	.01570	.11676	.85805	.04577	.30567	.10551	.10011	.01721	.02064
Y-axis	.93349	.06209	.01945	.00317	.06381	.23447	.06229	.07477	.00396	.10449	.03339

Variables	12	13	14	15	16
SNA	.03745	.00100	.00048	.00090	.00003
SNB	.05604	.00891	.00097	.00014	.00004
ANB	.03231	.01390	.00055	.00008	.00002
WITS	.02625	.00001	.00000	.00000	.00000
SNPg	.05494	.01024	.00052	.00079	.00007
ANPg	.02774	.01686	.00035	.00053	.00005
PgNB	.00723	.00861	.00000	.00000	.00000
NSBa	.01024	.00002	.00000	.00000	.00000
GntgoAr	.06090	.00005	.00000	.00000	.00000
ML_NSL	.04817	.00008	.00007	.00008	.00059
NL_NSL	.01151	.00011	.00003	.00004	.00029
ML_NL	.04367	.00007	.00007	.00008	.00058
FH_NSL	.02052	.00008	.00000	.00000	.00000
INDEX	.00521	.00001	.00000	.00000	.00000
ForeHead	.00293	.00008	.00000	.00000	.00000
Y-axis	.20922	.00010	.00000	.00000	.00000

VARIMAX rotated correlations between components and DEPENDENT variable

	Can. Var.									
DEP. VAR.	1	2	3	4	5	6	7	8	9	10
SNA	.89406	.31729	.05022	.16287	.11930	.08577	.06324	.12500	.15116	.07227
SNB	.92848	.21063	.06108	.06045	.06631	.05670	.12737	.15555	.16109	.00585
ANB	.04638	.94597	.01843	.18505	.09643	.05336	.11300	.05253	.01500	.14052
WITS	.31435	.85692	.11632	.12779	.07839	.02765	.12963	.08434	.07550	.22793
SNPg	.90699	.25960	.09037	.17608	.04784	.07188	.13146	.13206	.13964	.01939
ANPg	.06624	.83721	.06174	.49318	.09931	.01624	.10408	.01714	.00936	.13212
PgNB	.05849	.23668	.11474	.95083	.05571	.06275	.04978	.06657	.05482	.04644
NSBa	.35762	.11236	.04652	.07558	.03734	.19132	.12470	.86802	.21046	.00059
GntgoAr	.02871	.07575	.98267	.05210	.11131	.03692	.02806	.03271	.01004	.01559
ML_NSL	.59185	.16133	.55252	.23359	.17777	.04145	.08697	.03105	.09107	.44294
NL_NSL	.35161	.09659	.01044	.09519	.30491	.04591	.85118	.13504	.08370	.00956
ML_NL	.43293	.11763	.56232	.19257	.33420	.01975	.33382	.03509	.05187	.45953
FH_NSL	.48015	.05657	.01810	.07739	.08582	.12432	.08652	.26021	.81287	.02622
Index	.08398	.08120	.19003	.06536	.94312	.04791	.21505	.02918	.06061	.05296
ForeHead	.11738	.03848	.02528	.05499	.04184	.97675	.02980	.13500	.07537	.00710
Y-axis	.82967	.31713	.03881	.23253	.08032	.04696	.11003	.12734	.06391	.26371

Transformation Matrix

	1	2	3	4	5	6	7	8	9	10
1	.79797	.37579	.18950	.17974	.00542	.12157	.15349	.21888	.21507	.14587
2	.28402	.53750	.29549	.44086	.40173	.16073	.18551	.21993	.20629	.19026
3	.19907	.62288	.59800	.05338	.32572	.01148	.22640	.10964	.00082	.20601
4	.09772	.25637	.20172	.57301	.41265	.09510	.56285	.17432	.15790	.06511
5	.23076	.05657	.06891	.21906	.19869	.85230	.14316	.29935	.11326	.04451
6	.38255	.21591	.59010	.34651	.10298	.04572	.31001	.39083	.26884	.07023
7	.09044	.24803	.30047	.30144	.43724	.41309	.26320	.50549	.21207	.13255
8	.12386	.03463	.01179	.29130	.35935	.15235	.41998	.13309	.73794	.08644
9	.03458	.04398	.12729	.20448	.38730	.16495	.45971	.58585	.44886	.07492
10	.09534	.04122	.13744	.23781	.20448	.02530	.01945	.05006	.10078	.92643

Appendix C

Pearson correlation coefficients between the changes of variables from the age of 6 to 18 years. Coefficients have been corrected for the influence of sex by calculating partial correlation coefficients.

all coefficients $p < 0.01$; those in **bold** $p < 0.001$

	ΔSNA	ΔSNB	ΔSNPg	ΔANB	ΔANPg	ΔML-NSL	ΔNL-NSL	ΔML-NL	Δ GntgoAr	ΔNSBa	ΔFH-NSL	ΔOrbNA	ΔFore Head	ΔS-N	ΔN-Gn	ΔCross	Δ Ar-Progn	ΔPgNB	ΔChin	ΔSymph	Δ N-Sp'	Δ Sp'-Gn	ΔIndex	ΔY-axis
ΔS-NA	.	**0.846**	**0.832**		**0.520**	0.450	**0.568**			**0.536**	0.459										0.449			**0.609**
ΔS-NB	**0.846**	.	**0.942**			**0.592**	**0.540**			**0.628**	**0.609**													**0.756**
ΔSNPg	**0.832**	**0.942**	.			**0.674**	**0.592**			**0.687**	**0.619**													**0.825**
ΔANB				.	**0.840**																			
ΔANPg	**0.520**			**0.840**	.																			
ΔMLNSL	0.450	**0.592**	**0.674**			.	**0.546**	**0.746**	**0.666**	0.429					0.503									**0.812**
ΔNL-NSL	**0.568**	**0.540**	**0.592**			**0.546**	.			**0.682**	0.552										**0.544**		0.454	**0.552**
ΔMLNL						**0.746**		.	**0.707**					0.441								0.508	0.427	**0.520**
ΔGntgoAr						**0.666**		**0.707**	.													0.436		
ΔNSBa	**0.536**	**0.628**	**0.687**			0.429	**0.682**			.	0.531		0.508											0.427
ΔFHNSL	0.459	**0.609**	**0.619**				0.552			0.531	.					0.498	0.467							
ΔOrbNAmm												.			0.488							0.549		
ΔForeHead incl.											0.508			.										
ΔSN								0.441						.			0.482							
ΔNGn						0.503						0.488			.	**0.663**	**0.531**				**0.644**	**0.863**		**0.658**
ΔCross											0.498				**0.663**	.	**0.816**				0.470	**0.544**		
ΔArProgn											0.467			0.482	**0.531**	**0.816**	.					0.450		
ΔPgNBmm																		.	**0.680**					
ΔChin																		**0.680**	.					
ΔSymph width																					.			
ΔNSp'	0.449						**0.544**								**0.644**	0.470					.		**0.567**	**0.570**
ΔSp'Gn								0.508	0.436			0.549			**0.863**	**0.544**	0.450					.	**0.697**	0.472
ΔIndex							0.454	0.427													**0.567**	**0.697**	.	
ΔYaxis	**0.609**	**0.756**	**0.825**			**0.812**	**0.552**	**0.520**		0.427					**0.658**						**0.570**	0.472		.

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