Statistical variation of Three Dimensional face models

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Abstract

Human face is a fascinating subject, which has attracted the attention of artists, poets, and scientists. In this study, we are attempting to employ anthropometry, statistics, and information technology to construct a three-dimensional model of the Caucasian face. We shed light on the applications of the study and the modeling technique in plastic, aesthetic, and reconstructive surgery.

In our approach, we use eight scans of male Caucasian, aged between 25-35 years, with no moustache, no beard, no eye glasses and with neutral face expression. For data acquisition, we use a three-dimensional laser scanner. The scans are annotated with 64 predefined, manually positioned anthropometric landmarks from which 71 anthropometric measurements and three major indices are calculated. The faces are aligned using Procrustes alignment to build a coarse correspondence from the anthropometric landmarks sets. Then a dense point correspondence is built using pseudo-landmarks. We show a model for the Caucasian face and its variations. The model is close to the one mentioned in the literature. We demonstrate that laser scanner might be a useful tool to give acceptable measurements. We provide anthropometric description for our results that support the argument of using anthropometric landmarks in modeling the human face variations. It is hoped that the technique can be used to gain quantitative understanding of the human face that is essential issue in planning surgical corrections of defects whether congenital or traumatic.
Acknowledgement

This study is the product of months of dedicated work with the support and cooperation of many people. Jon Sporring has a unique teaching approach that makes even the most difficult problems easy to understand. Working under has supervision has helped me to develop a deeper understanding of the statistical shape analysis in medical images. Ole Fogh Olsen’s observations about the work have contributed to the study in many ways. Dr. Salah S. AlBundi has provided unlimited support throughout the months of work; he saved no efforts in providing the necessary materials for the work and reading the proof. Dr. Adil A. AlKufaishi’s professional reading has corrected many spelling and linguistic mistakes. Mads Nielsen has helped me to figure out the project. I acknowledge also the support of Per Larsen and Tron Darvann from the 3D lab and Jon Betelsen from the DIKU.
Introduction

Human face is a fascinating subject, which has attracted the attention of artists, poets, and scientists. On the other hand, surgery is an extremely challenging field of research, which has been more than any other discipline of fundamental importance for human existence. In this study we are attempting to employ anthropometry\(^1\), statistics, and information technology to construct a three-dimensional model of the human face. Such a model can be used in plastic surgery and its related disciplines, forensic medicine, anthropology\(^2\), orthodontics, psychology, surgical simulation, face recognition, and in many other applications.

Although, information technology has revolutionized countless scientific fields, it is only in the last few years that plastic surgeons have sought the help of information technology. The three-dimensional measurements and characterisation of facial deformity is one of those areas where the plastic surgeons have sought the help of information technology. Recent innovations in laser scanning technology provide a potentially useful technique for accurate three-dimensional documentation of the face. Under certain constraints, the results obtained from the three-dimensional laser scanner are very close to those obtained from the anthropometric facial measurements on real subjects \([\text{Bush 95}]\).

In this study we use three-dimensional laser scanner to generate three-dimensional scans of eight Caucasian\(^3\) faces. Each of those scans is annotated using 64 predefined anatomical landmarks. The annotation or setting the landmark needs a good knowledge in Anatomy. There are some attempts to make automatic landmark positioning system \([\text{Naftel et al 2002}]\), however, manual setting of landmarks is still the best option to create a biologically accurate model by reducing the correspondence errors as much as possible. Those landmarks are the same that are used by anthropologists and plastic surgeons to quantitatively describe the human face. The landmarks are used to generate 71 facial measurements, which in turn are used to obtain three facial indices. Facial indices provide a reliable and measurable facial description. Having annotated the scans, we conduct a generalised Procrustes analysis followed by principal component analysis to characterise the modes of variations in the sample.

To conduct dense correspondence, we choose one of the scans, which is good regarding coverage, and lack of holes, to be the base mesh. The areas of the neck and ears are not present in all the scans and not important as well for the purpose of this study. Therefore, we snip off those areas in the base mesh so that they are not sampled when the dense correspondence is made. We bring the surfaces into close alignment using the alignment vectors from the previous step, and then dense point correspondence is made by finding the corresponding points to those on the base mesh. This is done by measuring the shortest Euclidean distance. The vertices are treated now as pseudo-landmarks and generalised Procrustes analysis followed by principal component analysis is conducted to characterise the modes of variations in the sample.

We show the modes of variation from the mean shape and discuss them in the light of anthropometry and we demonstrate the usefulness of anthropometric landmarks to quantitatively describe the human face. We show as well that the mean face is representative for the sample. By comparing our results to the results that are mentioned in literature, we conclude that three-dimensional laser scanner can be used to obtain good representation of the human face.

The study is composed of five sections. In the first section we introduce the study and give an overall view about it.

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1 Anthropometry is the scientific description of the physical characteristics of the human body.

2 Anthropology is the science that deals with the study of human culture and evolution; it seeks to produce useful generalizations about people and their behaviour and to arrive at an unbiased understanding of the human nature.

3 Caucasian refers to European, Middle Easterner and Mediterranean people.
Figure 1.1 the sample, which has been used. Eight Caucasian faces age 25-35 years, with no moustache, no beard and with no eyeglasses.
In the second section we discuss the Embryology, Anatomy, and the Anthropometry of the human face. We believe that studying the development of the human face is necessary to understand facial variations and birth defects. The Anatomy of the face will cast a light on the important structures in the face that are referred to throughout the study and the relations of those structures to each other. Anthropometry is introduced at the end of this section with a short historical review. The anthropometric landmarks, anthropometric measurements and the anthropometric facial indices are introduced with details. We end this section with a discussion of sources of errors in anthropometry to show that anthropometry using the special tools is not free from errors. In section two we have quoted extensively from [Moore 87], [Kolar & Salter 96] and [Moore 99], and referred to this throughout the text. The objective is to introduce the technical terms as they are mentioned in the textbooks of Embryology, Anatomy, Anthropology and Surgery.

In section three we discuss the potential and the possible applications of this study in plastic, reconstructive and aesthetic surgery as well as in related disciplines. To demonstrate the importance of anthropometric landmarks we discuss a real clinical example. We end the section with a short introduction to growth studies.

In section four we introduce and discuss the methods we have used and the results that we have obtained. We start the section by introducing the theoretical concepts of our work. This is followed by few words about experimenting with two-dimensional data and three-dimensional data using non-anthropometric landmarks. We proceed with three-dimensional data using anthropometric landmarks. The difficulties, the problems and the constraints using anthropometric landmarks are discussed. A coarse correspondence is explained and implemented. The results are discussed with and without scaling of Eigen vectors, using a threshold value to separate the major changes from the minor ones. An anthropometric interpretation of the results is provided. We compare the results of facial indices with the literature [Farkas 87] [Farkas 94] and we show that our results are within three standard deviations from the mean indices. We show that dense point correspondence can capture subtle variations that might have been escaped the detection by coarse correspondence. Variations in soft tissue like fullness of the cheeks; the size and the shape of lips are examples of shape variation captured by the dense point correspondence. We end the section with a short discussion of the drawbacks in the study that we could not avoid because of limitations in time and resources.

Section five includes our conclusions. Efforts are made to make this section comprehensible enough, yet brief.
Section two

Embryology, anatomy and anthropometry of the human face
“We created man from a quintessence (gentle extraction) of clay. We then placed him as a drop (Nuffah) in a place of settlement firmly fixed, then We made the drop into an Alaqah (leech-like) and then We changed the leech-like structure into a Mudgha (chedewed-like substance), then We made out of that Mudgha bones (skeleton, Izam) then We clothed the bones with flesh (muscles, Lahm), then We developed out of him another creation. So blessed be Allah the best to creat. After that, at length you will die. Again, on the day of Judgment, will you be raised up”.

Quran-Surah Al-Mu’minun, 12-16
See Moore, the developing human
2.1. Embryology of the face

2.1.1. The first three weeks

Human development is a continuous process that begins at fertilisation, when a sperm unites with an ovum to form a unicellular organism called a zygote. This cell marks the beginnings of each of us as a unique individual [Moore 82]. The unicellular organism, or zygote, becomes progressively transformed into a multi-cellular human being through the division, migration, growth and differentiation of cells (see Figure 2.1). For purpose of study, this transformation is divided into a series of changes that take place from the first week of gestation until labour, which usually takes place in 38-40th week. However it should be emphasised that the transformation process is a continuous one although it undergoes acceleration at certain stages and deceleration at others. Human development continues after birth e.g. the brain size increases three times between birth and the age of sixteen; therefore, birth is merely a dramatic event during development resulting in a distinct change in environment [Moore 82].

![Figure 2.1](image1)

*Figure 2.1 (a) shows the developing embryo from the two-cell stage to the late blastocyst stage from Keith L. Moore [Moore 2001]. (b) shows the implantation site and the differentiation of cells to epiblast and hypoblast [Sadler 2001].*

After fertilization, and as it passes along the uterine tube, the fertilized ovum undergoes a series of divisions producing a structure called ‘morula’, which in turn continues to divide until it forms a sac-like structure called ‘blastocyst’. The blastocyst is composed of a collection of cells known as the inner cell mass and a thin layer of cells known as ‘cytotrophoblast’. During the 2nd week, the inner cell mass differentiates into a two-layered disc, bi-laminar embryonic disc which
consists of epiblast on the outermost surface and hypoblast on the innermost surface (see Figure 2.1 (b)).

During the third week many cells migrate from a thickened area in the midline of the epiblast, the primitive streak, inwardly to form a layer of cells between the epiblast and the hypoblast known as the intraembryonic mesoderm, which is also known as mesenchyme or mesenchymal cells. Some cells of the mesoderm invade the hypoblastic layer forming a new layer known as the embryonic endoderm. The rest of the epiblastic cells form the ectoderm. From those three germ layers, the ectoderm, the mesoderm and the endoderm (see Figure 2.2), the various organs and tissues of the body are derived through division, aggregation, and differentiation.

Figure 2.2. The development of the embryo at the third week, three germ layers can be distinguished, the ectoderm, the mesoderm and the endoderm. From those three layers the various organs are derived [Sadler 95].

It is worth noting that the term *embryonic period* describes the prenatal development from the second week of gestation after the embryonic disk forms, to the end of the eighth week by which all the main organ systems have begun to develop but the function of most organs is minimal. The *fetal period* follows the embryonic period and continues until birth. However, in this study we are interested mainly in the embryonic period because the beginnings of all major external and internal structures develop during this period.

### 2.1.2. The Fourth Week

The external features of the embryo become distinct after the fourth week. The brachial apparatus is the part of the growing embryo that is responsible for the formation of future head and neck region.

We study the fate of the brachial arches and how they contribute to the formation of the face. The word brachial is derived from the Greek brachia, meaning gill. The brachial apparatus supports the gills in the fish and that is how the word found its way to the evolutionary studies of embryo.
The brachial arches (pharyngeal arches) are derived from the neural crest cells as those cells migrate into the future head and neck region early in the fourth week. The brachial apparatus consist of (1) brachial arches, (2) pharyngeal pouches, (3) brachial grooves, and (4) brachial membranes. The arrows in Figure 2.3 point to the brachial arches from which the head and neck will form.

Figure 2.3 the arrows point to the brachial (pharyngeal) arches from which the future head and neck region will form [Sadler 2001].

During the fourth week the cranial region of human embryo resembles fish embryo of comparable stage (see Figure 2.4.A). The five facial primordia appear as five prominences (elevations) around the stomodeum (primitive mouth). The term primordium refers to the first trace or indication of an organ or structure, i.e. its earliest stage of development. These five prominences (see Figure 2.4.A) are:
1. The frontal prominence, which will form the cranial boundary of stomodeum.
2. The paired maxillary prominences of the first brachial arch form the lateral boundaries, or sides of the stomodeum.
3. The paired mandibular prominences of the same arch will form the caudal boundary of the stomodeum as can be seen in (Figure 2.4A-E).

The mesoderm of the five facial primordia is continuous, i.e. there are no internal divisions corresponding to the grooves that demarcate the prominences externally. The development of the face occurs mainly between the fifth and the eighth weeks while facial proportions develop during the fetal period. Facial proportions continue to develop until adulthood due to the changes in the size of air sinuses and changes in the brain size. The medial ends of the two mandibular prominences merge during the fourth week and the mandible or the lower jaw is formed. Therefore, the mandible is the first part of the face to form.

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4 Neural crest represents primitive sensory cells which migrate from the neural plate which appears as a 'midline thickening of the ectoderm' along its central axis. The neural plate forms the neural tube an subsequently the central nervous system, while the neural crest develop into sensory nerve cells, peripheral nerves and autonomic nervous system.

5 Cranial: of or relating to the skull.

6 Caudal: Pertaining to the tail.
2.1.3. The fifth to eighth weeks

By the end of the fourth week, bilateral oval-shaped thickenings of the surface ectoderm, called the nasal placodes, develop on each side of the lower part of the nasofrontal prominence (see Figure 2.4.E). These nasal placodes with the maxillary prominences will form the nostrils and the future nose. They will give rise also to the nasal air sinuses and nasolacrimal groove.

The eyes will slightly move forward on the face by the end of the fifth week and the external ear begins to develop as can be seen in (Figure 2.4.H). It should be mentioned in this regard that the eyes are derived from the ectoderm like the brain; however, eye development is beyond the scope of this study.

By the end of the sixth and seventh weeks the medial nasal prominences merge with each other and form the inter-maxillary segment (Figure 2.4 F-G). This segment will give rise to (1) the philtrum of the upper lip, (2) the pre-maxillary part of the maxilla and its associated gingiva (gum), and (3) the primary palate. The lateral parts of the upper lip, most of the maxilla and the secondary palate form from the maxillary prominences. These prominences merge laterally with the mandibular prominences. The mesenchyme of the second brachial arch invades the primitive lips and cheeks giving rise to the facial muscles. These muscles of facial expressions are supplied by the Facial nerve, the nerve of the second brachial arch. The mesenchyme of the first pair of brachial arches gives rise to the muscles of mastication, which are innervated by the Trigeminal nerve, the nerve of the first brachial arch.

The frontonasal prominence forms the forehead, the dorsum, and the apex of the nose. The sides (alae) of the nose are derived from the lateral nasal prominences (Figure 2.4.G). The maxillary prominences form the upper cheek regions and most of the upper lip, the chin, and the lower cheek regions. The facial prominences form in addition to the above-mentioned fleshy derivatives, various bones e.g. the frontonasal prominences give rise to nasal bones.

Final development of the face occurs slowly and results mainly from changes in the proportion and relative position of the facial components. During the early fetal period, the nose is flattened and the mandible is underdeveloped (Figure 2.4.H); they obtain their characteristic form when the facial development is complete (see Figure 2.4.J). The brain enlarges, creating a prominent forehead; the eyes move medially, and the external ears rise. The smallness of the face at birth is due to (1) the rudimentary upper and lower jaws, (2) the unerupted teeth, and (3) the small size of the nasal cavities and maxillary sinuses. [Moore 82].

Furthermore, The skull of a newborn infant is disproportionately large compared with other parts of the facial skeleton. Facial skeleton forms approximately one-eighth of the skull while in adult it forms one third of the skull [Moore 99] ☞
Figure 2.4 A-E shows the human face development from the brachial arches, the left column is anterior view while the right one is lateral view [Moore 98].
Figure 2.4 F-I shows the human face development from the brachial arches, the left column is anterior view while the right one is lateral view [Moore 98].
2.2. Anatomy of the face

The purpose of this section is to introduce the anatomical terms and concepts that will be frequently discussed in the later sections. We concentrate mainly on the skull and face as these two parts account for the face shape, which is the core issue in this study. We use the terminology and classification as mentioned in [Moore 99]. Attention is focused on the parts of skull and face that will be used as craniofacial landmarks.

2.2.1. The skull

The skull is the bony skeleton of the head that is formed by the neurocranium and the facial skeleton (Figure 2.5). The neurocranium protects the brain and its related tissues. The facial skeleton consists of the bones surrounding the mouth, and nose and contributing to the orbits.

The neurocranium in adult is formed by: A frontal bone, paired parietal bones, paired temporal bones, an occipital bone, a sphenoid bone and an ethmoid bone.

The facial skeleton forms the anterior part of the skull containing the orbits, nasal cavities, maxilla and mandible (upper and lower jaw). The facial skeleton consists of 14 irregular bones as
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shown in (Figures 2.5 - 2.7). These bones are: lacrimal, nasal, maxilla, zygomatic, palatine and the inferior nasal conchae bones (all are paired bones) in addition to an unpaired mandible and a vomer. The maxilla forms the upper jaw while the mandible forms the lower jaw.

Figure 2.6 shows the anterior view of the skull; the facial skeleton is formed of 14 irregular bones some of them are shown in this view [Moore 99].

The frontal bone forms the forehead. In fetal life the frontal suture separates the two halves of the frontal bone. **Glabella**, a smooth prominence, most marked in males, on the frontal bone superior to root of nose, lies on frontal suture line; it is the most anterior projecting part of the forehead (Figure. 2.6&2.7). **Nasion** represents the intersection of the frontal and nasal bones; in most people it is related to a distinctly depressed area (the bridge of nose). The supraorbital margin forms the boundary between the frontal bone and the orbits. The zygomatic bones form the prominence of the cheeks (Figure. 2.6&2.7) and contribute to the formation of the orbits. The mental protuberance forms the prominence of the chin. It is a triangular elevation of the bone inferior to the mandibular symphysis (Figure. 2.6&2.7).

The mandible is the most dynamic of our bones; its size and shape and the number of teeth it normally bears undergo considerable changes with age [Moore 99]. The mandible changes with the change of teeth from deciduous to permanent teeth. Following complete loss of teeth in old age, the alveoli begin to fill in with bone and the alveolar processes begin to resorb.
As stated earlier, an increase in the size of paranasal sinuses (air filled extensions of the nasal cavities in certain cranial bones) causes enlargement of the facial region.

Abnormalities in suture closure in infancy give rise to craniosynostosis, which is a group of deformities in the shape of the skull; some of them are associated with neurological abnormalities. An example of craniosynostosis is scaphocephaly in which the skull is long, narrow and wedge-shaped.

2.2.2. The face

The face is the anterior aspect of the head that extends from the forehead to the chin and from one ear to the other. Bones of the facial skeleton determine the shape of the face. Buccal fat pads in the cheeks and the facial muscles contribute to the final shape of the face. The facial muscles are in the subcutaneous tissue; they are attached to the bones of the skull. These muscles move the skin and change facial expressions, hence the name muscles of facial expression. The muscles of facial expression surround the orifices of the mouth, the eyes and the nose acting as sphincters and dilators (see Figure 2.8).

The skin of the face is connected to the bones by bands of connective tissue. We shall not elaborate more on the anatomy of the face for this is beyond the scope of this study, however we refer interested readers to K.L.Moore textbook of anatomy [Moore 99].
Figure 2.8 anterior and lateral views of the muscles of facial expression; note that they surround the orifices and act as dilators and sphincters. [Moore 99].
2.3. **Anthropometry of the face**

Humans have long been keenly interested in depicting the characteristics of human anatomy. The Sumerians, who lived in the southern part of Iraq five thousands years ago; were the first to study human anatomy using a scientific approach [Kramer 89]. In classical Greece and Rome, artists used numerous canons, rules of simple proportions, to describe the ideal form of the human figure. The splendid works of Leonardo Da Vinci and Michel Anglo are in large part inspired by fascination with the aesthetic values of the ideal human form.

Anthropometry, the measurement of living subjects, was first developed by a German anatomist, Johanne Sigismund Elsholtz for his doctoral thesis at the university of Padua in 1654 [Kolar and Salter 96]. Throughout the last century, anthropometry witnessed an extensive development. However, the first clinical program in craniofacial anthropometry was carried out at Charles University, Prague in 1960s as part of an extensive, long-term study of children with cleft lip and palate [Kolar & Salter 96].

Anthropometric evaluation begins with the identification of particular locations on a subject, called landmark points; defined in terms of visible or palpable features (skin or bones) on the subject. A series of measurements between these landmarks is then taken using carefully specified procedures and measuring instruments (such as callipers, levels and measuring tape). As a result, repeated measurements of the same individual (taken a few days apart) are very reliable, and measurements of different individuals can be successfully compared [DeCarlo 98].

The selection of potential craniofacial measurements is almost limitless. However, we introduce here the craniofacial landmarks and the craniofacial measurements that are frequently used in plastic and reconstructive surgery. The landmarks and the measurements are taken from [Kolar and Salter 96].

Reference should be made to Figures 2.9, 2.10 and 2.11 that illustrate the landmarks. Shaded areas in the tables below indicate landmarks and measurements that were not used in this study (see section 4.4 for further explanation).

### 2.3.1. Craniofacial landmarks

<p>| Table 2.1 Craniofacial landmarks of the head |</p>
<table>
<thead>
<tr>
<th>No.</th>
<th>Landmark</th>
<th>Region</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>Frankfort horizontal plane</td>
<td>General</td>
<td>A horizontal line from the top of the external auditory canal to the lowest point on the inferior border of the orbit.</td>
</tr>
<tr>
<td>II.</td>
<td>Rest position</td>
<td>General</td>
<td>The inclination of a line from the top of the external auditory meatus to the lowest point on the inferior orbital rim when the subject’s head is in normal, relaxed position.</td>
</tr>
</tbody>
</table>

<p>| Table 2.2 Craniofacial landmarks of the face |</p>
<table>
<thead>
<tr>
<th>No.</th>
<th>Landmark</th>
<th>Region</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Euryon (eu)</td>
<td>Head</td>
<td>The most lateral point on the head</td>
</tr>
<tr>
<td>2.</td>
<td>Frontotemporal (ft)</td>
<td>Head</td>
<td>The most medial point on the temporal crest of the frontal bone.</td>
</tr>
<tr>
<td>3.</td>
<td>Frontozygomaticus (fz)</td>
<td>Head</td>
<td>The most lateral point on the frontozygomatic suture</td>
</tr>
<tr>
<td>4.</td>
<td>Glabella (g) or nasal eminence</td>
<td>Head</td>
<td>The most prominent point in the median sagittal plane between the supra-orbital ridges</td>
</tr>
<tr>
<td>5.</td>
<td>Ophyron (on) or point intersocilier</td>
<td>Head</td>
<td>The point at the mid-plane of a line tangent to the upper limits of the eyebrows (sci-sci).</td>
</tr>
<tr>
<td>6.</td>
<td>Opisthorcranion (op) or occipital point</td>
<td>Head</td>
<td>The most prominent posterior point of the occiput.</td>
</tr>
<tr>
<td>7.</td>
<td>Porion (po)</td>
<td>Head</td>
<td>The most superior point on the upper margin of the external auditory meatus when the head is in the Frankfort horizontal plane.</td>
</tr>
</tbody>
</table>
8. Tragion (t)  Head  Located at the notch above the tragus of the ear, the cartilaginous projection in the front of the external auditory canal, where the upper edge of the cartilage disappears into the skin of the face.

9. Trichion (tr)  Head  Midpoint of the hairline

10. Vertex (v)  Head  The highest point of the head with the subject in the Frankfurt horizontal plane.

Figure 2.9 shows the cranio-facial landmarks super-imposed on photograph of a young boy [Kolar and Salter 96].

Table 2.3 Craniofacial landmarks of the face—continued

<table>
<thead>
<tr>
<th>No.</th>
<th>Landmark</th>
<th>Region</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Condylion laterale (cdl)</td>
<td>Face</td>
<td>The most lateral point on the mandibular condyle</td>
</tr>
<tr>
<td>12</td>
<td>Gnathion (gn) or Menton</td>
<td>Face</td>
<td>The lowest point in the midline on the lower border of the chin</td>
</tr>
<tr>
<td>13</td>
<td>Gonion (go)</td>
<td>Face</td>
<td>The most lateral point at the angle of the mandible</td>
</tr>
<tr>
<td>14</td>
<td>Nasion (n)</td>
<td>Face</td>
<td>The midpoint of the nasofrontal suture</td>
</tr>
<tr>
<td>15</td>
<td>Pogonion (pg)</td>
<td>Face</td>
<td>The most anterior point in the middle of the soft tissue chin.</td>
</tr>
<tr>
<td>16</td>
<td>Sublabial (sl)</td>
<td>Face</td>
<td>The midpoint of the Labiomial sulcus</td>
</tr>
<tr>
<td>17</td>
<td>Subnasal (sn)</td>
<td>Face</td>
<td>The junction between the lower border of the nasal septum, the</td>
</tr>
</tbody>
</table>
partition that divides the nostrils, and the cutaneous portion of the upper lip in the midline.

<table>
<thead>
<tr>
<th>No.</th>
<th>Landmark</th>
<th>Region</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>Stomion (sto) point buccal</td>
<td>Face</td>
<td>The mid point of the labial fissure when the lips are closed naturally.</td>
</tr>
<tr>
<td>19</td>
<td>Zygion (zy)</td>
<td>Face</td>
<td>The most lateral point on the zygomatic arch</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2.4</th>
<th>Craniofacial landmarks of the orbits</th>
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</thead>
<tbody>
<tr>
<td>No.</td>
<td>Landmark</td>
</tr>
<tr>
<td>20.</td>
<td>Endocanthion (en)</td>
</tr>
<tr>
<td>21.</td>
<td>Exocanthion (ex)</td>
</tr>
<tr>
<td>22.</td>
<td>Orbitale (or)</td>
</tr>
<tr>
<td>23.</td>
<td>Orbitale superius (os)</td>
</tr>
<tr>
<td>24.</td>
<td>Palpebrale inferius (pi)</td>
</tr>
<tr>
<td>25.</td>
<td>Palpebrale superius (ps)</td>
</tr>
<tr>
<td>26.</td>
<td>Superciliare (sci)</td>
</tr>
</tbody>
</table>

Figure 2.10 (a) shows the main cranial landmarks and (b) a profile that shows some of the facial landmarks. [Kolar and Salter 96].

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<thead>
<tr>
<th>Table 2.5</th>
<th>Craniofacial landmarks of the nose</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>Landmark</td>
</tr>
<tr>
<td>26.</td>
<td>Alar curvature point (ac)</td>
</tr>
<tr>
<td>27.</td>
<td>Alare (al)</td>
</tr>
<tr>
<td>28.</td>
<td>Columella apex (c’)</td>
</tr>
<tr>
<td>29.</td>
<td>Maxillofrontal</td>
</tr>
</tbody>
</table>
Table 2.6  Craniofacial landmarks of the orolabial region

<table>
<thead>
<tr>
<th>No.</th>
<th>Landmark</th>
<th>Region</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>Cheilion (ch)</td>
<td>Orolabial</td>
<td>The outer corner of the mouth where the outer edges of the upper and lower vermilion meet.</td>
</tr>
<tr>
<td>35</td>
<td>Crista philtrum (cph)</td>
<td>Orolabial</td>
<td>The point on the crest of the philtrum, the vertical groove in the median portion of the upper lip, just above the vermilion border.</td>
</tr>
<tr>
<td>36</td>
<td>Labial inferius (li)</td>
<td>Orolabial</td>
<td>The mid point of the vermilion border of the lower lip.</td>
</tr>
<tr>
<td>37</td>
<td>Labial superius (ls)</td>
<td>Orolabial</td>
<td>The mid point of the vermilion border of the upper lip.</td>
</tr>
<tr>
<td>38</td>
<td>Labiale superius lateralis (ls’)</td>
<td>Orolabial</td>
<td>The point on the upper vermilion border directly inferior to Subalare (sbal).</td>
</tr>
</tbody>
</table>

Table 2.7  Craniofacial landmarks of the ears

<table>
<thead>
<tr>
<th>No.</th>
<th>Landmark</th>
<th>Region</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>Otobasion inferius (obi)</td>
<td>Ears</td>
<td>The lowest point of attachment of the external ear to the head.</td>
</tr>
<tr>
<td>40</td>
<td>Otobasion superius (obs)</td>
<td>Ears</td>
<td>The highest point of attachment of the external ear to the head.</td>
</tr>
<tr>
<td>41</td>
<td>Postaurale (pa)</td>
<td>Ears</td>
<td>The most posterior point on the free margin of the ear.</td>
</tr>
</tbody>
</table>
2.3.2. Anthropometric measurements

Table 2.8 Cranial measurements:

<table>
<thead>
<tr>
<th>Landmarks</th>
<th>Measurement Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>eu-eu</td>
<td>Maximum cranial breadth</td>
</tr>
<tr>
<td>ft-ft</td>
<td>Minimum frontal breadth</td>
</tr>
<tr>
<td>t-t</td>
<td>Cranial base width</td>
</tr>
<tr>
<td>fz-fz</td>
<td>Supraorbital breadth</td>
</tr>
<tr>
<td>fz-g</td>
<td>Superior orbital breadth</td>
</tr>
<tr>
<td>g-op</td>
<td>Maximum cranial length</td>
</tr>
<tr>
<td>tr-g</td>
<td>Forehead height I</td>
</tr>
<tr>
<td>tr-n</td>
<td>Forehead height II</td>
</tr>
<tr>
<td>v-n</td>
<td>Anterior head height</td>
</tr>
<tr>
<td>v-po</td>
<td>Auricular head height</td>
</tr>
<tr>
<td>v-gn</td>
<td>Total Craniofacial height</td>
</tr>
<tr>
<td>on-op</td>
<td>Head circumference</td>
</tr>
<tr>
<td>fz-g-fz</td>
<td>Superior orbital contour and superior orbital rim contours</td>
</tr>
</tbody>
</table>

Table 2.9 Facial measurements:

<table>
<thead>
<tr>
<th>Landmarks</th>
<th>Measurement Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>zy-zy</td>
<td>Maximum facial breadth</td>
</tr>
<tr>
<td>go-go</td>
<td>Mandible breadth</td>
</tr>
<tr>
<td>g-t</td>
<td>Supraorbital depth</td>
</tr>
<tr>
<td>n-t</td>
<td>Upper third face depth</td>
</tr>
<tr>
<td>Ex-t</td>
<td>Orbito-tragial depth</td>
</tr>
<tr>
<td>sn-t</td>
<td>Maxillary depth</td>
</tr>
<tr>
<td>gn-t</td>
<td>Mandibular depth</td>
</tr>
<tr>
<td>gn-go</td>
<td>Mandibular body length</td>
</tr>
<tr>
<td>tr-gn</td>
<td>Physiognomical face height</td>
</tr>
<tr>
<td>n-gn</td>
<td>Morphological face height</td>
</tr>
<tr>
<td>n-sto</td>
<td>Upper face height</td>
</tr>
<tr>
<td>sn-gn</td>
<td>Lower face height</td>
</tr>
<tr>
<td>sto-gn</td>
<td>Anterior mandibular height</td>
</tr>
<tr>
<td>sl-gn</td>
<td>Chin height</td>
</tr>
<tr>
<td>ex-go</td>
<td>Lateral facial height</td>
</tr>
<tr>
<td>go-cdl</td>
<td>Mandibular ramus height</td>
</tr>
<tr>
<td>t-g-t</td>
<td>Supraorbital arc and half-arcs</td>
</tr>
<tr>
<td>t-sn-t</td>
<td>Maxillary arc and half arcs</td>
</tr>
<tr>
<td>t-gn-t</td>
<td>Mandibular arc and half arcs</td>
</tr>
</tbody>
</table>

Angles and inclination
<table>
<thead>
<tr>
<th>Li-sl-pg</th>
<th>Labiomental angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-sn</td>
<td>Upper face inclination</td>
</tr>
<tr>
<td>Sn-pg</td>
<td>Lower face inclination</td>
</tr>
<tr>
<td>Li-pg</td>
<td>Lower third face inclination</td>
</tr>
<tr>
<td>Sl-pg</td>
<td>Chin inclination</td>
</tr>
<tr>
<td>G-pg</td>
<td>General profile angle</td>
</tr>
</tbody>
</table>

**Table 2.10 Orbital measurements:**

<table>
<thead>
<tr>
<th>Landmarks</th>
<th>Measurement Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>En-en</td>
<td>Intercanal width</td>
</tr>
<tr>
<td>Ex-ex</td>
<td>Biocular width</td>
</tr>
<tr>
<td>En-ex</td>
<td>Eye fissure length</td>
</tr>
<tr>
<td>Ps-pi</td>
<td>Eye fissure height</td>
</tr>
<tr>
<td>Os-or</td>
<td>Orbital height</td>
</tr>
<tr>
<td>Os-ps</td>
<td>Upper eyelid height</td>
</tr>
<tr>
<td>Pi-or</td>
<td>Lower eyelid height</td>
</tr>
</tbody>
</table>

**Angles and inclinations**

| En-ex     | Eye fissure inclination, orbital inclination |

**Table 2.11 Nasal measurements:**

<table>
<thead>
<tr>
<th>Landmarks</th>
<th>Measurement Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mf-mf</td>
<td>Nasal root width</td>
</tr>
<tr>
<td>Al-al</td>
<td>Nose width, Columella width</td>
</tr>
<tr>
<td>Sbal-sn</td>
<td>Nostril floor width, Ala thickness</td>
</tr>
<tr>
<td>Sn-prn</td>
<td>Nasal tip protrusion</td>
</tr>
<tr>
<td>En-m'</td>
<td>Nasal root height</td>
</tr>
<tr>
<td>En-m''</td>
<td>Nasal root slope</td>
</tr>
<tr>
<td>Ac-prn</td>
<td>Ala length</td>
</tr>
<tr>
<td>Sn’-c</td>
<td>Columella height</td>
</tr>
<tr>
<td>N-sn</td>
<td>Nose height</td>
</tr>
<tr>
<td>N-prn</td>
<td>Nasal bridge length</td>
</tr>
<tr>
<td>Ac-prn</td>
<td>Ala surface length</td>
</tr>
</tbody>
</table>

**Table 2.12 Orolabial measurements:**

<table>
<thead>
<tr>
<th>Landmarks</th>
<th>Measurement Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cph-cph</td>
<td>Philtrum width</td>
</tr>
<tr>
<td>Ch-ch</td>
<td>Labial fissure width</td>
</tr>
<tr>
<td>Ch-sto</td>
<td>Labial fissure half-width</td>
</tr>
<tr>
<td>Sn-sto</td>
<td>Upper lip height</td>
</tr>
<tr>
<td>Sn-ls</td>
<td>Philtrum length</td>
</tr>
<tr>
<td>Ls-sto</td>
<td>Upper vermilion height</td>
</tr>
<tr>
<td>Sto-li</td>
<td>Lower vermilion height</td>
</tr>
<tr>
<td>Li-sl</td>
<td>Cutaneous lower lip height</td>
</tr>
<tr>
<td>Sto-sl</td>
<td>Lower lip height</td>
</tr>
<tr>
<td>Sbal-ls'</td>
<td>Lateral lip height</td>
</tr>
</tbody>
</table>

**Angles and inclination**

| Sn-ls     | Upper lip inclination    |
Table 2.13 Ear measurements:

<table>
<thead>
<tr>
<th>Landmarks</th>
<th>Measurement Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>pra-pra</td>
<td>Ear width</td>
</tr>
<tr>
<td>sa-sba</td>
<td>Ear length</td>
</tr>
<tr>
<td>obs-obi</td>
<td>Ear insertion</td>
</tr>
<tr>
<td>sa-sba</td>
<td>Ear inclination</td>
</tr>
<tr>
<td>g-ls, t, pi, ac</td>
<td>Ear location</td>
</tr>
</tbody>
</table>

2.3.3 Anthropometric indices

In both the abstract and the concrete worlds, comparison is the method by which the quality of an idea, living creature or inanimate object is judged. Indices are sensitive and useful descriptors of facial proportions. In the past few decades modified versions of indices have been used in medical practice and research. They can demonstrate the degree of disproportions in various parts of human body caused by hormonal and other disorders, congenital anomalies or trauma [Farkas 87].

The number of indices is unlimited; they can involve all parts of the body, depending on the requirements of the medical or other biological disciplines.

In the formulation of the index, the smaller measurement is multiplied by 100 (numerator) and divided by the larger measurement (denominator). Thus, the smaller measurement is expressed as a percentage of the larger. The general formula is [Farkas 87]:

\[
\text{Index (I)} = \frac{\text{Numerator (smaller measurement)} \times 100}{\text{Denominator (larger measurement)}}
\]

We will mention here only examples of the most commonly used indices; the interested reader is referred to [Farkas 87].

**Cephalic index** = \(\frac{\text{Maximal width of the head (eu-eu) \times 100}}{\text{Maximal length of the head (g-op)}}\)

**Facial index** = \(\frac{\text{Morphological face height (n-gn) \times 100}}{\text{Bi-zygomatic face width (zy-zy)}}\)

**Upper face index** = \(\frac{\text{Upper face height (n-sto) \times 100}}{\text{Bi-zygomatic face width (zy-zy)}}\)

**Nasal index** = \(\frac{\text{Nose width (al-al) \times 100}}{\text{Nose height (n-sn)}}\)
It should be noted, that indices developed for a certain population might be used in another population provided that specific ethnic differences between the two populations are known [Farkas 87].

![Vertical and horizontal linear measurements](image)

Figure 2.12 illustrates the vertical and the horizontal linear measurements [Farkas 94].

2.3.4 sources of error in anthropometry

The aim of this section is to demonstrate the sources of error in anthropometry –where real subjects and tools are used. In section 4.4.1 we discuss the sources of error associated with the three-dimensional laser scanner. The commonest sources of error are:

1. Improper identification of landmarks. Soft tissue landmarks are readily identifiable in a healthy person’s face. However, they are difficult to locate on a deformed face [Farkas 94]. Examples of especially difficult landmarks are: vertex (v), eurion (eu-eu), glabella (g), frontotemporal (ft) and trichion (tr) in the head region and zygion (zy), gonion (go), progonion and gnathion (gn) in the face region [Farkas 94].

2. Inadequate use of measuring equipment. Standard measurements require the use of standard instruments.

3. Improper measuring technique. For instance, the examiner should be familiar with (a) the areas in which the tip of the instrument used should be pressed on bony surface to obtain correct measurements and (b) the areas where the instrument barely touches the skin surface at measurement.

Thus, anthropometry is not void of errors even if high degree of precision is used in the measurement.
Section three

Applications in plastic, aesthetic and reconstructive surgery
"The pursuit of truth and beauty is a sphere of activity in which we are permitted to remain children all our lives."

*Albert Einstein*
3.1 Applications

In this section we are mainly concerned with possible applications of this study in plastic, aesthetic and reconstructive surgery. Needless to say, that the method should be tailored to the specific type of application. The main applications are:

1. **Improving the clinical evaluation of the patient.** This is done through better assessment of facial morphology using quantitative tools, which are the anthropometric measures, rather than using visual impressions and/or scanty measurements (see Figure 3.1 that shows a visual impression approach to describe the human face).

2. **Improving surgical planning and corrections of dysmorphology** due to using the quantitative tools. The problem of trying to analyse exactly what is wrong with the face and, therefore, what must be corrected is often more difficult than may be apparent at first (see Figure 3.2 that shows some deformations compared with normal). For example, procedures for the correction of the facial features of Down’s syndrome were worked out in a very simplistic and arbitrary manner in the late 1970’s. Although these produced changes in the facial appearance, they rarely produced complete correction but rather an amelioration of the signs of the deformity. By analysing anthropometric data, it became obvious that one of the significant features was relative recession of the forehead. The surgeons then corrected patients by forehead advancement, producing radical correction of the deformity when combined with mid-face correction [Kolar & Salter 96]. Furthermore, the surgeon will benefit from such a system in surgical planning to explore what can be done practically and, using these concepts, to see how movement of one part of Craniofacial skeleton may affect the proportions of another part and whether harmony will necessarily be improved or even diminished.

---

Reconstructive surgery is concerned with the restoration of the normal while the ultimate aim of aesthetic surgery is to create an above-average or attractive face.
3. **Improving the follow up of the patient.** Follow up of patients using anthropometric procedures is enormously important and it is a very humbling experience (see Figure 3.3). The surgeon first finds out that he has not achieved what he set out to achieve. Long-term follow up enables the surgeon to see how face is growing and this soon gets rid of the naïve concept of many surgeons who believe that if they put the skeleton of a young child into the correct position it will grow continuously along the ideal lines [Kolar & Salter 96].

Since the proportion indices are sensitive indicators of any growth disturbances, using them in follow up can detect areas that are severely behind the normal development in the face of a young child. It will also show whether the facial proportions become worse with age.

Figure 3.3 the value of anthropometric measurements in assessing surgical cause and effect. Left: pre-operative patient with a base bony width (X-X) of 33 mm. Right: the same patient at 18 months post-operatively, the base bony width (X-X) is 29 mm. The surgical procedure was a definite narrowing of the nose using low-to-low osteotomies, but with no open roof dorsally. [Farkas 94]

4. **Pooling the quantitative data** from patients with the same diagnosis to identify characteristic patterns of dysmorphology and the extent of morphological variation in these syndromes.

---

8 Harmony and disharmony refer to the mind’s interpretation of the facial relationships based strictly on visual observations.
5. **Growth studies**\(^9\) for the normal as well as the abnormal growth. This will be discussed in more details below. One application of growth studies is in forensic medicine to trace missing children (see Figure 3.5).

![Fig. 3.5](image)

**Figure 3.5** tracing a missing child depending on anthropometric growth studies. Upper left the anthropometric measurements are conducted using the child photograph; Upper right anthropometric profiles; lower left the child face at age of eight years and lower right at age of eighteen years. [Farkas 94]

6. **Attractiveness studies**\(^10\), the statistical anthropometric analysis can be used in attractiveness studies of the human face. Farkas and his colleagues conducted one of the largest studies in North America using anthropometric measurements and indices [Farkas et al 87].

7. **Design of better implants** for plastic, aesthetic and reconstructive surgery.

8. **Classification, analysis and visualisation of data**, making it beneficial for the plastic surgeons, anthropologists, orthodontics, paediatricians and psychologists for evaluation, diagnosis and treatment. Anthropologist and surgeons working with dysmorphology in the craniofacial region need to analyse and study massive amount of data. Therefore, using information technology can increase the benefits and decrease the efforts of data analysis and interpretation [Kolar & Salter 96].

9. **Preserving the data**. The three-dimensional laser scanner is a non-invasive technique that outlives x-ray and CT scan. The data can be preserved and used in later study and analysis.

10. **Surgical simulation, virtual reality, and Computer graphics applications**. The rich descriptions of human geometry developed in anthropometry provide an invaluable resource for human modelling in computer graphics [DeCarlo 98].

We discuss the application of anthropometric measures in clinical evaluation, surgical planning, treatment, and follow up of patients with dysmorphology using Down’s syndrome as an example. Then we discuss the growth studies as they represent an important application of this study.

---

\(^9\) Studies of human growth i.e. increase in the dimensions of human body.
\(^10\) These are the studies of proportions (canons) of the attractive and non-attractive human faces.
3.2 Clinical example

Down’s syndrome

Craniofacial anthropometry can be applied to clinical subjects at several levels. The most basic application is the presentation of a single patient’s finding at a single examination using the measurements and proportions that mostly attain to surgeon’s need. Proper clinical evaluation includes the calculation and analysis of the proportions of the head and the face showing their relation to mean values and normal limits. The proportions provide measures of the deformities and guidelines for surgical planning. However, the number of measurements and proportions needed to identify the anomalies is somewhat subjective. The morphology of the head and neck is not simple. Patients with craniofacial anomalies exhibit a wide range of skeletal and soft tissue defects that differ from one patient to another and from one syndrome to another [Kolar & Salter 96].

Clinical features

The clinical literature is descriptive. The diagnostic characteristics typically rely on visual evaluation of the presenting deformities, sometimes supplemented by radiographic analysis. Because of the nature of perception, it is possible to misinterpret the gestalt of a complex object such as the head and face, seeing some defects that are not there and overlooking others that are present. Anthropometric examinations can reveal more complex patterns of dysmorphology [Kolar & Salter 96]. Down syndrome is the most common human malformation, with an incidence of about 2.5:1000 births. There is a generalised growth deficit in children with Down syndrome. Craniofacial features include a small, brachycephalic skull with a flat occiput, malar hypoplasia, large tongue, receding chin, upslanted eye fissures, epicanthal folds, short, saddle-shaped nose, hypotonic lower lip, small ears (see Figure 3.4) [Kolar & Salter 96].

![Figure 3.4](image)

Figure 3.4 the clinical features in Down syndrome (a) as a newborn and (b) as a toddler. Note the clearly up slanting eye fissure, the speckled eyes, the large tongue and the receding chin [Zitelli 2002].

Anthropometric clinical features

Analysis of anthropometric data illustrates three basic points about this syndrome. The first is the wide extent of the anomalies. Of the 120 variables (82 measurements, 38 proportions) for which sufficient data are available, 91 (63 measurements, 28 proportions) differ significantly from the normal standards at p<0.05 or less. Second, with only three exceptions, all of the abnormal linear measurements are significantly smaller than normal. Several of the mean angles and
inclinations (six of 11) are significantly greater than average but these are relational rather than dimensional and are affected by relative reductions in the measurements. The third point is that the reductions are disproportionate, producing abnormalities in shape as well as size [Kolar & Salter 96]. Detailed anthropometric findings in Down syndrome reveal the followings (see section 2.3 for interpretation of craniofacial measurements and indices):

The skull is reduced in size in all directions. However, the decrease in length is greater than that in width, resulting in relative brachycephaly\(^\text{11}\). The forehead is an exception to the other cranial findings. Although the minimum frontal breadth (ft-ft) is reduced, the hairline is significantly higher than normal, as indicated by the forehead heights (tr-g, tr-n), and is disproportionate to the low anterior cranial height (v-n), as well as being relatively protruded.

The upper face is reduced in all directions, with the most extensive deficiencies in the sagital dimensions (n-t and sn-t). On the other hand, the mandible is reduced in depth (gn-t) and width (go-go) but not vertically (sto-gn). Sagitally, there is a progressive increase in the extent of the deficiency from the mandible (gn-t) to the maxilla (sn-t) to the upper face at Nasion (n-t). As a result the entire face profile is protruded, with both upper face (g-sn) and lower face (sn-pg) inclinations protruded.

In the orbital region, the reductions in the eye fissures are relatively greater in length (ex-ex) than height (ps-pi), producing an unusual rounded shape to the openings. The nose is reduced in size, though the nasal root is wide (mf-mf) and low (en-m’) with an increased nasofrontal angle. The soft tissue is normal (al-al). The root is relatively lower than the tip, which accounts for the saddle shape nose. The nose is short and wide for the face. The labial fissure (ch-ch) and philtrum (cph-cph) are narrow and the upper lip is relatively protruded. The ears are reduced in size, more in length (sa-sba) than width (pra-pa) and are relatively short for the face [Kolar & Salter 96].

### Surgical Planning and Correction

Detailed surgical planning using the anthropometry is specific to the deformities presented by the individual patient. Planning requires consideration of normal morphology and dysmorphology, both measurements and proportions. The areas of normal morphology provide a template on which to calculate the changes in the regions of dysmorphology needed to achieve the most normal overall result. The proportions provide a quantitative image of the gestalt of the patient’s dysmorphology.

The individual measurements indicate the size and direction of change needed to correct the disproportions that produce this dysmorphology [Kolar & Salter 96]. Surgery often occurs in several stages over a period of years, with each procedure building on the results of previous operations, or dependent on a specific level of development of the structures involved.

The usual surgical correction involves several well-known techniques. A bone graft to the nasal bridge is intended to correct the saddle-nose and remove the epicanthal folds, while lowering the lateral canthal ligaments improves the abnormal upslants of the eye fissures. Bone implants or fat pad transposition, are intended to build up the cheekbones, while implants or a genioplasty correct the receding chin.

However, anthropometric findings indicate that advancing the chin point only increases the already protruded facial profile, while advancing cheekbones will flatten the profile between the upper face and lower orbital rims. Thus, it is necessary to conduct special reconstructive procedures, LeFort III advancement of the upper face with advancement of orbital bandeau, to correct the most significant anomalies in Down syndrome [Kolar & Salter 96].

\(^{11}\) Short head
3.3 Growth studies

Before conducting any growth study, certain factors should be considered. The first is the population to be studied. Although most of the researches were conducted on European groups, the absence of adequate comparative data for non-European is increasingly becoming a problem for analysing patterns of dysmorphology or planning surgical correction. The second factor is the choice of the measurements to be made. It is recommended to use those measurements that are useful clinically [Kolar & Salter 96]. The third factor is to define the age intervals that will provide the maximum information from the anthropometric data. The fourth is to separate the males from females in each age group because combining will ignore normal sexual dimorphism at any age and eliminate the ability to study sex differences in the normal growth curve, both timing and velocity. The time and resources will determine the nature of the growth study. There are three basic types of growth studies, cross-sectional, longitudinal, and linked longitudinal or cross-sequential.

Cross-sectional studies

A cross-sectional study involves measuring a group of subjects once over a relatively short period of time. A sample of 25-30 males and females at each age group is the minimum to do this. Up to 50 subjects per group provide much more reliable results especially in heterogeneous population.

The advantage of this type of study is the relatively short time of study because each subject is measured once only. Disadvantages are (i) lack of information on the variation of individual growth patterns, including timing and velocity. (ii) Sampling error is common because of the large number of separate samples needed to construct the overall growth data [Kolar & Salter].

Longitudinal studies

Longitudinal growth studies involve long-term follow up of a group of subjects from birth to adulthood, typically 18-20 years of age. A sample size of 60-100 is theoretically enough to conduct such studies. However, this is not practical because many of the subjects drop out of the project with time. Therefore, it is better to have a large enough initial study group (three to four times the size of the final target group to get statistically valid data).

Advantages are (i) they provide information on actual growth patterns including individual variation in timing and velocity as well as overall group standards. (ii) They provide summary of morphological variations for each age group.

Disadvantages are (i) longer time is needed to complete the study. However it is possible to analyse and present segments of the data as the study sample ages rather than waiting until the end of the study. (ii) A significant amount of data will be lost through attrition within the research group before the study is completed. (iii) Susceptible to sampling error [Kolar & Salter 96].

Linked longitudinal (cross-sequential) studies

As the name implies, those studies involve both cross-sectional and longitudinal studies. Multiple groups of subjects are examined, as in the cross-sectional research. However, each group is followed up for several years. Full longitudinal growth data is derived by overlapping the subjects’ age intervals so that there is roughly the same number of observations over each age interval and there are no clear breaks in the growth data [Kolar & Salter 96].

Advantages are (i) gaining shorter time (ii) obtaining information on individual growth data (iii) Less attrition of data because of shorter time. A disadvantage might be the loss of data on growth velocity and timing because of the shorter follow up.

An example of this type of studies is [Hutton et al 2002] where it is shown that growth pattern is linear up to the age of 18 years. Principal component analysis of the results shows that the first mode of variation has a strong correlation with the age of the subject while modes 2 and 3 show changes in face shape that involve identity and facial expression.
Section four

Method and results
“An expert is merely a man who has made all the mistakes he can in a very narrow field”

Niels Bohr
4. Method

4.1 Theory

In this section we explain the theoretical concepts of the study. We start by describing the alignment algorithm that we use, followed by a brief description of the statistical analysis of the aligned data. We show why it is important to construct a model and how the model should be constructed. We end the section by outlining the concept of dense point correspondence.

4.1.1 Alignment

We start this section by introducing some concepts that will be frequently used in the following sections. Shape is all the geometrical information that remains when location, scale and rotation effects are filtered out from an object. The landmark, on the other hand, is a point of correspondence on each object that matches between and within population. There are three basic types of landmarks [Dryden 98]:

1. **Anatomical landmark** which is a point assigned by an expert that corresponds between organisms in some biologically meaningful way, e.g. the corner of an eye or the meeting of two sutures on a skull. Anthropometric landmarks that we use in this study are anatomical landmarks.

2. **Mathematical landmarks** are points located on an object according to some mathematical or geometrical property of the figure, e.g. at a point of high curvature or at an extreme point.

3. **Pseudo-landmarks** are constructed points on an organism, located either around the outline or in between anatomical or mathematical landmarks. We use pseudo-landmarks for dense correspondence in section 4.4.2.

**Generalized Procrustes analysis (GPA):** is the term used when several objects are fitted using Procrustes superimposition. To make the generalized Procrustes analysis, we follow the algorithm mentioned in [Bookstein 97].

Each face can be represented by a shape vector of concatenated \( x, y \) and \( z \) coordinates for all \( n \) landmarks.

\[
\mathbf{z}_i = [x_1, y_1, z_1, \ldots, x_n, y_n, z_n]^T
\]

(1)

To use the minimum of the sums of squares between corresponding landmarks sets, we connect each landmark to the centre of gravity of the landmarks set then we proceed with position normalisation i.e. translating each set of landmarks so that its centre of gravity or centroid directly overlies the centroid of the other set. This is done in the following way:

\[
\bar{z} = \frac{1}{n} \sum_{n=1}^{n} \bar{z}_n
\]

\[
z'_i = z'_i - \bar{z}
\]

(2)

Where

\( \bar{z} = \text{mean} \)

This is followed by scaling normalisation i.e. rescale the sum of square distance to unity; in other words the sum of squares of the points in a landmark set around their centre of gravity is constrained to be exactly one [Bookstein 97].

The scaling parameter is the square root of the summed squared distances between the landmarks and their centroid as follows:
\[ V = \sum_{n=1}^{n} |z_n'|^2 \]

This normalisation, which includes scaling, and translation is done by the function `normalise.m`, (see the appendix A). By removing the effects of translation and scaling, we aim at retrieving the shape (see the definition of the shape above).

Figure 4.1 shows the minimization of Procrustes distance between two quadrilateral shapes (first row). Landmarks in each shape are connected to its centroid and then for each shape, the sum of squares of the distances is scaled to unity (second row). The two shapes are superimposed by superimposing their centroids (third row left) and then rotate each shape (third row right) to minimize the sum of squared distances between matched landmarks (fourth row left). The squared Procrustes distance between the original shapes is the minimum sum of squares between corresponding points; it is proportional to the total area of circles shown here (fourth row right). The shape and the comments are taken from [Bookstein 97].

Then we identify the rotation that minimises the sum of squares of the residual distances between matched landmarks [Bookstein 97].
This is the minimisation of the Procrustes distance. The Procrustes distance is the Euclidean distance between shapes superimposed so as to minimize the sum of squared distances between homologous landmarks.

In two-dimensional data this is done as follows:

Assuming that we have two complex vectors:

\[ z_j = (z_{j1}, ..., z_{jn})' \]

where \( j = 1, 2 \) with \( \sum jz_{ij} = 0 \) and \( \sum jz_{ij}z_{ij} = 1 \) those constraints represent the position and the scaling normalisation which have been already done in equation (2) and (3). Note that \( z_{ij}' \) here is the conjugate part of the complex number. The mean for this sample of the complex vectors, is the shape \( z \) that is the first Eigen vector of the matrix \( \sum jz_jz_j' \), \( n*n \) matrix.

Alignment of the second vector on the first is given by:

\[ z_2 \to (\sum jz_{ij}z_{ij}')z_2 \] (4)

The Procrustes distance between the two vectors is given by:

\[ PD^2(z_1, z_2) = 1 - |\sum jz_{ij}z_{ij}'|^2 \] (5)

In three-dimensional data this is done as follows:

If we have two shapes; mathematically speaking two vectors \( X_1 \) and \( X_2 \) which are \( n*p \) dimension (\( p=2 \) or \( 3 \)) for the coordinates of \( n \) landmarks \( (n \geq p) \). Then after centring and rescaling explained above, the singular value decomposition of \( X_1^T X_2 \) is \( UDV' \) where \( U \) is \( n*p \) column-orthogonal matrix, \( D \) is \( p*p \) diagonal matrix with all its elements are positive or zero (the singular values) and \( V' \) is \( p*p \) orthogonal matrix. It follows that the minimisation of Procrustes distance between the two shapes or in other words the superimposing of \( X_2 \) upon \( X_1 \) is just the matrix \( VU' \), which is a \( 2*2 \), or \( 3*3 \) matrix depending on the size of \( p \). (See appendix A, matlab function \texttt{minimizeprocrustes.m} and \texttt{main.m} the latter takes care of all the alignment procedures and return the aligned shapes in a large array).

4.1.2 Modelling shape variation:

Principal component analysis (PCA) of the sample covariance matrix provides a very effective means of analysing the main modes of variation in shape. It is useful as well to reduce the dimensionality of the problem. By carrying out PCA we are decomposing variability (the total sum of Procrustes distance) into orthogonal components, with each PC successively explaining the highest variability in the data, subjected to being orthogonal to the higher PC’s [Dryden 98].

We calculate the sample covariance matrix of the aligned shapes as in [Cootes 98]:

\[ D = [ (z_1 - \bar{z}) | ... | (z_n - \bar{z}) ] \] (6)

Where:

\( D \) is a matrix of \( n*p*s \) i.e. number of landmarks for each shape by the dimension of the shape by the number of the shapes in the sample.

\[ S = \frac{1}{s-1}DD^T \] (7)

The Eigen values and Eigen vectors are calculated from the covariance matrix. Then the percentage of variation will be:
Percent of variation \[ \frac{\text{Percent of variation}}{\sum_{i} \lambda_i} = \frac{100 \lambda_i}{\sum_{i} \lambda_i} \] (8)

Where \( \lambda_i, i = 1,...,t \) is the \( i \)’th Eigen value. Each Eigen value gives the variance of the data about the mean in the direction of the corresponding Eigen vector. Therefore, one useful aspect of the percentage of variation is how many Eigen vectors are to be picked up. The routine is to pick up the number of Eigen vectors that explain 98% of variation and exclude the remainder 2% which is usually attributed to the noise.

The new shape is generated according to formula mentioned in [Cootes and Taylor 2001] with some modifications. If \( \Phi \) contains \( t \) Eigen vectors corresponding to the largest Eigen values, then the new shape is

\[ z_{\text{new}} \approx \bar{z} + b_i \Phi_i \]

Where
\[ \bar{z} = \text{mean} \]
\[ \Phi = (\Phi_1 | \Phi_2 | ... | \Phi_t) \]
\[ \Phi_i = i^{th} \text{Eigen vector} \]
\[ b_i = i^{th} \text{parameter} \]

The vector \( b \) defines a set of parameters of a deformable model. By varying the elements of \( b \) we can vary the shape \( z_{\text{new}} \) using equation (9). The variance of the \( i \)’th parameter, \( b_i \), across the sample is given by \( \lambda_i \). By applying limits of \( \pm 3 \sqrt{\lambda_i} \) to the parameter \( b_i \) we ensure that the shape generated is similar to those in the sample (see appendix A, matlab function covariance.m).

For the dense correspondence (see 4.1.4) we use huge data files, therefore, the covariance matrix will be very huge one. To avoid having to Eigen-decompose a very large \( S \) matrix we compute a smaller \( s \times s \) matrix \( T \):

\[ T = \frac{1}{s-1} D^T D \] (10)

The first \( s \) Eigen values of \( S \) are the same as those of \( T \); the remainders are zeros. We can compute the first Eigen vectors \( e_i \) of \( T \) using:

\[ \Phi_i = De_i \] (11)

The computed Eigen vectors can be treated as deformations of the whole mesh and can be directly added to the coordinates of the vertices of the mean mesh to synthesis the new faces as in equation (9). (See appendix A, matlab function covarianceModified.m).

4.1.3 Constructing the model
A useful approach in pattern analysis and pattern theory is to use Bayesian probability theory [Hallinan et al. 98]. In the Bayesian approach we wish to infer the state of the world \( S \), which we shall call the model, given some measurement \( I \). In this study \( S \) represents the model of the human face we are aiming to construct, while \( I \) represents the data or information that we have, such data could be an image for example.
The \textit{a posteriori probability} of the model of the world given the measurement

\[
P(S \mid I) = \frac{P(I \mid S)P(S)}{P(I)} \quad \text{(Bayes’ theorem)}
\]

Where

- \(P(S \mid I)\) is the probability of the model given the measurement.
- \(P(I \mid S)\) is the probability of observing the measurement given the model (the likelihood function).
- \(P(S)\) is the probability of the model (prior model).

Bayesian model can be used to find MAP (maximum a posteriori) which is a sort of probabilistic inference such as finding the most probable estimate of the world depending on particular signal. Another use is to sample from the model, fixing some of the world variables \(S\), and use this distribution to construct sample signals \(I\) generated by various classes of objects or events [Hallinan et al. 98].

Patterns in signals can considered from the perspective of information theory. The idea is to seek a method of encoding \(I\), which minimizes its expected length; taking the advantage of patterns possessed by most \(I\) to encode them in a compressed form. We use various auxiliary variables \(S\) to encode \(I\) as follows:

\[
\text{length(code}(I, S)) = \text{length(code}(S)) + \text{length(code}(I \text{ deviating from } S)).
\]  

So the problem is, for a given \(I\), to find \(S\) leading to the shortest encoding of \(I\), and moreover, to find the encoding scheme leading to the shortest expected coding of all \(I\)'s. The optimal choice of \(S\) is called the \textit{minimum description length} or MDL estimate of \(S\). [Hallinan et al. 98].

\[
\text{MDL est. of } S = \arg \min \left[ \text{length(code}(S)) + \text{length(code}(I \text{ deviating from } S)) \right]
\]  

Shannon’s optimal coding theorem provides the link between information theoretic approach and Bayesian approach. This theorem models that given a class of signals \(I\), the coding scheme for such signals for which a random signal has the smallest expected length satisfies:

\[
\text{Length(code}(I)) = - \log_2 p(I)
\]  

This theorem can be applied to encoding \(S\) and to encoding \(I\) given \(S\). For these encodings;

\[
\text{Len(code}(S)) = - \log_2 p(S)
\]  

\[
\text{Len(code}(I \text{ deviating } S)) = - \log_2 p(I \mid S).
\]

Thus we obtain:

\[
- \log_2 p(S \mid I) = - \log_2 p(I \mid S) - \log_2 p(S) + \log_2 p(I)
\]

By solving equation (18) we get equation (15) and find that the most probable estimate of \(S\) is the same as the MDL estimate.

From all the above we conclude that the model can be expressed by the mean and the variations from the mean. The variations are the Eigen vectors, therefore, the less Eigen vectors we
use in our model the better compression we perform. However, this is a matter of complexity versus the noise because the more Eigen vectors we use to express our model, the more precise is the model and the more complex it is at the same time. At any rate, the aim is to have a model that is able to express any given face by using the mean and the Eigen vectors.

4.1.4 The Dense point correspondence

A measure of shape distance, such as full Procrustes distance, gives us a numerical measure of shape comparison, but this global shape measure does not indicate locally where the objects differ and the manner of difference [Dryden 98]. By global difference we mean large-scale trends, such as an overall affine transformation. Local differences, on the other hand, are on a smaller scale, for example highlighting changes in a few nearby landmarks. Global differences are smooth changes between the figures, whereas local changes are the remainder of the components of deformation and are less smooth [Dryden 98]. This concept can be applied to the human face. The points in between well-defined landmarks, such as points on the cheeks and across the forehead have no precise biological correspondence and yet aspects of their shape contain useful biological information. To catch this extra information, dense correspondence is employed [Hutton et al 2002]. Generalized Procrustes analysis is used to align the sets of landmarks as explained in 4.1.1. Having brought all the surfaces into close alignment, a dense correspondence is made by taking the closest point on each surface from each vertex in a base mesh [Hutton et al 2002].

The base mesh to be used is one of the scans in the sample, which is particularly good regarding coverage, and lack of holes. This base mesh is used to sample the other meshes by finding the closest point, where the closest point is the point that has the minimum Euclidian distance to a vertex in the base mesh. A defect in the target mesh like a spike (one significantly misplaced vertex), hole, or triangulation error, will cause the target mesh not to be locally manifold, therefore, should be treated. A spike in one of the surfaces is unlikely to be sampled since the surfaces are in close alignment. Similarly, a hole in a target mesh will result in the base mesh sampling points around the edge of the hole [Hutton et al 2002]. Figure 4.2 illustrates how a hole in the target mesh is treated.
Thus, vertex displacement tends not to be correlated with other shape changes and therefore not represented in the most significant principal components. New meshes are generated from the correspondence between the base mesh and other meshes. Vertices in those new meshes are treated as landmarks and generalized Procrustes analysis is conducted followed by principal component analysis to capture the local differences in the scans.
4.2 Experimenting with two-dimensional data

We start experimenting with two-dimensional images of the faces that are downloaded from the Internet. The quality of those images is not so high. However, it is adequate to start experimenting the annotation, the alignment and later on the principal component analysis. Figure 4.3 shows the eleven test images while figure 4.4 shows an example of annotating one of those images.

![Figure 4.3](image1.png)

**Figure 4.3** The eleven faces images that were used as test images. Most of them are movie stars as those images are the easiest to find.

![Figure 4.4](image2.png)

**Figure 4.4** The 22 landmarks are shown as blue points superimposed on one of the shapes.

Twenty-two landmarks are used; the position of those landmarks is designed to show the gross face features so the landmarks are set to the eyes, the nose, the lips, the chin and the forehead. After normalisation and minimisation of Procrustes distance as mentioned in section 4.1.1 we conducted principal component analysis of the data. Since this step is just an experimental one we shall not elaborate on the results. However, it is worth to mention that, many mistakes, committed in this experiment, alerted us to take more meticulous care while dealing with the three-dimensional data. For example we have learned from this experiment that the sequence of annotation is of vital importance to attain reasonable results. The two-dimensional data analysis ended when we added an arbitrary third dimension. The idea is to make smooth transformation from 2D to 3D. Now we are ready to deal with real 3D images.

4.3 Three-dimensional data analysis using non-anthropometric landmarks

A Preliminary test

Eleven face images are used as a preliminary test of PCA of the faces. The images are collected using the three-dimensional laser scanner Minolta VI-900 Non-Contact Vivid 3D digitizer. It uses laser beam which is "Eye safe" Class 1 (FDA), maximum 30mW, 690nm ([http://www.minoltausa.com/vivid/default.asp](http://www.minoltausa.com/vivid/default.asp)).

The laser scanner offers a fast, non-invasive way to collect a permanent database of three-dimensional surface contours of the face and head, which can be saved for future study as new quantitative methods are developed. Compared to the conventional x-ray equipment, the cost is low. Because the system uses light scans instead of radiation, and because it is non-invasive, it can be used for scanning normal subjects in sufficient numbers to establish a comparative craniofacial database, although this is yet to be done [Kolar & Salter 96]. However, laser scanner cannot identify the underlying skeletal anatomy, a fact that limits, to some extent, its advantages.
Two images are taken for each subject; one with the subject head rotated (+15°) and the other with (-15°) rotation. This is necessary to get good view of the nose and ears (to get rid of the shadows). The two images are registered and the holes are filled automatically to get the final image. The subjects are asked to close the eyes to decrease the danger of exposing the eyes to laser beams, however the risk of damage to their eyes by laser beams is insignificant in this wavelength as the effect of laser beam and its significance depends on wavelength, intensity of the radiation and the absorption characteristics of different eye tissues.

No other constraints are considered while taking the images i.e. illumination, head position, number of shots, hair coverage (the scanner has a problem with visualising the hair and this affect the skull measurements), better view of the ears and so on. Race and gender are not considered as constraints at this stage. Absence of constraints on head position, hair covering … etc led to some problems later on when annotating the images with the anthropometric landmarks. Therefore, it is essential to make constraints in the process of data acquisition. Variation in head position and inclination cause significant changes in the digitised image due to alteration in the orientation of curved surfaces on the face with respect to the plane of light projected by the laser scanner. However, the effect of head inclination on the reliability of landmark localisation is specific for each landmark [Bush 95].

Fourteen landmarks are used. Those landmarks are chosen to give very simple yet informative visualization of the face. We are using landmarker TCL/VTK ready-to-use software that is provided by [Tron Darvann (unpublished)]. The annotation file is saved as a log file that will be interpreted and used in matlab (See appendix A, matlab function convert.m). This step is necessary since the software of the landmarker is not compatible with matlab.

The employed landmarks were:
Point 1: left corner of the left eye
Point 2: right corner of the left eye
Point 3: left corner of the right eye
Point 4: right corner of the right eye
Point 5: origin of the nose (between the two eyebrows)
Point 6: tip of the nose.
Point 7: left corner of the mouth
Point 8: right corner of the mouth
Point 9: left tempo-mandibular joint
Point 10: chin
Point 11: right tempo-mandibular joint
Point 12: left corner of the forehead
Point 13: mid of the forehead
Point 14: right corner of the forehead

Figure.4.5 (a) shows an example of image, which is taken using the laser scanner before making annotation while (Figure.4.5 (b)) shows the visualization of one of the images. We can see clearly the gross features of the face represented by different colors.

Normalization is done as in the two-dimensional image data with exception that we have a third dimension here. Minimization of Procrustes distance is done using the singular value decomposition as explained in section 4.1.1. Then we align the eleven shapes with each other iteratively by normalizing each shape and aligning it with the new shape until all the shapes are aligned or yet more exactly, are super positioned on each other.

The shapes before alignment are shown in (Figure.4.6 (a)) while the aligned shapes can be seen in Figure.4.6 (b) and another view in figure 4.7. We can see by looking at (Figure.4.6 (b)) we can see that we have an acceptable alignment of the shapes.
Figure 4.5 (a) shows an example of three-dimensional image taken by the laser scanner before annotation as it appears in the TCL landmarker GUI. (b) Shows an example of visualisation of one of the images using fourteen landmarks that are chosen to give simple yet informative representation.

Figure 4.6 shows the eleven shapes before alignment (a) and after alignment (b). It can be seen that there is apparently acceptable alignment.

Now we can conduct the statistical analysis of the data as explained in section 4.1.2 the results are shown in (Figure 4.7) that demonstrates the percentage of variation of the data set that we have used. Note that the first three principal components account for more than 72% of variation.

Figure 4.7 shows the mean face and the variations associated with the first principal component

4.8 shows the first 10 principal components and the percentage of variation they account to.
There are several ways to visualize the effect of each PC [Dryden 98]:

1. Evaluate and plot an icon\(^{12}\) for a few values of \(b \in [-3,3]\), where \(b=0\) corresponds to the full Procrustes mean shape. The plot could be either separate or superimposed.
2. Draw vectors from the mean shape to the shape at \(b=+3\) and/or \(b=-3\) to understand the structure of shape variability. The plots should clearly label which directions correspond to positive and negative \(b\) if both values are used.
3. Superimposed a square grid on the mean shape and deform the grid to icons in either direction along each principal component.
4. Animate the sequence of icons backwards and forwards along the range \(b \in [-3,3]\). This dynamic method is perhaps the most effective for displaying each PC. Therefore, we use it in this study in addition to the first method (see figure 4.7).

The changes related to each of the ten principal components are mentioned below. It is worth to mention that describing the changes becomes more difficult after the first four PC’s. Moreover, principal component analysis cannot show more than one change at a time unless the changes are combined. For instance, PCA cannot show vertical scale changes and then after horizontal scale changes. However, PCA can show a combination of the vertical and horizontal changes as shown below.

Another note is that the PCA expresses the linear changes; therefore it is limited in the sense that it cannot express the more natural non-linear changes. The results are shown in table 4.1\(^{16}\). Table 4.1 shows the percentage of variations and the changes associated with each of the first ten principal components.

<table>
<thead>
<tr>
<th>PC</th>
<th>Percentage</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>31%</td>
<td>Vertical scaling</td>
</tr>
<tr>
<td>Second</td>
<td>27.5%</td>
<td>Horizontal scaling</td>
</tr>
<tr>
<td>Third</td>
<td>12.5%</td>
<td>Rotation around the Z-axis</td>
</tr>
<tr>
<td>Fourth</td>
<td>9%</td>
<td>Rotation around the Z-axis</td>
</tr>
<tr>
<td>Fifth</td>
<td>7%</td>
<td>Rotation around X-axis</td>
</tr>
<tr>
<td>Sixth</td>
<td>4%</td>
<td>Vertical scaling plus inward rotation</td>
</tr>
<tr>
<td>Seventh</td>
<td>3.5%</td>
<td>There is extreme scaling on horizontal and vertical axis</td>
</tr>
<tr>
<td>Eighth</td>
<td>2.5%</td>
<td>There is extreme rotation around X-axis with pronounced shape distortion</td>
</tr>
<tr>
<td>Ninth</td>
<td>1%</td>
<td>Oblique stretching of the shape plus pronounced distortion</td>
</tr>
<tr>
<td>Tenth</td>
<td>&lt; 1%</td>
<td>Disharmonised stretching along X and Y-axis with severe distortion of the shape features</td>
</tr>
</tbody>
</table>

\(^{12}\) An icon is a particular member of the shape set, which is taken as being representative of the shape [Dryden 1998].
4.4 Three-dimensional data analysis using anthropometric and pseudo-landmarks

4.4.1 Coarse correspondence (using anthropometric landmarks)

We start this section by discussing the used anthropometric landmarks, measurements and proportions. We then tackle some problems that were encountered during annotating the face, the constraints used, and we end up with presenting the results of the statistical analysis of the data.

Anthropometric landmarks

The idea of using the anthropometric landmark has been introduced in the previous sections (see section 3.1). Here we are using 64 landmarks that are defined as anatomical landmarks [Kolar and Salter 96] to compute 71 measurements and 12 angles.

The tables in section 2.3 show the landmarks that are used. Those that are not used are shaded in dark grey. The main reason of not using some of the landmarks is that they could not be measured either because of inadequacy in data acquisition or because of difficulty to design the relevant tests that measure them, as for example Vertex and Frankfort horizontal plane respectively.

It should be mentioned first that good knowledge of Anatomy is mandatory for landmarking. Second, that annotation might be a tedious and time-consuming process and it is more tedious in 3D than in 2D because the image might require frequent manipulation to display the appropriate landmarks in the correct sequence. Locating the landmarks may introduce an additional source of error through difference in identification.

Anthropometric measurements

Anthropometric landmarks by themselves are not important. However, measurements and proportions between those landmarks are of vital importance both in anthropology and plastic surgery. There are two types of anthropometric measurements:

1. Linear measurements and those include horizontal and vertical measurements.
2. Angles and inclinations.

Although we measure some angles and inclinations, we concentrate mainly on the linear measurements. The angles and inclinations measurements are shown in table B-3 in Appendix B. However, the angles and inclinations measurements that have been excluded - due to the absence of one or another landmark or due to difficulties in measurement - are shown shaded in the tables. The excluded angles and inclinations measurements are:

1. Forehead inclination.
2. Orbital rim inclination
4. Nasolabial angle
5. Nasal tip angle.
7. Ear protrusion.
8. Ear inclination.
9. Ear location.

Annotation

To make the annotation more accurate we start as a rule from the right to the left, with reference to annotating person’s hand, if the point lies on both sides. Moreover, the plan of annotation is to take each area, annotate it and then move to the other area e.g. the head area should be fully annotated before annotating the face area. Those precautions are necessary because the series of points after annotation should be the same for all the annotated images e.g. the landmark “eu rt” should be the first landmark in all the images. Some of the problems encountered during annotation are solvable with extra time; others need new data acquisition i.e. new images to be
taken under certain constraints. The third type of problems is inherently difficult to solve. Problems with the suggested solutions are mentioned below; however there might be better solutions.

1. Difficulty to set a landmark on bony prominence because in reality bony landmarks are usually palpated. This is particularly well demonstrated in the anatomical sites characterised by smooth gradations in the surface contour such as glabella (g) and zygion (zy) (see figure 2.6) [Bush et al 95]. The suggested solution is to use high-resolution images, better illumination techniques and meticulous care while setting the landmarks.

2. Difficulty to set a landmark where the point of the landmark may trespass the area of another landmark. This could be overcome by making changes in the landmarker software so that the landmarker points becomes smaller or by zooming in the view so that more area will be available for annotation. However, zooming ameliorates the problem rather than solves it.

3. The orbit landmarks could not be completed due to the fact that the 3D images were acquired while the eyes were closed to minimise the danger of the laser beam.

4. It is difficult to conduct the measurements that depend on the angles and inclination angles. Therefore, some of those measurements were excluded for the time being.

Constraints on data acquisition
We use the following constraints in data acquisition:
1. Male.
2. Age 25-35.
3. Caucasian race.
4. With no moustache or beard.
5. With no eyeglasses.
6. Approximately neutral facial expression.

Sources of error in anthropometry using 3D laser scanner
In two studies [Bush et al 95] and [Baca et al 94], the potential sources of error were identified using a life sized plaster anthropomorphic model. These sources include:
1. Motion artefacts. Significant motion degrades the image.
2. Biological variation. The pliability of facial soft tissue may result in subtle changes in the three-dimensional surface associated with variations in expression, fatigue…etc.
3. Errors associated with laser digitisation i.e. data acquisition which depend largely on head position, inclination…etc.
4. Errors in interactive localisation of the anatomic landmarks. Good knowledge of anatomy is needed so that the user can identify and localise the landmarks on the screen.
5. Inter-observer variability.

Therefore, we believe that using more constraints on data acquisition should improve the results in a pronounced way, these constraints might be:
1. Illumination for better visualization of the details of the face, especially the soft tissue where some landmarks are set.
2. Showing the details of the ear, nose and eyes. This may involve more than two images for each subject.
3. Setting some standardised positions and inclinations while acquiring the data so that the angles and inclinations can be reliably measured.
4. Standardising the treatment of the hair for example with bath head covers.
5. Excluding the landmarks that are difficult to be visualised and/or localised i.e. show high variance in localisation e.g. peri-alar landmarks (al. and ac.) [Bush et al 95].
Statistical analysis of the data

Now we show an example of annotation in (Figure.4.9) Note that the landmarks are connected for the purpose of visualisation i.e. not all the lines connecting the landmarks are anthropometrically meaningful although some of them are. Note also that the green dots are the landmarks that were not connected. We use the same algorithm mentioned in section 4.1.1 to align the shapes. However, of the eleven faces we use in section 4.3, we have only eight faces now due to exclusion of three faces for three different reasons. One of the faces was non-Caucasian, the other one was not a male and the third one was excluded because of inadequate data acquisition, which made it impossible to set many of the anthropometric landmarks. (Figure.4.10 (a)) shows the eight faces used in this preliminary test before their alignment and (Figure.4.10 (b)) after their alignment. Figure.4.12 shows the linear anthropometric measurements connecting the landmarks. Those lines and their proportions will be used later on in the analysis of the faces. Since the angles are better shown as numbers rather than lines, we do not visualise the angles here. The results of the angles and inclinations measurements are shown in table B-3 appendix B.

Figure.4.9 shows an example of annotation of the face using the anthropometric landmarks. The landmarks were connected for the purpose of visualisation. The green dots indicate non-connected landmarks.
Figure 4.10 the faces of eight Caucasian, males, and aged 25-35, with no moustache or beard are shown here (a) before alignment and (b) after alignment.

Figure 4.11 another view of the eight faces, here we can see clearly the three-dimensional nature of the data and the effects of changing the view angle.

Table 4.2 shows the changes associated with each of the principal components

<table>
<thead>
<tr>
<th>PC</th>
<th>Percentage</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>27%</td>
<td>Vertical scaling</td>
</tr>
<tr>
<td>Second</td>
<td>16%</td>
<td>Vertical scaling plus inward folding</td>
</tr>
<tr>
<td>Third</td>
<td>15%</td>
<td>Horizontal plus vertical scaling</td>
</tr>
<tr>
<td>Fourth</td>
<td>14%</td>
<td>Vertical scaling plus outward unfolding, pronounced more in the lower part of the face.</td>
</tr>
<tr>
<td>Fifth</td>
<td>12.5%</td>
<td>Horizontal, to less extent vertical scaling plus minor degree of rotation around the vertical axis.</td>
</tr>
<tr>
<td>Sixth</td>
<td>10%</td>
<td>Outward unfolding towards more circular shape with some rotation around the vertical axis.</td>
</tr>
<tr>
<td>Seventh</td>
<td>7%</td>
<td>Minor vertical scaling plus left to right rotation around the vertical axis.</td>
</tr>
<tr>
<td>Eighth</td>
<td>1%</td>
<td>Outward unfolding with minor vertical scale changes and rotation around the vertical axis.</td>
</tr>
<tr>
<td>Ninth</td>
<td>1%</td>
<td>Change in vertical scale plus some inward folding</td>
</tr>
<tr>
<td>Tenth</td>
<td>1%</td>
<td>Very minor diffused changes</td>
</tr>
</tbody>
</table>
It is clear that the variations are so diffused among the first seven principal components. The only available explanation is the presence of points that increase the amount of variation. To roll out this possibility we designed a matlab function to make a coarse ordering of the points and exclude those that might increase the diffusion of the PC’s. However, no such landmarks were detected (see Appendix A, matlab function coarseOrder.m). It is worth noting that in comparison with section 4.3 where only 14 points are used, we find that we have 58% of variation in the first three PC’s (72% in section 4.3). On the other hand, using 55 landmarks (anthropometric and non-anthropometric) did not improve the results markedly. One explanation might be due to increase in the number of landmarks or their independencies (if there are strong dependencies between landmarks, then only few PC’s may capture a large percentage of variability) [Dryden 98].

Many methods were suggested to choose the number of PC’s [Cootes and Taylor 2001]. Here we try to choose the number of PC’s that describes 98% of the variations assuming that the residual variations are related mainly to noise.

![Figure 4.12](image)

Figure 4.12 shows the anthropometric measurements as cyan lines that connect the landmarks. Note now that the green dots, which are not connected in the previous Figures, are connected now since they are parts of the anthropometric measurements.

Since visual impressions are very subjective, we use quantitative analysis to describe the results. The values of the craniofacial measurements are saved in a file then a threshold value is set to separate the major from minor changes. The threshold value is experimental one. Table 4.3 shows the results when setting the threshold value to >0.15.

It is worth to mention that the changes shown in table 4.3 are the changes associated with the scaled Eigen values. Therefore, we can see major changes even with the eighth, ninth and tenth principal components although they represent altogether less that 2% and they are usually attributed to noise. This can be checked easily by multiplying the Eigen vectors by the variance so they are scaled according to the amount of variation each of them catches. Table 4.4 shows the result of multiplying...
Eigen vectors by the variance. Note that the last four principal components are not contributing to the changes any more.

Table 4.3 shows the changes in the anthropometric measurements associated with the first tenth principal components. The Eigen values are scaled.

<table>
<thead>
<tr>
<th>First</th>
<th>Second</th>
<th>Third</th>
<th>Fourth</th>
<th>Fifth</th>
<th>Sixth</th>
<th>Seventh</th>
<th>Eighth</th>
<th>Ninth</th>
<th>Tenth</th>
</tr>
</thead>
<tbody>
<tr>
<td>tr-g</td>
<td>tr-g</td>
<td>go-go</td>
<td>eu-eu</td>
<td>eu-eu</td>
<td>tr-g</td>
<td>tr-g</td>
<td>tr-g</td>
<td>tr-g</td>
<td>sbal.rt-ls'.rt</td>
</tr>
<tr>
<td>tr-n</td>
<td>fz-g-fz</td>
<td>gn-go.rt</td>
<td>fz-g-fz</td>
<td>tr-ft</td>
<td>tr-g</td>
<td>gn-go.rt</td>
<td>ac.lt-prn</td>
<td>tr-n</td>
<td>sbal.lt-ls'.lt</td>
</tr>
<tr>
<td>tr-gn</td>
<td>gn-go.rt</td>
<td>tr-gn</td>
<td>n-gn</td>
<td>go-go</td>
<td>tr-n</td>
<td>go.lt-cdl.lt</td>
<td>cph-cph</td>
<td>gn-go.rt</td>
<td>pa.rt-pra.rt</td>
</tr>
<tr>
<td>sn-prn</td>
<td>gn-go.lt</td>
<td>ex.rt-go.rt</td>
<td>ex.rt-go.rt</td>
<td>gn-go.lt</td>
<td>fz-g-fz</td>
<td>t.rt-g-l.t</td>
<td>ch-ch</td>
<td>pa.rt-pra.rt</td>
<td>obs.rt-obi.rt</td>
</tr>
<tr>
<td>n-prn</td>
<td>t.rt-sn-llt</td>
<td>sn-prn</td>
<td>t.rt-sn-llt</td>
<td>tr-gn</td>
<td>li-sl</td>
<td>t.rt-gn-l.t</td>
<td>pa.rt-pra.rt</td>
<td>pa.lt-pra.lt</td>
<td>pa.lt-pra.lt</td>
</tr>
<tr>
<td></td>
<td>obs.rt-obi.rt</td>
<td>n-prn</td>
<td>pa.rt-pra.rt</td>
<td>n-gn</td>
<td>sa.rt-sba.rt</td>
<td>li-sl</td>
<td>pa.lt-pra.lt</td>
<td>sa.lt-sba.lt</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>obs.lt-obi.li</td>
<td>pa.lt-pra.lt</td>
<td>-</td>
<td>go.lt-cdl.lt</td>
<td>-</td>
<td>pa.lt-pra.lt</td>
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<td></td>
<td>-</td>
<td>-</td>
<td>obs.lt-obi.li</td>
<td>-</td>
<td>ex-ex</td>
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<td>sbal.lt-ls'.lt</td>
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<td></td>
<td>-</td>
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<td>pa.rt-pra.rt</td>
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<td></td>
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<td>obs.rt-obi.rt</td>
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</tbody>
</table>

Table 4.4 shows the changes in the anthropometric measurements associated with the first five principal components. The Eigen values are not scaled.

<table>
<thead>
<tr>
<th>First</th>
<th>Second</th>
<th>Third</th>
<th>Fourth</th>
<th>Fifth</th>
<th>Sixth</th>
<th>Seventh</th>
<th>Eighth</th>
<th>Ninth</th>
<th>Tenth</th>
</tr>
</thead>
<tbody>
<tr>
<td>tr-g</td>
<td>fz-g-fz</td>
<td>go-go</td>
<td>fz-g-fz</td>
<td>pa.rt-pra.rt</td>
<td>tr-n</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>tr-n</td>
<td>gn-go.rt</td>
<td>gn-go.rt</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>go-go</td>
<td>t.rt-sn-llt</td>
<td>ex.rt-go.rt</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>tr-gn</td>
<td>obs.rt-obi.rt</td>
<td>pa.rt-pra.rt</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>obs.rt-obi.rt</td>
<td>obs.lt-obi.li</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>

Using a threshold value might be tempting, however, it carries two potential risks, which are:

1. The risk of missing a major change because the value is less than the threshold value by a negligible difference.

2. The threshold value is just an experimental value, meaning that it cannot be considered constant for all the cases. Therefore, visual assessment is indispensable.
Figure 4.15 First mode of variation (a) view from below to demonstrate the nasal projection and (b) another view shows the changes in the forehead height associated with the first mode of variation.

Figure 4.16 shows the second mode of variation (a) viewed from acute angle and (b) a topographic view. Note that some changes are identical to the first mode of variation while new changes appear in the mandibular length and the size of the nose.

Figure 4.17 shows the third mode of variation. See the changes in the size of the ears. Mandibular breadth change is also clear.

Figure 4.18 shows the fourth mode of variation. See the changes in lower lip.
We give a brief anthropometric analysis of the changes that are shown in table 4.3 and table 4.4. The first principal component (see table 4.3) is associated with changes in forehead height (tr-g, tr-n) in addition to changes in physiognomical face height (tr-gn). This correlates well with the visual impressions of vertical scaling. The protrusion of nasal tip (see figure 4.15 (a)) and changes in nasal bridge length are another two important changes (sn-prn, n-prn respectively).

The second principal component includes a combination of changes. The superior orbital contour and the superior orbital rim contour (fz-g-fz) show pronounced changes. The mandibular body length (gn-go.rt, gn-go.lt) is worth to notice. With the changes in maxillary arc and half arcs (t.rt-sn-t.lt), this PC can be safely associated with the structure of the lower face and the orbits. Ear insertion (obs.rt-obi.rt, obs.lt-obi.lt) shows a change as well.

The most noticeable changes associated with the third principal component are mandibular breadth (go-go) and the later facial height (ex-go), the later is unilaterally seen, which is unexpected behaviour because we assume symmetry in the face unless prove otherwise. Other changes in nasal tip protrusion (sn-prn, n-prn), ear insertion (obs.lt-obi.lt), ear width (pa.rt-pra.rt), physiognomical face height (tr-gn), and mandibular body length (gn-go.rt); occur as well.

The fourth principal component is associated with the horizontal scaling of the face as the maximum cranial breadth changes (eu-eu) with it; and vertical scaling as the morphological face height changes (n-gn). Other changes are later facial height (ex.rt-go.rt), maxillary arcs and half arcs (t.rt-sn-t.lt) and ear width (pa.rt-pra.rt).

The other components can be discussed in the same manner because we are concerned here with the major modes of variation.

The proportions or indices are of vital importance in characterizing the human face. Section 3.1 provides more information about their applications. There are countless proportions (see section 2.3.3), however, we have chosen only three of the major proportions as examples. The results show that the proportions we obtained correlate well with the proportions that are mentioned in the relevant literature [Farkas 87]. Figures 4.13, 4.14 and 4.15 show the mean shape, which is mentioned in the literature, in comparison with the eight faces in the study. For more information see table 1 in appendix B.

Most of the results lie around 3 standard deviations see figure 4.21 for the facial index and around two standard deviations for the nasal index see figure 4.22. This is still reasonable though not optimal. Despite the fact that the normal range is two standard deviations, one standard deviation is very important in plastic surgery. There might be many explanations for those results:

1. The sample size: larger sample size would certainly improve the results.
2. The number of landmarks, measurements and proportions (indices): We use 64 landmarks, 71 measurements and 3 indices, compared to [Farkas 87] where 129 indices were used for example.
3. The technique of data acquisition: while we use the 3D laser scanner to obtain the results, [Farkas 87] [Farkas 94] used the ordinary system of anthropometric measurements.

Figure 4.21 shows the facial index (horizontal) against upper face height (vertical). The inner ellipse represents one standard deviation while the outer one represents two standard deviations. Most of results lie within three standard deviations.

Figure 4.22 shows the nasal index (horizontal) against upper face height (vertical). The inner ellipse represents one standard deviation while the outer one represents two standard deviations. Most of results lie within two standard deviations.

4. The results shown in [Farkas 87] include different age groups while we are comparing our results with the oldest age group in the above mentioned study i.e.18 years. The facial proportions are manifested well at age of 18 years, however those proportions continue to change in a minor way with age.
However, the angles and inclinations do not correlate well with the literature. This might raise the question of the sample size and its statistical validity. The study of Farkas and his colleagues, with which we compare our results, used 1197 males and 1367 females over a period of 15 years using 129 measurements, which is much more larger than our sample. The reason of choosing this study is that it is one of the first and most reliable studies where anthropometry was used as a tool for plastic and reconstructive surgery.

Figure 4.23 shows a plot of the Eigen values. Note that Eigen values are sorted in descending order.

Figure 4.24 scatter plot of mode 1 (horizontal) against mode 2 (vertical), showing a reasonable Gaussian distribution.

4.4.2 Dense point correspondence

The concept of the dense point correspondence is explained in section 4.1.4. In this section we discuss the method, which has been used to make the dense point correspondence. The three-dimensional image files acquired using the 3D laser surface scanner are saved as VRML format. We made some modifications in the function that reads the files (see Appendix A, matlab function convertMod.m) in order to enable it to interpret the VRML format. However, since matlab is slow and the files are huge (more than 100 kb each), we edit each file manually separating it into points’ coordinates and index of coordinates to be loaded and used later on in matlab. This step has saved so much time and memory.

We choose as a base mesh one of the scans in sample, which is good regarding coverage, and lack of holes. The scans in the sample (including the base mesh) often include significant neck and ear areas that are not present in all scans. We snip off these areas by editing the base mesh so that it contains only the desired areas (see figure 4.25). Thus, the areas of neck and head in the target scans are not sampled. This has further reduced the computation time.

The surfaces are aligned following the same way explained in 4.1.1. The normalisation vector and the rotation matrix, which are used to align shapes making the coarse correspondence, are used to align the target meshes to the base mesh. This is clear since in coarse correspondence we used the anatomical landmarks so we know before hand which landmark is corresponding to which on the shapes e.g. landmark number one is homologous in all the shapes.

Having brought all the surfaces into close alignment, a dense correspondence is made by taking the closest point on each surface from each vertex in the base mesh. There are many algorithms to do this [Hutton et al 2002]. However, we use a brut force algorithm to find the corresponding points to those on the base mesh. The technique is simple; finding the minimum Euclidean distance between a point in the target mesh and a vertex in the base mesh, yet it has some disadvantages. For example a vertex in the target mesh may correspond to many vertices in the base mesh another disadvantage is the possibility of having a polygon, which is corresponding to the base mesh but flipped. Fortunately, by making a close alignment, we reduce the effect of those disadvantages to a
negligible effect. The image files converted now to simple text files, which are so huge (100 kb each), this has led to difficult problems:

![Image](image.jpg)

**Figure 4.25** The scan, which has been used as a base mesh (a) shown after editing it to snip off the neck and ears (b) the mesh visualised front view (c) a profile.

1. Rendering such huge files in matlab using windows machine is slow and inefficient. Therefore, visualising the modes of variations needs a powerful machine (with at least 2 Gh processor and 4 Gb RAM).
2. Computing the correspondence of shapes takes so much time. On 2 Gh processor and 2 Gb machine it takes about three hours to run through all the scans. However, we used a powerful machine provided by the 3D-lab with 2Gh processor and 4 Gb RAM. On this machine it takes only 10-12 minutes to run through all the shapes.

Indeed, this part was the most difficult one in the study because of the huge size of each file, the need of powerful computer and the difficulty of visualising as well as of testing the results.

Having made the dense correspondence and constructed the meshes accordingly, the vertices are treated as pseudo-landmark (see 4.1.1) and generalised Procrustes analysis is conducted to model the shape variations. It is worth noting that we re-align the meshes before we conduct the statistical shape modelling. The result of the principal component analysis is shown in figure 4.25. The first three principal components capture 66% of variation (see figure 4.26), which is good representation of the variations. We show the mean shape or the mean mesh (see figure 4.27) to make comparison easy with the changes produced later on by the various modes of variations.

Dense correspondence, where we use pseudo-landmarks, shows new modes of variation in addition to those that occur with coarse corresponding, where we use the anatomical landmarks sets. Variations in soft tissue, that escape detection by coarse correspondence, are captured by the dense correspondence. Changes in forehead, cheeks, nose size, lips and orbit can be easily pointed out. The first mode of variation (see figure 4.28) is associated mainly with vertical scaling of the face. This feature has been easily captured using a small number (14) of non-anthropometric landmarks (see section 4.3) and using large number (64) of anthropometric landmarks (see section 4.4) so it is not unique for the dense correspondence. What is unique for the dense correspondence is the changes in fullness of the cheeks, an important feature in the face that cannot be detected using the anthropometric landmarks. Another important change is the supra-orbital ridge and orbital size especially on the left side.

The second mode of variation (see figure 4.29) has some of the first mode components in addition to smooth changes in the supra-orbital ridge and the size of the mandible.
The third mode (see figure 4.30) is mainly concerned with chin protrusion and left facial changes. A pronounced change in the left orbit size and to a less extent the right orbit size can be seen. Nasal size and protrusion changes occur but less prominent than in the first and second PC’s. The changes become smooth and unmarked with the fourth mode of variation (see figure 4.31) they are a combination of changes that have been seen with the previous three PC’s. One feature to be noticed is the change in the soft tissue of the infra-orbital region, a very important region for the aesthetic surgeons.

Figure 4.26 principal component analysis for the meshes obtained after the dense Correspondence. Note that the first three principal components account for 66% of the variations.

Figure 4.27 the mean shape generated from the reconstructed meshes after dense correspondence with the base mesh. For unknown reason, which might be a bug in the program; the right side of the face is not completely shown in the reconstructed meshes.

Figure 4.28. Three examples of the changes associated with the first mode of variation.
Figure 4.29. Three examples of the changes associated with the second mode of variation

Figure 4.30. Three examples of the changes associated with the third mode of variation

Figure 4.31. Three examples of the changes associated with the fourth mode of variation
4.5 Drawbacks of the study and their causes

We are aware of many drawbacks that might have been noted in this study. We, by discussing those drawbacks, are apologizing for them and at the same time explaining the reasons that have produced them. Some of the drawbacks are listed below:

1. Absence of error analysis.
2. Small sample size.
3. Visualization of the results could have been better if more time or more help have been offered. This is especially relevant to section 4.4 where we had challenging problems to make a movie that visualize the changes. Rendering the huge 3D images in matlab is extremely slow especially when using Windows.
4. Absence of test(s) of the model against non-Caucasian face.

The main causes for those drawbacks are:

1. The limitation of time and resources.
2. The inter-disciplinary nature of the study that forced the efforts to diffuse in many directions.
3. The sparseness or scarcity of references joining anthropometry, statistics and image analysis.
Section five

Conclusion
“Life is the art of drawing sufficient conclusions from insufficient premises”

Samuel Butler
In this study we analyse the scans of eight male Caucasian faces; their ages ranging between 25 and 35 years. The scans that are acquired by a three-dimensional laser surface scanner, are automatically registered and manually annotated with 64 predefined anthropometric landmarks from which we calculate 71 anthropometric measurements, 12 angles and inclinations and three major anthropometric indices. The annotated scans are converted to a matlab readable format from which we obtain eight landmarks sets. We use generalised Procrustes analysis to align those landmarks sets. Statistical analysis of the data shows that the first three principal components account for 58% of the variations. The first mode of variation (27%) is mainly associated with vertical scaling while the second mode (16%) accounts for a combination of changes. To demonstrate the descriptive power of anthropometry of the human face, we describe the modes of variations using subjective visual impression, quantitative analysis with thresholding and anthropometric oriented analysis. We show the mean face, which represents our suggested model, and we show the variations from this model. The eight faces have a reasonable Gaussian distribution around their mean.

Being a powerful descriptive means of the human face, we use the anthropometric facial indices of the mean face and the other faces to compare our results with those that are mentioned in the relevant literature. Most of our results lie within three standard deviations for the three major anthropometric indices that are chosen for the purpose of comparison. The difference from the literature might be attributed to errors in data acquisition.

After bringing all the faces into close alignment, we conduct a dense point correspondence using a brut force technique to assemble the meshes corresponding to a base mesh that we choose. The base mesh is chosen from the sample and it should be good regarding coverage and absence of holes. Having made the dense correspondence with the base mesh, we re-construct the meshes by excluding the vertices that have no correspondence to the base mesh. We employ the generalised Procrustes analysis followed by statistical analysis of the data, which shows that the first three principal components now account for 66% of the variations.

We show that the dense point correspondence capture subtle changes that might escape the detection of coarse correspondence. Changes in the soft tissue like the fullness of the cheeks, size of the nose, shape of the forehead, size and shape of the lips are examples of the changes detected using the dense point correspondence.

It is hoped that the technique can be used to gain quantitative understanding of the human face that is essential issue in planning surgical corrections of defects whether congenital or traumatic.

References:


