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A Longitudinal Study of Facial Growth in Infants using a Three-Dimensional Imaging Technique

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List of Publications

The following publications were based on the data presented in this thesis and are included in Appendix 3.

White, J. E., Ayoub, A. F., Hosey, M. T., Bock, M., Bowman, A., Bowman, J., Siebert, J. P., & Ray, A. 2004, Three-dimensional facial characteristics of Caucasian infants without cleft and correlation with body measurements, *Cleft Palate-Craniofacial Journal*, vol. 41, no. 6, pp. 593-602.

Ayoub, A., Garrahy, A., Hood, C., White, J., Bock, M., Siebert, J. P., Spencer, R., & Ray, A. 2003, Validation of a vision-based, three-dimensional facial imaging system, *Cleft Palate-Craniofacial Journal*, vol. 40, no. 5, pp. 523-529.

Hood, C. A., Hosey, M. T., Bock, M., White, J., Ray, A., & Ayoub, A. F. 2004, Facial characterization of infants with cleft lip and palate using a three-dimensional capture technique, *Cleft Palate-Craniofacial Journal*, vol. 41, no. 1, pp. 27-35.

Summary

Introduction & Aims

Information relating to the normal growth and development of the facial soft tissues is essential in diagnosis, treatment planning and outcome assessment for patients with facial deformities. Review of the literature has shown minimal normative data for infants up to 2 years of age and a complete lack of longitudinal and three dimensional (3D) data. This study therefore aimed to measure the facial morphology and growth of 100 infants in the West of Scotland from the age of 3 months to 2 years using a three dimensional imaging system, C3D. One of the aims of the study was to validate the use of the C3D system to measure facial morphology in infants. Further aims were to establish references values for facial dimensions in infants, to establish the normal growth of facial parameters from 3 months to 2 years, to correlate facial and body growth, to ascertain any sexual dimorphism, to establish the degree of facial asymmetry and to determine any longitudinal changes in facial asymmetry in infants faces.

Materials & Method

One hundred infants were recruited to take part in the study and asked to attend at the ages of 3 months, 6 months, 1 year and 2 years. At each visit 3D images of their faces were recorded as well as body weight, length and head circumference. One image of each infant was selected at each age for the analysis. Anatomic landmarks were located on the 3D facial models and their 3D coordinates derived. Interlandmark distances and angles were measured and the means and standard deviations for a variety of facial parameters were calculated. A 3D facial asymmetry score was calculated for each infant and the most asymmetric region of the face determined. T tests, paired t tests and correlation coefficients were applied to determine any sexual dimorphism, right or left sided dominance, correlation with body measurements, longitudinal change in asymmetry and any gender differences in asymmetry.

Validation

Validation of the method was divided into investigation of the system error, landmark reproducibility and repeatability of facial expressions.

The system error was quantified by comparing the 3D landmark coordinates of facial casts recorded using the C3D system to the coordinates obtained using a highly accurate coordinate measuring machine. The system error, which included operator, capture and registration error, was found to be 0.83 mm. The system was therefore determined to be accurate enough for the study of facial morphology and growth in infants.

The second investigation established the reproducibility of landmark identification by repeated location of landmarks on 3D models of infants faces at 3 months and 1 year. All of the landmarks chosen for this study had reproducibility scores of less than 0.7 mm which was judged to be clinically acceptable.

Investigation of the repeatability of facial expressions found that both the lips together and lips apart expressions were repeatable in this group of infants, with mean error standard deviations ranging from 0.21 mm to 1.78 mm. There was no difference in repeatability of either expression. Significant differences were found between measurements recorded with the lips together and the lips apart. It was therefore concluded that the lips apart expression, found in most infants, was suitable for analysis of facial morphology, but that the measurements of models with lips together and lips apart could not be combined for the analysis. The lips together models were therefore excluded from the analysis.

Results

Eighty three infants at 3 months, 93 infants at 6 months, 91 infants at 1 year and 92 infants at 2 years were successfully captured with a lips apart pose. Reference values for facial dimensions in infants at these ages were established. Significant gender differences were found for most facial measurements at all ages with the males being larger than the females. These differences were greatest for face height, depths and widths with mean differences ranging from 1.7 to 4.0 mm. No gender differences were found in any of the angles measured. Several dimensions on the right side of the face were found to be significantly larger than the left. This was most marked for face depths with mean differences of 0.8 mm. The range of normal facial asymmetry scores was determined. No significant difference in asymmetry was found between the males and females. The upper face was found to be the most asymmetric region studied and the nostrils were the least asymmetric. Correlation of facial measurements with body dimensions found weak but significant correlations with the highest correlation coefficient of 0.69 between face depth and body weight. Nasal tip protrusion, nostril dimensions and lip heights were not correlated with body dimensions.

Seventy one infants, 37 males and 34 females, were successfully captured at all four ages with the lips apart and were included in the longitudinal analysis. The longitudinal changes in facial parameters were established from 3 months to 2 years and mean growth curves produced. The fastest growth was found from 3 to 6 months and the slowest from 1 to 2 years. There was no correlation between growth of the face and growth in body weight, length and head circumference. Significant reductions in the overall facial asymmetry score were found from 3 months to 2 years. The clinical significance of this reduction is still to be determined.

Conclusions

The normal facial morphology and growth established in this study could form a baseline for diagnosis of facial syndromes and to allow quantification of facial deformity. The measurements may be a useful adjunct to treatment planning in infants with facial anomalies such as cleft lip and palate. This data will also allow objective assessment of surgical outcomes and assessment of post surgical growth.

The analysis of the data in this thesis is only the first stage in the investigation of the 3D facial models collected for this study. Further analysis of the 3D landmark configurations, curves and conformed meshes will allow more comprehensive understanding of the 3D facial morphology and growth in infants from 3 months to 2 years.

1 Introduction

1.1 Background

1.1.1 Growth and Development

1.1.1.1 Prenatal Growth of the Face

Formation of the face starts around 24 days in utero when the maxillary and mandibular processes can first be identified. This is followed by development of the nasal placodes at 28 days, which soon differentiate into the medial and lateral nasal processes. Fusion of these processes around 38 days completes the recognisable outline of the face (Ten Cate 1989).

At about 3 months of intrauterine life the head takes up almost 50% of the total body length. The cranium is large relative to the face representing more than half the total head. By the time of birth the trunk and limbs have grown faster than the head and face so that the proportion of the entire body devoted to the head has decreased to about 30%.

1.1.1.2 Body Growth from Birth to Adult

At birth the legs represent about one third of the total body length, while in the adult they represent about half. There is also more growth of the lower limbs than upper limbs during postnatal life. Not all of the tissue systems of the body grow at the same rate. The muscular and skeletal elements grow faster than the brain and central nervous system. This is reflected in the relative size of the head, which progressively decreases to about 12% of the adult. All of these changes suggest an axis of increased growth extending from the head towards the feet and has been called the cephalocaudal growth gradient (Proffit 2000). This growth gradient is present even within the head and face. A newborn infant has a much larger cranium and a much smaller face compared to the adult therefore the face grows more than the cranium after birth. The mandible also tends to grow more and later than the maxilla.

Important concepts in the study of growth and development are variability and timing. It can be difficult to decide whether an individual is merely at the extreme of normal variation or falls outside the normal range. It is useful to evaluate a child relative to peers on a standard growth chart, commonly used to measure height, weight and head circumference (Gairdner & Pearson 1971). These growth charts can be used in two ways. A child who falls beyond the range of 97% of the population should receive special study before being accepted as an extreme of the normal population. Growth charts can also be used to follow an individual child over time to evaluate whether there is an unexpected change in growth pattern. Variation in timing of growth, arising because the same event can happen for different individuals at different times, can also make the study of growth difficult.

1.1.1.3 Facial Growth

Growth of the face is a differential process, in which some parts grow more or less than others and in a multitude of regional growth directions (Enlow & Dale 1989). Growth of the facial hard tissues has been extensively investigated however there are very few studies investigating soft tissue growth, especially in infants. In the study of facial growth, the concept that soft tissue components directly reflect underlying skeletal components has lead to a clinical dependence upon evaluation of the hard tissues. Results of previous studies do not support this concept (Subtelny & Rochester 1959). Study of soft tissue growth as well as hard tissue growth is therefore required to understand facial growth fully. Analysis of the soft tissue facial configuration of normal infants would also facilitate surgical planning and allow the scale of the deformity to be quantified in infants with facial deformities. It would also aid the objective assessment of surgical outcome. In a study of 3 month infants with cleft lip and palate, the authors concluded that the full expression of their data awaited similar studies in age matched non-cleft infants (Fisher et al. 1999).

1.1.1.4 Linking Facial and Body Growth

Studies relating facial and body growth are usually limited to the time of the adolescent growth spurt (Baume, Buschang, & Weinstein 1983;Bishara et al. 1981). A study of 50 children from 1 month to 30 years using serial cephalograms, concluded that the face showed the characteristic skeletal growth pattern, including distinct adolescent changes, with the time of maximum growth spurt occurring usually a little after the spurt in body height (Bambha 1961). The measurements of the subjects below 5 years of age were not

presented due to small numbers in this age group. No other studies relating facial soft tissue to body growth in infants have been found in the literature.

1.1.2 Study Design

1.1.2.1 Cross Sectional Studies

Cross sectional studies measure individuals at only one time point, although different ages can be represented in the population. It is quicker, easier and less expensive to carry out a cross sectional study and it is usually possible to recruit a representative population sample. One investigator can usually collect all the data which reduces error. Usually large numbers of subjects are required to derive growth data from a cross sectional study however even then variability within the sample can conceal details of the growth pattern (Farkas 1996). Cross sectional studies have contributed greatly to the present knowledge of human growth.

1.1.2.2 Longitudinal Studies

Longitudinal studies, taking repeated measurements of the same individuals over time, provide a great deal of data from a relatively small number of subjects. This data can highlight individual variations, particularly those influenced by timing such as the pubertal growth spurt, which may not be detected in a cross sectional study. Longitudinal analysis gives more consistent and meaningful results because growth changes are often subtle and not always observed when data is evaluated cross sectionally (Bishara & Jakobsen 1985). However there are many disadvantages of longitudinal studies. They take longer to carry out than cross sectional ones and are more expensive. Often several investigators are required to carry out the data collection over a long period of time. The sample size of longitudinal studies is often small due to the loss of subjects. This sample size reduction is inevitable due to absence, illness, migration or withdrawal from the study. Even if a study group is a representative population sample at the start, a sampling bias is introduced during the long term period of the study. Loss of validity of the data is also a potential problem in long term studies (Farkas 1996).

1.2 Assessment of Facial Morphology & Growth

1.2.1 Bone

The majority of research into facial morphology and growth has concentrated on the assessment of hard tissues. There are several methods of assessing bone growth; the most common methods are outlined below.

1.2.1.1 Craniometry

Craniometry was the first approach to studying growth and was based on measurements of skulls found among human remains. By comparison of measurements of progressively older samples growth information was deduced (Sarnat 1997). It has the advantage that precise measurements can be made on dried skulls but the disadvantage is that all data must be cross sectional and measurements must be made on a large number of bones of varying ages and, often, unknown histories. This technique has also been used to study asymmetry of the skull (Woo 1931).

1.2.1.2 Direct Anthropometry

Anthropometry, measuring distances and angles directly on the face, can be used on living subjects to measure the facial skeleton but has the disadvantage of overlying soft tissue preventing accurate measurement of bone underneath. Good correlations between anthropometric measurements and radiographic measurements have been found however the measurements were not identical and some differed by as much as 45 % (Farkas et al. 1999). This technique will be discussed more fully under soft tissue measurement in section 1.2.2.1. It does have the advantage of allowing longitudinal data collection and has provided valuable data on human facial proportions and growth (Farkas 1994a).

1.2.1.3 Impressions & Casts

Duplication of various parts of the body is possible by taking impressions. The shapes of the orbit, eye and maxillary sinuses of animals have been studied using impressions but all these experiments involved sacrificing the animals (Sarnat 1997). The only impressions useful in measuring bone growth in humans are impressions of the dental arches which allow measurement of the teeth and alveolar processes of the maxilla and mandible.

1.2.1.4 Vital Markers & Radioisotopes

Injection of vital markers such as alizarin red, which are incorporated into the bone during growth, have been used to study growth of bones in animals by studying sections of the bone microscopically. Radioisotopes can also be injected into animals and used to study growth by sectioning the tissues and examining them radiographically (Sarnat 1997). Both of these methods have improved our understanding of bone growth and remodelling however they involve sacrificing the animals and cannot be used in human growth research although radioisotopes can be used in the study of condylar hyperplasia (Gray et al. 1994).

1.2.1.5 Cephalometric Radiographs

This technique depends on precisely orientating the head before taking a radiograph with known magnification. It allows direct measurement of bone and also allows the same individual to be followed over time. Its disadvantages include the fact that a two dimensional representation of a three dimensional structure is produced and the subject is exposed to radiation. Despite these problems, lateral cephalometric radiographs have formed the basis of most of our understanding of craniofacial growth in humans.

The three-dimensional cephalogram has been described (Grayson et al. 1988). This was a method of stereolocation of cephalometric landmarks by combining point locations from lateral and posteroanterior cephalograms. The authors stated that there was some compromise in accuracy of this system but they recommended the routine application of biplane cephalograms in the planning and monitoring of craniofacial surgery.

1.2.1.6 Implant Markers

Metallic implants in the facial bones of healthy growing subjects have been used to study facial growth (Bjork 1968). In these studies the subjects were followed longitudinally after insertion of metallic implants into the maxilla, mandible and other facial bones and serial cephalometric radiographs were recorded of the faces. These studies have been essential in our understanding of growth rotations but this method could not be applied nowadays to a large group of non patient subjects.

1.2.1.7 Computed Tomography

Computed tomography (CT) can be used to study facial growth. Cross sectional imaging or spiral scanning of the face can be used to reconstruct a computerised 3D model of the soft and hard tissues of the face. The error of 3 dimensional CT data is considered to be minimal and it is useful in diagnosis and treatment planning of patients with craniofacial abnormalities (Fisher et al. 1999). The high radiation dose and the necessity for sedation or even general anaesthesia in infants preclude its use to study facial growth in a non patient population.

1.2.1.8 Magnetic Resonance Imaging

Magnetic resonance imaging may be used to study facial growth. It does not involve a radiation dose which is its main advantage. The major limiting factor of MRI is its cost relative to other imaging techniques (Browne, Golding, & Watt-Smith 2001). Similar to CT scanning, sedation or anaesthesia may be required to obtain images of infants.

1.2.2 Soft Tissue

1.2.2.1 Direct Anthropometry

Anthropometry, measuring the face directly using sliding and spreading calipers, was introduced by Hrdlicka in 1920. It has been used extensively to collect normative data (Farkas & Posnick 1992;Goldstein 1936) and study craniofacial abnormalities such as cleft lip and palate in adolescent and adult populations (Farkas, Hajnis, & Posnick 1993). The technique is highly operator dependant, takes a prolonged time and requires a great deal of subject cooperation. The precision and repeatability of linear anthropometric measurements have been evaluated (Ward & Jamison 1991). In general the measurements were reliable and in no case did separate measurements differ by more than 4%. However, the level of accuracy possible in measuring the faces of children is greatly influenced by age, duration of examination, and cooperation and there is very limited normative data available for children from birth to 3 years (Farkas 1996). The technique has some advantages including the ability to locate landmarks by palpation and being able to record measurements in areas covered by hair, such as head circumference. However the analysis is limited to linear and angular measurements and the three dimensional relationship of the landmarks is not recorded.

1.2.2.2 Direct Digitisation

Electromagnetic three dimensional digitisers can be used directly on living faces to supply the coordinates of facial landmarks. In a preliminary evaluation of a 3D digitiser landmarks were identified and marked on the face prior to digitisation (Ferrario et al. 1998a). During data collection the subjects sat still with the head fixed to the chair back with a headframe. The eyes were closed and the teeth in occlusion. An operator located each landmark with a hand held probe to record the coordinates and data collection lasted about 90 seconds. Repeat digitisation influenced the measurements by about 1%. This method has the advantage that the landmarks are identified directly on the subjects face rather than on a reconstruction of the face. Its main disadvantage is the compliance required which makes its use in infants impractical.

1.2.2.3 Facial Casts

It is possible to record an impression of the face and then produce a stone cast of the face which can be measured directly by anthropometric means or by 3D digitising devices (Ferrario et al. 1998a;Spencer, Hathaway, & Speculand 1996). The technique of recording an impression of the face is labour intensive and requires a great deal of patient cooperation. The soft tissues may be compressed during impression taking and the materials are not completely dimensionally stable. This method has been used to record the faces of cleft infants under general anaesthetic prior to surgery (Ayoub et al. 2003) and also in non anaesthetised infants (Bacher et al. 1998). A 3D digitiser has been used to analyse plaster models of the nose (Mishima et al. 1996). This method is not suitable to apply in a large study of the population to record normative data.

1.2.2.4 Radiographs

Lateral cephalometric radiographs can be used to study the soft tissue profile as well as hard tissues (Subtelny & Rochester 1959). This data is widely available for adolescent and adult subjects but less frequently employed in infants and children. The soft tissue data provided by lateral cephalometric radiographs is limited to the 2D midline but does provide useful and reliable information and comparison with the hard tissues underneath is possible.

1.2.2.5 Photographs

Standardised photographs can be used to assess the soft tissues in profile and frontal views. Standardisation can be achieved by imaging the subjects in the natural head position, or using a photographic grid or cephalostat. This standardisation is more difficult to achieve in asymmetric patients such as those with cleft lip and palate and also in young children (Vegter & Hage 2000). In a study comparing direct anthropometry and photogrammetry only 20 of the 104 anthropometric measurements available on the face were found to be measured reliably on photographs (Farkas, Bryson, & Klotz 1980). Systematic differences have been found between photogrammetric measurements and caliper derived measurements even when the landmarks were premarked on the face (Shaner et al. 1998). The two dimensional nature of photographs, the lack of standardisation and the presence of photographic distortion are possible reasons for these differences (Farkas 1994c). Despite the availability of this technique, the precise standardisation required and the minimal numbers of reliable measurements achievable make photogrammetry unsuitable for use in studying facial morphology in infants.

1.2.2.6 Video Imaging

Video taping is an established method for recording some clinical investigations such as nasendoscopy and videofluoroscopy. It has the advantage of being able to record the face in motion and illustrates functional as well as aesthetic disorders. In a study using video recordings of cleft children considerable cooperation during filming was required and the authors concluded that the technique was most suited to children over 9 or 10 years old (Morrant & Shaw 1996). Only subjective panel assessments of the video images were performed in this study.

Analysis of movements of the face is also of interest to surgeons. A method to assess facial mobility has been described which involves attaching reflective markers to the skin and using a 3D video-based tracking system (Trotman, Stohler, & Johnston, Jr. 1998). A similar technique has been described in Japan to record facial expressions with three synchronised video cameras (Mishima et al. 2004). In these studies the markers were tracked across the image sequences and the three-dimensional coordinates were calculated. The authors concluded that lip movement could be successfully analysed using these systems. A further method allowed collection of the data without the use of reflective markers but with just a pen mark (Giovanoli et al. 2003). These techniques must require considerable subject cooperation and may not be suitable for use in young subjects.

1.2.2.7 Computed Tomography

The soft tissues of the face can be recorded and measured on 3D computer tomography (CT) scans. The main advantage of this technique is that both hard and soft tissue landmarks can be evaluated. Although the accuracy of CT soft tissue measurements remains to be verified, the accuracy of hard tissue landmarks has been shown to be less than 0.5 mm (Richtsmeier et al. 1995). The main disadvantages of this technique are the high radiation dose and need for sedation in infants which preclude its use in a non patient population. Further disadvantages include the lack of surface texture on the 3D model and the fact the eyes are closed while the infant is scanned. These problems may prevent accurate identification of landmarks on the vermilion border and around the eyes. Texture mapping of colour photographs onto 3D soft tissue CT scans has been described (Xia et al. 2000) which may solve the texture problem.

1.2.2.8 Magnetic Resonance Imaging

Magnetic resolution images (MRI) can be used, like CT, to visualise the hard and soft tissues. Scanning of the face was reported to take 3 minutes and 20 seconds with a 1.5 mm slice thickness and 1 mm interslice gap (Gosain et al. 1996). This technique is useful to compare hard and soft tissues, and distinguish muscle, skin and fat tissue but the skin and soft tissue boundary is also recorded. The slices could be constructed into a 3D model of the face (Linney et al. 1993). The lack of ionising radiation is a major advantage over CT. This technique does not appear to have been used to study infant's faces due the time required for each scan and the need to sedate infants prior to image capture.

1.2.2.9 Ultrasonography

Conventional ultrasonography uses two dimensional (2D) imaging techniques and requires contact between the transducer and the target. Deformable tissues, such as the lips would be depressed during scanning therefore this technique cannot be used to examine facial morphology. 3D ultrasonography combined with techniques of immersing the face in water for about 20 seconds during scanning has been described (Deng et al. 2000;Smith & Throckmorton 2004). In the latter study the method is described as simple and reliable and individual tissues can be distinguished. It is not suitable for use in children but may be useful in adults and has the advantage of being able to record facial expressions.

1.2.2.10 Facial Three-Dimensional Morphometry

Three dimensional coordinates of facial landmarks can be recorded with the ELITE system (Ferrario et al. 1996c). The system consisted of two charged coupled device (CCD) cameras, real time hardware for the recognition of markers and software for the 3D reconstruction of the landmark coordinates. Landmarks were first located on the face by inspection and palpation and marked with pencil. On the centre of each point a 2 mm reflexive marker was fixed. The subject sat with the teeth in occlusion in front of the two cameras. The CCD cameras lit up the markers with an infrared stroboscope and the centres of gravity of these points were recognised and recorded by the system. The subject had to rotate 90° to allow a second acquisition to collect data for the whole face. Each acquisition took only 0.1 seconds. The combined error of the system was estimated to be about 0.1 mm, and the error for duplicate landmark identification was about 2 mm. This technique has been used to study facial morphometry in adults and children from 6 years of age (Ferrario et al. 1998b). The main disadvantages of the technique are the need for considerable subject cooperation, the limited number of landmarks & size of the markers necessitating 2 mm separation between the landmarks. The technique also lacks a 3D facial image display since only the landmarks are recorded.

1.2.2.11 Laser Scanning

A laser optical light scanner for scanning the face was first described in 1985 (Arridge et al. 1985). The system consisted of two vertically fanned out low power laser beams which were projected on to the face and viewed from an oblique angle by a television camera. The video image is processed and transformed into a set of 3D coordinates. In order to scan the whole face the subject was asked to sit still with the face relaxed and the eyes closed. The motorised chair was rotated and the face was scanned over a period of about 10 seconds. A 3D model of the face, without surface texture, was produced. The accuracy of the system was tested by comparing the direct and laser scanned anthropometric measurements in a group of adult subjects. The most reliable measurements were found to be in the nasal and circumoral regions with mean differences of less than 1 mm (Aung, Ngim, & Lee 1995). This system has been used to capture 3D models of the face in children as young as 5 years of age (Nute & Moss 2000). The authors state the main disadvantage of the system is its cost. Further disadvantages include lack of surface texture and the considerable cooperation required to sit still for 10 seconds. It is therefore impractical for use in capturing the faces of infants and young children.

Other laser scanning systems have been reported including a system which allowed superimposition of a colour image of the face onto the 3D model and allowed image capture with the eyes open (Bush & Antonyshyn 1996). This system required 17 seconds to complete the digitisation.

More recently a laser surface scanner was described which allows capture of infant faces (Da Silveira et al. 2003). A series of 5 different scans from different views were taken of the infant's head, each scan taking approximately one second. Computer software allowed combination of the images to create a 360° 3D image. The authors state that frequently babies do not remain still long enough to have the scanning completed creating distortions of the 3D mesh. They suggest an ideal set up would include two or three laser scanners to allow scanning to be performed simultaneously however the cost of such a system would be the main deterrent.

1.2.2.12 Patterned Light Scanning

Several patterned or structured light scanners have been described in the literature. The earliest of these used moiré stripes which were projected onto the face while photographs were taken. The face had to be positioned carefully. Analysis of a moiré photograph was a laborious process but the system could be used in infants (Kawai et al. 1990).

A modification of this technique called three-directional photography has been reported (Motoyoshi, Namura, & Arai 1992). In this system a subject was photographed from three directions simultaneously while points, rather than stripes, were projected onto the face. An image scanner directly read the photographs which were then transmitted to a computer and the coordinates of each point were automatically calculated. A 3D display of the points could be produced although without surface texture. The greatest error standard deviation was 0.24 mm in the horizontal dimension however the limit of the system was 1.5 mm between measurement points. The speed of data capture and the positioning of the subject were not detailed in this article but this system may be applicable in infants.

An optical facial surface scanner has been described (Vannier et al. 1993). The scanner consisted of six sensors to provide full coverage of the head. Each sensor contained a pattern projector and a solid state video camera. As the pattern of light was projected onto the subject, the cameras detected, digitised and transmitted a sequence of images to a processor for surface triangulation, calibration and fusion. The acquisition of data took 0.75 seconds and the authors state it was one of the few 3D surface scanners capable of

scanning small children (Bhatia et al. 1994). The system accuracy was found to be 0.25 mm however the location error of landmarks was reported to have a mean of 3.8 mm in the horizontal dimension.

A range camera and 3D measuring programme have been used to study Scandinavian infants from the age of one month (Strömland et al. 1999). A projector illuminated the subject with a sequence of nine different light patterns that were generated by a liquid crystal shutter. A fully illuminated image of the face was also taken on which the landmarks were manually located. A 3D image was computed and the 3D coordinates of the landmarks derived. The total image recording time was less than one second. Compared to measurements made by caliper, the systematic error was 1 mm.

A liquid crystal range finder has been described (Yamada et al. 1998). This device consisted of a measuring head, an image processor, a monitor and a workstation. The facial surface was scanned in 1 second and 3D coordinates were derived from a triangulation calculation. The spatial accuracy of this system was reported to be within 0.5 mm. Landmarks were extracted automatically and the reproducibility was 0.3 mm (Yamada et al. 1999). This technique has been applied to cleft and control subjects to measure facial morphology in Japanese subjects (Yamada et al. 2002). The data did not extend to the ears and a second scan was required to capture the detail of the nose. Although the capture time of 1 second is considered an improvement relative to previous methods, extrinsic and intrinsic movement of an infant's face is still possible in this time.

A structured light scanner, the Rainbow 3D Camera system (Genex Technologies Inc.) has now become commercially available (Geng 1996). It has a central light source with two cameras and a digital camera. Using a structured light design, in which colour patterns are projected onto the objects surface, 3D coordinates are determined by calculating the exact distance between points on the object's surface and the focal plane of the camera. The system has been evaluated (Lee, Han, & Trotman 2004;Weinberg et al. 2004). The former study concluded that the accuracy was best for images recorded from frontal views. The latter study found high levels of precision and fairly good congruence with traditional anthropometry. Both studies conclude that the field of view of a single capture could not cover the whole face and merging of more than one capture would be necessary to capture the whole face. This would introduce another level of error which is still to be evaluated. This system may be suitable for studying the faces infants and young children.

A patterned light scanner using infrared light has recently been described (Littlefield et al. 2004). It comprises 18 triangulated digital cameras, 12 of these capture shape data and the other 6 capture the black and white surface texture. The 360° image of the head is captured within 0.008 seconds. This system has been developed for use in infants to study cranial morphology but it can also capture the face. It has been demonstrated to be accurate to within 0.24 mm. Structured light scanners could only capture one surface at a time because the patterns projected by multiple projectors interfered with each other. The advantage of using infrared light is that it overcame the problems with interference and enabled the capture of an entire infant head in a single shot. Despite some disadvantages such as cost, size of the equipment and lack of detail captured around the ears this system will allow the study of craniofacial deformities, monitoring of growth and evaluation of surgical outcomes in infants.

1.2.2.13 Stereophotogrammetry

Stereophotogrammetry is a method of 3D imaging based on camera to camera baseline triangulation. It was first described in the medical literature in 1967 (Burke & Beard 1967). This early technique involved capture of the images and plotting of contour maps. This was a skilled and time consuming process but accurate 3D landmark coordinates could be derived from the data. This technique has been mainly used to study facial growth from the age of 9 (Burke & Hughes-Lawson 1988b), however one case report followed a subject from 3 weeks to 10 years of age (Burke 1983). In this study the early records were taken with a portable camera and without head positioning and are presumably not so accurate.

A similar method has been applied to study facial asymmetry in control and cleft children from 4 years of age (Ras et al. 1995a). Several other stereophotogrammetry systems applied to capture the face have been described. These include the Spatial Vision System (Bowskill, Baldock, & Booth 1997), several stereophotogrammetry systems (Meintjes et al. 2002;Rasse, Forkert, & Waldhausl 1991;Shaner et al. 2000) and video-based stereophotogrammetry (Stevens 1997).

A computerised stereophotogrammetry system, C3D, has been described (Ayoub et al. 1996). This technique utilised 2 stereo pairs of cameras to capture the whole face, produced a black and white 3D facial image and allowed measurement of anatomic landmarks. Later modification of the technique allowed overlay of colour texture on the 3D model and image capture in under a second (Siebert & Marshall 2000). One of the major advantages of this technique is that it is a full field one, producing 3D information from the

whole face without the need for scanning. It has been used to record 3D records of study models (Bell, Ayoub, & Siebert 2003), to study the facial soft tissue changes following orthognathic surgery (Hajeer et al. 2002), to study the effects of twin block therapy (Bourne, Kerr, & Ayoub 2001) and to assess the reproducibility of facial expressions (Johnston et al. 2003). It is suitable for use in studying infants. This system is described in more detail in section 2.3.1.2.

1.3 Statistical Analysis of Facial Morphology and Growth

1.3.1 Landmarks

A landmark is a point of correspondence on each object that matches within populations (Dryden & Mardia 1998). Landmarks can be anatomical, mathematical or pseudo-landmarks. Anatomic landmarks correspond in a biologically meaningful way, such as the corner of the eye or tip of the nose. Mathematical landmarks are located according to some geometric property of the object, such as maximum concavity. Pseudo landmarks are constructed points such as a point at the intersection of two lines. The most commonly used method of analysing the morphology of the face is by identification of anatomic landmarks.

Many soft tissue anatomic landmarks have been defined on the face. The most frequently used definitions are those by Farkas (Farkas 1994a). Landmarks are usually located by a trained operator and, similar to many cephalometric studies, this is often the greatest source of error. Recently there has been some progress in the development of software which allows automatic extraction of landmarks (Naftel & Trenouth 2004;Yamada et al. 1999). These techniques are actually semi automatic since they rely on the initial landmarks being located by an operator however they do reduce operator time and will in the future improve the reproducibility of landmark location.

1.3.2 Interlandmark Distances and Angles

Measurements of interlandmark distances provide size based data and limited morphological information. Angles are size independent and may have some more shape information but fail to fully describe the shape in detail. Although conventional linear and angular analysis has many disadvantages it still has a significant role in evaluation of craniofacial form being simple to comprehend and allowing comparison with the results of

previous studies. Some authors have suggested the analysis of proportions of the face is more informative than simple measurement analysis (Koury & Epker 1992).

1.3.3 Statistical Shape Analysis

The analysis of 3D shape beyond the simple analysis of interlandmark distances and angles is the subject of a great deal of statistical research. The majority of the techniques are based on geometric morphometrics. This is a method where the coordinates of the landmarks are statistically analysed rather than interlandmark distances (O'Higgins & Jones 1998). Three dimensional coordinates are defined in three planes; the x axis is the horizontal plane, the y axis the vertical plane and the z axis the anteroposterior plane.

One problem with geometric morphometrics is presentation of the results in a manner comprehensible to non statisticians. A colour scale to illustrate 3D facial change has been developed (McCance et al. 1997). It is a useful tool to illustrate change in a clear manner. The statistical methods commonly found in the medical literature and used to assess facial morphometry are outlined below.

1.3.3.1 Mesh Diagram Analysis

The mesh diagram analysis is a proportionate analysis of the position of conventional landmarks on the face within a rectilinear coordinate system whereby the horizontal and vertical coordinates are distorted to reveal deviations in the location of landmarks from the norm (Moorrees, Efstratiadis, & Kent, Jr. 1991). A modified computerised mesh diagram analysis has been proposed (Ferrario et al. 1996a). This method can be applied to study growth in lateral cephalograms but has been superseded by the techniques outlined below.

1.3.3.2 Tensor Analysis

Tensor analysis is a method of cephalometric analysis that computes alterations in shape and size without the need for measurement or superimposition. A triangle connecting three landmarks on a cephalogram is first defined then a circle is drawn such that it contacts all three sides. If a homologous triangle is drawn on a later cephalogram deformation of the first triangle into the second would transform the circle into an ellipse. The amount and direction of these distortions may be calculated and the lengths of the axes of shape deformation are measured. The ratio of the lengths of the two axes is a measure of the change in shape. This technique does have several disadvantages. These relate to the

difficulty in identifying points sufficiently precisely, the problems with small triangles and the difficulty in interpreting the results (Battagel 1995). A further disadvantage is that only relative not absolute shape change is measured.

1.3.3.3 Euclidean Distance Matrix Analysis

Euclidean Distance Matrix Analysis (EDMA) is a method of analysis of interlandmark distances (Lele & Richtsmeier 1991). It examines differences between subjects in terms of ratios between interlandmark distances. It is usually applied to sets of distances representing every possible distance between the chosen landmarks since such a set enables complete reconstruction of landmark coordinates. The result is that very large matrices have to be interpreted. An advantage of this technique is that issues concerning superimposition are avoided however visualisation and interpretation of the results is difficult. The bootstrap is a complex mathematical method which is needed for the statistical analysis of this data (Ayoub, Stirrups, & Moos 1994).

1.3.3.4 Procrustes Analysis

Generalised Procrustes analysis is a mathematical method of manipulating configurations of landmarks so that they can be compared independently of size and position. The configurations are first scaled to a common size and then rotated and translated to achieve a best fit. A mean configuration can then be calculated and a Procrustes residual can be calculated for each landmark which is the difference between the landmark position and the mean (Dryden & Mardia 1998). Ordinary partial Procrustes analysis is an adaptation of this method where the initial scaling is omitted so that both size and shape can be studied. Procrustes superimposition is often used to precede other morphometric techniques if purely shape information is to be derived.

1.3.3.5 Principal Component Analysis

The use of principal component analysis (PCA) to assess face change in primates has been described (O'Higgins & Jones 1998). The main idea of this technique is to regard the landmark configuration as a vector of multivariate observations. The linear combination of the elements of this vector which accounts for the maximum amount of variation in the data can then be identified. This can be expressed in the form of configurations which show the principal mode of shape change in the whole sample of facial data. The results of applying this technique to study growth in three cases revealed the subtle changes in shape

that continue after change in size ceased (Hennessy & Moss 2001). The authors conclude this method would provide a means of analysing normal and pathological craniofacial growth.

1.3.3.6 Thin Plate Spline Analysis

Thin plate spline (TPS) transformation produces a rigorous quantitative analysis of the spatial organisation of shape change (Bookstein 1991). In this method the differences in two configurations of landmarks are expressed as a continuous deformation by using regression functions in which homologous points are matched between forms to minimise bending energy. The bending energy is visualised as an infinitely thin metal sheet draped over a set of landmarks. The surface of the sheet demonstrates pairwise displacements of each landmark as a deformation. If two forms were identical then the sheet would be flat. TPS produces a visually appealing representation between forms. This technique has been used in many applications including the analysis of mandibular growth (Franchi, Baccetti, & McNamara, Jr. 2001).

1.3.3.7 Finite Element Analysis

Finite element morphometry (FEM) calculates the strains that represent the hypothetical forces required to distort one form to another. The forms of the two averaged landmark configurations are divided into triangles. These triangles are the finite elements. The amount of deformation of the finite elements of the reference and target forms provides a numerical representation of form change. The output can be expressed as a size ratio, shape ratio and the angle of maximum strain value for each element (Moss et al. 1985). Similar to EDMA, FEM is independent of registration difficulties however it is not suitable for the individual case assessment. It is also only suitable for use in two dimensional data and has been used extensively in cephalometry (Ayoub & Stirrups 1993;Singh & Clark 2003;Singh, McNamara, Jr., & Lozanoff 1999). Recently a generic 3D finite element model of the face soft tissues was developed to predict soft tissue deformations following orthognathic surgery (Chabanas, Luboz, & Payan 2003).

1.3.3.8 Fourier Functions

Fourier analysis involves imbedding a set of closely spaced observed measurements on the boundary of a form into a mathematical function. This enables a mathematical description of the outline of an object, quantitative analysis of global shape characteristics and

comparison of outlines of different objects. Fourier analysis does not require landmarks for the analysis which is a major advantage and it is independent of reference planes. Elliptical Fourier analysis (EFA) was developed to investigate more complex morphological forms. The outcome is a set of numbers which when plotted produce ellipses and when these are summed they combine into the observed form. This is an excellent method of analysing the outline of curving forms and has been applied to the soft tissue profile of the face, from photographs or cephalograms (Darwis, Messer, & Thomas 2003). The greatest limitation of EFA is that it can only be used with two dimensional images.

1.3.3.9 Medial Axis Analysis

Median axes are a geometric transformation of an outline identifying a branching set of points constituting the middle of a form. These can be considered as conjoined centres of circles maximally contacting the shape boundary. Where a circle contacts more than two points on the shape boundary, a branch point is identified for the medial axis. The medial axes begin and end where anatomical structures of the bilateral sides converge on the image. This axis provides shape information independent of size. A series of measurements can also be derived and statistically tested (McIntyre & Mossey 2003). This technique has not been widely used for the examination of craniofacial morphology however it has been used to investigate the mandible in mandibulofacial dysostosis (Grayson, Bookstein, & McCarthy 1986).

1.3.3.10 Fundamental Surface Types

An objective decomposition of the facial surface into regions of fundamental surface type has been described. These types are humps or ridges, valleys or grooves, saddle surfaces, flat regions and peaks or bulges. Each surface point on the face is classified as belonging to one of these eight surface types by computing values of the Gaussian and mean curvatures. The advantage of this method is that it is independent of surface orientation. This method has been applied to investigate facial surface change after orthognathic surgery (Coombes et al. 1991) and in a twin study to determine the relative contribution of genetics and environment to various facial parameters (Naini & Moss 2004).

1.3.3.11 Curves

Landmarks are a starting point for the analysis of facial shape but they contain only a very small proportion of the available information from a 3D image. The 3D shape of a curve

can be recorded as a series of closely approximating landmarks. These can be generated as the landmarks along the shortest distance from one anatomic landmark to another along the surface of the 3D model. Examples of curves of interest in the face would be the curve of the profile or the nasal rim. Curve analysis could be used to give more detailed information about the shape of the face (Bock & Bowman 2005).

1.3.3.12 Meshes

3D shape analysis can be extended beyond landmarks and curves to surface data. This can be expressed as sets of points with correspondence across different images (Ju & Siebert 2001). A conformed mesh of an infants face would allow analysis of the entire surface of the face. Application of a similar technique, dense surface models, has been applied to demonstrate the differences between control and syndromic faces captured using a stereophotogrammetry system (Hammond et al. 2004).

1.3.3.13 Volume

A method of measuring the volume of facial swelling has been described (Bowskill et al. 1997). In this technique pre and post operation facial 3D models were registered using surface matching which minimised the mean square distance between points on the two surfaces. In order for the swelling to be determined the pre-operation face volume was subtracted from the post-operative volume. The mean volumetric error was calculated to be 3.2% and the mean registration error was 1 mm. The authors advised that this was a best case error since the images were of a cast and not a live subject. Similar methods of measuring facial swelling have been described (Bhatia et al. 1994;Yip, Smith, & Yoshino 2004). In the latter method the facial models were registered on the unchanged upper face. In a validation of this method the overall percentage difference for the volumetric comparisons ranged from 0.1% to 2.3%. A further method of measuring volume, as a measure of asymmetry, has been described (O'Grady & Antonyshyn 1999). In this method the volume was determined by superimposing and subtracting one facial half from a mirror image of the contralateral half. In a validation exercise the volume was overestimated by 16% however the technique is potentially very useful. Facial volume analysis has also been applied to study facial growth (Ferrario et al. 1998c). This technique involved locating 3D landmarks on the face and connecting them in a series of triangles with a posterior plane. Only the approximate volume of the face is therefore quantified and the results cannot be compared to other techniques which measure the whole surface of the face.

The problem with all methods of facial volume assessment is that the area under measurement needs to be closed, like a sphere or cube. The surface of the face does not have an inherent volume therefore a plane would have to be constructed to form the posterior border of a face and close the volume. When examining pre and post operative swelling, if the swelling is localised, the overlap of the two images may give a closed volume. However, in the assessment of facial growth the best fit of two models would probably not provide a closed volume. A border would have to be constructed to close the volume between two models. The location of this plane or border could have a dramatic effect on the volume and render the analysis meaningless.

Curve analysis, conformed meshes and volume analysis are currently under investigation by.researchers in the Department of Computing Science and Department of Statistics at the University of Glasgow.

1.3.4 Assessment of Asymmetry

Asymmetry is one aspect of facial morphometry of great interest in the medical literature. Several methods of assessing facial asymmetry have been proposed, from simple comparisons of bilateral interlandmark distances to more complex 3D indices. A brief review of these methods is given below.

1.3.4.1 Visual Assessment

Qualitative assessment of asymmetry can be judged by a panel, usually by examining 2D photographs or radiographs. A study rating nasolabial appearance, including asymmetry, in a sample of cleft children was carried out (Asher-McDade et al. 1991). This was done by a panel of orthodontists using a visual analogue score. One problem with this method was that the lack of standardisation of position during recording of the photograph or radiograph could influence the interpretation of the asymmetry. The authors concluded that this method is sensitive and workable in cleft patients. In order to assess asymmetry in a non patient population an objective and qualitative method is required.

1.3.4.2 Paired Measurements

Comparison of paired measurements of the face, such as right and left palpebral fissure width, is a simple procedure giving results which are easily understood. This technique is common in the literature and has been carried out using measurements from photographs

(Hurwitz et al. 1999), radiographs (Peck & Peck 1970), on anthropometric measurements (Farkas & Cheung 1981) and on 3D models (Shaner et al. 2000). This technique has also been applied to angular measurements (Namano et al. 2000). In these studies the results were analysed with paired t tests to test for significant differences.

1.3.4.3 Symmetry about a Midline

This has been the most common technique described in the orthodontic literature. A midline of the face was first defined then the distances from this plane to the landmarks of interest were measured. The problem with this method is that small differences in the definition of the midline could make significant differences to the results. A further problem is that the most common midlines are based on landmarks around the eyes. The eyes are generally regarded as stable but most changes in interocular width occur in the first two years of life. Use of these midlines therefore may not be valid when studying facial asymmetry in infants. An example of a midline of the face used to assess asymmetry is the line from the midpoint of the interpupillary line to the midpoint of the upper lip (Peck & Peck 1970).

1.3.4.4 Measurements of Areas and Curves

A method of assessing facial asymmetry by calculating the areas of triangles of the face has been described (Shah & Joshi 1978;Vig & Hewitt 1975). Both studies analysed posteroanterior cephalograms and defined triangles with apices located at anatomic landmarks. The mean differences between the right and left sides of the face were analysed using t tests. The authors conclude their triangulation method is a valuable procedure for the analysis of over-all facial asymmetry in terms of its components.

A simple method of assessing asymmetry of the nose and mouth using tracings of photographs has been introduced (Coghlan, Matthews, & Pigott 1987). The tracings of one side were reflected onto another about a symmetry axis and the area of non overlap or the distance from one curved outline to the other was calculated. A range of different axes of symmetry were automatically tested and that giving the minimum area of non overlap was used. The technique was tested on a group of photographs of cleft and control subjects. The curve method was found to be slightly better and gave better results for the assessment of asymmetry of the nostrils. The method was found to be reproducible and there was a reasonable correlation with subjective assessments with correlation coefficients around 0.6.

The photographs had to be taken under carefully controlled conditions and the authors state that it was difficult to ensure the necessary cooperation in patients younger than 5 years.

A mathematical method of assessing nasal asymmetry was described (Russell, Waldman, & Lee 2000). This technique was based on video images of nasal casts which were recorded at precise orientations of the casts. The nostrils were analysed for area, perimeter, centroid, principal axis, moments about the major and minor axes, anisometry, bulkiness, lateral offset, internostril angle and rotational angle. This is an objective and qualitative method to assess nasal morphology and has been applied to cleft and control subjects. It is however still a 2D analysis of 3D shape.

1.3.4.5 3D Asymmetry Measurement

Unfortunately all of the methods described above provide a set of measurements that describe only local imbalances and do not allow analysis of the whole face. A further disadvantage of these methods is that none of them take into account the position of the landmarks in relation to each other. It is therefore possible to conclude, wrongly, that symmetry exists in an asymmetric case. Since asymmetry of the face occurs in all three dimensions a valid 3D analysis is required (Ras et al. 1995b).

A method of assessing asymmetry in 3D using lateral and posteroanterior cephalograms was described (Mulick 1965). In this technique the 3D coordinates of landmarks located on both lateral and PA cephalograms were calculated. The distance of these landmarks from a midline landmark was the measurement of asymmetry. Cranial landmarks were measured to the ethmoid triad point, maxillary landmarks to the anterior nasal spine and mandibular landmarks to the point menton. Distance to a midline point rather than an axis was suggested as a method of reducing error and removing the influence of head position. High errors in calculating 3D coordinates from lateral and posteroanterior cephalograms have been reported and this method has been superseded by 3D imaging techniques (Dean et al. 2000).

A further method of assessing facial asymmetry in 3D by comparing the areas of triangles on laser scanned images of the face has been suggested (Moss et al. 1991). This differed from the 2D assessments because the triangles were not projections but the actual triangles connecting the points in 3D. The results were illustrated by plotting the different triangles of the face against the areas, with the right and left side data on opposite sides of the x axis. This provided a clear display of the results.

A technique of computing 3D asymmetry vectors which allowed both the quantification of the absolute degree of asymmetry, and its 3D direction and verse has been described (Ferrario et al. 1994b). This was based on 3D landmark coordinate data but also depended on defining a plane of symmetry. This passed through the point nasion and was perpendicular to the plane through the lateral canthi. A similar method calculating the distance of the minimal movement required to attain symmetrical position of bilateral landmarks was used to quantify facial asymmetry (Ras et al. 1995b). This method was applied to 3D images of the face captured with a stereophotogrammetry system and was based on the definition of a midsagittal plane which was perpendicular to and bisecting the line connecting the lateral canthi. The validity of this method was tested by comparing the results of the analysis of operated unilateral cleft lip and palate patients and non cleft subjects. As expected more asymmetry was found in the cleft cases. Another similar technique was applied to laser scanned images (O'Grady & Antonyshyn 1999). In this study the amount of asymmetry was further quantified in all three dimensions. All of these methods had the same disadvantages of the 2D techniques based on a midline.

Euclidean distance matrix analysis (EDMA) can be applied to each side of the face separately and then tested for homogeneity, which provides a comprehensive analysis of symmetry. It was found in a study investigating several asymmetry measurements that only 85% of EDMA ratios correctly identified symmetry (O'Grady & Antonyshyn 1999). In this study a further four methods of evaluating symmetry were investigated. These were landmark-independent morphometric techniques. The first involved tracing a contour and saving it as a 3D object. The actual 3D length of the object was determined and compared with the contralateral measurement to reveal any asymmetry. An extension of this technique allowed calculation of the area of bilateral surface patches. The problem with surface patch analysis is that a small difference in definition of the patch can lead to large differences in the measurement of the area. Patches need to be clearly defined and outlined, and the reproducibility tested. The final techniques validated in this study were clearance vector mapping and volume of asymmetry. The vectors described a difference between two superimposed surfaces by graphically and numerically defining the distances between the two surfaces. The method of aligning the two models was not explained. Volume of asymmetry was determined using the same method to superimpose and subtract one facial half from a mirror image of the contralateral half. These methods were helpful in describing asymmetry of a surface where anatomic landmarks were few or absent, such as the cheek. The volume was overestimated by 16% using this method however this is a promising technique and merits further study.

A method of aligning 3D models and investigating the 3D coordinates and coordinate direction angles of the landmarks has been described (Shaner et al. 2000). This was based on a mathematical transformation to align the models with no change in scale. All of the models were aligned to the same coordinate system with the origin approximately in the centre of the head. The coordinate direction angles were the angles between the vectors from the origin to the landmarks and the x, y and z axes respectively. This system has some advantages including individual evaluation of each landmark in all three planes however the lack of scaling may lead to larger faces being found to be more asymmetrical than smaller ones.

A technique for quantifying asymmetry of a 3D landmark configuration has been outlined (Mardia, Bookstein, & Moreton 2000). The method involves using Procrustes analysis to align a landmark configuration with its mirror image. The residual discrepancy between landmarks is a measure of asymmetry. This technique was used to study the nasal symmetry of cleft infants (Maull et al. 1999). In this study casts of the nose were scanned in 3D and the nose outline was defined according to peripheral anatomic landmarks. The symmetry of each nose was determined by performing a best fit superimposition of the surface with its mirror image. The result was expressed as an asymmetry index which was the mean squared distance between surface points and their antimeres after reflection. The number of points used and the method of identifying homologous points are unclear in this study however the method has many advantages including not needing to define a midplane and making full use of the 3D data. A modification of this technique is used in the study presented in this thesis and in a related study of cleft lip and palate (Hood et al. 2003). It has also been applied to study facial asymmetry in patients undergoing orthognathic surgery (Hajeer, Ayoub, & Millett 2004).

1.4 Previous Studies of Facial Morphology and Growth

1.4.1 Bone

1.4.1.1 Growth of the Facial Skeleton

Most studies of the hard tissues of the face have been carried out using lateral and posteroanterior cephalometric radiographs. Several longitudinal studies of facial growth have been carried out including the Bolton Growth Study (Hans, Broadbent, Jr., & Nelson 1994), the Fels Growth Study (Lewis, Roche, & Wagner 1985), the Nijmegen Growth Study (Prahl-Andersen & Kowalski 1976), the Michigan Growth Study (Riolo et al. 1974),

the Belfast Growth Study (Adams 1972) and the Iowa Growth Study (Bishara 2000). The material from these studies has led to a reasonable understanding of growth of the face from infancy to adulthood although most studies concentrate on the changes from 5 to 18 years of age. Only the Bolton Study and Fels Study recorded lateral cephalograms in infants (Hunter, Baumrind, & Moyers 1993). An outline of the general findings is given below.

The head of the newborn infant compared to that of the adult shows that the infant has a relatively much larger cranium and a much smaller face. The infant and young child are characterised by a round and wide appearing face because lateral facial growth occurs earlier and to a greater extent than vertical growth. A baby's face also appears rather flat since the nose is small relative to the broad but short face. The forehead is upright and bulbous because forward growth of the face has not yet occurred. Buccal and labial fat pads give a full appearance to the cheeks. The mandibular ramus is short because it is linked with the later maturing nasal and dental regions. During later childhood and adolescence vertical nasal enlargement keeps pace with growing body and lung size and dental and other oral components approach adult sizes and configuration (Enlow & Hans 1996). The mandible tends to grow more and later than the maxilla. The face has been shown to experience a pubertal growth spurt at about the same time as that in body height (Nanda 1955). More recently it has been demonstrated that facial growth continues from late adolescence to adulthood (West & McNamara, Jr. 1999). Using anthropometric methods Hellman concluded that between the ages of 3 and 22 years facial growth was greatest in the anteroposterior direction, less in the vertical direction and least in the transverse dimension (Hellman 1932).

1.4.1.2 Sexual Dimorphism in the Facial Skeleton

Sexual dimorphism is a usual finding in cephalometric studies of craniofacial growth (Ingerslev & Solow 1975;Nanda et al. 1990;Sinclair & Little 1985;Snodell, Nanda, & Currier 1993;Subtelny & Rochester 1959;Ursi et al. 1993). Generally these studies reported larger facial dimensions in males but no significant differences in the angular measurements suggesting no difference in shape. Males were also shown to have more post pubertal growth and greater late skeletal and dental changes.

The age of appearance of sexual dimorphism in the skeletal components of the face is unclear. A study of 32 subjects from 6 to 18 years of age from the Bolton study indicated that sexual dimorphism started at 9 years of age and was most apparent at 14 years of age

and onwards (Ursi et al. 1993). Limited cephalometric analysis of infants exists however sex differences in facial skeletal dimensions were documented as young as 6 months in the infants in the Bolton study (Subtelny & Rochester 1959).

Further study of the lateral and posteroanterior cephalograms of the Bolton subjects from 3 to 18 years of age was carried out to establish 3D landmark coordinates (Dean et al. 2000). The data was subjected to Procrustes analysis to remove the effects of size and analysed using principle component analysis. Male shape change peaked at 15 whereas no maximum was found in females. The interoperator error of 4.3 mm for landmark location may limit the usefulness of this 3D cephalometry.

1.4.1.3 Skeletal Asymmetry

Asymmetry of the facial skeleton is found in normal subjects. The most frequent method employed to assess asymmetry of the facial skeletal has been posteroanterior cephalometry. An investigation into facial asymmetry was carried out in London on a normal group of 63 children with an age range from 9 to 18 years (Vig & Hewitt 1975). Facial asymmetry was measured by calculating the areas of triangles of the face with apices located at anatomic landmarks. The mean differences between the right and left sides of the face were analysed. An overall facial asymmetry with the left side being larger was demonstrated.

The same method was used to study a group of 43 subjects in India with ages ranging from 18 to 25 years (Shah & Joshi 1978). They were selected on the basis having a symmetrical face, judged subjectively, and normal occlusion with no mandibular deviation. The authors concluded that normal faces do exhibit skeletal asymmetry suggesting that soft tissues try to minimise any underlying skeletal asymmetry. Facial structures were found to be larger on the right side of the face in this study.

A further study of 64 adult subjects in Canada showed a larger left side of the face (Chebib & Chamma 1981). This study of posteroanterior cephalograms assessed asymmetry by defining two axes, a midsagittal axis and a lateral axis. Several indices were calculated according to these axes. No significant sex differences in asymmetry were detected. No significant asymmetry was found in the orbital region and the maxillary dentoalveolar midsagittal structures and the chin point displayed the greatest deviations.

A study of posteroanterior cephalograms of adults with aesthetically pleasing faces found that asymmetry of the face increased from the orbits to the mandible (Peck, Peck, & Kataja 1991). Asymmetry was quantified in this study by measuring the distances of bilateral landmarks from a midline reference plane. The mean asymmetries for the dimensions studied demonstrated right side bias however this was not statistically significant.

A three year longitudinal study of facial asymmetry in 6 sets of triplets ranging from the age of 9 to 15 years at the start of the study was carried out (Mulick 1965). Three dimensional coordinates of landmarks were determined by calculation from their positions in both lateral and posteroanterior cephalograms. The 3D distance of these landmarks from a midline landmark was used as the measurement of asymmetry. Cross sectional evaluation showed different amounts of asymmetry in the various craniofacial regions with the greatest asymmetry in the maxillary structures, and the least in the cranial base. Serial evaluation showed no change in the individual's asymmetry over time.

1.4.2 Soft Tissues

1.4.2.1 Soft Tissue Profile – Studies from 5 Years to Adulthood

Limited information about the facial soft tissues can be obtained from lateral cephalograms and standardised lateral photographs. Several studies have investigated the soft tissue profile and relationship of the hard and soft tissues in adolescents and adults using lateral cephalograms.

In a longitudinal study of 40 subjects in Denver who were followed from 7 to 18 years of age it was found that the vertical dimension of the nose increased until 18 years of age. About 80% of the upper nose height had been completed by the age of 7. The upper nose height increased 3 times more than the lower nose height. Nose depth was 67-70% complete at 7 years. Small changes in upper lip length indicated that those with a short upper lip at the age of 7 will continue to have a short upper lip at 18 (Nanda et al. 1990).

A study of 64 subjects from the Bolton study with serial lateral cephalograms taken in the mixed dentition (7-9 years), the early permanent dentition (11-13 years) and early adulthood (16-18 years) was carried out to investigate the development of the nose and soft tissue profile (Genecov, Sinclair, & Dechow 1990). An interesting finding of this study was that although there were significant and complex changes in the nasal tip projection

the angular characteristics such as the nasolabial angle and the positional relationships of the nose lips and chin remained virtually unchanged during the 10 year period evaluated.

A longitudinal study of 35 subjects from Iowa with annual cephalograms from 5 to 17 years of age plus further radiographs at 25 and 45 years of age found that the angle of soft tissue convexity that excludes the nose (nasion-subnasale-pogonion) expressed little change from 5 to 45 years (Bishara et al. 1998). It was also found that the upper and lower lips become more retruded in relation to Rickett's aesthetic line, the line from the tip of the nose to the chin, from 15 to 45 years of age.

Fourier analysis has been used in the assessment of facial soft tissue profile in lateral cephalograms from subjects in the Bolton study (Ferrario et al. 2002). The study concluded that facial soft tissue size and shape were significantly determined by age and that hard and soft tissue changes were not correlated linearly.

Tensor analysis has also been applied in the study of the soft tissue profile from 7 to 20 years of age (Battagel 1994). The soft tissue points were shown to grow in a predominately horizontal direction. This suggests more proportionate increase in soft tissue dimensions in comparison with the underlying hard tissues around puberty. This is contrary to the findings of Subtelny (Subtelny & Rochester 1959).

Numerous studies of the facial profile have been carried out using photographs (Bearn, Sandy, & Shaw 2002;Bishara, Jorgensen, & Jakobsen 1995;Ferrario et al. 1993a;Peck & Peck 1970). These studies have mainly concentrated on adolescents and adults and on the effects of orthodontic treatment or orthognathic surgery. Errors from photographic analysis are likely to be larger than those due to digitization of a radiograph (Benson & Richmond 1997). In a study of soft tissue profiles of photographs of young adults a high method error and large variability were also found for the nasolabial and mentolabial angles (Fernandez-Riveiro et al. 2003).

1.4.2.2 Soft Tissue Profile – Studies in Infancy

There are very few cephalometric studies of the soft tissue profile in infants. This is probably due to the difficulty in obtaining reproducible radiographs in this age group. Recently techniques for obtaining infant cephalograms have improved (Hermann et al. 2001) however it is no longer considered ethical to radiograph children purely for growth studies and it is unlikely that more studies of this type will be undertaken.

One early study in this area was carried out by Subtelny & Rochester in 1959. They examined a series of lateral cephalograms of 30 subjects from 3 months to 18 years of age from the Bolton Growth Study. Although it is not explained fully in the paper it appears that all the information relating to infants less than 1 year old was grouped together into a 6 month category. It was found that from 6 months to 4 years of age there was a marked and rapid increase in soft tissue and mandibular prognathism. Prognathism in this study was measured by Down's facial angle, the angle between the basion-nasion line and the nasion-pogonion line and a modification of this angle was used to measure soft tissue prognathism. He also compared soft tissue profile (nasion-subnasale-pogonion) to skeletal profile (nasion-point A-pogonion) and found skeletal facial convexity decreased with age. Soft tissue convexity also decreased up to 3 years of age but then there was a reversal in the trend with soft tissue convexity increasing from 3 to 6 years. The conclusion was that from 6 months to 18 years the minimal change in soft tissue profile was due to a greater increase in soft tissue thickness overlying point A as the skeletal profile straightened. Soft tissue profile measurement including the nose (nasion-pronasale-pogonion) also decreased in convexity up to 3 years and then there was a marked and continued increase in convexity until 18 years of age. This was interpreted as evidence that the forward growth of the nose, from 3 to 18 years, was greater than that of the other soft tissues of the face. This was further studied by measuring nasal dorsum length (nasion-pronasale) from 1 to 18 years. This was found to increase at all stages with no reduction in growth rate with increasing age. In conclusion the author states that all parts of the soft tissue contour do not directly follow the underlying skeletal profile. Some areas, such as the soft tissue overlying point A, were found to diverge from underlying skeletal structures while other areas such as soft tissue pogonion showed a strong tendency to follow skeletal changes (Subtelny & Rochester 1959).

A study comparing craniofacial morphology in children with cleft lip and palate with a control group of age and sex matched children was undertaken in Barcelona (Casal et al. 1997). The control group comprised 22 infants with ages ranging from 20 to 35 months who had lateral cephalograms recorded at the request of an otorhinolaryngologist. These children had acute respiratory tract infections which were mostly viral. Inclusion criteria included absence of facial congenital malformations and gross craniofacial dysmorphology. Lateral cephalograms were recorded in a specially designed paediatric cephalostat. Several skeletal measurements and three soft tissue measurements were presented. Due to the nature of the study the control group was split into 4 groups with average ages ranging from 20.8 months to 34.7 months. It was therefore difficult to draw any conclusions regarding normal morphology of the soft tissue profile from this sample.

A further problem with this study was that the control group, radiographed due to nose and throat pathology, may not have been representative of the normal population since the craniofacial morphology of children with enlarged adenoids and tonsils has been shown to be different to normal children (Behlfelt et al. 1990;Linder-Aronson 1970).

No other cephalometric or photogrammetric studies of normal infants and reporting soft tissue parameters have been found in the literature.

1.4.2.3 Direct Anthropometric Data

Comprehensive normative data on the facial dimensions of North American Caucasians from 1 to 18 years of age have been published (Farkas et al. 1992b;Farkas et al. 1992c;Farkas, Posnick, & Hreczko 1992a). Presentation of the results is split into 5 regions, the head, face, orbits, nasolabial region and ear. Each region of the face was examined in at least 1500 subjects in this cross sectional study. Only 160 children under 4 years of age were examined, including at least 30 subjects at 1 year and 51 subjects at 2 years. No report of the error of the method is included in this study. In a later report the author stated that 'interobserver testing carried out in 16 major measurements of the head and face, showed high correlation in our findings'(Farkas 1996). However, the details of this error study are not readily available. The precision and repeatability of linear anthropometric measurements have been evaluated in a separate study (Ward & Jamison 1991). In general the measurements were reliable and in no case did separate measurements differ by more than 4%.

A summary of the direct anthropometric results for the face, orbits and nasolabial region is given below. By 1 year the width of the mandible was highly developed (80%) while its height reached only 67% of the eventual adult size. The mandible showed significant development from 1 to 5 years while face height, width and the two face depth measurements exhibited continuous gradual growth after 5 years. In general the face matured between 12 and 15 years in males and 2 years younger in females.

In the orbital region only intercanthal and biocular widths were reported. The average total growth in intercanthal width from 1 to 18 years was 5.2 mm, and 12.5 mm for biocular width. Intercanthal width showed little growth after 1 year, in contrast biocular width showed greater growth before and after 5 years of age. Intercanthal width reached maturity at 8 years in females and 11 years in males, biocular width at 13 in females and 15 in males.

In the nasolabial region the upper lip, nose height and nasal tip protrusion grew rapidly between 1 and 4 years. The cutaneous upper lip height reached adult size in 3 year old females and 6 year old males. Growth of the nose between 5 and 18 years was significantly greater than that of the upper lip. Nose width and height were fully developed in females by age 12 and in males by age 14 or 15.

More detailed information and further data relating to a small number of younger subjects was later published by the same researchers (Farkas 1994a). This included some measurements of the face and nose for 8 infants from 0-5 months and 20 infants from 6-12 months of age. Orbital measurements were given for 8 infants from 0-5 months and 8 infants from 6-12 months. Some lip measurements were reported for 8 infants from 0-5 months and 19 infants from 6-12 months of age. These measurements had been omitted from previous reports due to the small sample size and difficulties obtaining reliable measurements in uncooperative infants. These measurements cannot be regarded as reliable population norms for infants less than 12 months.

Proportional indices, based on direct anthropometric measurements for the face of children between 1 and 5 years, have recently been published (Farkas et al. 2003). The study group consisted of 284 healthy North American white children. Proportions within the mean $\pm$ 1 SD were harmonious and values at the level of mean $\pm$ 2 SD were called disharmonies. Disproportion above or below these values were called subnormal or supernormal. It has been suggested that proportional indices are more helpful clinically in diagnosing irregularities since it is the presence of disproportion, rather than abnormality in actual size, which determines whether surgery is required (Koury & Epker 1992).

A longitudinal direct anthropometric study of 126 children measured at 3 days then annually from 1 year to 5 years of age was carried out in Aberdeen (Low 1952). Various body parameters were measured including face length and breadth. Face length was found to increase 55% in the first two years of life in both males and females. Face width increased 30% in this time.

Growth charts for nose length, nasal protrusion and philtrum length have been produced based on a cross sectional direct anthropometric study in Switzerland (Zankl et al. 2002). From birth to 97 years 2500 subjects were examined including 50 newborns, 50 1 year olds and 50 2 year olds. No error study was included in this report. Separate growth charts for males and females from 0 to 90 years of age were presented for the three facial parameters. Philtrum length was found to peak in adolescence followed by a decline in early adulthood.

This study provides long term information on the changes in nasal and lip dimensions however it contains limited detail relating to the infants up to 2 years of age.

In a cross sectional direct anthropometric study of oral opening in 422 infants ranging from 6 weeks to 36 months, open and closed mouth breadths were measured (Nowak & Casamassimo 1994). The infants were grouped into 7 groups with the first group at 6 weeks then the other groups every 6 months of age. A minimum of 46 infants were measured at each age. The open mouth breadth was measured by opening the mouth of the infant with pressure from the operator's fingers until resistance was felt. The open mouth breadths were 5.6 to 9.0 mm less than the closed mouth measurements. No repeatability study appeared to have been carried out and these results may not be reliable.

Direct anthropometric study of newborns has been carried out as an aid to syndrome delineation. Orbital measurements in newborns have been studied in many investigations (el Shanti, al Lahham, & Batieha 2000;Feingold & Bossert 1974;Fok et al. 2003a;Laestadius, Aase, & Smith 1969;Madjarova et al. 1999;Merlob, Sivan, & Reisner 1984;Omotade 1990;Thomas, Gaitantzis, & Frias 1987). These direct anthropometric studies measured intercanthal, biocular and palpebral fissure widths in babies in the United States, Hong Kong, Bulgaria, Israel, Jordan, Nigeria and the UK. Anthropometric differences in these eye dimensions between ethnic groups and even between Caucasian groups were found to exist shortly after birth. A smaller number of studies also measured lip, mouth, ear and face dimensions in newborns (Feingold & Bossert 1974;Fok et al. 2003b;Fok et al. 2004;Madzharov & Madzharova 1992;Sivan, Merlob, & Reisner 1983). Findings of these studies show that measurements such as lip length and nose width can also be markedly different between ethnic groups.

No other detailed direct anthropometric measurements of the face have been found in the literature for Caucasian infants from birth to 2 years of age.

1.4.2.4 Three Dimensional Data

Short-base stereophotogrammetry has been used to study differential growth and development of the soft tissues of the face in a group of 52 children from the age of 9 to 16 years (Burke & Hughes-Lawson 1989a). This was a mixed longitudinal study with a minimum of 14 children examined at age 9 and a maximum of 41 children at 15. All of the children were like sexed twins. Thirteen face height and width measurements were investigated. In an error study the variance of the z coordinate was greater than the x or y

coordinate but the standard deviation was still only 0.28 mm. The measurements of intercanthal and palpebral fissure widths grew little, less than 2 mm from 9 to 16 years but were advanced in their development following a neural pattern. Mouth height and lip to chin distance changed less than 1 mm from 9 to 16 years. The remaining parameters grew between 3.2 and 11.3 mm but were less advanced in their development. An adolescent growth spurt in the 10 facial parameters below the eyes was previously demonstrated in a smaller longitudinal sample of the same subjects (Burke & Hughes-Lawson 1988a). Further study of the same group showed that nasal depth growth coincides with the adolescent growth spurt in standing height, but nasal width and height follow a pattern between the neural and skeletal patterns of growth (Burke & Hughes-Lawson 1989b). The only use of this technique to study infants was described in two longitudinal case reports of a female baby followed from 3 weeks to 10 years of age (Burke 1983;Burke 1980). These studies showed that at 3 weeks the mouth was shaped like a rosebud, with mouth width and height both measuring 20 mm. In the first 2 years mouth width increased greatly, from 20 mm to 36.6 mm, but mouth height decreased. The conclusions of these studies were that growth of most facial parameters was very rapid in the first year, less rapid in the second year, slow and irregular from 3 to 9 and then accelerated again at the age of 10. These studies, although limited in sample size and landmark numbers were the first longitudinal studies of facial growth in 3D.

An 18 month longitudinal study of 59 subjects from 9 to 10.5 years of age was carried out using stereophotogrammetry (Ras et al. 1996). A repeatability study found absolute differences between repeated measurements to be less than 2%. Three paired distances, three paired angles and one midline angle were determined. Significant changes in facial morphology due to growth and development were shown, although these differences were only 0.8 to 1.5 mm. No significant changes in angular measurements were determined. This short term study shows that stereophotogrammetry is a suitable method to study growth and development of the face.

Normal facial growth and development was analysed through 3D facial morphometry in a mixed longitudinal and cross sectional study (Ferrario et al. 1999). Over one thousand subjects were examined from 6 years to young adulthood with a minimum of 80 subjects at each age. In the longitudinal component of this study 391 subjects were followed up to 4 years between the ages of 6 and 12 years and 143 children were followed for 3 years from 11 to 15 years. The remainder of the study sample were examined only once. Markers were fixed to the face overlying 22 landmarks and recording of their positions in 3D was carried out using automated infrared photogrammetry. The system error was previously reported to

be about 0.1 mm and the error for duplicate landmark identification was about 2 mm (Ferrario et al. 1996c). Reference data for six angular and six linear measurements were provided as well as growth charts for each parameter from 6 years to adulthood. Comparison of some of the angular measurements with conventional soft tissue cephalometric references showed a good agreement. This study provided a comprehensive analysis of facial growth from 6 years to young adulthood. The lack of surface data and image production is a disadvantage but the main problem with this technique is the subject cooperation required and it has therefore not been applied to subjects under 5 years of age.

Laser scanning was used to study facial morphology in a cross sectional group of 132 subjects from 5 to 10 years of age (Nute & Moss 2000). This was illustrated by determining an average male and female face at each age, superimposing these averages and colour coding the changes. The results of the error study were presented using the same colour coding and showed some differences around the nose and chin of up to 3 mm when the scanning and landmarking were repeated. However no dimensional differences were found on most of the face indicating a consistent technique of scan acquisition and landmarking. Face height was found to increase annually by 3 to 4 mm. Midface prominence and width altered less than 1 mm each year. Mandibular width increased by 1 to 3 mm a year and mandibular prominence also increased. Nose height and prominence and alar base width increased by 2 mm per year on average but dorsum width changed less than 1 mm per year. The dimensions changed more than cephalometric and anthropometric studies have shown in similar age groups, probably due to the fact that soft tissues were included in this study. This study was reported to serve as a basis for a longitudinal study. Although this technique could be useful in studying growth in children the speed of capture makes it unsuitable for use in infants.

Reference values of facial features in white Scandinavian children were ascertained using a structured light range camera technique (Strömland et al. 1999). A total of 613 subjects with an age range of 1 month to 18 years were examined in this cross sectional study. Around 20 males and 20 females were examined in each of the infant, 1 year and 2 year age groups. The systematic error was previously reported as less than 3.2%, corresponding to about 1 mm. The repeatability of measurements was less than 1 mm within observers but between observers this error increased to 3 to 4 mm (Strömland et al. 1998). The dimensions of 7 midfacial features were measured and presented as growth curves. Growth was found to be fastest for outer canthal distance and least for inner canthal distance. The fastest period of growth for all features in both sexes occurred during the first 2 years of life. The rate of growth then slowed between 3 to 6 years and after 7 years the growth was

even slower. The details of the subjects in the infant group, such as their mean age and lip position, are unclear in this study. The presentation of the results simply in the form of growth curves from 1 month to 18 years makes interpretation of the 1 month to 2 year results difficult. This study therefore adds little to the understanding of facial morphology from birth to 2 years.

A cross sectional analysis of 3D facial form of normal Japanese children was carried out using a structured light scanner (Yamada et al. 2002). Three groups of children were examined; 97 children at 4 months, 54 at 1.5 years and 80 at 3.5 years. Sixteen landmarks in the midface and 16 nostril landmarks were extracted semi automatically. Body height, weight and head circumference were also recorded. The spatial accuracy of this system has been reported to be within 0.5 mm. The automatic landmark extraction programs had an accuracy of 1 mm or less (Yamada et al. 1999). Mean linear and angular measurements with standard deviations were presented for the males and females in the three age groups for a small selection of landmarks in the midface. In the infant group males had wider and larger noses as well as a sharper axial plane pronasale angle. Significant correlations were found between upper face, nose and mouth widths however upper lip height was not correlated with other facial dimensions. Minimal correlations were found between facial and body measurements. This study, although limited in its description of the infants and presenting only a small number of measurements, was a useful first step in quantifying facial morphology in 3D in infants.

Only these limited cross sectional cephalometric, anthropometric and three dimensional studies have been carried out on infants up to 2 years of age. No longitudinal studies of infants under 2 years have been carried out to assess facial morphology and growth in three dimensions.

1.4.2.5 Soft Tissue Sexual Dimorphism

Sexual dimorphism in the soft tissues of the face has been investigated in cephalometric studies, in photographs, using anthropometry and in several 3D studies.

Gender differences have been shown in several cephalometric studies of soft tissue growth. An early study found that females were more prognathic than males from 6 months to the 7 to 8 year stage but by 18 years of age there was no appreciable difference in prognathism between the sexes (Subtelny & Rochester 1959). There were no well defined sex differences in the convexity of the soft tissue facial profile in this group at any age. The

degree of increase in the nasal measurements from 1 to 18 years was approximately the same in males and females however the means of all the nasal measurements were greater in boys than girls at all ages. No sex differences were found in the upper or lower lip lengths.

Sexual dimorphism was found in the nose, lips and chin of subjects from 7 to 18 years of age in a more recent cephalometric study (Nanda et al. 1990). Males showed a larger increase in size of these structures and this extended over a longer period of time than in females. Confirmation of these gender differences in the soft tissue profile was found in a study of 82 subjects from age 9 to 22 years (Prahl-Andersen et al. 1995). In this study it was found that gender different growth patterns commenced at 9 years when the soft tissue structures of girls changed in size rapidly compared with boys. The boys reached a similar rate of growth at 12 years of age when the velocity curves overlapped. After this age the velocity curve decreased in girls and increased in boys until the final stage of the study. In a study of 35 subjects from 5 to 45 years of age it was found that similar direction and magnitude of changes occurred in males and females. The greatest changes occurred from 10 to 15 years in females but from 15 to 25 years in males (Bishara et al. 1998). Tensor analysis of lateral cephalometric data has shown some gender differences not revealed by conventional cephalometric analysis (Battagel 1994). In this study the females grew less than the males but differences in form were also found. The females developed squarer mandibles, more retrusive noses and less prominent chins from 7 to 20 years of age. The females showed relatively more vertical development than males.

Photographic studies have also confirmed this sexual dimorphism. Euclidean distance matrix analysis found a highly significant sexual dimorphism in photographs of adult faces showing that the form difference between male and female faces is both a size and shape difference (Ferrario et al. 1993b). Angular assessment of the soft tissue profile in young adults showed sexual differences in the nasofrontal, nasal vertical, nasal and nasal dorsum angles (Fernandez-Riveiro et al. 2003).

Direct anthropometry has shown consistent size differences in the faces of males and females (Farkas & Posnick 1992;Hellman 1932;Zankl et al. 2002). In the former study the face was found to mature between 12 and 15 years in males and 2 years younger in females. Proportional indices published recently for subjects aged 1 to 5 are provided separately for boys and girls due to these well recognised differences (Farkas et al. 2003).

A study of 52 pairs of like sexed twins using stereophotogrammetry, showed that girls were smaller than boys but were more advanced at comparable ages when compared to adult size (Burke & Hughes-Lawson 1989a). All linear parameters of the face were larger for boys except nasal dorsum. The nose showed a growth peak between 9 and 10 years for girls and between 13 and 14 years for boys.

Sexual dimorphism in 76 young adults was investigated using euclidean distance matrix analysis and 3D facial morphometry (Ferrario et al. 1994a). Males were found to be 6 to 7% larger than females, but no differences were found in 3D shape. A further study in 144 children of 6 to 10 years of age using Fourier analysis found no shape differences in soft tissue outline (Ferrario et al. 1996b). The soft tissue outline in this study was a series of straight lines connecting 6 midline landmarks and not the true soft tissue profile. In a further large mixed longitudinal and cross sectional study of 1348 subjects from 6 years to young adulthood, most linear distances were significantly larger in males than females (Ferrario et al. 1998b). Angular measurements did not show a corresponding sexual dimorphism. The male versus female comparisons within each age group suggested a sexual dimorphism in the timing of soft tissue growth.

A group of 132 British children aged 5 to 10 years had their faces scanned using a laser surface scanner (Nute & Moss 2000). Males were generally larger than females with the greatest differences in face heights of 7 to 9 mm, and the least in midface dimensions with 1 to 3 mm differences. Shape analysis was not reported for this sample.

In a study of Scandinavian children using a structured light range camera technique a total of 613 subjects with an age range of 1 month to 18 years were examined (Strömland et al. 1999). In this cross sectional study all the facial features of boys, except intercanthal distance, were larger than girls at all ages. From birth to 1 year the intercanthal distance of girls was larger than boys, thereafter the boys were larger.

A cross sectional study of Japanese children using a structured light scanner found only minor gender differences (Yamada et al. 2002). In the 4 month group consisting of 97 subjects, males were found to have wider and larger noses and a sharper axial plane pronasale angle. In the 1.5 year group with 54 subjects male subjects had a sharper sagittal plane pronasale angle. In the 3.5 year group with 80 subjects differences were found in the size of the nose and lip with the males yielding larger values.

1.4.2.6 Soft Tissue Asymmetry

Asymmetry of the soft tissues of the face has been studied in photographs, video images, using anthropometric measurements and using 3D imaging techniques.

A study of asymmetry in a group of 108 subjects, with an age range of 20 to 27 years, was carried out using standardised photographs (Ferrario et al. 1993a). A certain degree of asymmetry in the soft tissues was found however this was less than the skeletal asymmetry found by other investigators (Shah & Joshi 1978;Vig & Hewitt 1975).

An investigation of nasal morphology in cleft and control subjects used video images of nasal casts to assess several nostril asymmetry parameters (Russell et al. 2000). There were 19 subjects in the control group with a mean age of 14 years. The noncleft subjects were found to have a right nostril which was more elliptical in shape and the left nostril was rounder. The left nostril was also found to be a more irregular shape than the right.

A direct anthropometric study of 308 subjects was undertaken to determine the degree of facial asymmetry in normal individuals (Farkas & Cheung 1981). Three age groups were examined; 6 year olds, 12 year olds and 18 year olds with at least 50 males and 50 females at each age. Six paired measurements were analysed. The asymmetries which were found were generally mild with the asymmetric measurements having an average difference of 3 mm. Asymmetries were more common in the measurements involving midline landmarks. Longer measurements were found on the right side of the mandible in both sexes in all three age groups. Few of the measurements had significant correlations with each other. The authors suggest that a balance of asymmetries may account for the lack of obvious clinical asymmetry. Sex and age did not influence the prevalence of asymmetries significantly.

A cross sectional study of asymmetry in 24 pairs of twins from 7 to 20 years was carried using stereophotogrammetry (Burke 1971). Paired interlandmark distances were investigated. Two of the parameters measured were larger on the left and two were larger on the right. All of the mean differences were less than 1 mm with a range from 0 to 6.6 mm. Subsequently 6 pairs of twins were followed from 8 to 19 years with annual serial records using the same system (Burke & Healy 1993). Asymmetry was found to be small but significant in 12 of the 60 parameters measured, however asymmetry could not be related to age.

In a study of cleft lip and palate with 80 control subjects aged 9 years, left-right dominance was described (Ras et al. 1994). Using stereophotogrammetry 3D coordinates of 26 facial landmarks were determined. A reference plane was constructed in the midline and the x, y and z coordinates of the landmarks were determined according to this plane. Asymmetry was calculated in the x, y and z planes separately by comparing the distances of the paired landmarks to horizontal, vertical and sagittal planes. The control subjects showed left side dominance in the transverse dimension, right side dominance in the sagittal direction and no particular dominance in the vertical direction. In a further mixed longitudinal study of 63 controls aged 6 to 12 years using the same technique an increase in the asymmetry in the basal region of the nose with growth was shown. Left-right dominance was not found to alter with growth (Ras et al. 1995a).

An investigation of asymmetry in a group of 80 young adults was carried out using 3D facial morphometry (Ferrario et al. 1994b). Three dimensional asymmetry vectors were calculated after defining a symmetry plane. Asymmetry was evident especially in the middle and lower thirds of the face. The right side of the face was larger than the left, with some degree of rotation. A later study investigating the effects of age and sex on soft tissue facial asymmetry was carried out on 314 subjects from 12 to 56 years of age using the same methodology (Ferrario et al. 2001). A slight soft tissue facial asymmetry was found in normal subjects, with mean total asymmetry vectors ranging from 7 to 8 mm. No gender or age related differences were found. Endocanthion was the least asymmetric landmark whereas tragion, gonion and zygion were the most asymmetric.

An investigation of asymmetry in a group of 70 normal subjects from 1 to 63 years of age was carried out using stereophotogrammetry (Shaner et al. 2000). Paired interlandmark measurements and the 3D coordinates of the landmarks were investigated. The results were presented for the males and females separately however all of the ages were grouped together. It was therefore not possible to separate the asymmetry in the younger subjects from older subjects. Significant asymmetries between paired measurements were found in 7 males and 6 females, with differences ranging from 0.9 to 3.2 mm. The means from the right side of the face usually had the greatest values. In the assessment of the 3D coordinates, the x coordinates were all greater on the right side indicating these landmarks were more laterally placed. No side consistently exhibited a greater upper or lower position of the y coordinates or a more anterior or posterior position of the z coordinates. The authors conclude that the variations in the literature on the findings of facial asymmetry were the results of the wide varieties of subjects, types of data, techniques of data capture and differences in treatment of the data.

1.5 Aims of the Thesis

The aims of this thesis were:

1. To validate the use of the C3D system to assess facial morphology and growth in infants including establishing the system error, the reproducibility of landmark location and the repeatability of facial expressions in infants.
2. To establish reference values for the normal facial dimensions and growth of infants at 3 months, 6 months, 1 year and 2 years of age by capturing their faces using a 3D imaging system.
3. To determine the correlation of facial dimensions with body weight, length and head circumference at each of these ages and to correlate facial and body growth.
4. To ascertain any sexual dimorphism in infants faces at these ages and to establish any gender differences in growth.
5. To establish the degree of facial asymmetry of infants at these ages, to determine any change in facial asymmetry with growth and to discover which areas of the face are most asymmetric in infants.
6. To provide three dimensional facial images of normal infants at 3 months, 6 months, 1 year and 2 years of age for more complex analysis of facial shape and changes in shape of the face with growth to be undertaken in future research.

1.6 Hypotheses

The hypotheses of this study were that:

1. The C3D system was a valid and reproducible method of recording and measuring infants faces in three dimensions.
2. There was a significant correlation between facial and body dimensions and growth in infants.
3. The facial dimensions of male infants were larger than females but there was no difference in growth of the males and females.
4. There was some asymmetry in normal infants faces but that there was no difference in asymmetry between males and females and no change in asymmetry with growth.

2 Materials & Method

2.1 Study Design

This was a longitudinal study of facial growth in healthy infants from 3 months to 2 years of age. The infants faces were captured using a three dimensional computerised imaging system, C3D®. These systems were situated at Glasgow Dental Hospital & School and at the Royal Hospital for Sick Children, Glasgow. The aim was to capture images of the infants at 12 weeks, 24 weeks, 1 year and 2 years of age within the range of 10% above or below these exact ages,

This data was collected in order to establish normative data for these age groups. It has been used as a control data for comparison with a matched sample of children with cleft lip, or cleft lip and palate.

Ethics committee approval was obtained from both Glasgow Dental Hospital & School and at the Royal Hospital for Sick Children, Glasgow, prior to starting this study.

2.2 Subjects

2.2.1 Recruitment

It was estimated that 60 infants were required to form a control group for the larger cleft study in order to provide 3 times the number of controls as predicted cleft cases. It was anticipated that there would be a significant drop out rate due to the longitudinal nature of the study and therefore it was decided to recruit 100 infants.

2.2.1.1 Inclusion and Exclusion Criteria

In order to have a homogenous study group, and provide normative data, all the children recruited were Caucasian, delivered at full term with no perinatal complications and had no craniofacial abnormalities.

2.2.1.2 Method of Recruitment

The initial stage of recruitment involved designing and printing information leaflets and posters and distributing these at local maternity wards, health centres, general medical practitioner surgeries, Glasgow Dental Hospital & School and at the Royal Hospital for Sick Children, Glasgow. The leaflets and posters contained information on what the study involved and how to contact the study operator. They also offered free copies of the 3D images and a free professional family photograph at the end of the study. The leaflet is shown in Figure 2.1.

Permission was sought from the North Glasgow Primary Care Trust to allow the author to attend maternity wards and immunisation clinics to recruit subjects personally. Parents were given an information leaflet, the study was explained and the parents contact details were collected if they agreed. A midwife at the Queen Mother's Hospital, Glasgow also took part in the recruitment. The parents were later contacted by phone and an initial appointment was arranged.

2.2.2 Subject Details

2.2.2.1 Consent and Parent Questionnaire

The parents were asked to complete a consent form, which had been approved by the local ethics committee, when they attended the first appointment. They were also asked to complete a questionnaire to obtain their contact details and information on their place of birth as well as the infant's birth weight, date of birth and whether they were breast feeding. The consent form and subject information form are shown in Appendices 1 and 2.

2.2.2.2 Deprivation Category

The families social circumstances were assessed using the Carstairs Index of Deprivation Category (depcat) which assigns subjects to a category from 1 to 7 according to their postcode, 1 being the most affluent and 7 the most deprived (Carstairs & Morris 1990;McLoone 1993).

Figure 2.1 Information Leaflet

At the end of the study we will offer you a free professional family photograph as a token of our appreciation for taking part.

What should I do now?

If your child is UNDER 3 MONTHS of age and you would like to take part in this study or would like more information please contact:

JILL WHITE
Clinical Lecturer in Orthodontics
Glasgow Dental Hospital & School
378 Sauchiehall Street
Glasgow G2 3JZ
Telephone: 0141 211 9699
Email: j.white@dental.gla.ac.uk

The study has been made possible by a grant from the Scottish Office.

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How Does Your Child's Face Grow?

We are inviting you and your child to take part in a study of how your child's face grows

Very little work has been done to find out how young children's faces grow.

We are planning to assess normal facial growth in 100 children in Glasgow over the next two years.

Cleft Lip and Palate

- One of the reasons for collecting this information is to help children with cleft lip and palate
- In the UK around one in 600 infants are born with cleft lip and/or palate

Clefts are surgically closed usually in the first year of life. We are studying the effects of surgery on babies with cleft lip and palate but because we don't know how a normal child's face develops we do not know how the surgery is affecting the cleft children's growth.

3 Dimensional Assessment of Facial Growth

We now have a new way of recording the shape of the face in three dimensions using two video cameras. This takes only one second and you can see the image on the computer screen 5 minutes later.

Your child is not exposed to any radiation.

The information collected is confidential and no child will be identified at any time.

What are we asking you to do?

The cameras are located at the Royal Hospital for Sick Children, Yorkhill and at Glasgow Dental Hospital and School, Sauchiehall Street. You can choose whichever is more convenient for you.

We are hoping to take pictures of your child's face four times over the next two years, at

- 3 months
- 6 months
- 1 year and
- 2 years of age

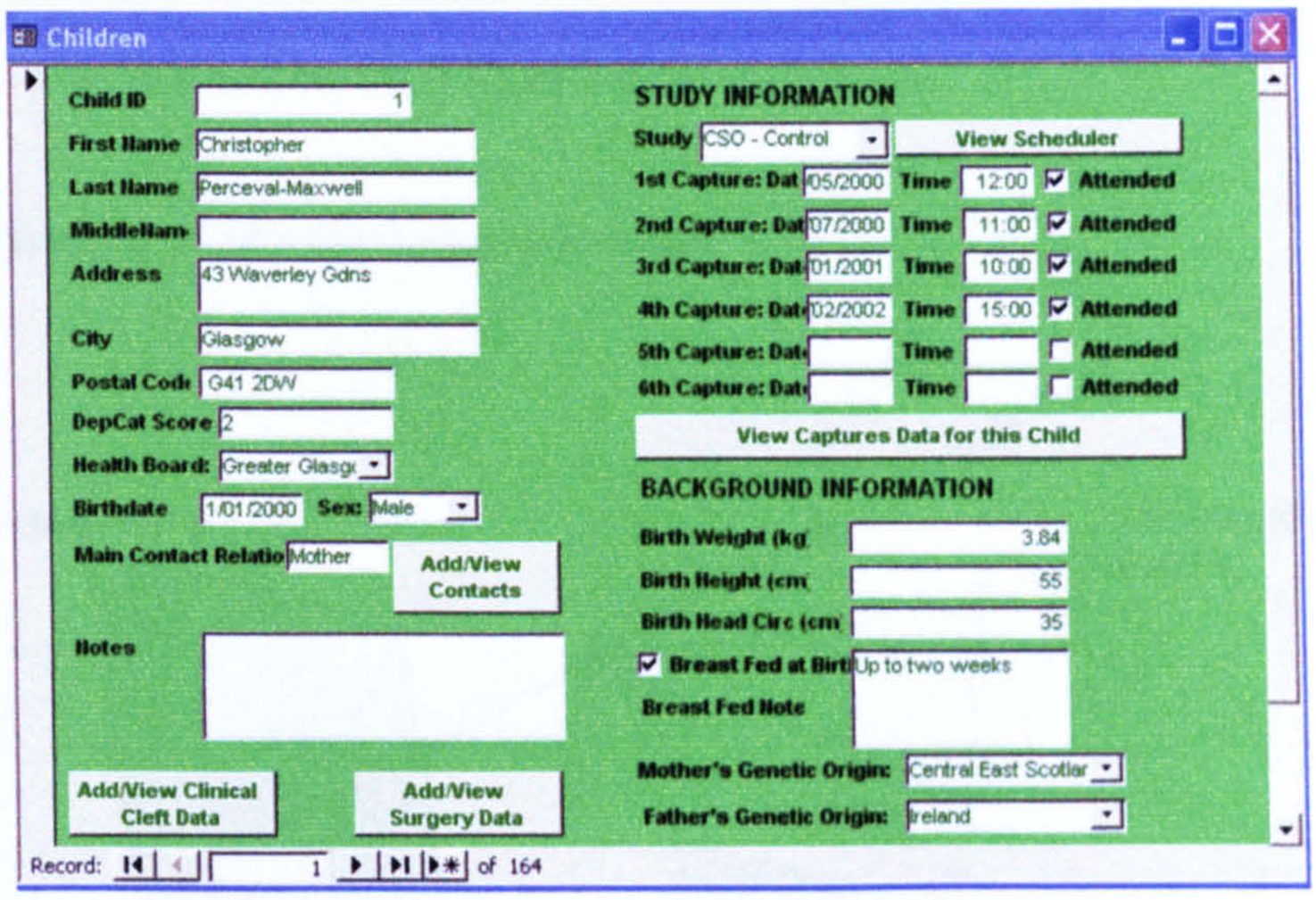
At each visit their height, weight and head circumference will also be measured. The visits will last at most 20-30 minutes.

A contribution will be made towards travel expenses, where necessary.

2.2.2.3 Database

All of the subject information, and later the capture information, were entered into a database with the parents consent. The database was specially designed for the project by the University of Glasgow Statistics Department using Microsoft Access. The information was stored on a secure computer which was not networked and could only be accessed by the researchers involved in the project. The data entry form is shown in Figure 2.2.

Figure 2.2 Access Database



2.2.3 Subject Attendance

Only those parents who were confident they would be able to attend on all 4 occasions were recruited. The initial appointments were arranged by telephone and confirmed by letter when the infant was 8-10 weeks old. At the first visit at least two additional methods of contact were established for each subject, such as a grandparent's address, a work telephone number or an email address. Travel expenses or car parking was paid at the end of each visit or the parents were sent parking vouchers with the confirmation letter. A letter containing travel instructions and a map was sent with this confirmation.

At the end of the first appointment a provisional time was arranged for the 6 month follow up. This was confirmed nearer the time by a telephone call and a letter. The one year follow up was arranged by telephone call then a letter. Forty two of the subjects changed address at least once during the course of the study and the additional contact details were often essential. It was much more difficult to arrange the two year visit since many of the mothers were either back at work or had a new baby. Several families had moved away from the Glasgow area and one had moved to Australia.

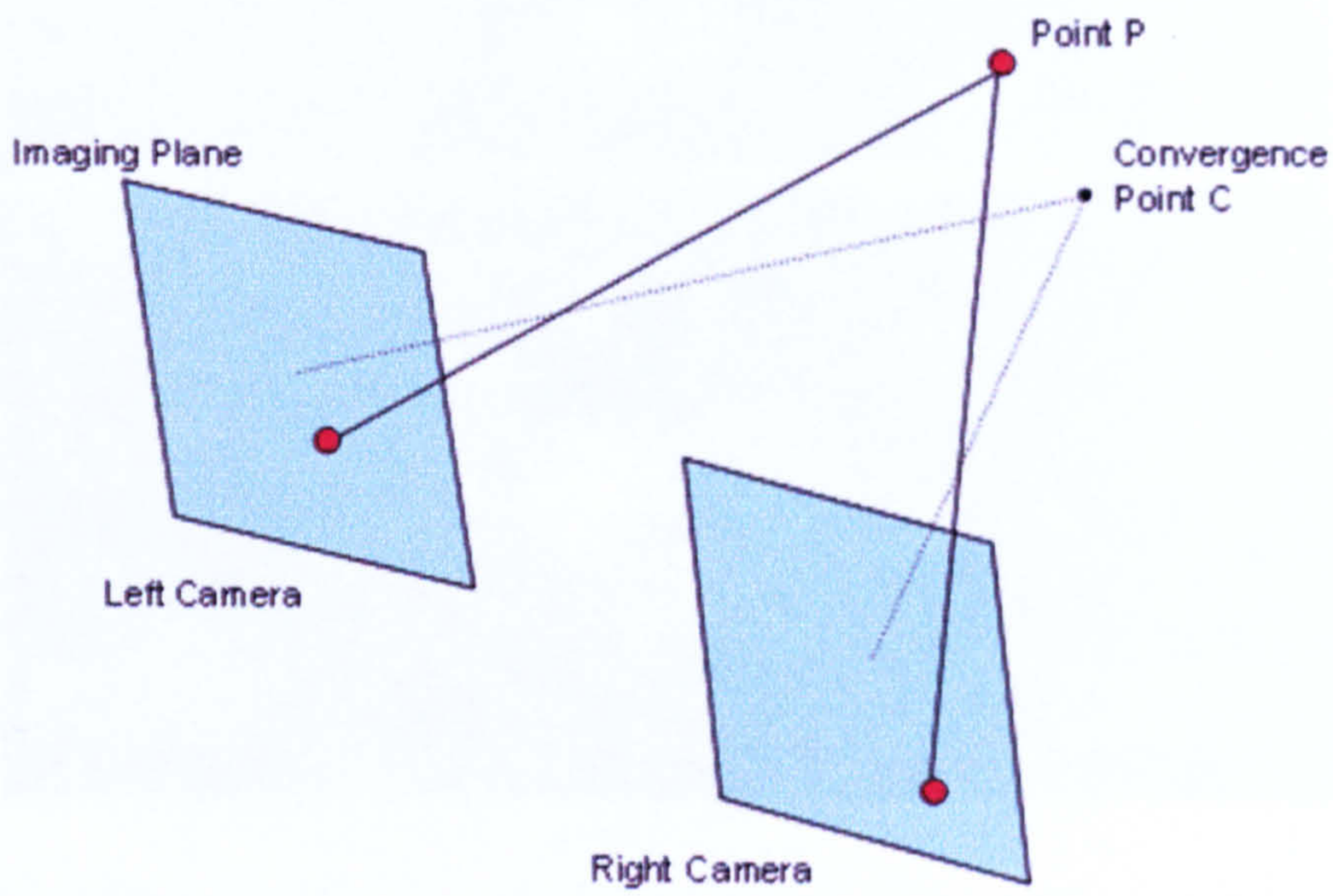
2.3 Data Collection

2.3.1 Computerised Stereophotogrammetry

2.3.1.1 Principles of Stereophotogrammetry

Stereophotogrammetry works using the same principle as human sight where depth is perceived due to the slight disparity between the views from two eyes. Stereophotogrammetry relies on camera to camera baseline triangulation to perform this depth sensing. This is illustrated in Figure 2.3.

Figure 2.3 Principle of Stereophotogrammetry



As shown in Figure 2.3, a point P in space will project to two slightly different locations on the imaging plane of each camera and the difference in location is termed disparity. This disparity increases as the point P is translated further in the depth axis from the convergence point C of the camera pair. The sign of the disparity is reversed depending on whether the imaged point lies in front or behind C. The magnitude and direction of these disparities can be decoded to produce a depth map if the geometry of the camera configuration is known (Siebert & Marshall 2000). The calibration procedure is explained in section 2.3.1.3.

2.3.1.2 C3D System Description

A computerised stereophotogrammetry system, C3D, was used in this study to capture a series of 3D images of the face of each child at each age (Ayoub et al. 1996).

This system had two pods, each pod consisting of two black & white cameras and one colour camera. The system is shown in Figure 2.4 and a close up image of the left pod is shown in Figure 2.5.

Figure 2.4 C3D System

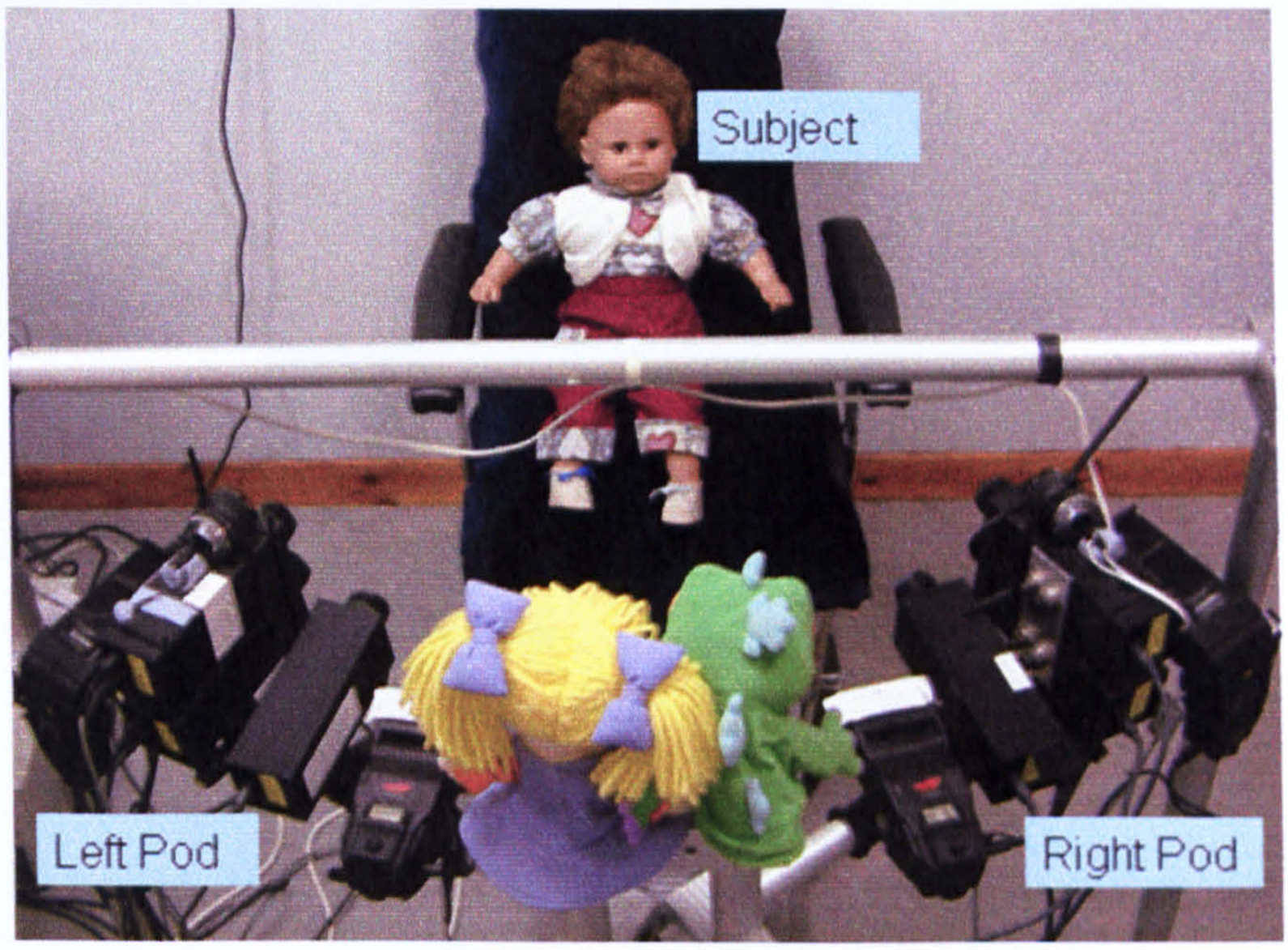
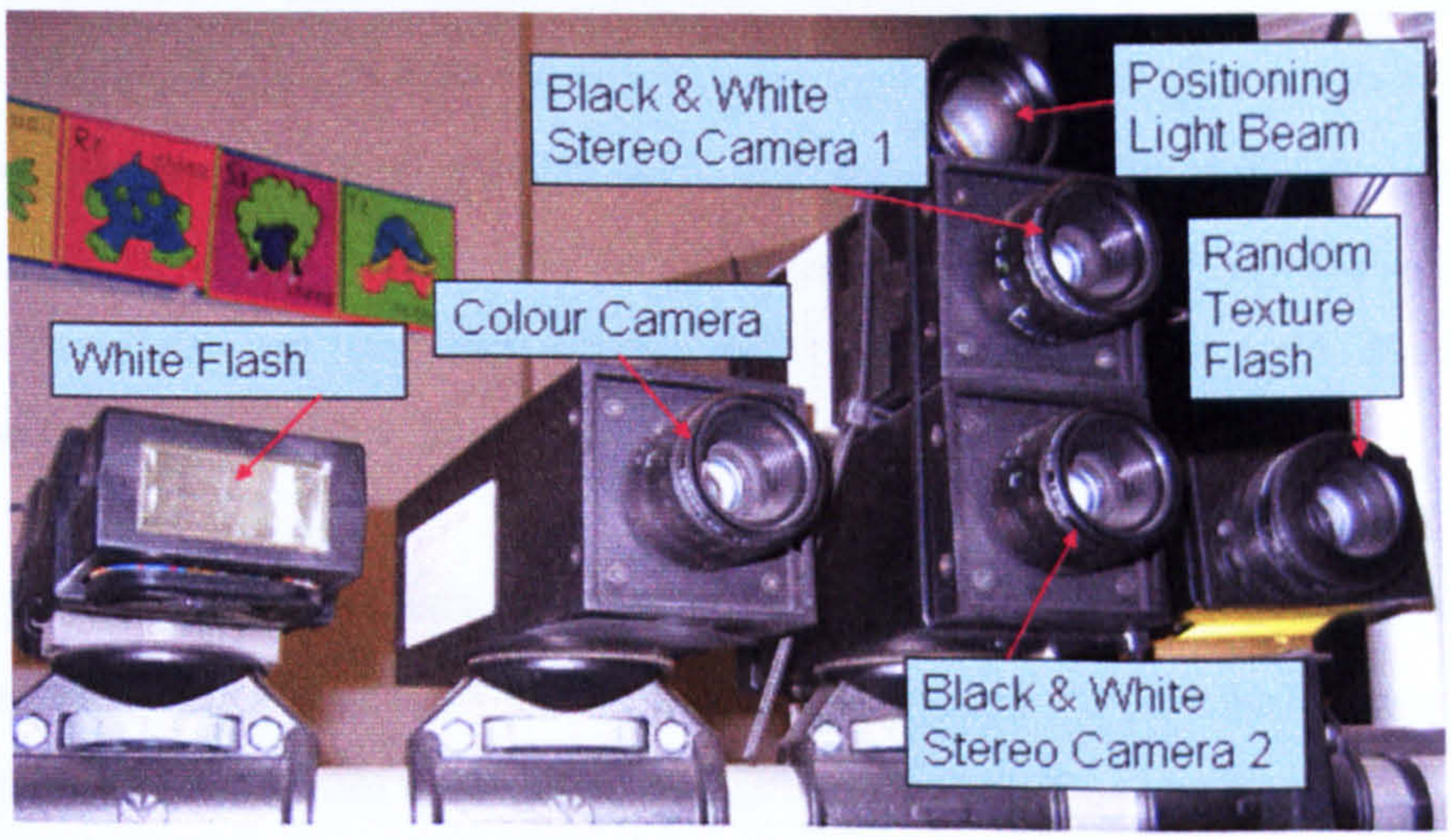


Figure 2.5 Left Pod



During image capture, a random texture pattern was projected onto the face and two black and white images were recorded by each pod. Thirty milliseconds (ms) later a colour image was recorded by each pod. The total image capture time was 50 ms. The three images captured by the right pod are shown in Figure 2.6.

Figure 2.6 Images Captured by the Right Pod

The determination of which point imaged on one camera corresponded to the point imaged on the other camera is called stereomatching. C3D adopts an algorithm based on multi-resolution image correlation based image matching to carry out this process (Zhengping 1988). The random texture pattern was projected onto the face to aid accurate stereomatching since the face is a relatively smooth object. A 3D model was generated using the principles of stereophotogrammetry described above and the calibration information (see section 2.3.1.3).

Two pods were used in this study to allow full coverage of the face from the hairline to the hyoid bone and from left to right ear. A 3D model of each side of the face was therefore created then the models from each pod were merged during the model building process and using the calibration data. This merging process produced some errors that could be seen on the model as a faint line running through the right eye and cheek. This is illustrated in

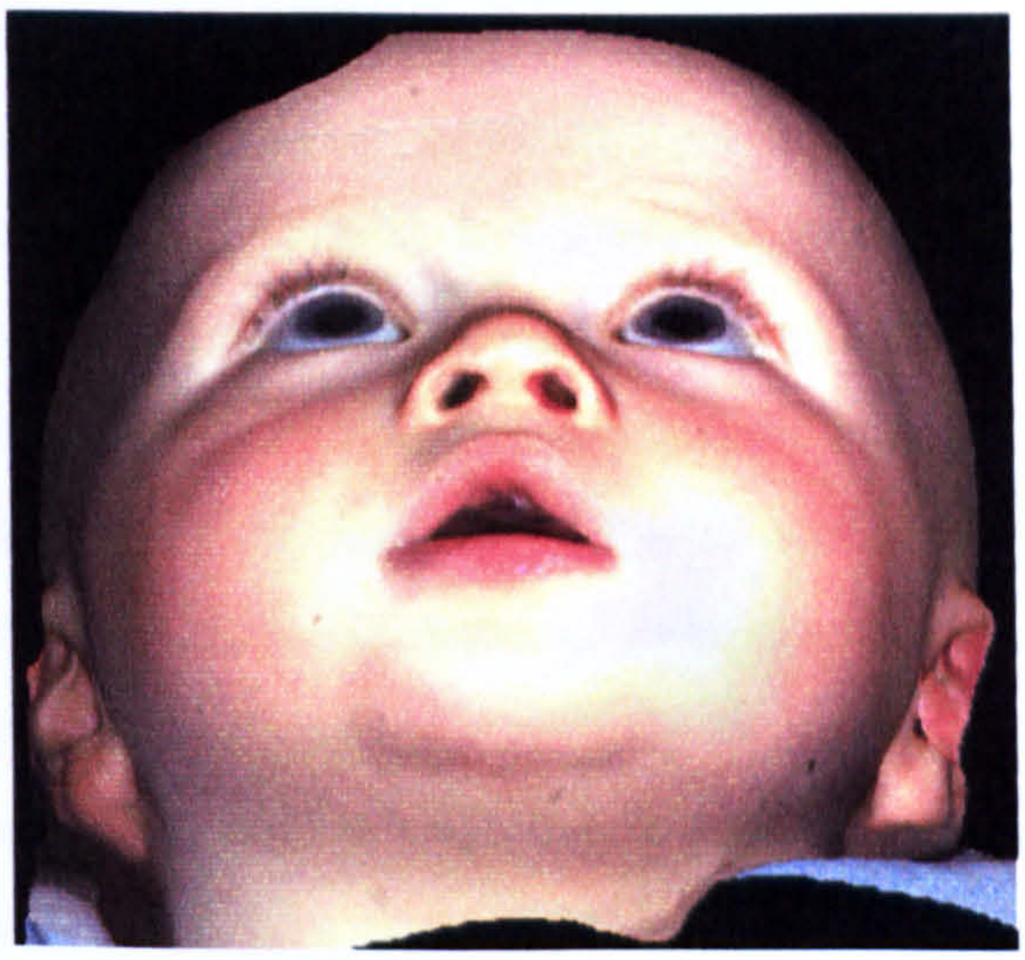
Figure 2.7a. Finally the colour image was overlaid to produce a photorealistic 3D model of the face. The models could be viewed from any direction and as a solid surface or as a triangular mesh. A selection of 3D models of a child at 1 year is shown in Figure 2.7 and a summary of the process of capturing and building 3D models in C3D is shown in Figure 2.12.

Figure 2.7 3D Facial Models of an Infant at 1 Year

a) Range Data

b) Colour Model

c) Triangular Mesh



d) Colour Model Tilted to 45°

2.3.1.3 C3D Calibration

A calibration was always carried out within an hour of the subject's appointment. This calibration was based on photogrammetric techniques and allowed the detailed geometric configuration of all the cameras to be determined. A calibration target comprising discs on a contrasting background and of accurately known dimensions was captured by the cameras in at least 3 different positions. This is shown in Figure 2.8.

Figure 2.8 Calibration

Once these images were recorded C3D was asked to calibrate the system. During the calibration process, which took around 5 minutes, images of the target from all the cameras were processed to find the central location of the discs and these coordinates were used to fit an approximate geometric model of each camera and its respective relative orientation to the target. This approximate model was then used to bootstrap a much more accurate model of the cameras which allowed computation of both intrinsic and extrinsic camera parameters. Since the full geometry of the camera system was deduced by calibration the disparities computed through stereomatching were used to project a notional ray from each corresponding pair of pixels in the stereo pairs and their intersection in 3D space was computed. This process results in the computation of a point cloud in 3D space (Siebert & Marshall 2000).

Merging of data from two pods was also achieved through calibration since the relative orientation of each pod to the calibration target was determined. This process enabled the point cloud captured from each pod to be transferred into the same coordinate frame.

2.3.2 Data Capture

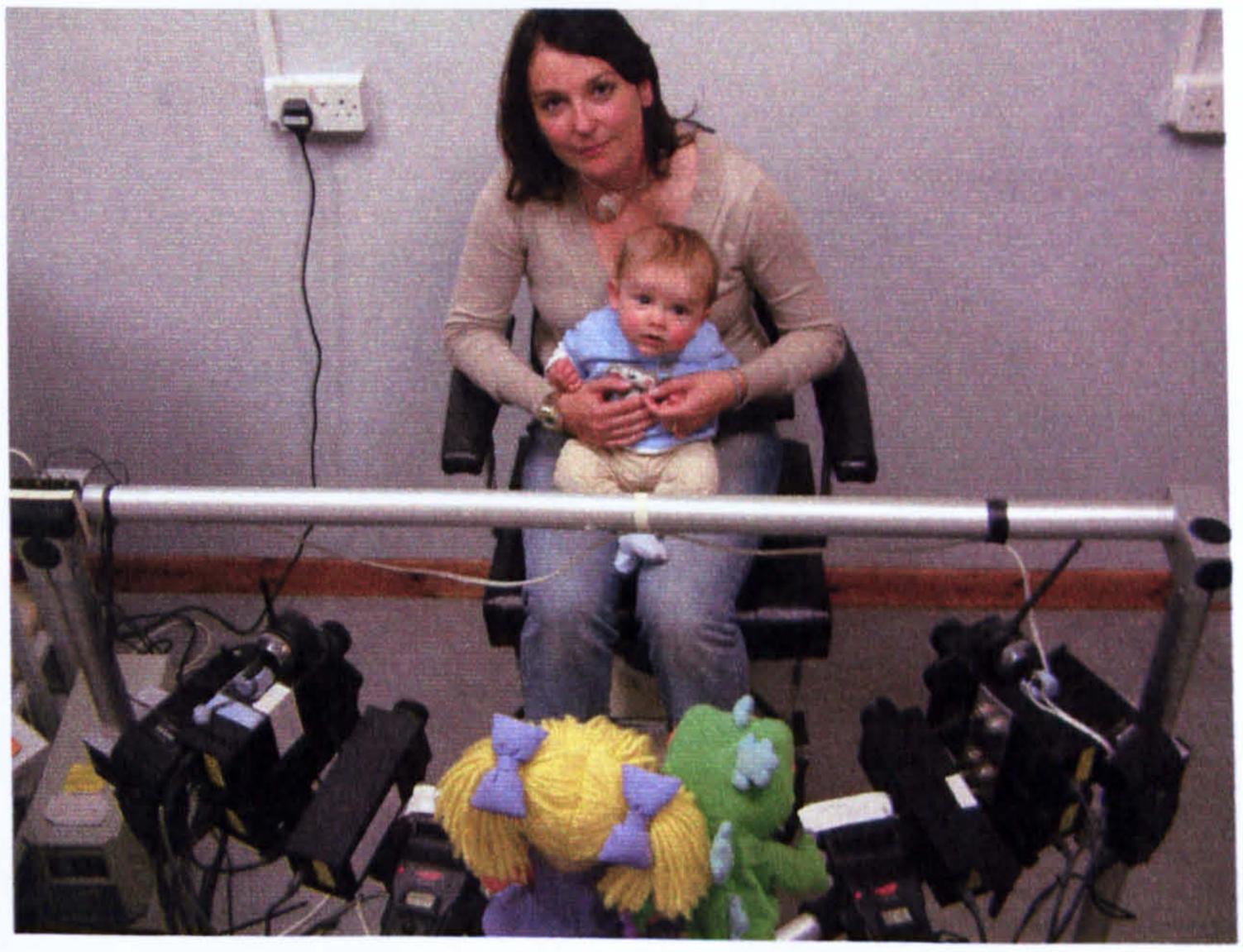
2.3.2.1 Initial Calibration

At least 3 images of the calibration plate were recorded in different positions prior to each subject's appointment. C3D then calibrated the system and reported a calibration error which was always below 0.1 mm. Occasionally, if two subjects attended within an hour of each other, the same calibration was used otherwise a new calibration was used for each attendance. The calibration was always checked at the end of the session, see 2.3.2.5.

2.3.2.2 Position

During image capture the child was seated on a parent's knee looking slightly upward. This is shown in Figure 2.9. Correct positioning of the child's face relative to the cameras was achieved by moving the chair up or down and occasionally by using a cushion to move the child forwards. Two beams of light were set up to converge and focus on a point on the infant's forehead and were used to confirm the child was in the correct position. A flashing light or toy was used to gain their attention immediately prior to capturing the image. A series of 6 to 10 sets of images was recorded for each child per visit. Each session lasted 15 to 30 minutes depending on the cooperation of the child. Most useful images were collected in the first 10 minutes of this time.

Figure 2.9 Position of Infant and Parent during Image Capture



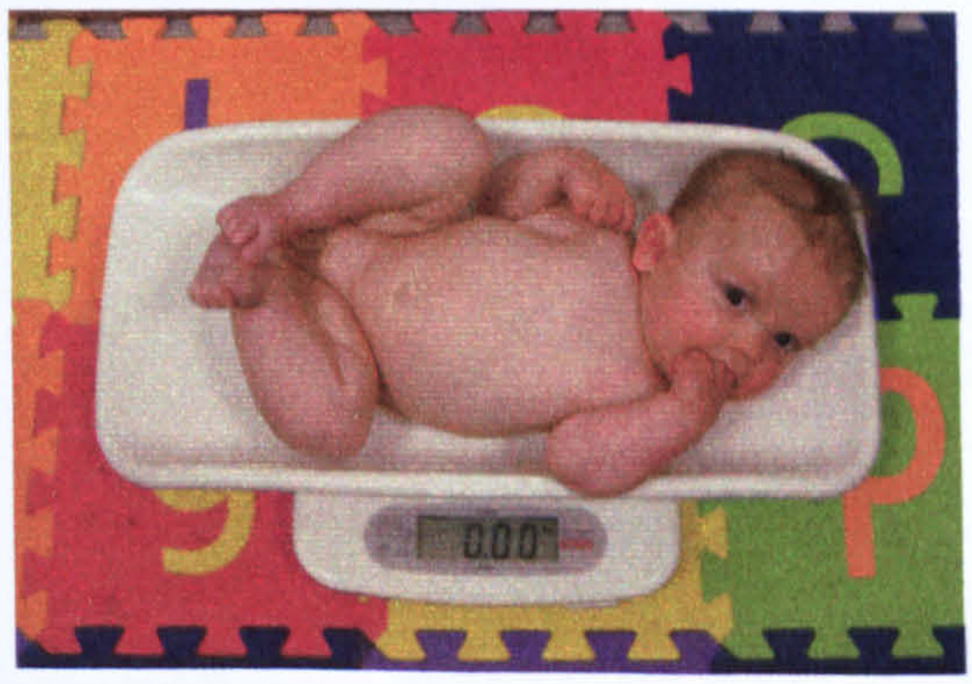
2.3.2.3 Expression

Initially it was expected that image capture would be carried out with the infants at rest in a lips together pose. Most of the infants in this study appeared to be at rest with a lips apart posture and it was usually impossible to capture them with their lips together. It was decided to take several images of each child and to investigate whether the lips apart, as well as the lips together pose, was reproducible in this group of infants (see section 3.3).

2.3.2.4 Body Measurements

At the end of each appointment the child's weight, length and head circumference were measured. The weight of the infants was recorded without clothing with digital scales (Seca Model 835). Length was measured with the Kiddimetre (Raven Equipment Limited), with the parent assisting in holding the infants head. Head circumference was recorded using the Lassoo head circumference tape (Child Growth Foundation).The operator was instructed in the correct use of these techniques by a clinical auxologist prior to the start of the study. Weight was recorded in kilograms (kg) to the second decimal place. Length and head circumference were measured in centimetres (cm) to the nearest 0.5 cm. This is illustrated in Figure 2.10.

Figure 2.10 Recording Body Measurements



2.3.2.5 Post Capture Calibration

After each capture session a further series of images of the calibration plate was collected and compared to the initial calibration using the check calibration facility within C3D. This confirmed there had been no movement of the system during the capture session.

2.3.3 Data Processing

2.3.3.1 3D Model Building

Following each capture session the calibration file was attached and all images that had been successfully captured were built to low resolution. The resulting low resolution models were examined and one or more models with smooth model surface and a relaxed facial expression were built to high resolution for each infant. This is shown in Figure 2.11. Most of these models were in a lips apart pose. The high resolution models were edited as much as possible to exclude peripheral data such as clothing and hair. A summary of the process of building and editing the 3D models is shown in Figure 2.12.

Figure 2.11 Images Viewed in C3D Software

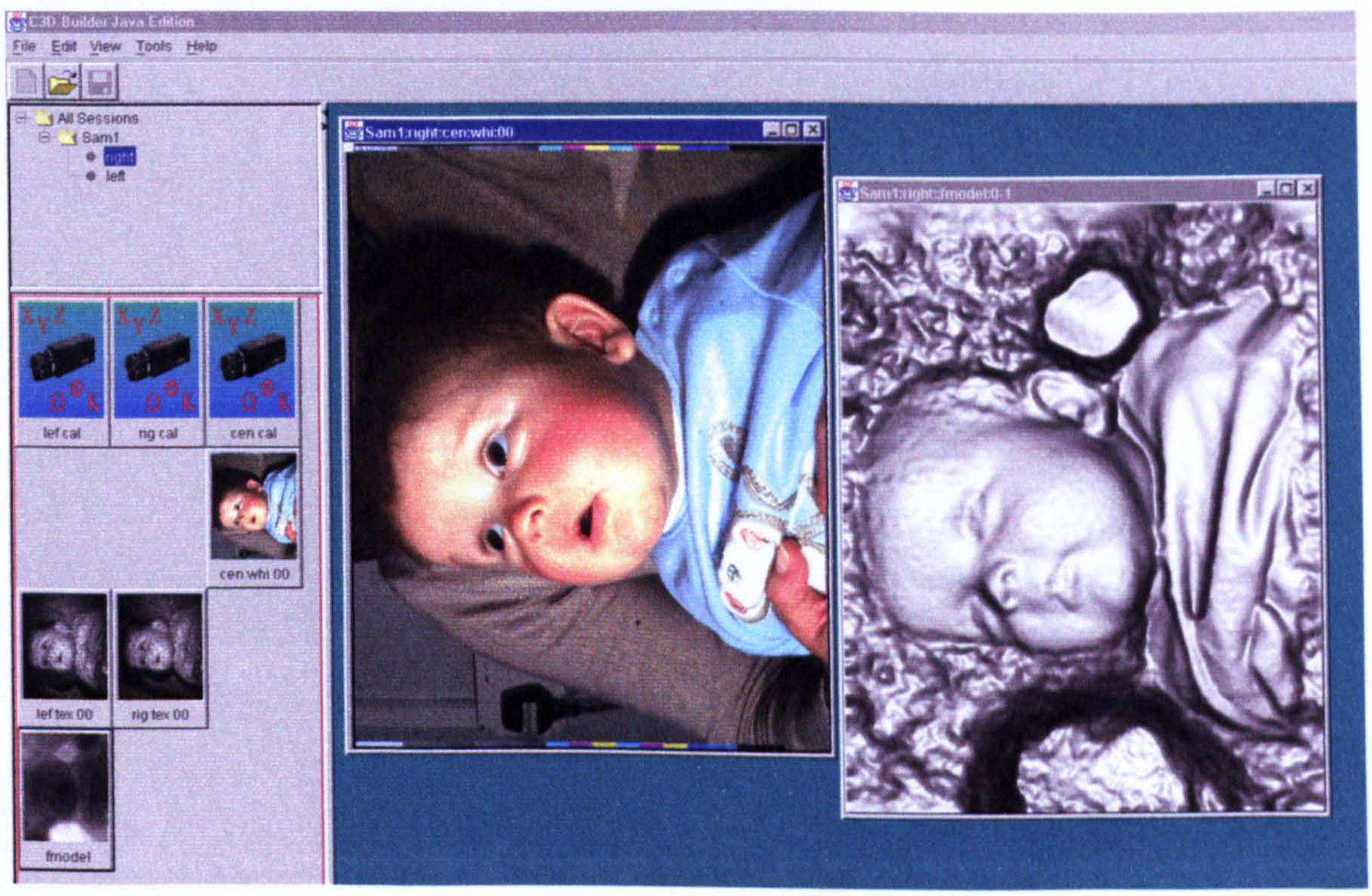
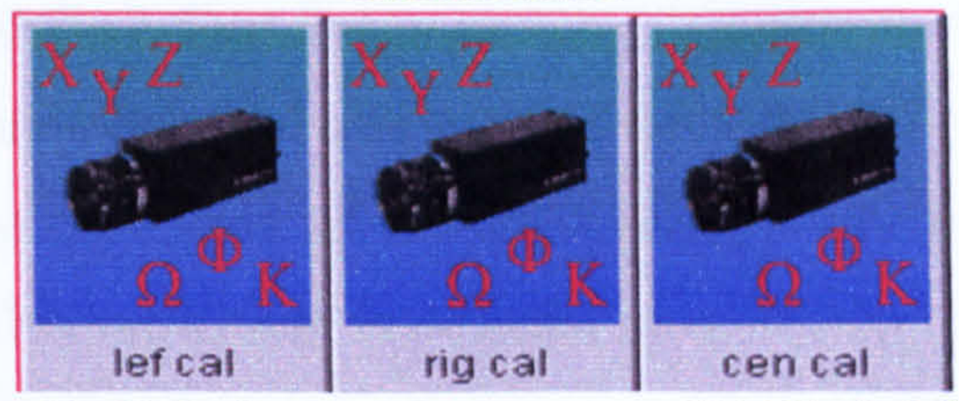


Figure 2.12 Summary of C3D Model Building

Black & White Images from Left Pod

Black & White Images from Right Pod

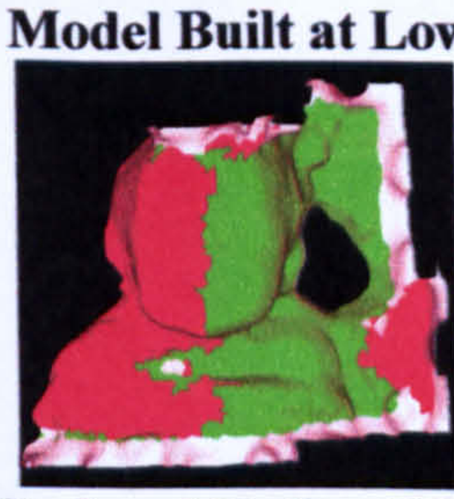
Calibration



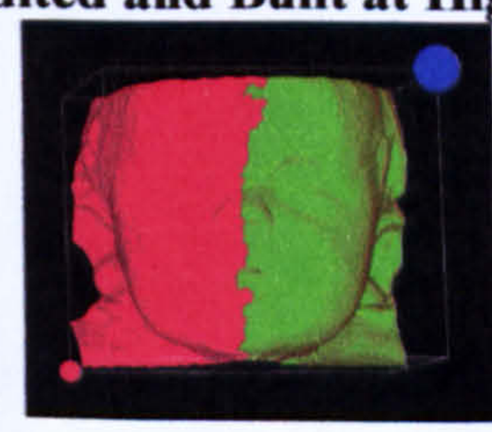
3D Model from Left Pod

3D Model from Right Pod

Merged 3D Model Built at Low Resolution



3D Model Edited and Built at High Resolution



Colour Image from Left Pod

Colour Image from Right Pod

Photorealistic 3D Model of the Face

2.3.3.2 3D Model Selection

One 3D model of each child, subjectively assessed as being at rest, with the lips apart, was selected for analysis.

During image selection and processing the images were also viewed in software (Check Align®) which allowed a visual check that the child had not moved between the black and white image capture and the colour image capture recorded 30 ms later. If the child was judged to have moved, another model was selected for analysis. This is illustrated in Figure 2.13 which shows some movement of the child between the black & white image and colour image capture. This movement is detected by a blurring of the outline of the face when gradually superimposing the colour image on the black and white image.

Figure 2.13 Check Align

At the start of the study there was a 100 ms interval between the black and white image capture and the colour image capture. It was found that the infants could move significantly during this interval and 6 of the initial capture sessions at the 3 month stage provided no useful data because the colour image could not be accurately overlaid on the 3D model. The system was subsequently altered so that there was only 30 ms between image capture and no other captures were unsuccessful due to this problem. This shorter interval between black and white image capture and the colour image capture did mean that the random textured pattern was often visible on the 3D colour models. This is shown in Figure 2.14.

Figure 2.14 Random Textured Pattern

a) Texture Pattern on 3 Month Model **b) No Texture Pattern on 1 Year Model**

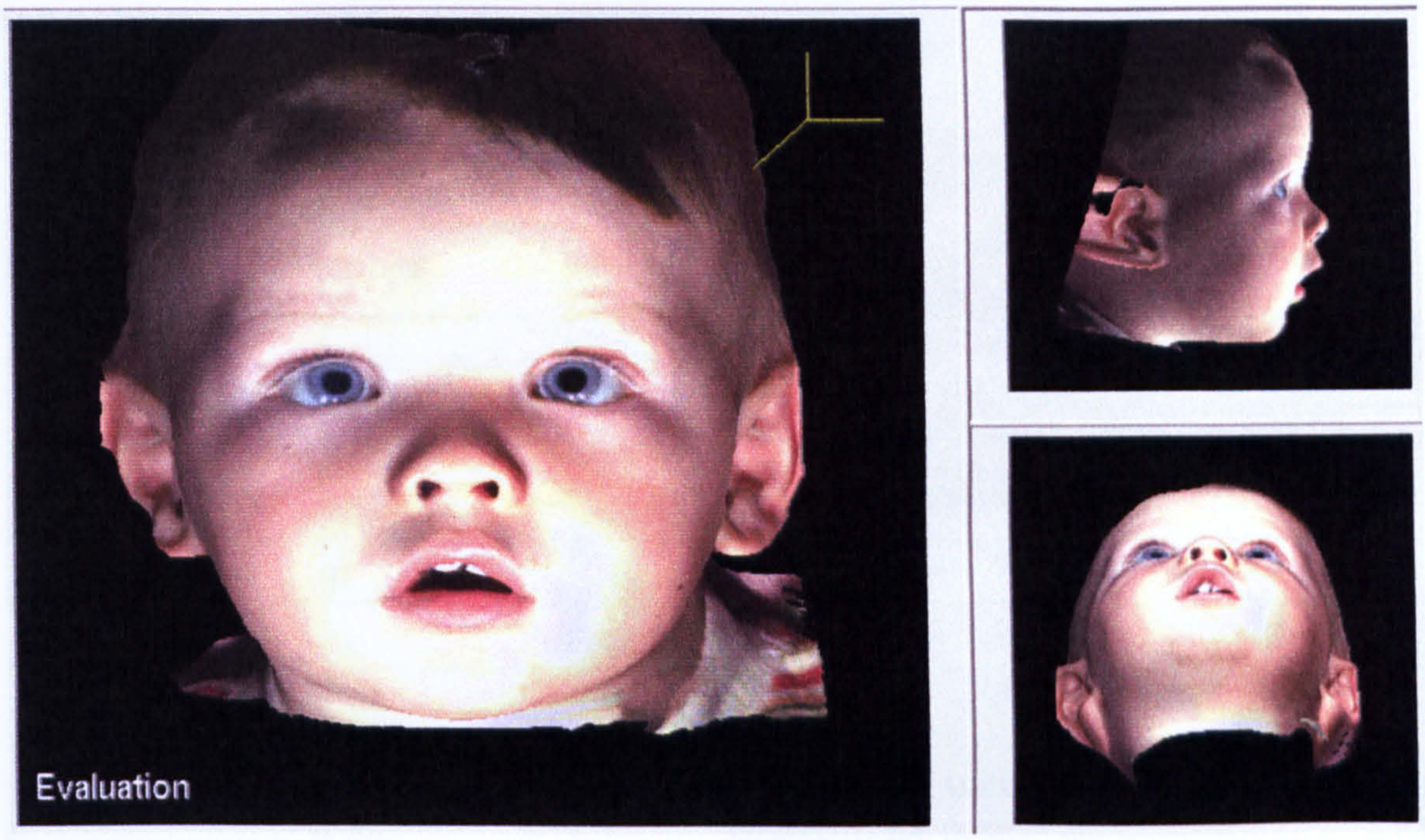
This minor problem was corrected midway through the study by increasing the intensity of the white flash when recording the colour images. The colour images captured at the one and two year stages therefore appear clearer although the underlying models and therefore the measurement data are equally good at the earlier ages.

2.3.3.3 Facial Analysis Tool

Following selection, building and editing of the 3D models the data was exported from C3D to Virtual Reality Modelling Language (VRML) format. This allowed the models to be viewed in custom designed software, the Facial Analysis Tool. This software enabled the model to be rotated, magnified and viewed with and without the colour image overlay. Anatomic landmarks were located and marked by an operator and the coordinates were stored. Landmark names, the order of marking and the measurements were specified by the operator. Measurements of interlandmark distances and angles were carried out

automatically. This software was designed and modified during the course of the study by the Computing Science Department of Glasgow University in collaboration with the clinical researchers at Glasgow Dental Hospital & School. The image of a 3D model loaded in this programme is shown in Figure 2.15.

Figure 2.15 3D Model Viewed in Facial Analysis Tool



The model was viewed in three windows and therefore in three different positions at one time. This aided greatly in landmark identification since, for example, while locating the tip of the nose the landmark position could be checked to be in the midline from the front and on the point of maximum protrusion from the profile. Modifications to the software, which were carried out during the study, are described in section 3.2.

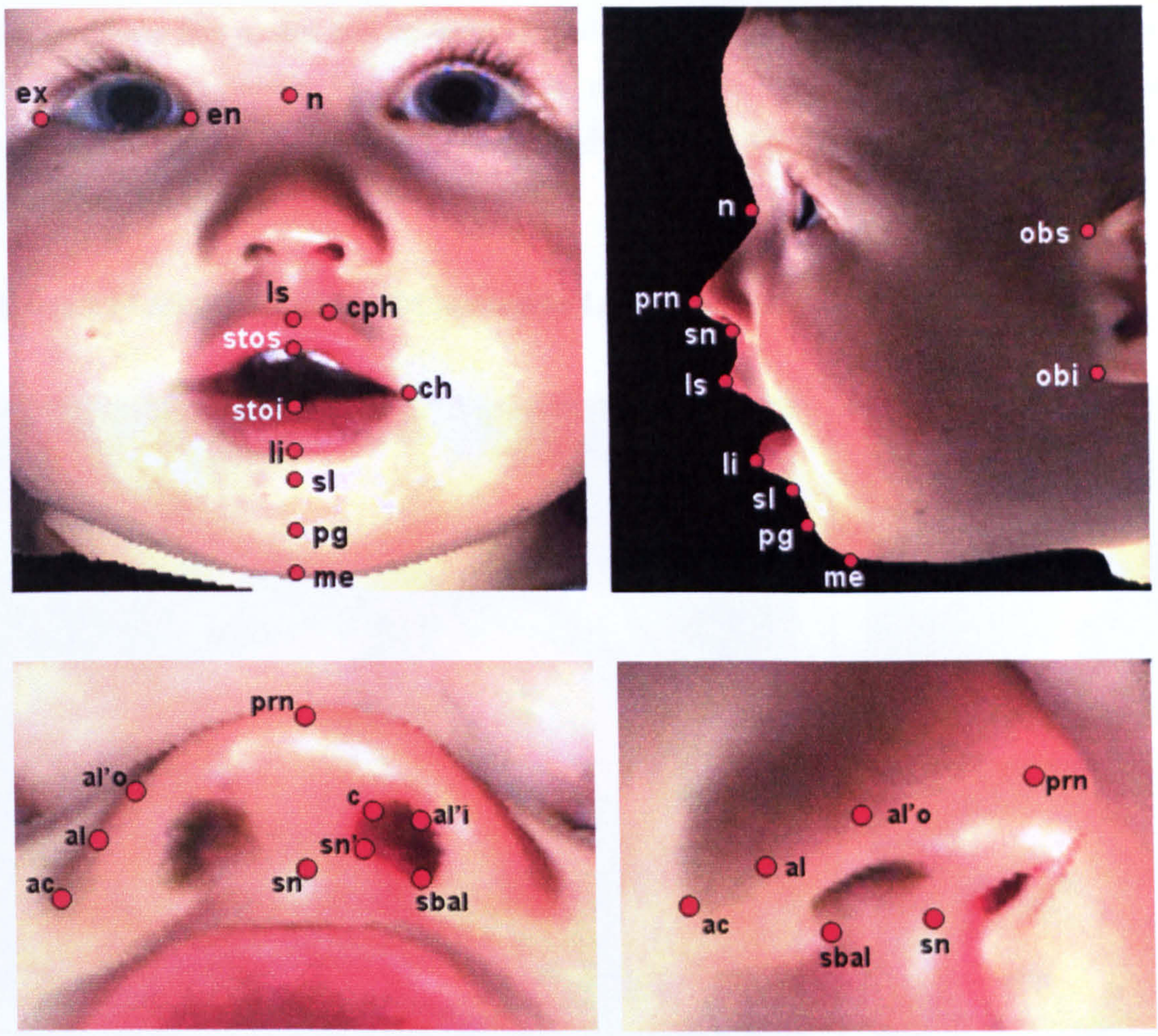
2.3.3.4 Landmark Location

The operator located 36 soft tissue landmarks on each selected model on one occasion. There were 10 midline landmarks and 13 bilateral landmarks. The landmark names and definitions are shown in Table 2.1 and illustrated in Figure 2.16.

Table 2.1 Landmarks Utilised for 3D Facial Model Analysis

Landmark Name	Landmark Abbreviation	Model Position	Definition
Alar Crest	acL, acR	60^0 tilt	The most lateral point in the curved base line of each ala
Alare	alL, alR	60^0 tilt	The most lateral point on each alar contour
Alare' Inner	al'iL, al'iR	60^0 tilt	The point on the inner aspect of each ala at its thinnest part
Alare' Outer	al'oL, al'oR	60^0 tilt	The point on the outer aspect of each ala at its thinnest part
Cheilion	chL, chR	face on	The point located at each labial commissure
Columella	cL, cR	60^0 tilt	The highest point on each columella where the nostril starts to curve laterally
Crista Philtri	cphL, cphR	face on	The point on each elevated margin of the philtrum just above the vermilion border
Endocanthion	enL, enR	face on	The point at the inner commissure of the eye
Exocanthion	exL, exR	face on	The point at the outer commissure of the eye
Labrale Inferius	li	face on	The midpoint of the lower vermilion border
Labrale Superius	ls	face on	The midpoint of the upper vermilion border
Menton	me	60^0 tilt	The lowest median point on the lower border of the mandible
Nasion	n	face on	The deepest point of the concavity of the bridge of the nose in the midline
Otobasion Inferius	obiL, obiR	90^0 right and left	The point of attachment of the helix of the ear in the temporal region
Otobasion Superius	obsL, obsR	90^0 right and left	The point of attachment of the ear lobe to the cheek
Pogonion	pg	face on	The most anterior point in the midline of the chin
Pronasale	prn	60^0 tilt	The most protruded point of the apex of the nose
Subalare	sbalL, sbalR	60^0 tilt	The point at the lower limit of each alar base where it disappears into the skin of the upper lip
Sublabiale	sl	face on	The point of maximum concavity in the midline between the lower lip and chin
Subnasale	sn	60^0 tilt	The midpoint of the angle of the columella base where the lower border of the nasal septum and the upper lip meet
Subnasale'	sn'L, sn'R	60^0 tilt	The point on each side of the columella at its thinnest part
Stomion Inferius	stoi	face on	The point in the midline on the upper border of the lower lip with the lips apart
Stomion Superius	stos	face on	The point in the midline on the lower border of the upper lip with the lips apart

Figure 2.16 Illustrations of Landmarks



These landmark definitions were essentially the same as those used in direct anthropometric studies with some minor changes (Farkas 1994a). These changes were made where the original definition depended on palpation of a bony landmark since this was not possible, or if the definition was unclear. Two new landmarks, stomion inferius and stomion superius, were added to allow measurement of the vermilion thickness with the lips apart.

A subset of 10 landmarks, identified as being less reproducibly located in the error study (see section 3.2), was located for a second time on each model, on a separate occasion. The mean of these duplicate landmark co-ordinates was calculated by the File Merge programme (section 3.2) and used in the analysis. If any landmarks were unclear on the 3D models, such as those under the chin or around the ears, they were recorded as missing.

A model with all the landmarks located in the Facial Analysis Tool is shown in Figure 2.17. An example of a landmark coordinate file is shown in Figure 2.18. The replicates column shows that n, stos and pg were located twice and the mean coordinates are given. The x-coordinate shown is the distance in metres in a horizontal direction from the convergence point of the cameras. The y-coordinate is the vertical displacement and the z-coordinate is the depth displacement.

Figure 2.17 3D Model with All Landmarks Located in Facial Analysis Tool

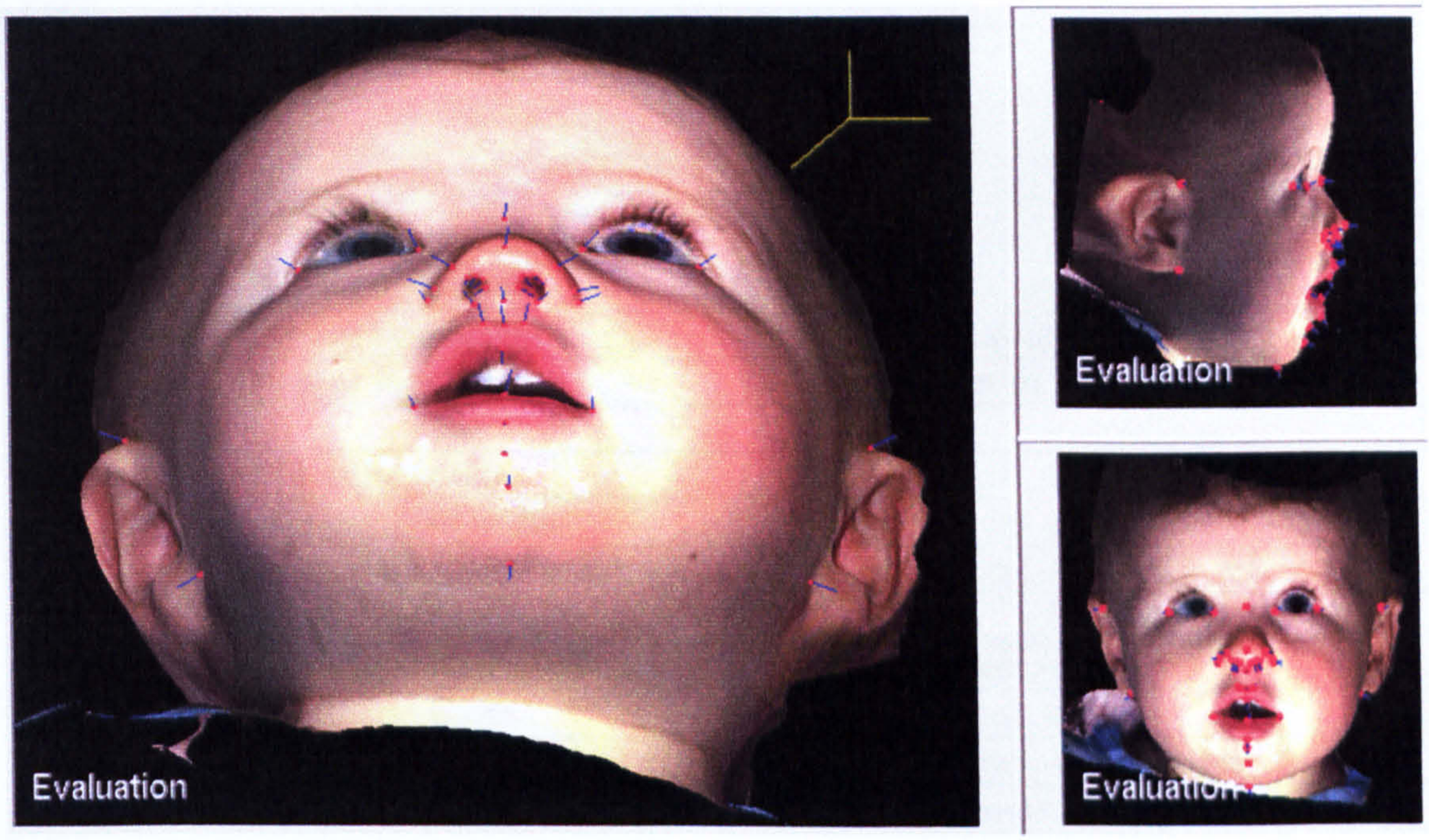


Figure 2.18 Landmark Coordinate File

JW011yo04D3 - Notepad

File Edit Format View Help

Model: JW0011y04v2.wrl
Date: Fri Dec 21 13:42:26 GMT 2001
Marked up by :jill

number	code	x-coordinate	y-coordinate	z-coordinate	replicate
1	exR	-0.0409307	0.0040548	0.0386332	1
2	enR	-0.0190472	0.0072637	0.0416675	1
3	n	-0.0037453	0.0143546	0.0453735	2
4	sto	0.0	0.0	0.0	0
5	stoi	-0.0024408	-0.0337317	0.0646802	1
6	stos	-0.0020998	-0.0221646	0.0657811	2
7	li	-0.0018765	-0.0396189	0.0667317	1
8	sl	-0.0018601	-0.0444492	0.0642179	1
9	pg	-0.6927884	-0.0515214	0.0678983	2

2.3.3.5 Measurements

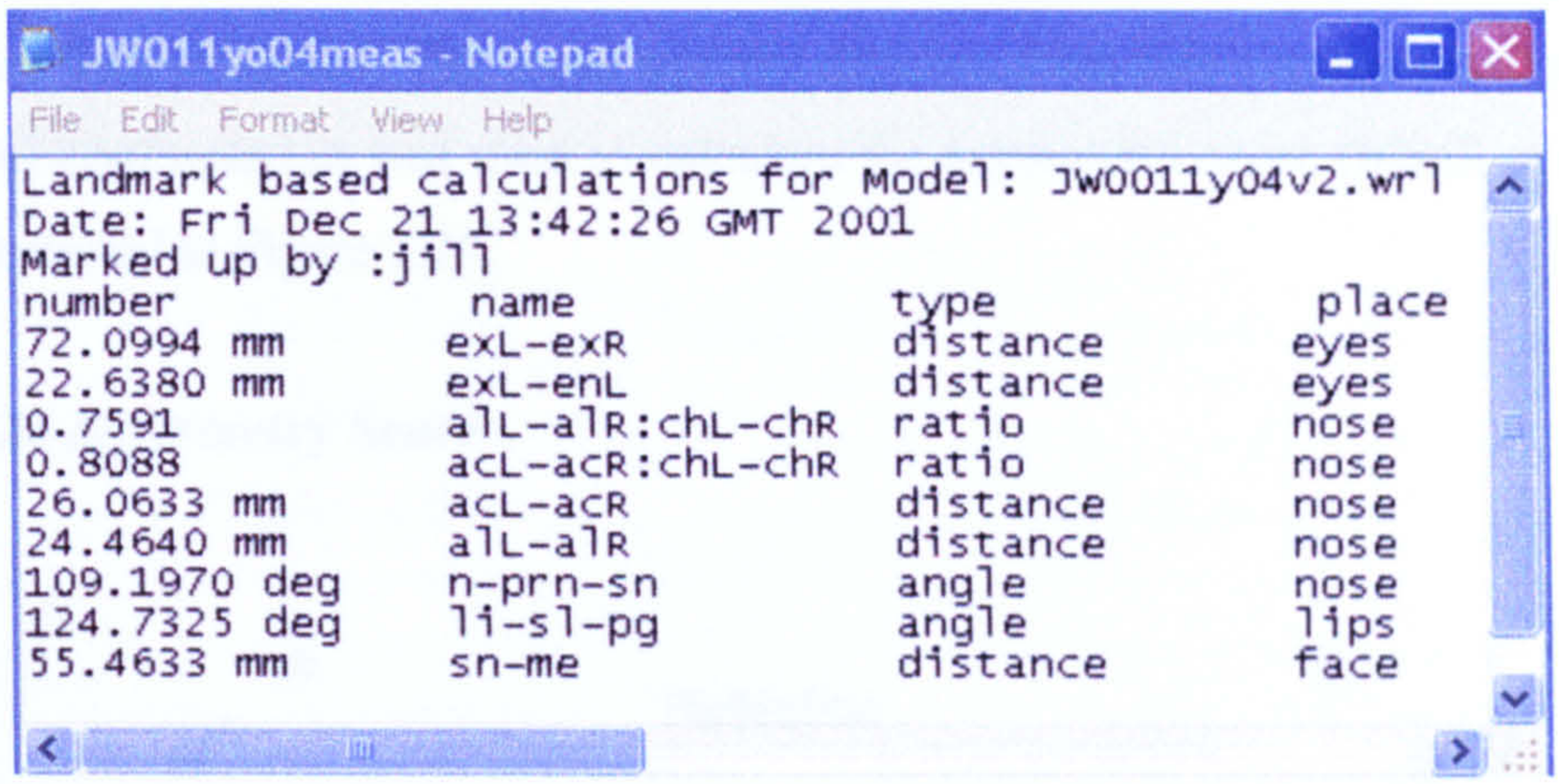
20 individual measurements, 10 bilateral measurements and 4 angles were chosen for the facial analysis. These measurements were chosen to cover the whole face with the minimum of repetition and the maximum clinical significance. The measurements are shown in Table 2.2.

Table 2.2 Measurements

Region	Measurement	Definition
Face		
	upper face depth left & right	obiL-n, obiR-n
	maxillary depth left & right	obiL-sn, obiR-sn
	mandibular depth left & right	obiL-pg, obiR-pg
	upper face width	obsL-obsR
	lower face width	obiL-obiR
	total face height	n-me
	lower face height	sn-me
	upper face height	n-sn
Eyes		
	biocular width	exL-exR
	intercanthal width	enL-enR
	palpebral fissure width left & right	exL-enL, exR-enR
Nose		
	anatomic nose width	acL-acR
	soft nose width	alL-alR
	alar length left & right	acL-prn, acR-prn
	nasal dorsum length	n-prn
	nasal tip protrusion	sn-prn
Nostrils		
	nostril long axis left & right	sbalL-cL, sbalR-cR
	nostril width left & right	sn'L-al'iL, sn'R-al'iR
	columella width	sn'L-sn'R
Upper Lip		
	mouth width	chL-chR
	upper vermilion length left & right	chL-cphL, chR-cphR
	philtrum width	cphL-cphR
	upper cutaneous lip height	ls-sn
	upper vermilion lip height	ls-stos
	upper lip height	sn-stos
Lower Lip		
	lower vermilion length left & right	chL-li, chR-li
	lower cutaneous lip height	sl-li
	lower vermilion lip height	li-stoi
	lower lip height	sl-stoi
Angles		
	nasal tip angle	n-prn-sn
	nasolabial angle	prn-sn-ls
	nasal tip horizontal displacement angle	acL-prn-acR
	labiomental angle	li-sl-pg

Linear and angular measurements between the landmarks were derived following landmark identification and using the Measurement Programme to generate measurement files (see section 3.2). An example of a measurement file is shown in Figure 2.19.

Figure 2.19 Measurement File



JW011yo04meas - Notepad

File Edit Format View Help

```
Landmark based calculations for Model: JW0011y04v2.wrl
Date: Fri Dec 21 13:42:26 GMT 2001
Marked up by :jill
number          name              type          place
72.0994 mm      exL-exR           distance      eyes
22.6380 mm      exL-enL           distance      eyes
0.7591          alL-alR:chL-chR   ratio         nose
0.8088          acL-acR:chL-chR   ratio         nose
26.0633 mm      acL-acR           distance      nose
24.4640 mm      alL-alR           distance      nose
109.1970 deg    n-prn-sn          angle         nose
124.7325 deg    li-sl-pg          angle         lips
55.4633 mm      sn-me             distance      face
```

2.4 Data Analysis

2.4.1 Cross Sectional Analysis

2.4.1.1 Linear and Angular Analysis

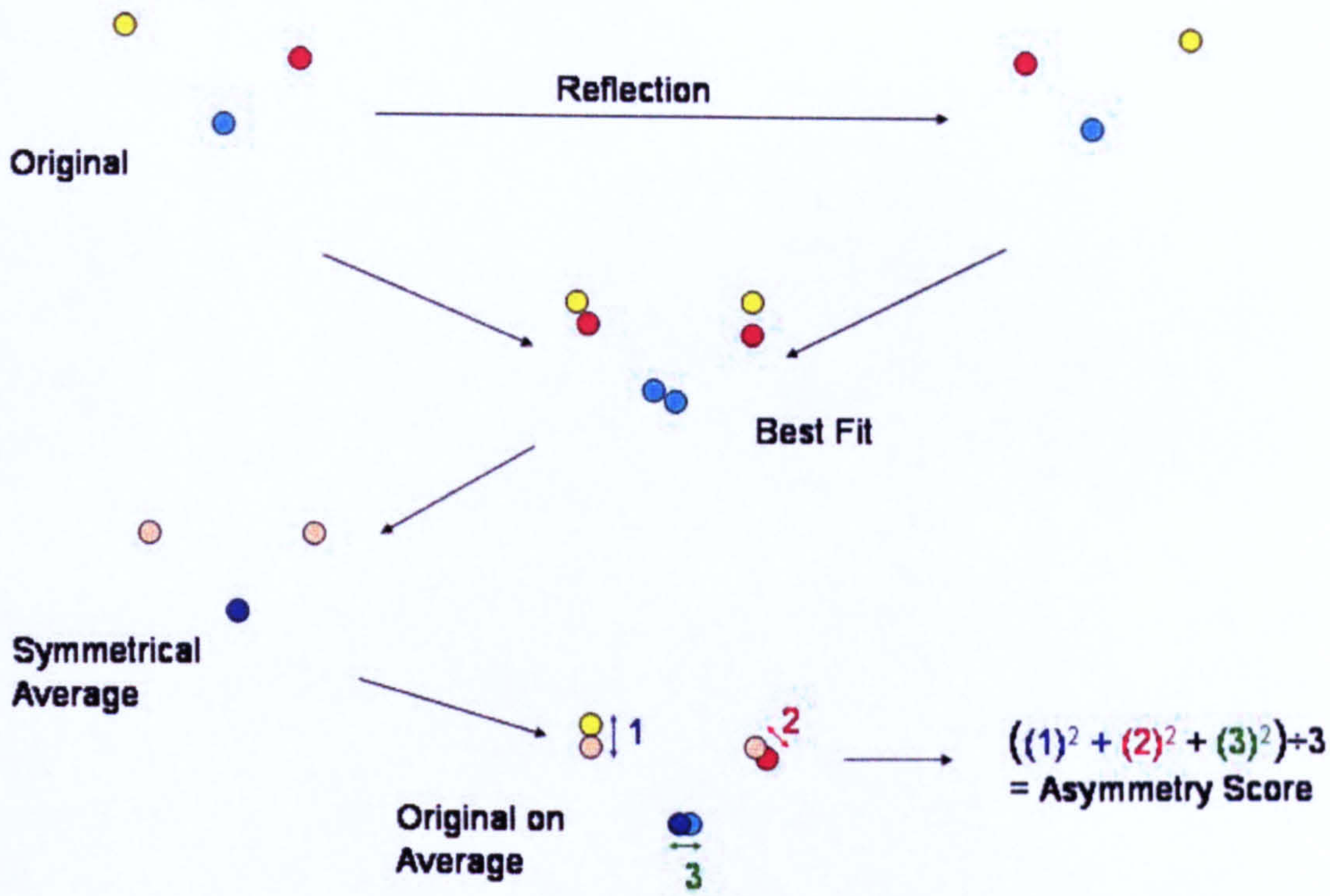
The measurements of all the subjects at each age were copied from the text file into an Excel file and the data was rearranged to allow simple analysis. The data was later copied into Minitab 12 for statistical analysis. The data was checked for normal distribution using box plots. Means and standard deviations were calculated. Two sample t tests were applied to determine any significant differences between males and females for each measurement. Paired t tests were used to determine any significant differences in bilateral measurements, such as right and left palpebral fissure widths. Pearson's correlation coefficients were calculated to determine any correlation between facial and body measurements.

2.4.1.2 Asymmetry

An asymmetry score which quantifies the level of asymmetry in an individual configuration of landmarks in 3D has been developed (Mardia et al. 2000).

In this method the landmark configurations were first scaled to a common size, each configuration was then reflected in an arbitrary plane and points forming pairs were relabelled. The original and reflected, relabelled configuration were then aligned via Ordinary Partial Procrustes Analysis (Dryden & Mardia 1998). This is a mathematical method of translation, rotation and superimposition of homologous sets of landmarks to obtain the best fit. The average configuration of the original and its corresponding reflected version was then produced. The mean squared distance from this average configuration to the original configuration was used to calculate the asymmetry score (Maull et al. 1999). This is illustrated in Figure 2.20.

Figure 2.20 Asymmetry Score



A perfectly symmetrical configuration of landmarks would therefore have an asymmetry score of zero. The scaling in the first stage of this process means that the asymmetry score is independent of size.

The asymmetry score may be calculated using any number of landmarks. In this study the asymmetry score was calculated using 4 midline and 10 bilateral landmarks in the midface. These are shown in Table 2.3. The ear landmarks were excluded from the asymmetry analysis since they were frequently missing on the 3D models. Lower lip and chin landmarks were excluded due to inconsistent lip positions (see section 6.2.3).

The asymmetry score was also split to give separate scores for different regions of the face. These regions were the upper face, nasal rim, nostrils and upper lip. The landmarks included in each region are shown in Table 2.3. The regional scores were calculated after alignment of the reflected relabelled configurations on all 24 midface landmarks. The overall asymmetry score was therefore a weighted average of the regional scores (Bock & Bowman 2005).

Table 2.3 Landmarks used in the Asymmetry Score

Face	Upper Face	Nasal Rim	Nostrils	Upper Lip
enL, enR	enL, enR			
n	n			
acL, acR		acL, acR		
alL, alR		alL, alR		
al'oL, al'oL		al'oL, al'oL		
prn		prn		
cL, cR			cL, cR	
sn'L, sn'R			sn'L, sn'R	
sbalL, sbalR			sbalL, sbalR	
al'iL, al'iR			al'iL, al'iR	
sn			sn	
chL, chR				chL, chR
cphL, cphR				cphL, cphR
ls				ls

The asymmetry scores, which were not normally distributed, were transformed using a fourth root transformation to achieve approximate normality and allow application of parametric tests. Means and standard deviations of these fourth root asymmetry scores (sqrt/sqrt AS) were calculated at each age and for each region of the face. Gender differences in the asymmetry scores were investigated using t tests. Differences in asymmetry scores of the different regions of the face were investigated using paired t tests. Correlation coefficients were calculated for the facial asymmetry score with the regional asymmetry scores and for the regional scores with each other.

2.4.2 Longitudinal Analysis

2.4.2.1 Longitudinal Changes in Distances and Angles

The changes in linear and angular measurements from 3 to 6 months, 6 months to 1 year and 1 to 2 years of age were calculated. This data was checked for normal distribution using box plots. The mean differences and standard deviations of the differences were calculated. Paired t tests were applied to assess whether there had been significant growth or change in these linear and angular measurements between these ages. Two sample t tests were used to determine whether there was any significant difference in growth between the males and females. Correlation coefficients were used to determine any correlation between growth of the face and body measurements and also between growth of the individual facial parameters.

2.4.2.2 Longitudinal Changes in Asymmetry

The changes in sqrt/sqrt asymmetry scores from 3 to 6 months, 6 months to 1 year, 1 to 2 years, 3 months to 1 year, 3 months to 2 years and 6 months to 2 years were calculated. Paired t tests were used to assess whether there had been any significant change in asymmetry scores between these ages. Two sample t tests were used to determine whether there was any significant difference in the change in asymmetry between the males and females. Correlation coefficients were calculated to investigate any correlation between changes in the different asymmetry scores.

3 Validation of the Method

3.1 Validation of C3D system

3.1.1 Introduction

C3D has previously been reported to be highly accurate but no previous studies have been undertaken to quantify the accuracy of the systems used to capture faces (Urquhart 1997).

This stage of the validation process was designed and carried out in conjunction with two other researchers who were using the same systems to capture infants with cleft lip and palate. One of these other researchers captured all of the images and then all three researchers were equally involved in the data processing, landmark location and data analysis. The results of this validation process have been reported elsewhere (Ayoub et al. 2003).

Four errors were analysed, operator error in locating the landmarks, capture error of repeated images, registration error of models captured in different positions, and C3D system error compared to a gold standard.

3.1.2 Validation Method

Twenty one stone casts of the faces of infants with cleft lip and/or palate were obtained by taking alginate impressions of the infants faces. These impressions were collected by a surgical colleague at the time of lip repair under a general anaesthetic. The casts showed good soft tissue detail around the lips, nose and closed eyes but did not extend to include the ears. Examples of two of the casts used in this study are shown in Figure 3.1.

Five points had been marked on each model with a black pen. The five landmarks were around the right and left corners of the mouth (chR, chL), around the right and left nostril (alR, alL) and the tip of the nose (prn). These points had been digitised twice using a Ferranti coordinate measuring machine (CMM) at the School of Manufacturing and Mechanical Engineering, University of Birmingham, UK. This machine works by using a probe to contact the five landmarks and digitise their 3D coordinates. The sum of the volumetric error of the coordinate measuring machine and maximum probe error was

reported to be 9.53 μm (Spencer et al. 1996). This can therefore be regarded as a gold standard for comparison with other techniques used to measure the face.

Figure 3.1 Examples of Stone Casts used in Validation Study

The same 21 casts were captured using the C3D system previously described. Examples of these casts captured using the C3D system are shown in Figure 3.1. Each cast was captured in four different positions. In the first position the cast was 50 cm from the cameras and facing forwards (centre). In the second position the cast was rotated 20° to the right (20°R) and in the third position the cast was rotated 20° to the left (20°L). Finally the cast was captured 10 cm closer to the cameras facing forwards (front).

One model of each cast in each position was built, edited and exported to VRML format. The models were viewed in the Facial Analysis Tool and three operators each located the five landmarks on each model in each position and the coordinates were recorded.

To assess operator error each operator located the landmarks on 6 randomly selected models on a second occasion. The differences between repeatedly placed landmarks were measured and the mean values for the six models were calculated for each combination of landmarks and for each operator separately.

In order to assess the capture error, a duplicate capture of each cast in each position was taken. These duplicate captures were carried out immediately after the initial capture without moving the cast. Duplicate models of six randomly selected captures were built, edited and exported and the landmarks located by each operator. The differences between the landmarks on the duplicate models were measured and the mean values for the six models were calculated for each combination of landmark and operator separately.

The registration error, the effect of the position of the cast relative to the cameras, was quantified by first aligning the landmarks of the same cast captured in different positions using Ordinary Partial Procrustes Analysis. This is a method to translate and rotate two or more configurations of landmarks to achieve a best fit. The distance between each corresponding landmark after superimposition represented the discrepancy. A series of pairwise comparisons were made of the landmark coordinates at different positions generating 6 comparisons for each of the 21 casts for each of the three operators.

Finally the C3D system error was quantified by using Ordinary Partial Procrustes Analysis to superimpose the landmarks captured with C3D with those collected by the CMM. The distance between each corresponding landmark after superimposition represented the magnitude of the discrepancy.

3.1.3 Validation Results

3.1.3.1 Operator Error

The results for the operator error are shown in Table 3.1.

Table 3.1 Operator Error Measured as the Mean Displacement in mm of Repeatedly Placed Landmarks

Landmark	Operator1	Operator 2	Operator 3	All
chL	0.16	0.18	0.24	0.19
chR	0.12	0.14	0.28	0.18
alL	0.14	0.08	0.26	0.16
alR	0.29	0.15	0.57	0.32
prn	0.21	0.04	0.30	0.20
Mean	0.18	0.12	0.30	0.20

The mean operator error was 0.20 mm. The minimum operator error was 0.08 mm and the maximum 0.57 mm. The landmark with the greatest error was alare right (alR), on the side of the nose. Operator 3 had greater errors than operators 1 and 2.

3.1.3.2 Capture Error

The results for the capture error are shown in Table 3.2.

Table 3.2 Capture Error Measured as the Mean Displacement, in mm, of Landmarks on Duplicate Models

Landmark	Operator1	Operator 2	Operator 3	All
chL	0.36	0.27	0.43	0.35
chR	0.35	0.36	0.56	0.43
alL	0.33	0.50	0.68	0.52
alR	0.93	0.10	1.50	0.91
prn	0.39	0.29	0.34	0.34
Mean	0.44	0.32	0.68	0.48

The mean discrepancy was 0.48 mm. The minimum discrepancy was 0.1 mm and the maximum 1.5 mm. The landmark alR had the greatest discrepancy. Operator 2 had a lower mean discrepancy than operators 1 and 3.

3.1.3.3 Registration Error

Table 3.3 summarises the results of the registration error.

Table 3.3 Registration Error Measured as the Mean Discrepancy between Different Positions, in mm.

Landmark	Centre v Front	Centre v 20°R	Centre v 20°L	Front v 20°R	Front v 20°L	20°R v 20°L	Mean
chL	0.46	0.38	0.32	0.33	0.37	0.31	0.36
chR	0.46	0.34	0.42	0.31	0.58	0.35	0.41
alL	0.45	0.37	0.36	0.37	0.43	0.52	0.42
alR	0.37	0.44	0.38	0.41	0.39	0.44	0.40
prn	0.51	0.45	0.58	0.42	0.54	0.49	0.50
Mean	0.46	0.39	0.42	0.37	0.47	0.42	0.42

The mean within landmark discrepancy was 0.42 mm, with the least discrepancy being 0.31 mm and the greatest 0.58 mm. The discrepancies in each of the pairwise comparisons were very similar. The point prn, on the tip of the nose, had a slightly higher discrepancy than the other landmarks.

3.1.3.4 C3D System Error

The results of comparing the C3D system with the coordinate measuring machine (CMM) are shown in Table 3.4.

Table 3.4 C3D System Error Measured as the Discrepancy between Landmarks, in mm, after Superimposing the C3D and CMM Coordinates

Landmark	20°L	20°R	Centre	Front	Mean
chL	0.63	0.54	0.63	0.64	0.61
chR	0.59	0.45	0.55	0.41	0.50
alL	0.87	0.75	0.77	0.86	0.81
alR	1.52	0.79	1.25	0.99	1.18
prn	1.46	0.73	1.20	1.11	1.14
Mean	1.02	0.63	0.86	0.79	0.83

The mean difference between C3D and CMM was 0.83 mm, with a minimum of 0.41 mm and a maximum of 1.52 mm. Rotating the cast 20° to the right or placing the cast in the front position produced the least discrepancy. When each position of the cast was considered, analysis of variance showed that the landmarks chL and chR had significantly smaller discrepancies than those associated with the rest of the landmarks.

3.1.4 Validation Discussion

3.1.4.1 Operator Error

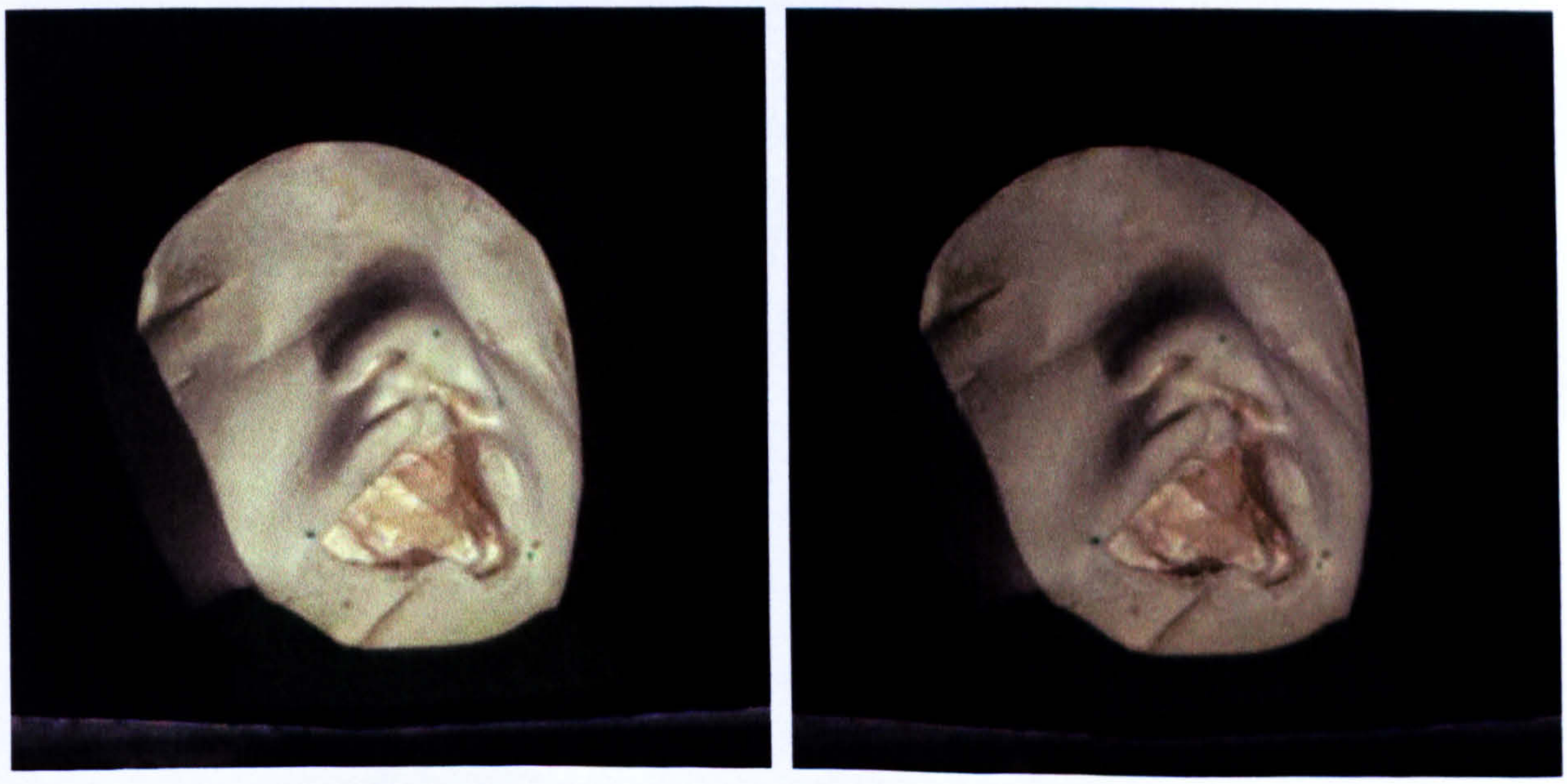
The mean error of each operator repeatedly locating a landmark which was already marked on the cast was low, with a mean value of 0.20 mm. Operator 3 had the greatest mean error for almost all of the landmarks. This difference was most marked for the landmark alare right. It is difficult to explain the operator difference since digitising a mark on a 3D model of a cast would not be strongly influenced by training or experience. The magnification and position of the models were not standardised during this investigation and it was possible that operator 3 tended to view the models and locate the landmarks with less magnification. The higher mean value of 0.32 mm for alare right was probably influenced by slightly poorer lighting on the right side of the face, see Figure 3.2, and by a few outliers. The outliers could have been due to locating the landmark in completely the wrong place. This could have arisen because the five landmarks in this study were simply located in order and numbered. It is possible that without a visible prompt and automatic

labelling of the landmarks that they could have been located in the wrong order or located twice in the same position. Every effort was made to minimise this possibility but it was agreed that a landmark prompt and labelling facility could have reduced this possible source of error. The problem with the lighting arose because the flash intensity had to be reduced in order to capture an image of the pale, smooth surface of the stone casts without reflection. The flash intensity was much greater for capturing infant faces and the problem of shadows on the side of the nose was greatly reduced in the clinical study.

3.1.4.2 Capture Error

It was not possible to measure capture error independently of operator error so capture error was therefore greater. Alare right had large errors of 0.93 mm for operator 1, and 1.50 mm for operator 3, however operator 2 had an error of 0.10 mm for this landmark. It is therefore unlikely that this is a true instability in the system. These discrepancies were possibly due to operators 1 and 3 labelling the landmarks incorrectly, see section 3.1.4.1, or mistakenly locating the landmark alare right on a shadow on the cast rather than the on the mark. The first capture tended to be brighter than the second capture, probably due to the additional time allowed for the flashes to charge up while the cast was being moved or changed. The mark was therefore easier to locate on the first, brighter capture. This is illustrated in Figure 3.2. There was no concern that this finding would be repeated in the subsequent study since it was an error in locating the mark on the cast rather than in locating the anatomic landmark.

Figure 3.2 Duplicate Images of Cast Showing Difficulty Locating Alare Right



a) Brighter First Capture **b) Darker Second Capture**

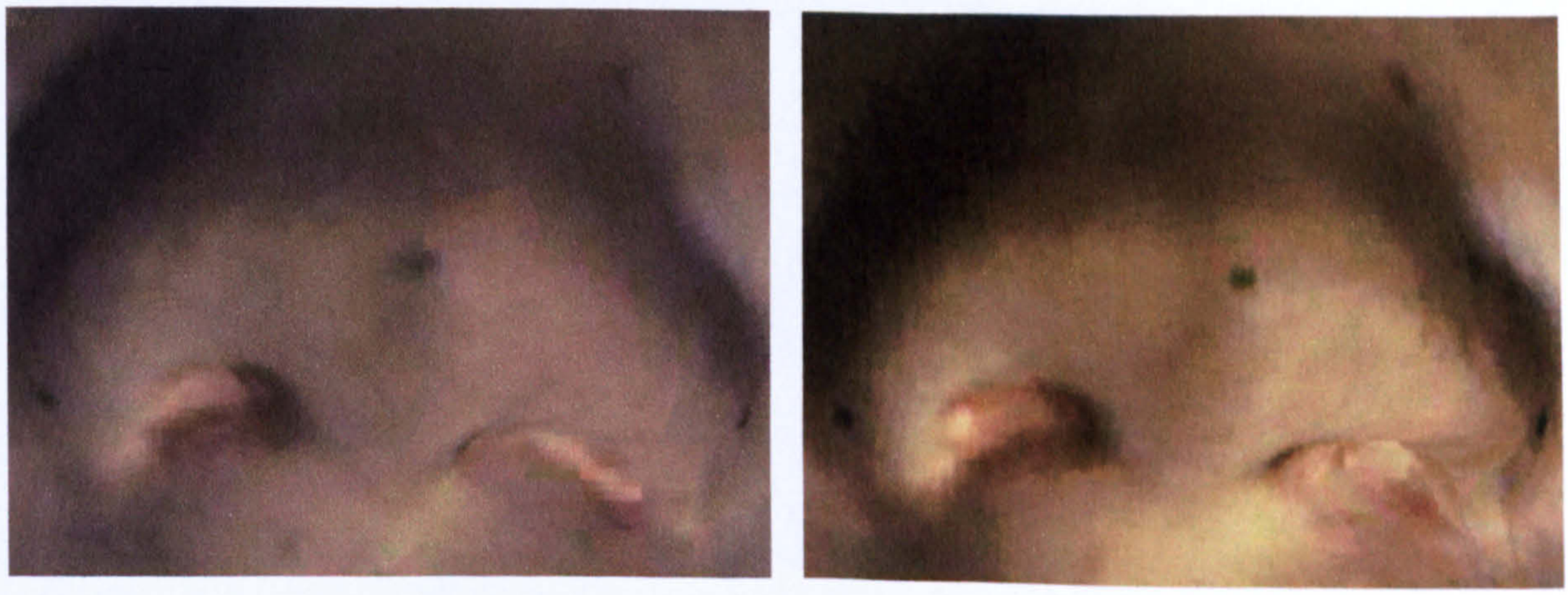
A second problem was that the marks were not actually located on the casts in the correct anatomic position of alare and in areas of decreased illumination the operators may have placed the landmark in the correct anatomic position rather than on the poorly illuminated mark. Allowing a landmark to be recorded as missing would have reduced the tendency to guess and would have improved the overall error as well as the capture error. The facility to record a landmark as missing was subsequently incorporated into the Facial Analysis Tool.

Despite these relatively increased errors and problems with illumination and labelling, the mean discrepancy of 0.48 mm, including operator error, showed minimal instability in the C3D system.

3.1.4.3 Registration Error

The mean discrepancy between positions of the landmarks was 0.42 mm with little variation in the pairwise comparisons. The point prn had a slight tendency to have greater discrepancy than the other points with the greatest difference of 0.58 mm between the centre position versus the 20°L. These discrepancies could be explained by differences in lighting but could also be influenced by the merging of the images from the right and left colour cameras. The merging usually created a thin line running down the cast and often caused a blurring of the mark prn which was in the midline. The images captured to the right or left had the merge line running through the nostril and the point prn was clearer. This is illustrated in Figure 3.3.

Figure 3.3 Images Captured in Different Positions showing the Merge Line Affecting the Clarity of Landmarks



a) Centre **b) 20° Left**

Despite these observations there was a minimal effect of positioning the cast relative to the cameras. This meant that in the subsequent study the infants could be positioned anywhere from 40 to 50 cm from the cameras. Although they could be positioned 20° left or right, it was aimed to capture them facing forwards to optimise the lighting on both sides of the face. The merge line was not perceived to be a problem since the landmarks would be located according to anatomic definitions rather than locating a coloured mark.

3.1.4.4 C3D System Error

The mean difference between C3D and CMM was 0.83 mm. The points at the corners of the mouth had smaller discrepancies than the other landmarks and this was probably due to the relative clarity of these marks on all of the casts. Rotating the cast 20° to the right or placing the cast in the front position produced the least discrepancy. The front position produced the best lighting conditions however it was difficult to explain the difference between the right and left rotations. One suggestion was that since the majority of the cases had left sided clefts, rotation to the right allowed improved lighting of the cleft side. It is likely that a repeated validation study with coloured life size models of infants faces and clearer markings would achieve a lower system error.

3.1.5 Validation Conclusions

The error of the C3D imaging system used in this study was comparable to that of other 3D imaging systems such as laser scanning and structured light scanners (Bush & Antonyshyn 1996;Yamada et al. 1999). It confirms the reliability of the system and validates its use to collect data for analysis of facial morphology in infants. The problems with landmark labelling, missing landmarks and flash intensity were all resolved prior to the clinical study.

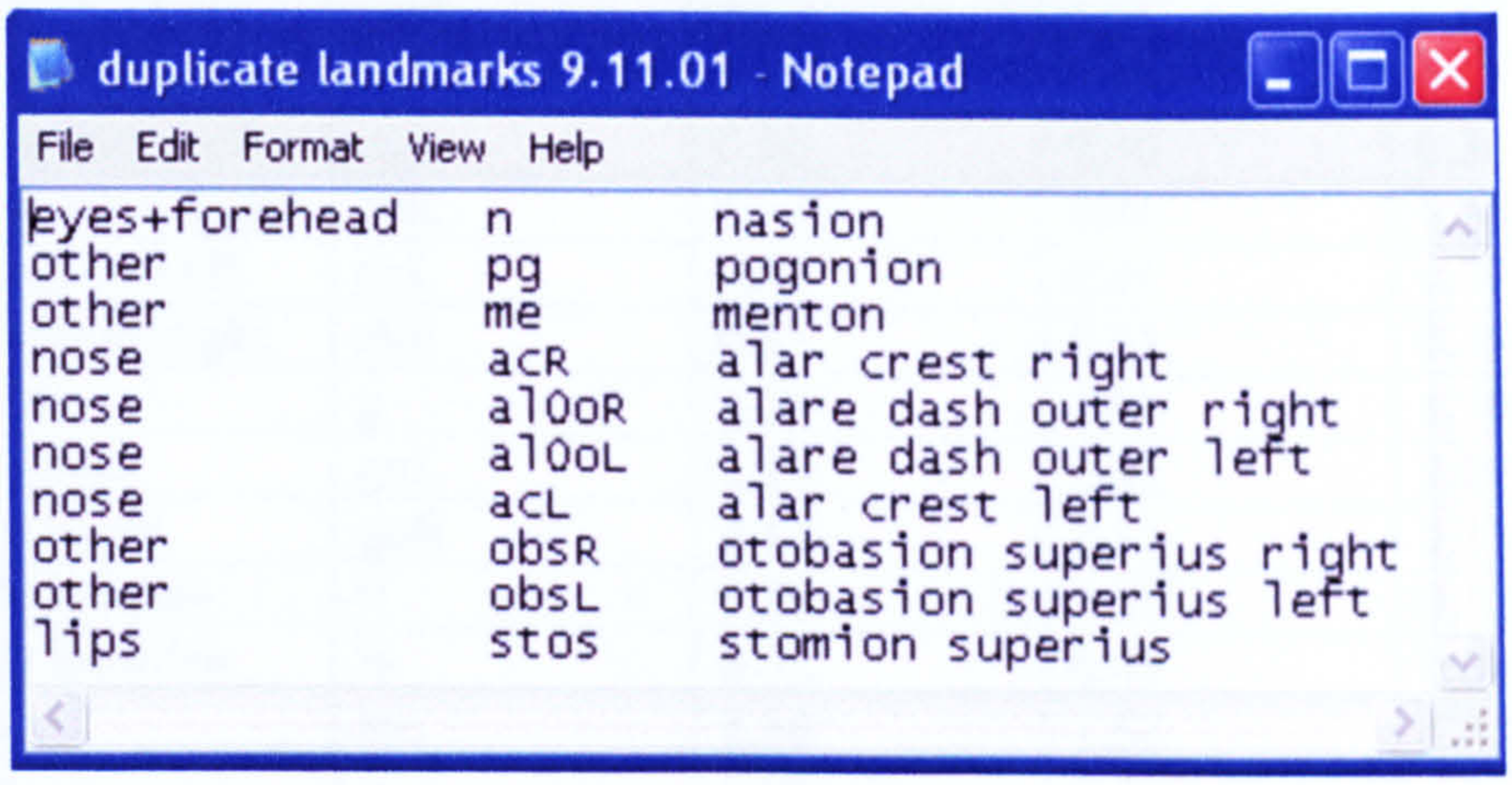
3.2 Landmark Identification

3.2.1 Pilot Study

3.2.1.1 Pilot Study Method

Before deciding on the definitive list of landmarks a pilot study was carried out to determine subjectively which landmarks could be clearly seen on the models and to determine objectively the reproducibility of these landmarks. Eleven subjects were chosen randomly out of those who had attended at both 3 and 6 months. Thirty six landmarks were investigated to cover the whole face. Following the initial validation study, modifications were made to the Facial Analysis Tool which allowed a list of landmarks to be defined by the operator in a text file, loaded into the Facial Analysis Tool and the operator prompted to place each landmark in turn. An example of a landmark list file is shown in Figure 3.4.

Figure 3.4 Landmark List File



These landmarks were located and saved as a series of x, y and z coordinates in a labelled text file. The magnification and orientation of the models were at the operator's discretion during this pilot study. The landmarks were located on each of the 3 and 6 month models on three separate occasions. This amounted to a total of 66 landmark files. As a measure of reproducibility, the square root of the mean squared distance, in mm, of each of the three repeatedly placed landmarks around their mean was calculated. This was called the reproducibility score.

Definitions of the landmarks used in the definitive study are given in Table 2.1. Several additional landmarks were investigated in the pilot study. Trichion was defined as the point on the hairline in the midline of the forehead, glabella was the most prominent midline

point between the eyebrows, gonion was the most lateral point on the mandibular angle close to bony gonion and identified by palpation, and tragion was the notch on the upper margin of the tragus of the ear (Farkas 1994b). Cheek was the point at the intersection between Camper's plane and a line connecting exocanthion and cheilion (Ferrario et al. 1997).

3.2.1.2 Pilot Study Results

The results of the pilot study are shown in Table 3.5.

Table 3.5 Landmark Reproducibility Scores for the Pilot Study

Landmark Name	Landmark Abbreviation	Repro score at 3 months*	Repro score at 6 months*	Overall repro score*
Alar Crest Left	acL	0.54	0.55	0.55
Alar Crest Right	acR	0.87	0.72	0.79
Alare Left	alL	**1.15**	**1.49**	**1.33**
Alare Right	alR	**1.64**	**1.81**	**1.73**
Cheek Left	chkL	**1.29**	**1.27**	**1.28**
Cheek Right	chkR	**1.02**	**1.17**	**1.10**
Cheilion Left	chL	0.42	0.33	0.37
Cheilion Right	chR	0.44	0.41	0.42
Columella Right	cR	0.29	0.65	0.48
Columella Left	cL	0.32	0.66	0.50
Crista Philtri Left	cphL	0.43	0.51	0.47
Crista Philtri Right	cphR	0.39	0.43	0.41
Endocanthion Left	enL	0.36	0.36	0.36
Endocanthion Right	enR	0.35	0.41	0.38
Exocanthion Left	exL	0.32	0.41	0.37
Exocanthion Right	exR	0.35	0.41	0.38
Glabella	g	**1.59**	**1.94**	**1.78**
Gonion Left	goL	**2.19**	**2.02**	**2.07**
Gonion Right	goR	**2.17**	**2.11**	**2.13**
Labrale Inferius	li	0.48	0.55	0.52
Labrale Superius	ls	0.32	0.43	0.38
Menton	me	**1.30**	**1.54**	**1.43**
Nasion	n	0.90	0.86	0.88
Pogonion	pg	0.89	**1.02**	0.96
Pronasale	prn	0.56	0.80	0.68
Stomion Inferius	stoi	0.35	0.42	0.39
Stomion Superius	stos	0.62	0.66	0.64
Subalare Left	sbalL	0.41	0.47	0.44
Subalare Right	sbalR	0.45	0.43	0.44
Sublabiale	sl	0.45	0.57	0.51
Subnasale	sn	0.38	0.45	0.42
Subnasale' Left	sn'L	0.43	0.37	0.40
Subnasale' Right	sn'R	0.39	0.37	0.38
Tragion Left	tL	0.95	0.94	0.94
Tragion Right	tR	**1.17**	**1.14**	**1.15**
Trichion	tr	**2.07**	**1.63**	**1.83**

*Reproducibility scores (repro score) shown in mm. Scores >1 mm are highlighted in **bold**.

Ten of the landmarks were found to have reproducibility scores greater than 1 mm in both the 3 and 6 month models. Fifteen of the landmarks had reproducibility scores below 0.5 mm and the remaining 11 landmarks were between 0.5 mm and 1 mm. Paired t tests found a weakly (p=0.04) significant difference between the reproducibility scores at 3 and 6 months, with the 3 month models having slightly lower scores.

3.2.1.3 Pilot Study Discussion & Conclusions

The landmarks gonion right and left had reproducibility scores greater than 2 mm. These points were difficult to locate on the infants since they were often obscured by soft tissue. The definition of gonion depends on palpation of the angle of the mandible and this was not possible in 3D models. It was decided not to include gonion in the definitive study for these reasons.

The next least reproducible landmarks were trichion and glabella. Trichion was unclear in most of the infants who had little hair. Glabella could not be reproducibly located on the infants most of whom had pale eyebrows and minimal protuberance in this area. It was decided to exclude these landmarks from further study.

Alare right, alare left and menton also had a poor reproducibility however it was believed that this could be greatly improved by clarifying the definitions and standardising the position of the models during landmark location.

Tragion right and left had reproducibility scores around 1.1 mm. These points were difficult to locate on the model due to lack of light around the ear. Although it was desirable to include these landmarks in the study it was felt by all the operators in the project that tragion could not be clearly seen on the 3D models and it was decided to exclude it from the study. It was decided to investigate whether any other landmarks around the ear could be reproducibly located.

The cheek landmarks proved difficult to find on the 3D models and had reproducibility scores of around 1.2 mm. It was decided to exclude these landmarks from the definitive study.

Due to the poor reproducibility of several landmarks which were believed to be important it was decided to repeat the study with some modifications to the landmark definitions and standardising the position of the face during landmark location.

3.2.2 Definitive Study of Landmark Reproducibility

3.2.2.1 Definitive Study Method

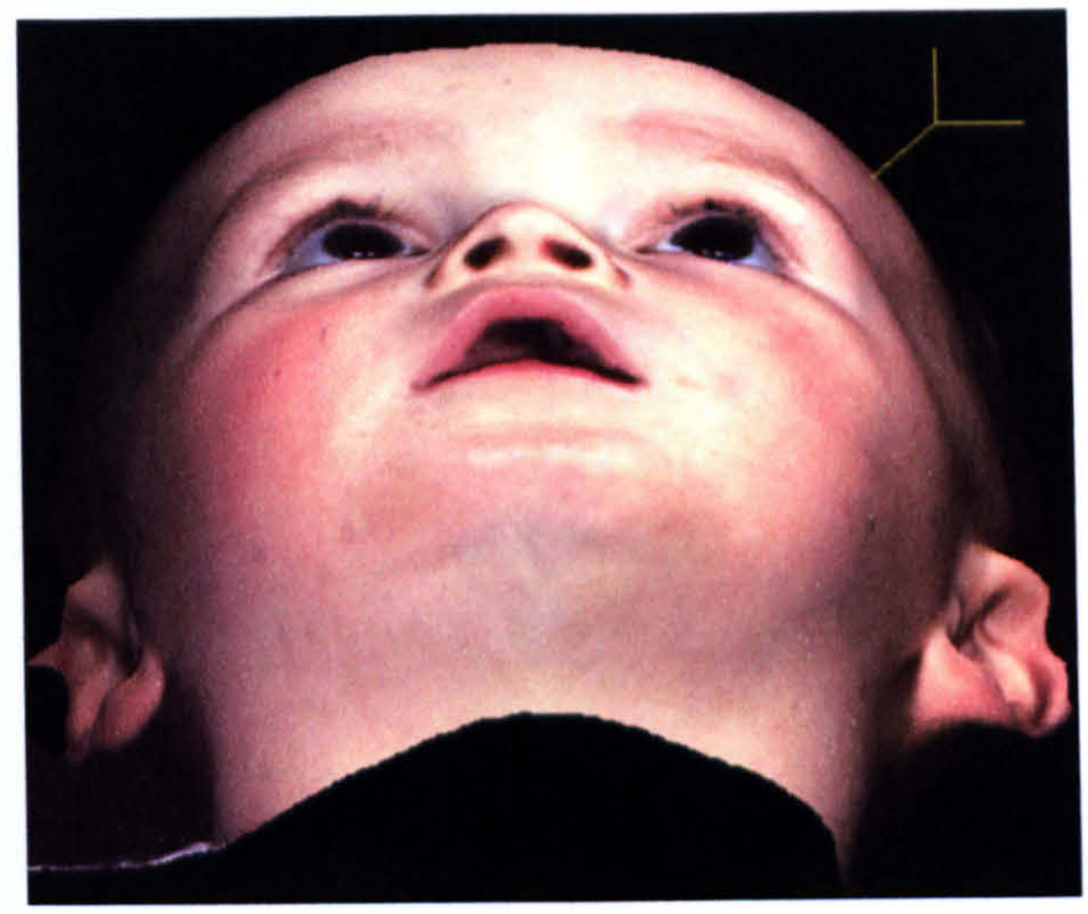
Thirty six soft tissue landmarks were chosen for investigation following the pilot study. Nine landmarks were excluded from the 36 landmarks investigated previously. The additional landmarks alare' outer and alare' inner were added to the investigation in an attempt to produce more detailed information around the nostrils. Stomion allowed measurement of the lips when the lips were together. Otobasion inferius and otobasion superius, the upper and lower attachments of the ear to the face, were added in an attempt to find a reproducible landmark around the ears to substitute for tragion and allow measurement of facial depths.

Landmark definitions were further improved by specifying the exact position of the model during landmark location. Firstly a method of standardising the position of the model was developed. A modification to the Facial Analysis Tool was made which allowed three landmarks to be located and saved and the model positioned according to these landmarks. These three landmarks were chosen to be endocanthion left, endocanthion right and sublabiale. These were found to be three of the most reproducibly located landmarks in the pilot study and were clear and relatively easy to locate in all the models as well as in the cleft lip and palate subjects in the larger study. The model could then be orientated relative to the plane passing through these three points.

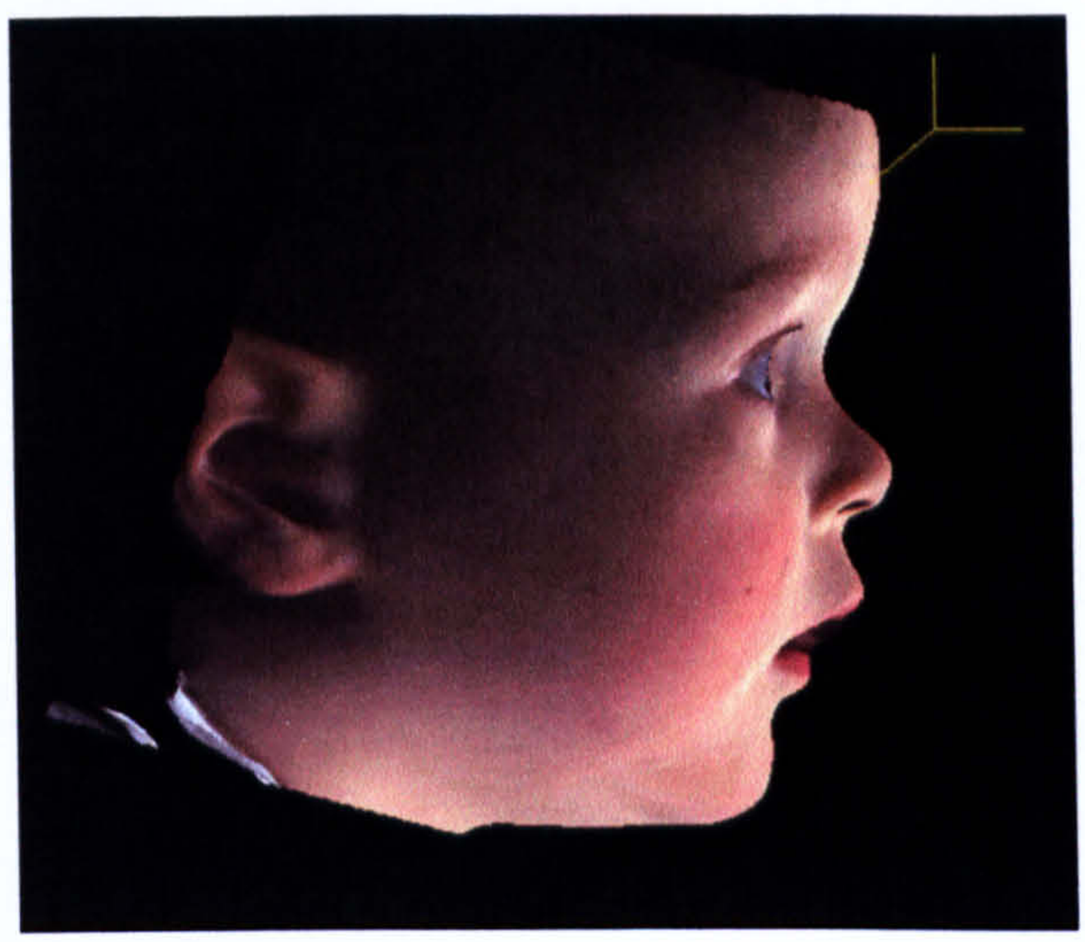
Most landmarks were located while the reference plane was parallel to the screen. This position was called face on. The landmarks around the nostrils and under the chin were located when the face was tilted 60^0 upwards and those around the ears were located at 90^0 left and 90^0 right. One position was viewed on the main window and the other positions were viewed in two smaller windows simultaneously aiding in accurate landmark identification. This is shown in Figure 2.15. The model position for each landmark is shown in Table 2.1 and the positions are illustrated in Figure 3.5.

Figure 3.5 Positions of 3D Models during Landmark Location

a) Face on



b) 60° tilt



c) 90° Right

d) 90° Left

In the definitive landmark reproducibility study, 11 subjects were randomly selected from the group that had no missing landmarks and had attended at 3 months and 1 year. The error of soft tissue landmark identification was assessed by locating the 36 landmarks on these subjects' 3 month and 1 year models on three separate occasions using the standardised positioning described above. The reproducibility score, the square root of the mean squared distance, in mm, of each of the three repeatedly placed points around their mean was calculated.

3.2.2.2 Definitive Study Results

The results of the definitive reproducibility study are shown in Table 3.6 and Figure 3.6.

Table 3.6 Landmark Reproducibility

Landmark Name	Landmark Abbreviation	Repro score at 3 months*	Repro score at 1 year*	Overall repro score*
Alar Crest Left	acL	0.68	0.61	**0.64**
Alar Crest Right	acR	0.53	0.52	**0.53**
Alare Left	alL	0.46	0.43	0.45
Alare Right	alR	0.57	0.42	0.49
Alare' Inner Left	al'iL	0.51	0.23	0.37
Alare' Inner Right	al'iR	0.23	0.31	0.27
Alare' Outer Left	al0oL	**0.98**	0.41	**0.70**
Alare' Outer Right	al0oR	0.63	0.50	**0.56**
Cheilion Left	chL	0.22	0.25	0.24
Cheilion Right	chR	0.27	0.43	0.36
Columella Left	cL	0.29	0.29	0.29
Columella Right	cR	0.26	0.29	0.28
Crista Philtri Left	cphL	0.39	0.36	0.37
Crista Philtri Right	cphR	0.38	0.43	0.40
Endocanthion Left	enL	0.29	0.27	0.28
Endocanthion Right	enR	0.28	0.24	0.26
Exocanthion Left	exL	0.28	0.30	0.29
Exocanthion Right	exR	0.49	0.32	0.40
Labrale Inferius	li	0.41	0.43	0.42
Labrale Superius	ls	0.35	0.33	0.34
Menton	me	1.13	0.88	**0.99**
Nasion	n	0.62	0.63	**0.63**
Otobasion Inferius Left	obiL	0.46	0.33	0.39
Otobasion Inferius Right	obiR	0.36	0.36	0.36
Otobasion Superius Left	obsL	0.48	0.92	**0.70**
Otobasion Superius Right	obsR	0.65	0.71	**0.68**
Pogonion	pg	0.87	0.75	**0.81**
Pronasale	prn	0.43	0.42	0.42
Subalare Left	sbalL	0.50	0.39	0.44
Subalare Right	sbalR	0.47	0.50	0.48
Sublabiale	sl	0.38	0.51	0.45
Subnasale	sn	0.31	0.35	0.33
Subnasale' Left	sn'L	0.28	0.26	0.27
Subnasale' Right	sn'R	0.36	0.31	0.33
Stomion Inferius	stoi	0.33	0.31	0.32
Stomion Superius	stos	**0.99**	0.44	**0.72**

*Reproducibility scores (repro score) shown in mm. Overall reproducibility scores >0.5 mm are shown in **bold**. Scores affected by outliers are in **bold and underlined**.

An outlier of 3.9 mm accounted for the relatively increased reproducibility score for stos at 3 months. A further outlier of 3.6 mm accounted for the difference between the reproducibility score for al'oL at 3 months and 1 year. It is probable that while locating these landmarks on one of the three repetitions the landmark was located in completely the wrong place due to operator error. Despite these outliers paired t tests showed no statistically significant differences between the 3 month and 1 year reproducibility scores.

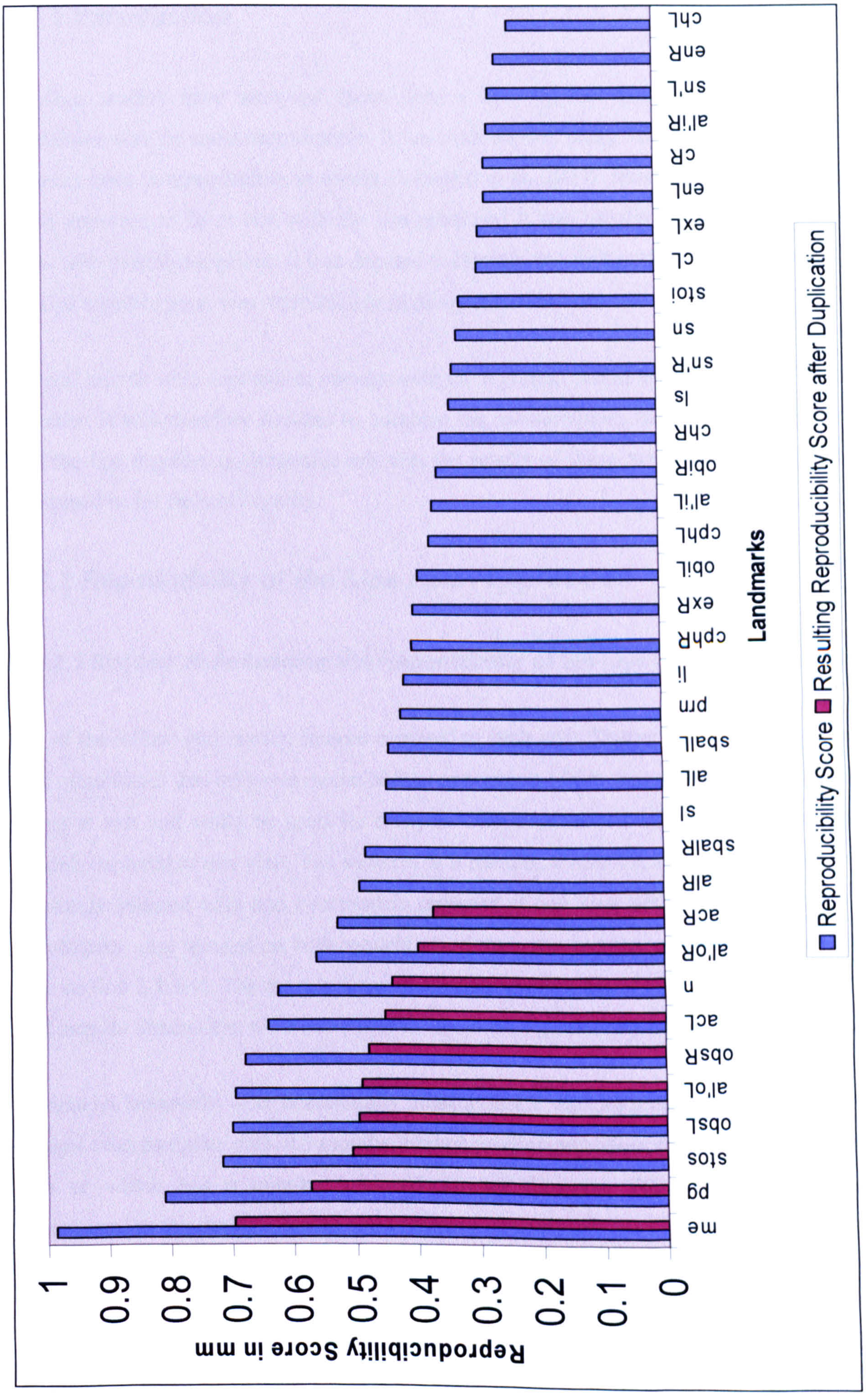
3.2.2.3 Definitive Study Discussion & Conclusions

Twenty six landmarks were found to have an overall reproducibility score of less than 0.5 mm and were assessed as being reliable. Locating the landmarks on more than one occasion and using the mean position would reduce the reproducibility score. This is a technique commonly employed in the cephalometric literature to reduce landmark location errors (Houston et al. 1986). Locating the landmarks on a number (n) of separate occasions would reduce the reproducibility score (rs) according to the equation $rs/\sqrt{(n)}$. A further programme was therefore developed to calculate the mean of two or more sets of landmarks and was called the File Merge programme.

It was decided to locate the 10 landmarks with overall reproducibility scores >0.5 mm on two occasions in order to reduce the reproducibility score by a factor of $\sqrt{2}$. Figure 3.6 shows the resulting overall reproducibility score for all of the landmarks.

The resulting reproducibility scores were all below 0.7 mm which was judged to be clinically acceptable.

Figure 3.6 Overall Reproducibility Scores for all Landmarks and Resulting Score after Duplicate Location



3.3 Repeatability of Facial Expressions

3.3.1 Introduction

Previous studies have analysed faces with a lips together pose assuming that this expression was the most reproducible. It has been shown, using 3D imaging, that the lips together pose is reproducible in adults (Johnston et al. 2003). Most of the infants in this study appeared to be at rest with the lips apart and it was usually impossible to capture them with their lips together. It was decided to investigate whether the lips apart, as well as the lips together pose, was reproducible in this group of infants.

Several infants were captured at one age with the lips apart and at another age with the lips together. It was therefore decided to compare the measurements taken with the lips apart and the lips together to determine whether the results of these two expressions could be combined in the definitive study.

3.3.2 Repeatability of the Lips Apart Expression

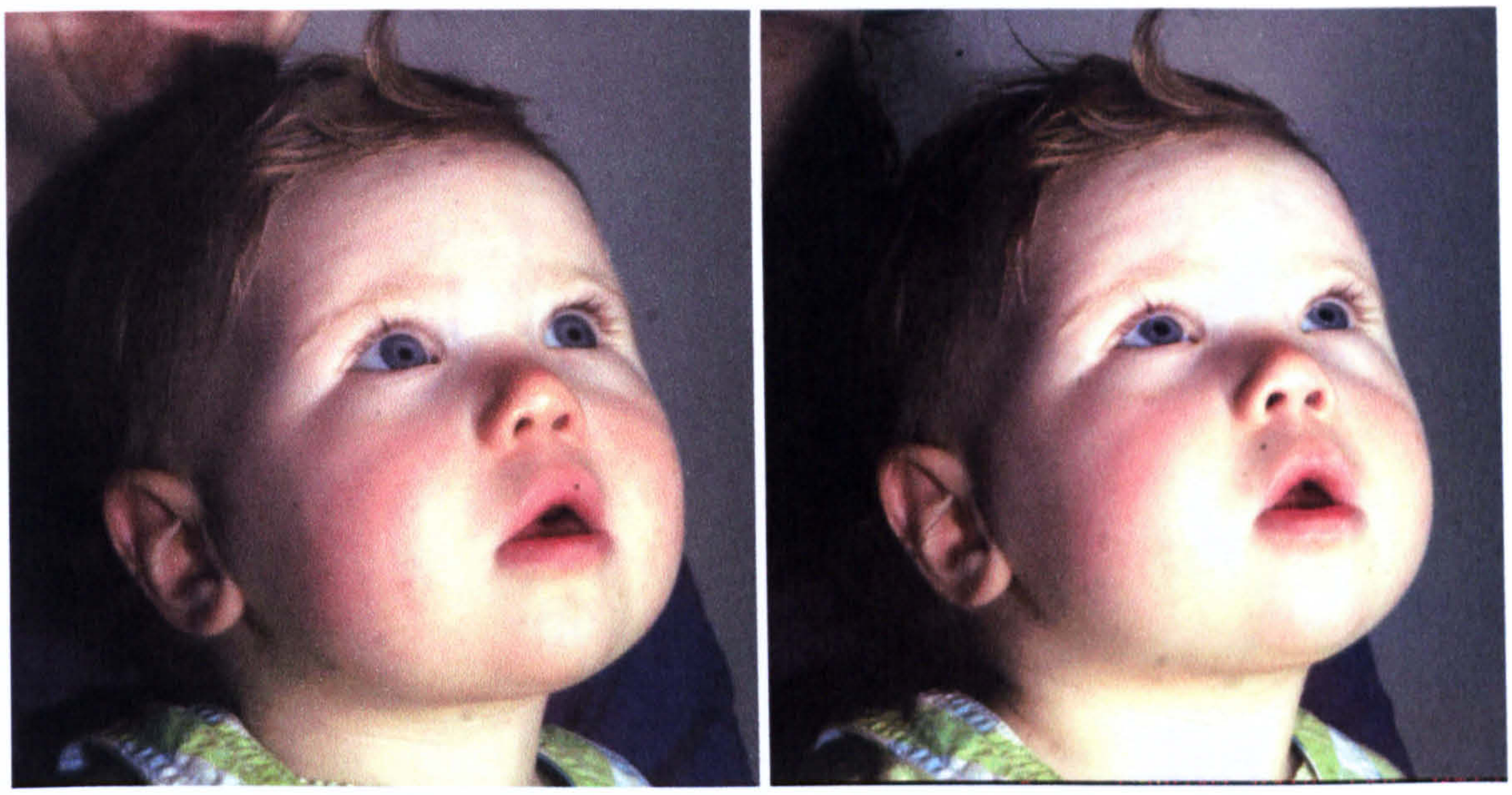
3.3.2.1 Method of Assessing the Repeatability of the Lips Apart Expression

All of the infants had several images captured at each visit. During building and editing it was often found that only one model had an expression which was subjectively assessed as being at rest and could be used for analysis. However several infants had two or more models captured at one visit. Ten subjects at 3 months, 6 months, 1 year and 2 years were randomly selected who had two models captured at one visit with the lips apart at rest. Landmarks were located on both models using the same protocol as previously described (see section 2.3.3.4). The models from each subject were marked consecutively. The linear and angular dimensions were compared to assess the repeatability of the facial expression.

Peripheral landmarks were occasionally missing and it was not possible to find 10 pairs of images with complete data at 3 months. Eleven subjects were therefore chosen at 3 months, two of whom had a missing landmark around the ears. This allowed 10 pairs of measurements for the face depths and widths to be analysed and 11 pairs of measurements for the other distances and angles. Ten subjects were used at the other ages.

An example of 2 images of the same child on the same day used for the repeatability study is shown in Figure 3.7.

Figure 3.7 Images Used to Assess the Repeatability of the Lips Apart Expression



The standard deviation of repeated measurements on the same subject was the method chosen to represent measurement error (Bland & Altman 1986). An estimate of the standard deviation was calculated by the following equation $\sqrt{1/2n \sum(x_i - y_i)^2}$, where n is the number of subjects and the pairs of measurements are x_i and y_i for i = 1 to n . In other words taking the square root of the sum of all the differences squared divided by twice the number of subjects.

Statistical comparison of repeatability was carried out by calculating the F value. The F value equals the error variance of sample 1 divided by the error variance of sample 2, where sample 1 had the larger mean square and the error variance was the standard deviation squared. This F value was compared to tables of F values which can be found in statistical texts, with different tables for different significance levels (Neave 1981). The 95% level was chosen for this study. The tabulated F value selected for comparison depends on the degrees of freedom which, in this unusual instance, were equal to the number of subjects in each sample due to the nature of the repeatability measures which were based on differences. If the calculated F value was greater than or equal to the tabulated F value corresponding to the correct degrees of freedom then it could be concluded that there was a significant difference in the repeatability.

3.3.2.2 Results of the Repeatability of the Lips Apart Expression

The error standard deviations (Error SD) at the different ages and for the different facial measurements are shown in Table 3.7. The F values comparing the repeatability at 3

months and 6 months (3m-6m), 6 months and 1 year (6m-1y) and 1 year and 2 years (1y-2y) are also shown, with the significant differences highlighted in bold.

Table 3.7 Repeatability of Measurements with the Lips Apart

Measure	Error SD**	F Value*	Error SD**	F Value*	Error SD**	F Value*	Error SD**
Age	**3m**	**3m-6m**	**6m**	**6m-1y**	**1y**	**1y-2y**	**2y**
Face Depth							
obiL-n	0.79	2.17	0.54	**2.99**	0.93	2.01	0.65
obiR-n	0.87	1.01	0.87	1.74	0.66	1.10	0.69
obiL-sn	0.87	2.48	0.55	2.19	0.81	1.07	0.79
obiR-sn	0.79	1.95	0.57	1.23	0.63	1.19	0.69
obiL-pg	1.03	2.76	0.62	1.08	0.65	1.76	0.49
obiR-pg	1.03	1.01	1.02	2.92	0.60	1.80	0.80
Face Width							
obsR-obsL	1.01	1.48	1.23	1.57	0.98	1.08	1.02
obiR-obiL	1.06	1.59	0.84	2.03	0.59	**5.20**	1.34
Face Height							
n-me	1.41	1.58	1.12	2.51	1.78	2.33	1.16
sn-me	1.17	1.42	0.98	2.35	1.50	1.29	1.32
n-sn	0.72	1.61	0.57	2.18	0.84	1.36	0.72
Eyes							
exL-exR	0.65	1.50	0.53	2.33	0.81	1.07	0.78
enL-enR	0.72	1.49	0.59	1.14	0.63	2.16	0.43
exL-enL	0.36	1.26	0.40	1.09	0.42	1.13	0.39
exR-enR	0.76	2.31	0.50	1.57	0.63	1.84	0.46
Nose							
acL-acR	0.65	2.23	0.44	1.33	0.38	2.12	0.55
alL-alR	0.44	1.09	0.45	1.09	0.44	1.02	0.43
acL-prn	0.51	1.49	0.42	1.11	0.44	2.09	0.63
acR-prn	0.33	**2.92**	0.56	**3.12**	0.32	1.27	0.36
n-prn	0.78	1.50	0.64	1.14	0.68	1.16	0.73
sn-prn	0.39	1.82	0.29	**3.69**	0.56	1.20	0.62
Nostrils							
sbalL-cL	0.37	1.20	0.34	**3.09**	0.60	**4.40**	0.29
sbalR-cR	0.57	**3.52**	0.30	2.52	0.48	1.15	0.45
sn'L-al'iL	0.57	1.98	0.40	1.08	0.42	1.07	0.43
sn'R-al'iR	0.40	**3.51**	0.75	1.32	0.65	1.69	0.50
sn'R-sn'L	0.50	2.02	0.35	**3.20**	0.63	1.00	0.47
Upper Lip							
chR-chL	0.96	1.02	0.97	1.83	1.31	2.89	0.77
cphL-chL	0.64	2.43	0.75	2.43	0.48	1.06	0.50
cphR-chR	0.70	1.73	0.54	2.77	0.89	2.56	0.56
cphR-cphL	0.63	1.15	0.59	1.77	0.78	2.79	0.47
ls-sn	0.68	1.06	0.70	1.31	0.80	1.91	0.58
ls-stos	0.81	**4.24**	0.39	**9.79**	1.23	**6.74**	0.47
sn-stos	0.88	**3.34**	0.48	2.17	0.33	2.41	0.51
sbalL-chL	0.57	1.35	0.66	1.67	0.51	1.72	0.66
sbalR-chR	0.65	1.50	0.80	1.08	0.83	1.29	0.95

Lower Lip							
chL-li	0.64	1.44	0.53	1.71	0.69	1.43	0.58
chR-li	0.61	1.05	0.59	1.66	0.76	1.20	0.70
li-stoi	0.49	1.62	0.38	**5.16**	0.87	1.69	0.67
sl-li	0.63	1.50	0.51	1.88	0.70	1.52	0.86
sl-stoi	0.64	1.73	0.49	2.07	0.70	1.37	0.60
Angles							
acR-prn-acL	2.36	1.21	2.15	1.08	2.06	1.07	1.99
n-prn-sn	1.87	1.61	2.37	1.35	2.75	1.38	2.34
prn-sn-ls	3.22	1.79	2.41	1.53	2.98	1.40	2.51
li-sl-pg	8.13	1.92	5.87	1.23	6.52	**5.85**	2.70

** The error standard deviation (Error SD) is in mm for the distances and in degrees for the angles.
* F Value = error variance 1 / error variance 2, where error variance 1 is the greater value.
The F Values shown in **bold** show differences which were significant at the 95% level compared to tabulated F values with n degrees of freedom, where n = number of subjects.

The error standard deviation for the repeatability of all of the measurements in the lips apart position ranged from 0.29 to 1.78 mm. There was very little evidence of differences in variability with age.

The error standard deviation in face depth varied from 0.49 to 1.03 mm. The error standard deviation in face width ranged from 0.59 to 1.34 mm. The error standard deviation in face height varied from 0.57 to 1.78 mm. There was no difference in the repeatability of upper or lower face measurements. Upper left face depth (obiL-n) was significantly less repeatable at 1 year than 6 months and lower face width (obiR-obiL) repeatability was significantly poorer at 2 years than 1 year. The measurements incorporating the landmark menton had the least repeatability. The error standard deviations for all of these face measurements were greater than the measurements of the eyes, nose and lips reflecting the fact that these were larger measurements.

The error standard deviations around the eyes varied from 0.36 to 0.81 mm. The right palpebral fissure width had a greater variation than the left palpebral fissure width at all ages but this difference was only significant at 3 months.

The error standard deviations around the nose varied from 0.29 to 0.78 mm. Nose dorsum length (n-prn) had the greatest error standard deviation of all of the nose measurements at all ages. The error standard deviations around the nostrils ranged from 0.29 to 0.75 mm. The repeatability of nasal tip protrusion (sn-prn) was significantly better at 6 months than 1 year and the repeatability of the right alar length (acR-prn) was significantly worse at 6 months than at 3 months or 1 year. There were several significant differences in

repeatability of the nostril measurements but none of these differences were consistent over time.

The error standard deviations around the upper lip varied from 0.39 to 1.31 mm. Mouth width repeatability was poorer than the other lip measurements with error standard deviations of 0.77 to 1.31 mm. There were significant differences in the repeatability of upper cutaneous lip height (ls-stos) with this measurement being more repeatable at 6 months and 2 years than at 3 months or 1 year. Upper lip height was significantly more repeatable at 6 months than 3 months. The error standard deviations around the lower lip ranged from 0.38 to 0.87 mm. Lower cutaneous lip height (li-stoi) was more repeatable at 6 months than 1 year.

The error standard deviations of the angles varied from 1.87° to 8.13°. The greatest variation was in the labiomental angle (li-sl-pg). This angle was significantly more repeatable at 2 years than 1 year.

3.3.2.3 Discussion & Conclusions of the Repeatability of the Lips Apart Expression

This assessment of the repeatability of measurements incorporated several types of error. There was the error in the data capture procedure (see section 3.1) and in the landmark location process (see section 3.2). Finally there was the variation due to change in expression of the infants. It was not possible to study this variation without incorporating the first two errors. It may have been possible to reduce the landmark location error by marking the landmarks on the face prior to image capture as suggested in previous studies (Johnston et al. 2003;Shaner et al. 2000) however this would be very difficult in infants of two years and under. The repeatability measured in this study was the true repeatability of the measurements incorporating all the layers of error therefore gave the most clinically relevant information.

The lips apart expression appeared to be a fairly repeatable expression in this group of infants from 3 months to 2 years of age with very little evidence of differences in variability with age. The least repeatable measurements were the total face height (n-me) and lower face height measurements (sn-me). Some of this variation was due to the landmark location error of menton which had a reproducibility score of 0.7 mm. Some of the variation may also have been in the degree of opening of the mouth. The greatest error standard deviation was 1.78 mm for the total face height which is still fairly low.

The labiomental angle (li-sl-pg) had a poor repeatability with error standard deviations of 2.7 ° to 8.1°. It could have been anticipated that all the angles would have higher error standard deviations since they incorporated the landmark location error of three landmarks rather than two. It is likely that some of the variability in the labiomental angle reflected some real change in this measurement between images since this angle would be affected by any movement of the lower lip.

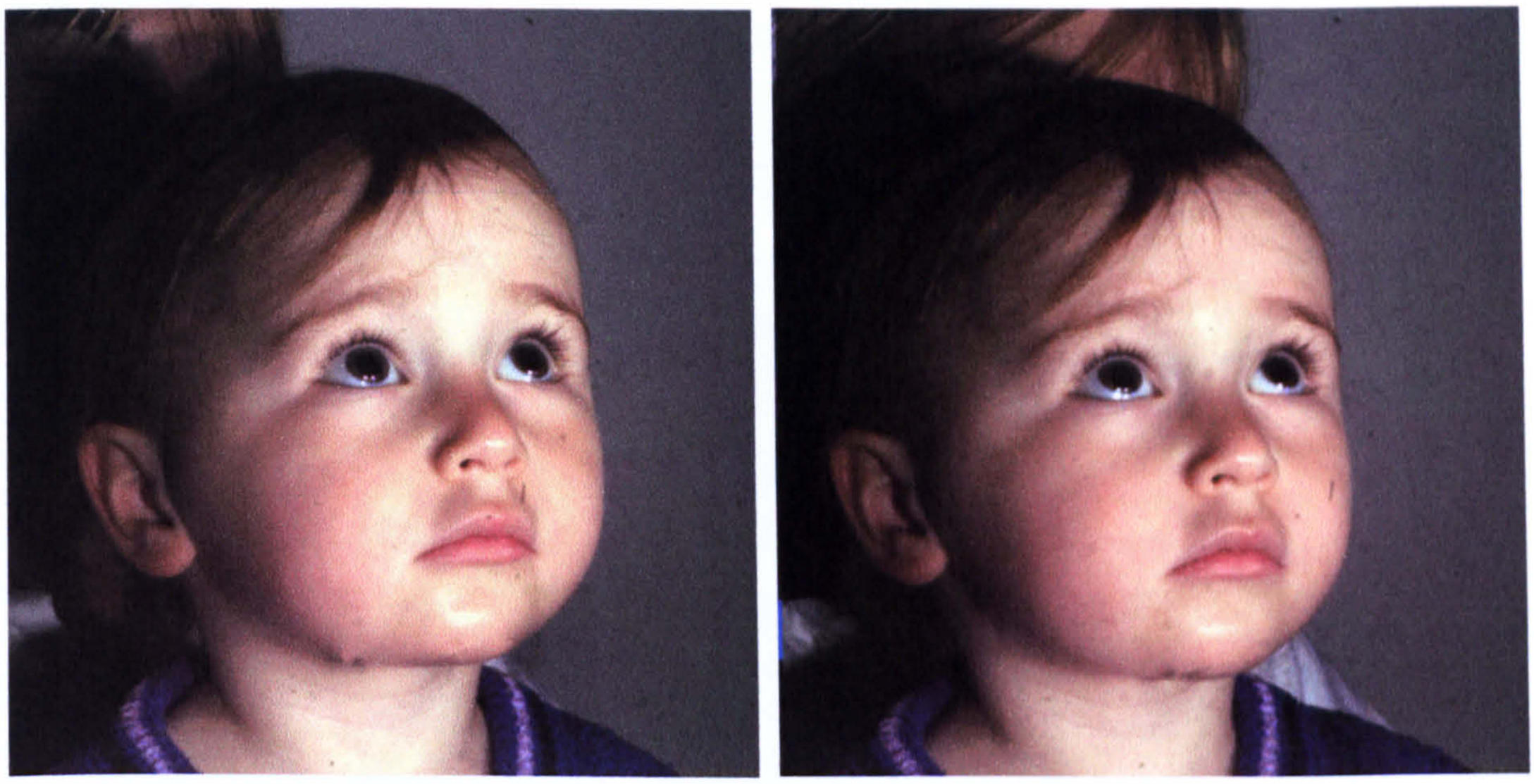
The most repeatable measurements were those around the eyes, nose and nostrils with error standard deviations comparable to the landmark location reproducibility scores of the landmarks in these areas. The right eye measurements are all less repeatable than the left eye, a fact consistent with the poorer reproducibility of locating the landmark exocanthion right. This was probably due to the slightly poorer lighting and quality of the models on the right side of the face.

3.3.3 Repeatability of the Lips Together Expression

3.3.3.1 Method of Assessing the Repeatability of the Lips Together Expression

Most infants were captured with the lips apart however a small number of infants appeared to be at rest with the lips together. Several infants could only be captured in a lips together pose. Ten subjects at each age were selected who had two models captured at one visit with the lips together. Landmarks were located on both models consecutively. The linear and angular results were compared to assess the repeatability of facial expression when the lips were together. Once again it was not possible to find 10 pairs of images without any missing landmarks at 3 months. The measurements 13 subjects were therefore analysed at 3 months. Examples of images used to assess the repeatability of the lips together expression are shown in Figure 3.8.

Figure 3.8 Examples of Images Used to Assess the Repeatability of the Lips Together Expression



The error standard deviation and F values were calculated to determine the measurement error and compare the repeatability at the different ages (see section 3.3 2.1).

3.3.3.2 Results of Assessing the Repeatability of the Lips Together Expression

The error standard deviation (Error SD) at the different ages and for the different facial measurements is shown in Table 3.8. The F values comparing the repeatability at 3 months and 6 months (3m-6m), 6 months and 1 year (6m-1y) and 1 year and 2 years (1y-2y) are also shown with the significant differences highlighted in bold.

Table 3.8 Repeatability of Measurements with the Lips Together

Measure	Error SD**	F Value*	Error SD**	F Value*	Error SD**	F Value*	Error SD**
Age	**3m**	**3m-6m**	**6m**	**6m-1y**	**1y**	**1y-2y**	**2y**
Face Depth							
obiL-n	0.61	**2.77**	1.02	1.21	1.12	**3.58**	0.59
obiR-n	1.05	1.44	0.87	1.02	0.88	1.53	0.71
obiL-sn	0.66	2.39	1.01	1.03	1.00	2.94	0.58
obiR-sn	1.10	1.78	0.79	1.09	0.82	1.26	0.73
obiL-pg	0.99	1.17	0.91	1.41	0.77	1.18	0.83
obiR-pg	0.86	1.03	0.88	2.53	0.55	**4.81**	1.21
Face Width							
obsR-obsL	0.99	2.34	0.65	**3.30**	1.17	1.37	1.37
obiR-obiL	0.86	2.67	1.41	1.29	1.60	1.49	1.31

Face Height							
n-me	1.88	1.05	1.83	**3.19**	1.03	1.12	1.09
sn-me	1.80	1.20	1.97	2.66	1.21	1.15	1.13
n-sn	0.48	2.03	0.68	1.74	0.52	1.72	0.68
Eyes							
exL-exR	0.36	**3.63**	0.69	1.36	0.80	1.51	0.65
enL-enR	0.35	**4.32**	0.73	1.20	0.80	**3.81**	0.41
exL-enL	0.27	1.41	0.32	1.07	0.31	1.74	0.41
exR-enR	0.41	1.60	0.52	1.75	0.39	1.13	0.42
Nose							
acL-acR	0.41	1.55	0.33	2.10	0.48	2.04	0.34
alL-alR	0.46	1.14	0.50	1.04	0.49	2.09	0.34
acL-prn	0.36	1.31	0.31	**3.87**	0.61	**3.25**	0.34
acR-prn	0.21	1.67	0.27	2.28	0.41	**3.23**	0.23
n-prn	0.57	2.47	0.36	2.40	0.56	1.04	0.55
sn-prn	0.50	1.25	0.56	1.86	0.41	1.13	0.44
Nostrils							
sbalL-cL	0.34	1.72	0.45	1.35	0.39	1.16	0.42
sbalR-cR	0.47	1.25	0.42	1.00	0.42	1.28	0.48
sn'L-al'iL	0.31	**3.04**	0.54	2.77	0.32	**4.44**	0.68
sn'R-al'iR	0.44	1.34	0.51	1.86	0.38	1.84	0.51
sn'R-sn'L	0.44	1.70	0.57	1.45	0.69	1.45	0.83
Upper Lip							
chR-chL	1.84	2.78	1.10	1.19	1.01	1.02	1.02
cphL-chL	0.98	1.28	0.86	1.19	0.79	1.50	0.65
cphR-chR	1.21	2.58	0.75	1.26	0.84	1.69	0.65
cphR-cphL	0.67	2.20	0.99	2.54	0.62	1.29	0.70
ls-sn	0.75	1.72	0.57	1.06	0.59	1.80	0.44
ls-sto	0.76	2.02	0.53	1.42	0.64	1.16	0.69
sn-sto	0.72	1.17	0.78	**4.87**	0.35	**3.14**	0.63
sbalL-chL	0.83	1.02	0.83	1.88	1.14	1.17	1.05
sbalR-chR	1.08	1.41	0.91	1.66	1.17	2.42	0.75
Lower Lip							
chL-li	1.23	**2.96**	0.72	1.42	0.86	2.05	0.60
chR-li	1.02	1.60	0.80	1.24	0.89	1.01	0.89
li-sto	0.74	1.77	0.56	1.01	0.56	2.01	0.79
sl-li	0.90	**3.26**	0.50	2.18	0.74	1.14	0.78
sl-sto	0.70	1.30	0.62	1.41	0.73	1.52	0.90
Angles							
acR-prn-acL	2.18	1.37	1.87	1.47	1.54	1.98	1.09
n-prn-sn	1.86	2.05	2.66	2.55	1.67	1.86	2.27
prn-sn-ls	3.62	1.53	2.93	1.88	4.01	1.18	4.36
li-sl-pg	9.07	1.63	7.11	**3.78**	3.66	1.25	4.10

**The error standard deviation (Error SD) is in mm for the distances and in degrees for the angles.
* F Value = error variance 1 / error variance 2, where error variance 1 is the greater value.
The F Values shown in **bold** show differences which were significant at the 95% level compared to tabulated F values with n degrees of freedom, where n = number of subjects.

The error standard deviation for the repeatability of all of the measurements in the lips together position ranged from 0.21 to 1.97 mm. There was very little evidence of differences in variability with age.

The error standard deviation in face depth varied from 0.55 to 1.21 mm. The error standard deviation in face width ranged from 0.65 to 1.60 mm. The error standard deviation in face height varied from 0.48 to 1.97 mm. Once again the measurements incorporating the landmark menton had the least repeatability. The repeatability of left upper face depth (obiL-n) was significantly greater at 3 months than 6 months and significantly greater at 2 years than 1 year but right mandibular length (obiR-pg) repeatability was significantly greater at 1 year than 2 years. There was no obvious difference in repeatability of face depth and width in the upper or lower face. Upper face width (obsR-obsL) was significantly more repeatable at 6 months than 1 year. Total face height (n-me) was significantly more repeatable at 1 year than 6 months. None of these differences were consistent over time. The error standard deviations for all of these face measurements were greater than the measurements of the eyes, nose and lips reflecting the fact that these were larger measurements.

The error standard deviations around the eyes varied from 0.27 to 0.80 mm. Similar to the lips apart results, the right palpebral fissure width had a greater variation than left palpebral fissure width however these differences were not significant. Biocular width (exR-exL) and intercanthal width (enR-enL) were significantly more repeatable at 3 months than 6 months and intercanthal width (enR-enL) was significantly more repeatable at 2 years than 1 year.

The error standard deviations around the nose varied from 0.21 to 0.61 mm. Left alar length (acL-prn) was significantly less repeatable at 1 year than at 6 months or 2 years and right alar length (acR-prn) was significantly less repeatable at 1 year than 2 years. The error standard deviations around the nostrils ranged from 0.31 to 0.83 mm. Left nostril width (sn'L-al'iL) was significantly more repeatable at 3 months than 6 months and more repeatable at 1 year than 2 years.

The error standard deviations around the upper lip varied from 0.44 to 1.84 mm. The least repeatable measurement was mouth width (chR-chL) at 3 months. Upper lip height (sn-sto) was significantly more repeatable at 1 year than at 6 months or 2 years. The error standard deviations around the lower lip ranged from 0.50 to 1.23 mm. Lower left vermilion length (chL-li) was significantly more repeatable at 6 months than 3 months and lower cutaneous lip height (sl-li) was significantly more repeatable at 3 months than 6 months.

The error standard deviations of the angles varied from 1.09° to 9.07°. The greatest variation was in the labiomental angle (li-sl-pg) at 3 months. This angle was significantly more repeatable at 1 year than 6 months.

3.3.3.3 Discussion & Conclusions of the Repeatability of the Lips Together Expression

The lips together expression appeared to be a fairly repeatable expression in this group of infants from 3 months to 2 years of age with little evidence of variation with age. The least repeatable measurements were the total face height (n-me) and lower face height measurements (sn-me). The greatest error standard deviation was 1.88 mm for the total face height which was still fairly low. Mouth width (chR-chL) and vermilion lengths (cph-ch, ch-li,) had poor repeatability at 3 months but this improved at the later stages. One explanation could be that the lip together expression was not the rest position for the majority of the infants at 3 months but was only achieved with active muscle contraction.

As expected, the most repeatable measurements were those around the eyes, nose and nostrils with error standard deviations comparable to the landmark location reproducibility scores of the landmarks in these areas. The right eye measurements were all less repeatable than the left eye, similar to the lips apart results, and consistent with the higher reproducibility score for exocanthion right. This was probably due to slightly poorer illumination on the right side of the face.

3.3.4 Comparison of the Repeatability of the Facial Expressions

3.3.4.1 Method of Comparing Repeatability

Statistical comparison of the repeatability of the lips apart and lips together expressions was carried out by calculating the F values and comparing these numbers to tables of F values (see section 3.3.2.1). F values were calculated to compare the lips apart and lips together expressions at 3 months, 6 months, 1 year and 2 years. If the calculated F value was greater than or equal to the tabulated value corresponding to the correct degrees of freedom then we could conclude that there was a significant difference in the repeatability.

3.3.4.2 Results of Comparing Repeatability of the Facial Expressions

The results of comparing the repeatability of the lips apart and lips together models are shown in Table 3.9

Table 3.9 Results of Comparing the Repeatability of the Facial Expressions

Measure	F *	95% F**	F *	95% F**	F *	95% F**	F *	95% F**
Age	**3m**		**6m**		**1y**		**2y**	
Face Depth								
obiL-n	1.66	2.72	**3.62**	2.98	1.46	2.98	1.02	2.98
obiR-n	1.46	2.85	1.01	2.98	1.77	2.98	1.05	2.98
obiL-sn	1.75	2.72	**3.39**	2.98	1.50	2.98	1.84	2.98
obiR-sn	1.93	2.85	1.92	2.98	1.70	2.98	1.13	2.98
obiL-pg	1.09	2.72	2.16	2.98	1.41	2.98	2.93	2.98
obiR-pg	1.41	2.95	1.36	2.98	1.18	2.98	2.26	2.98
Face Width								
obsR-obsL	1.05	2.72	**3.63**	2.98	1.43	2.98	1.81	2.98
obiR-obiL	1.51	3.11	2.81	2.98	**7.32**	2.98	1.06	2.98
Face Height								
n-me	1.77	2.82	2.67	2.98	**2.99**	2.98	1.15	2.98
sn-me	2.37	2.82	**4.05**	2.98	1.55	2.98	1.38	2.98
n-sn	2.28	2.82	1.43	2.98	2.64	2.98	1.13	2.98
Eyes								
exL-exR	**3.27**	2.64	1.67	2.98	1.03	2.98	1.45	2.98
enL-enR	**4.18**	2.64	1.54	2.98	1.62	2.98	1.09	2.98
exL-enL	1.72	2.64	1.54	2.98	1.79	2.98	1.10	2.98
exR-enR	**3.44**	2.64	1.07	2.98	2.55	2.98	1.22	2.98
Nose								
acL-acR	2.49	2.64	1.73	2.98	1.62	2.98	2.68	2.98
alL-alR	1.14	2.77	1.19	2.98	1.24	2.98	1.65	2.98
acL-prn	2.04	2.64	1.79	2.98	1.95	2.98	**3.49**	2.98
acR-prn	2.43	2.64	**4.26**	2.98	1.67	2.98	2.45	2.98
n-prn	1.88	2.64	3.10	2.98	1.47	2.98	1.78	2.98
sn-prn	1.60	2.77	**3.66**	2.98	1.87	2.98	2.00	2.98
Nostrils								
sbalL-cL	1.17	2.64	1.77	2.98	2.36	2.98	2.16	2.98
sbalR-cR	1.43	2.64	1.96	2.98	1.28	2.98	1.16	2.98
sn'L-al'iL	**3.39**	2.64	1.77	2.98	1.69	2.98	2.46	2.98
sn'R-al'iR	1.24	2.77	2.12	2.98	**3.00**	2.98	1.04	2.98
sn'R-sn'L	1.28	2.64	2.67	2.98	1.21	2.98	**3.09**	2.98

Upper Lip								
chR-chL	**3.69**	2.77	1.30	2.98	1.67	2.98	1.77	2.98
cphL-chL	2.31	2.77	1.33	2.98	2.70	2.98	1.69	2.98
cphR-chR	**2.93**	2.77	1.97	2.98	1.12	2.98	1.35	2.98
cphR-cphL	1.11	2.77	2.81	2.98	1.60	2.98	2.25	2.98
ls-sn	1.20	2.77	1.52	2.98	1.88	2.98	1.77	2.98
ls-sto	1.14	2.64	1.84	2.98	**3.74**	2.98	2.10	2.98
sn-sto	1.47	2.64	2.65	2.98	1.18	2.98	1.54	2.98
sbalL-chL	2.18	2.77	1.59	2.98	**5.01**	2.98	2.50	2.98
sbalR-chR	2.73	2.77	1.29	2.98	1.99	2.98	1.57	2.98
Lower Lip								
chL-li	**3.77**	2.77	1.84	2.98	1.52	2.98	1.06	2.98
chR-li	**2.80**	2.77	1.84	2.98	1.37	2.98	1.63	2.98
li-sto	2.32	2.77	2.13	2.98	2.46	2.98	1.38	2.98
sl-li	2.07	2.77	1.05	2.98	1.10	2.98	1.21	2.98
sl-sto	1.19	2.77	1.59	2.98	1.08	2.98	2.24	2.98
Angles								
acR-prn-acL	1.17	2.64	1.32	2.98	1.79	2.98	**3.32**	2.98
n-prn-sn	1.01	2.64	1.26	2.98	2.73	2.98	1.06	2.98
prn-sn-ls	1.26	2.77	1.48	2.98	1.82	2.98	3.01	2.98
li-sl-pg	1.24	2.77	1.47	2.98	**3.18**	2.98	2.31	2.98

* F Value = error variance 1 / error variance 2, where error variance 1 is the greater value
** 95% F = tabulated F value, with n degrees of freedom, above which the difference was significant at the 95% level, where n = number of subjects. Significant differences are shown in **bold**.

The mouth width (chR-chL), upper right vermilion length (cphR-chR) and lower vermilion lengths (chL-ls, chR-ls) were all significantly more repeatable in the lips apart models at 3 months but not at the older stages.

The eye measurements appeared to be more repeatable in the lips together than lips apart models at 3 months but this finding was not repeated at the later ages.

At each age a small number of the measurements were found to be significantly different in the two groups of models but these findings were not consistent. For example, lower face width (obiR-obiL) was found to be significantly more repeatable in the lips apart models at 1 year but this was not found at the other ages. Total face height (n-me) was significantly more repeatable in the lips together models at 1 year but not at the other ages.

3.3.4.3 Discussion & Conclusions of Comparing the Repeatability the Facial Expressions

There was little consistency in the findings of comparing the repeatability of the lips apart and lips together expressions and it was likely that some of the significant differences were chance findings due to some outliers and the fact that the test was repeated many times.

Overall there was very little difference in repeatability of the lips apart and the lips together expressions and it could be concluded that either expression was repeatable enough to study facial morphology in infants. There was a slight suggestion that the lips apart expression gave more repeatable measurements around the lips at 3 months.

3.3.5 Comparison of the Facial Expressions

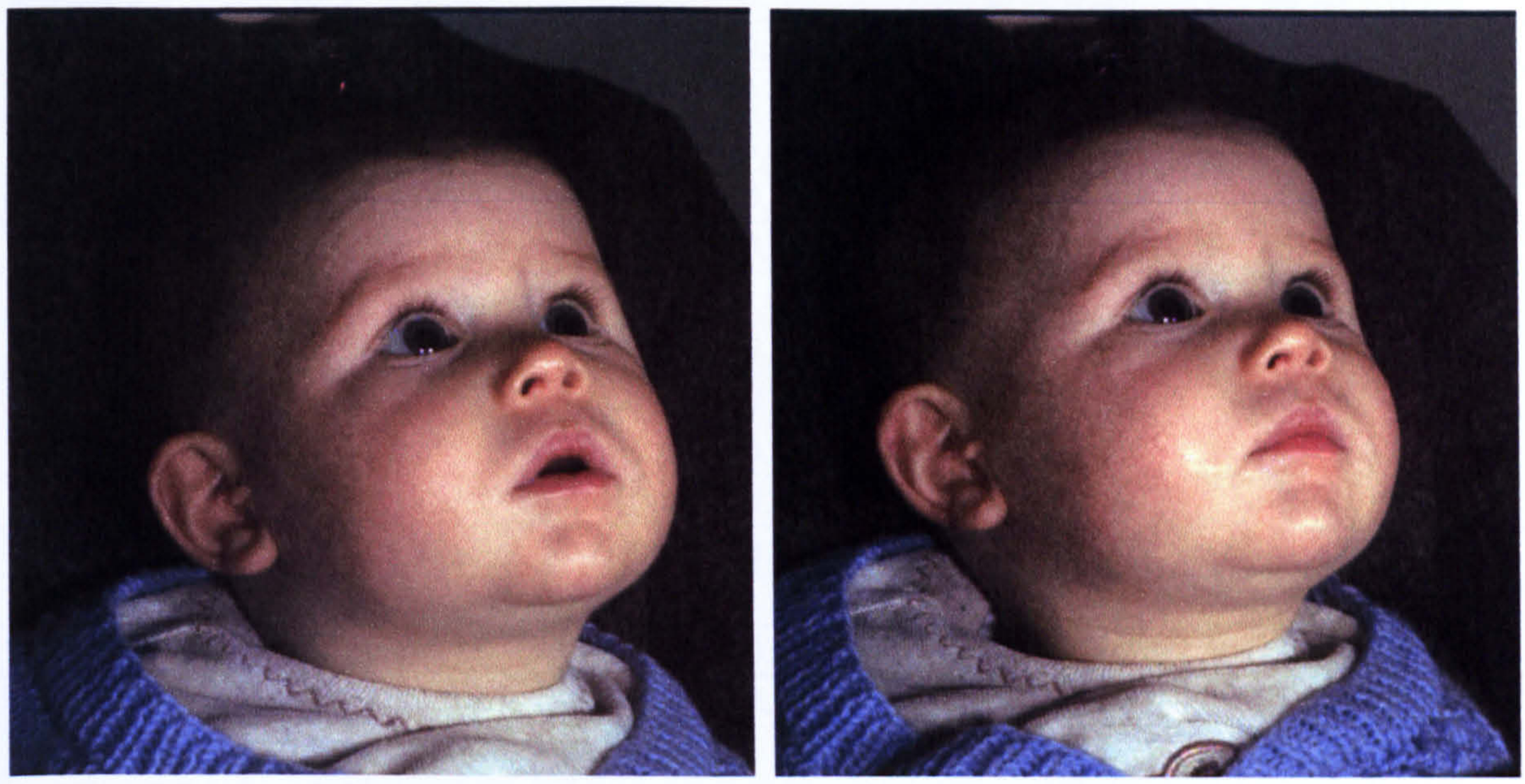
3.3.5.1 Introduction

The majority of the infants were captured at each age with the lips apart and since this was determined to be a fairly repeatable expression it was decided that the cross sectional analysis would focus only on this group. Several infants were captured at one age with the lips apart but at another age with the lips together. All of these subjects could have been excluded from the longitudinal analysis however this would leave a much smaller study sample. It was proposed that some information could be used in the longitudinal analysis from those infants with inconsistent expressions if it was possible to assess which measurements changed with parting the lips and if any were stable.

3.3.5.2 Method of Comparing the Facial Expressions

All of the subjects at each age with both a lips together and a lips apart model captured at one visit were selected. Landmarks were located on the two models of the same child consecutively. 13 pairs of models were available at 3 months, 11 at 6 months, 12 at 1 year and 15 at 2 years. The lips together measurements were subtracted from the lips apart measurements and the mean differences were calculated. Paired t tests were used to investigate if there were any significant differences in the measurements. This would determine whether any facial measurements were stable when parting the lips and which were altered.

Figure 3.9 Images Used to Compare the Lips Apart and Lips Together Expressions



3.3.5.3 Results of Comparing the Facial Expressions

The mean differences between the lips apart and lips together measurements are shown in Table 3.10. The differences were positive if the lips apart measurement was greater and negative if the lips together measurement was greater.

Table 3.10 Differences between the Lips Apart and Lips Together Measurements

Measure	Mean Diff**	P Value*	Mean Diff**	P Value*	Mean Diff**	P Value*	Mean Diff**	P Value*
Age	**3m**		**6m**		**1y**		**2y**	
Face Depth								
obiL-n	-0.10	0.83	0.24	0.54	0.34	0.49	0.46	0.21
obiR-n	0.20	0.77	0.21	0.54	-0.21	0.62	0.35	0.30
obiL-sn	0.15	0.75	0.28	0.48	0.29	0.45	0.37	0.27
obiR-sn	0.44	0.48	0.11	0.78	-0.47	0.24	0.53	0.15
obiL-pg	-0.34	0.29	0.19	0.54	-0.42	0.19	-0.14	0.61
obiR-pg	-0.12	0.82	-0.62	0.26	-0.85	0.08	0.03	0.94
Face Width								
obsR-obsL	0.45	0.46	-0.31	0.46	0.25	0.63	0.01	0.99
obiR-obiL	-0.41	0.63	0.44	0.40	0.23	0.59	0.19	0.71
Face Height								
n-me	3.19	**0.000**	3.23	**0.000**	4.49	**0.000**	3.15	**0.000**
sn-me	3.72	**0.000**	3.63	**0.000**	4.46	**0.000**	4.00	**0.000**
n-sn	-0.26	0.21	-0.19	0.50	0.33	0.15	-0.65	**0.008**
Eyes								
exL-exR	0.35	0.48	0.19	0.43	0.10	0.61	-0.34	0.23
enL-enR	0.07	0.81	0.26	0.48	0.34	0.45	0.17	0.33
exL-enL	-0.15	0.61	0.19	0.35	-0.33	0.08	-0.21	0.34
exR-enR	0.48	0.09	-0.26	0.23	0.12	0.60	-0.21	0.22

Nose								
acL-acR	-0.37	0.12	0.22	0.36	0.29	0.27	-0.23	0.25
alL-alR	0.13	0.47	0.09	0.70	0.42	0.09	-0.24	0.09
acL-prn	-0.33	0.33	0.12	0.66	0.18	0.31	-0.32	0.23
acR-prn	-0.07	0.60	0.11	0.62	0.24	0.11	0.06	0.69
n-prn	-0.03	0.92	0.31	0.31	0.16	0.45	-0.15	0.41
sn-prn	-0.29	0.26	-0.34	0.24	0.24	0.36	-0.51	**0.02**
Nostrils								
sbalL-cL	-0.02	0.88	-0.17	0.30	0.07	0.75	-0.18	0.20
sbalR-cR	0.04	0.73	-0.18	0.21	0.18	0.22	-0.14	0.42
sn'L-al'iL	0.04	0.81	-0.10	0.58	0.51	**0.003**	-0.19	0.45
sn'R-al'iR	-0.16	0.17	0.01	0.95	-0.16	0.31	-0.06	0.72
sn'R-sn'L	0.16	0.50	0.04	0.90	0.21	0.36	-0.15	0.43
Upper Lip								
chR-chL	-0.85	0.16	-0.74	0.18	-1.86	**0.000**	-0.85	0.13
cphL-chL	1.53	**0.005**	1.01	**0.04**	1.92	**0.001**	1.60	**0.000**
cphR-chR	1.00	**0.005**	1.56	**0.001**	1.58	**0.015**	2.30	**0.000**
cphR-cphL	0.19	0.32	0.18	0.50	-0.03	0.88	1.18	0.51
ls-sn	0.06	0.84	-0.03	0.94	-0.84	**0.005**	-0.21	0.40
ls-sto(s)	-0.27	0.44	-0.45	0.12	-1.17	**0.01**	-0.44	0.25
sn-sto(s)	-0.60	**0.05**	-0.69	**0.03**	-2.09	**0.000**	-0.95	**0.001**
sbalL-chL	1.66	**0.001**	1.43	**0.002**	1.63	**0.005**	1.42	**0.000**
sbalR-chR	1.60	**0.002**	2.20	**0.001**	1.40	0.06	2.40	**0.000**
Lower Lip								
chL-li	-0.01	0.98	0.49	0.07	-0.05	0.92	0.28	0.34
chR-li	0.00	1.0	-0.11	0.71	-0.27	0.51	0.58	0.12
li-sto	0.33	0.31	1.06	**0.002**	1.89	**0.001**	1.70	**0.000**
sl-li	-0.60	**0.002**	-0.55	0.18	-0.25	0.57	-0.66	0.06
sl-sto(i)	-0.98	**0.003**	-0.87	**0.03**	0.11	0.71	-0.97	**0.01**
Angles								
acR-prn-acL	-0.40	0.66	0.36	0.72	-0.15	0.91	-0.16	0.70
n-prn-sn	-0.48	0.56	-1.90	0.09	0.24	0.85	-1.12	0.18
prn-sn-ls	0.14	0.93	-1.37	0.48	-3.02	**0.05**	-2.77	**0.02**
li-sl-pg	-0.40	0.89	-8.15	**0.04**	-10.53	**0.006**	-8.06	**0.002**

**The mean difference (mean diff) shown is the lip apart measurement minus the lip together measurement in mm for distances, and in degrees for the angles.

*The P value is the result of paired t tests comparing the lip apart and lip together measurements. P values of less than or equal to 0.05 were judged to be significant and are shown in **bold**.

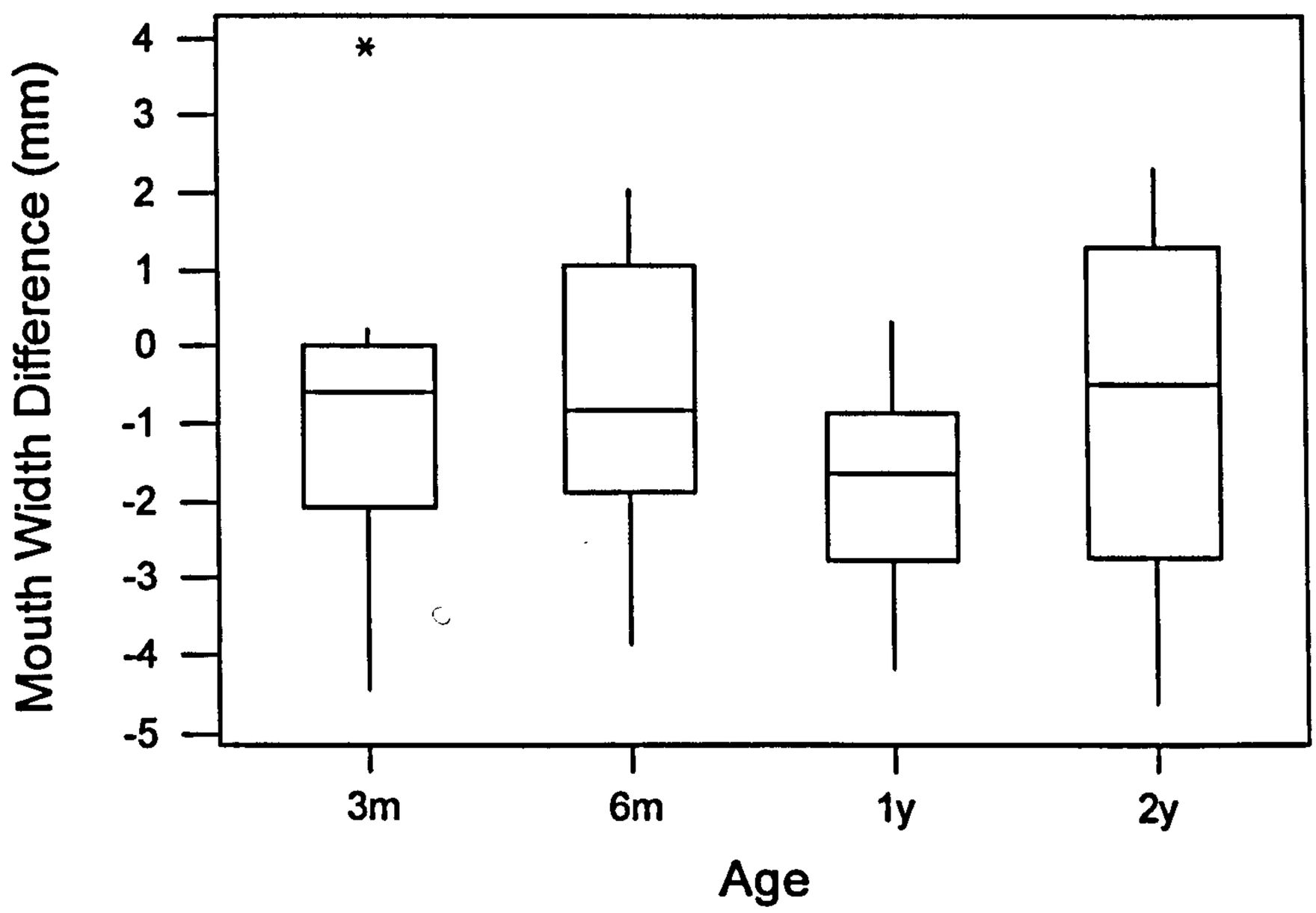
No significant differences were found in any of the face widths or depths measured including mandibular depth (obi-pg) at any age. Lower face height (sn-me) and total face height (n-me) significantly increased when parting the lips at all ages (p=0.000), with mean differences ranging from 3.15 to 4.49 mm. There was no significant difference in upper face height (n-sn) at 3 months, 6 months or 1 year. At 2 years a significant difference of 0.7 mm was found with the distance decreasing when the lips were together.

None of the measurements around the eyes, nose and nostrils were significantly different in the lips apart or lips together models at 3 or 6 months. At 1 and 2 years there were two

small but significant differences around the nose and nostrils. A significant difference (p=0.003) was found in the left nostril width at 1 year, with a mean difference of 0.51 mm. Nasal tip protrusion (sn-prn) was significantly (p=0.02) greater in the lips together models at 2 years with a mean difference of 0.51 mm.

The mouth width was not significantly different in the lips apart or lips together models at 3 months, 6 months or 2 years, although there was a tendency for the width to decrease when parting the lips. At these ages the p values were close to being significant (p=0.16, 0.18, 0.13). At 1 year the mouth width did significantly decrease when parting the lips (p=0.000). The standard deviation of the differences in the mouth widths was around 2 mm showing a large variation in the subjects. This is illustrated in Figure 3.10

Figure 3.10 Differences in Mouth Width between Lips Together and Lips Apart Expressions



Upper vermilion length (cphL-chL, cphR-chR) altered significantly with a mean decrease in length from lips apart to lips together poses of 1.5 mm on the left and 1.6 mm on the right at all ages. Philtrum width (cphR-cphL) did not appear to alter due to facial expression at any of the ages. There was a significant difference between the upper lip height (sn-sto) with the lips apart and the upper lip height (sn-stos) with the lips together with the upper lip height greater in the lip together pose at all ages with p values ranging from 0.00 to 0.05. This tendency was also shown in the upper cutaneous lip height (ls-sn) and upper vermilion height (ls-sto) although the differences were only significant at 1 year. Lateral lip heights (sbalL-chL, sbalR-chR) were also significantly altered at all ages with mean increases of 1.5 mm on the left and 1.9 mm on the right when the lips were parted.

Lower lip heights (sl-sto(i), sl-li) tended to decrease when parting the lips. At 3 months this difference was significant for both measurements. At 6 months there was no significant difference (p=0.18) in lower cutaneous lip height (sl-li), however there was still a significant difference (p=0.03) in lower lip height (sl-sto(i)). At 1 year neither of the lower lip heights was significantly different but at 2 years lower lip height (sl-sto) was significantly reduced and lower cutaneous lip height (sl-li) had a borderline significant difference (p=0.06). Lower vermilion height (li-sto(i)) increased at all ages with a mean increase of 1.3 mm when parting the lips. This difference was significant at all ages except 3 months.

There was no significant difference in any of the angles measured in the lips apart and lips together poses at 3 months but the labiomental angle (li-sl-pg) and nasolabial angle (prn-sn-ls) had differences with large standard deviations of 10.3° and 5.6° respectively. At 6 months, 1 and 2 years significant differences were found in the labiomental angle with a mean decrease in the angle when parting the lips of 9°. Nasolabial angle also tended to decrease when parting the lips from 6 months onwards with this difference being significant at 1 and 2 years (p=0.05,0.02).

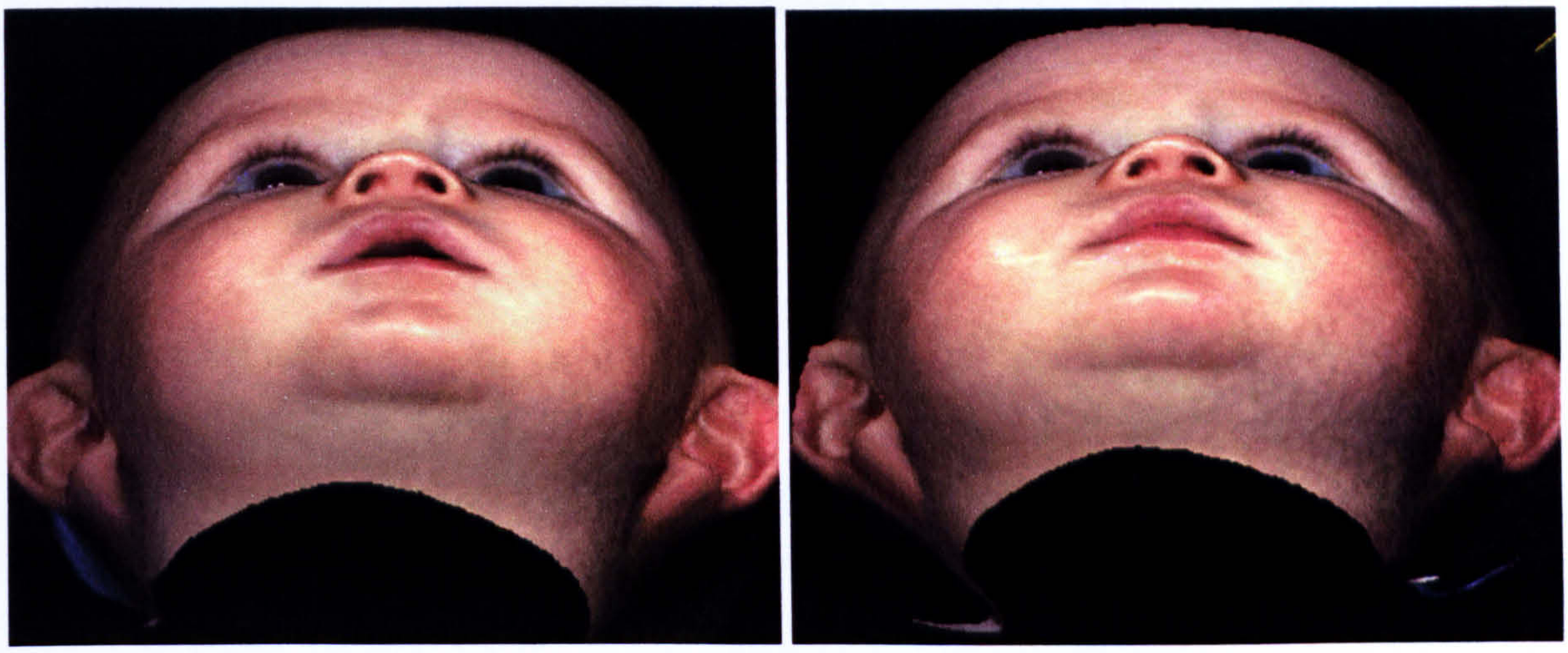
3.3.5.4 Discussion & Conclusions of Comparing the Facial Expressions

As anticipated the total and lower face height measurements were significantly increased by parting the lips. The face height measurements of the lips together models could therefore not be combined with those of lips apart models for the longitudinal analysis.

Upper face height and nasal tip protrusion significantly decreased when parting the lips at 2 years only. It was possible that this was only a chance finding due to repeated t tests. However there may have been a tendency to place the point subnasale (sn) slightly lower in the closed mouth models at 2 years since the nasolabial angle was altered by parting the lips. There were also several significant differences in the lip measurements when parting the lips. The only lip measurements not to show any significant effects were philtrum width and lower vermilion lengths. However, it was not possible to conclude that combining the philtrum width and lower vermilion lengths from lips together and lips apart models was justified. This was due to the fact that paired t tests were used to test for differences but not for equality. Some of the measurements around the lips had borderline significant differences (p=0.07, 0.12) and it would have been incorrect to conclude that the measurements were unaltered when parting the lips since the small differences may have been shown to be significant in a larger sample.

Few of the nose or nostril measurements showed significant changes when parting the lips. Two outliers with differences of 1.5 and 1.2 mm may have accounted for the finding that the left nostril width at 1 year was greater in the lips apart models. Several of the nose measurements did have borderline significant results, most notably soft nose width with p values of 0.09 at 1 and 2 years. Alare was one of the landmarks whose reproducibility improved greatly following standardising the position of the model during landmark location (see section 3.2). This standardised position was based on the plane passing through three points, endocanthion right and left and sublabiale. An alteration in position of the point sublabiale could have occurred if the chin moved when closing the lips resulting in a subtle difference in the standardised position. This could have lead to locating the nasal landmarks in a slightly different position on the lips together and lips apart models. An example of this subtle difference in the standardised position in the lips apart and lips together models at 60° tilt is shown in Figure 3.11.

Figure 3.11 Lips Apart and Lips Together Models Tilted to 60°



The landmarks which were influenced by the standardised positioning were alare, alare' outer, pronasale, stomion superius, stomion inferius, pogonion and menton. The only remaining measurements which may have been unchanged by parting the lips were upper face depth, face width, and measurements around the eyes and nostrils. Even some of these measurements had borderline significant differences.

Ninety three infants attended at all four ages and 71 of these had four images with a lips apart model. Since there were a reasonable number of cases with a lip apart expression at every age, it was concluded that all the results from lips together models would be excluded from this study, for both the cross sectional and longitudinal analysis, to reduce the possibility of any systematic bias.

4 Cross Sectional Results

4.1 Description of Subjects

4.1.1 Recruitment

One hundred subjects were recruited from March 2000 until October 2000, fifty females and fifty males. Fifty five subjects were recruited in the Queen Mother's Hospital maternity wards, eighteen at a local health centre immunisation clinic, twenty through personal contacts or at Glasgow Dental Hospital & School and the remainder through various means including breast feeding support groups at the Royal Hospital for Sick Children. All the infants recruited were born in the West of Scotland.

Ninety eight infants attended at 3 months, ninety seven attended at both 6 months and 1 year and ninety five attended at 2 years. Two of the subjects who had been recruited were unable to attend at 3 months and entered the study at 6 months. Three subjects therefore dropped out of the study after the first visit and a further two were lost to follow up after 1 year.

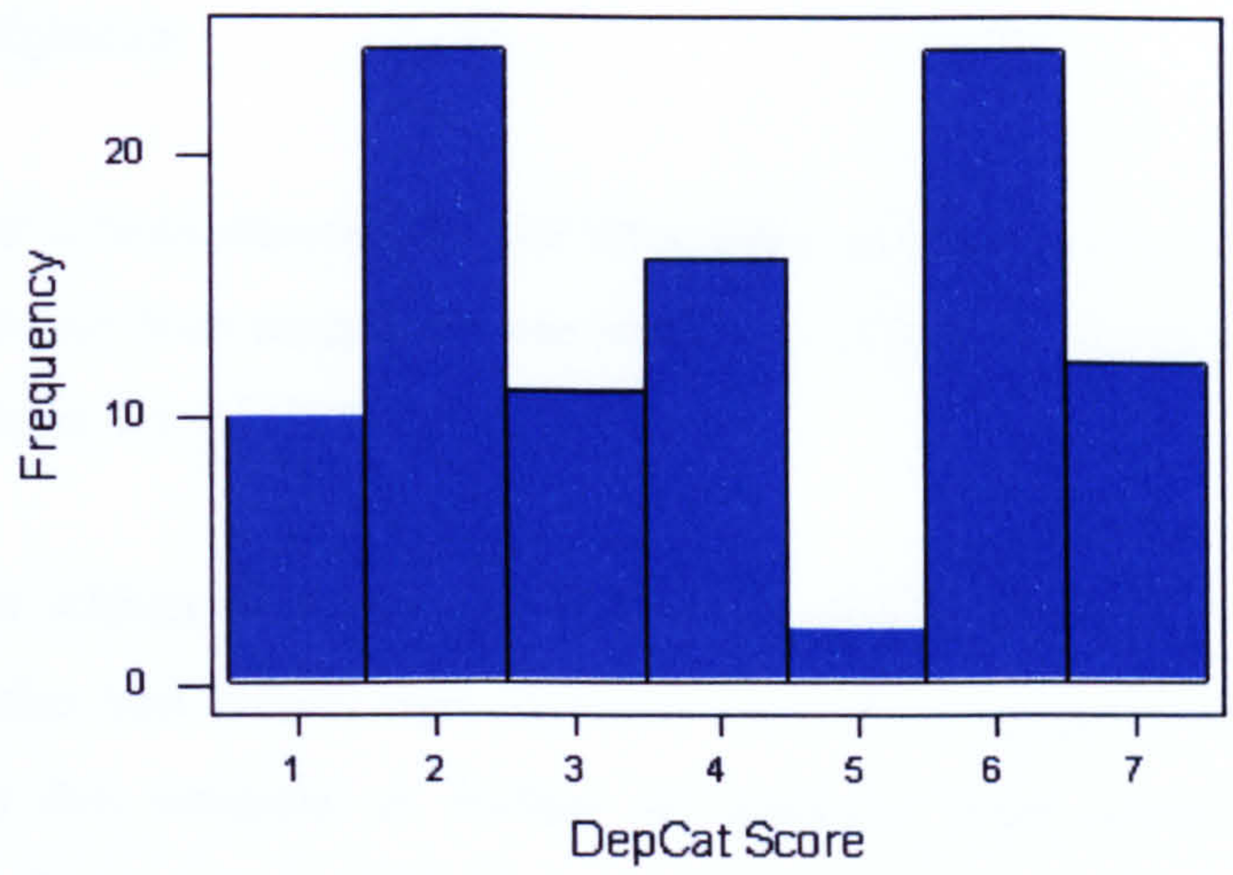
4.1.2 Birth Weight

The mean birth weight of the females was 3.38 $\pm$ 0.47 kg. The mean birth weight of the males was 3.75 $\pm$ 0.43 kg. Five of the females were under the 3rd centile (2.8 kg) for infants born at 40 weeks and one of the females was over the 97th centile (4.3 kg) (Gairdner & Pearson 1988b). One of the males was under the 3rd centile (2.85 kg) but none of the males was over the 97th centile (Gairdner & Pearson 1988a).

4.1.3 Deprivation Category

Thirty four of the infants were in deprivation category 1 or 2. Twenty nine were in deprivation categories 3 to 5. Thirty six were from the higher deprivation categories 6 and 7. Figure 4.1 shows peaks in frequency of depcat 2 and 6 reflecting the most common depcats around the area of the Queen Mother's Hospital and Glasgow Dental Hospital & School where most of the infants were recruited.

Figure 4.1 Depcat Distribution



4.1.4 Parental Birthplace

Seventy four of the mothers and sixty nine of the fathers were born in the West of Scotland. Six of the mothers and eight of the fathers were born elsewhere in Scotland and sixty six of the infants had two parents who were Scottish.

Fifteen of the mothers and twenty three of the fathers were born in England or Ireland. Five of the mothers but none of the fathers were born outside the UK or Ireland. These mothers were born in France, Germany, South Africa, South America or Australia. They were all Caucasian and claimed European descent.

4.1.5 Breast Feeding

Eighty two of the mothers reported to have been breast feeding at birth. Seventy of these were still breast feeding at the 3 month stage.

4.2 Three Months

4.2.1 Subjects

Ninety eight infants attended for the first data collection at the 3 month stage. Two of the infants who had been recruited were unable to attend at this stage. The subject details are shown in Table 4.1.

Eighty three infants, 41 males and 42 females were captured at 3 months with a lips apart pose. A further nine infants were captured with a lips together pose and their results are not included in this analysis. A further six captures were unsuccessful due to technical problems at the start of the study (see section 2.3.3.2).

The mean age at the three month stage was 84 days with a standard deviation (±) of 7 days. The oldest child was 100 days and the youngest 71 days. T tests showed there was no statistically significant difference in the age of the males compared to the females.

Table 4.1 Subject Details at 3 Months

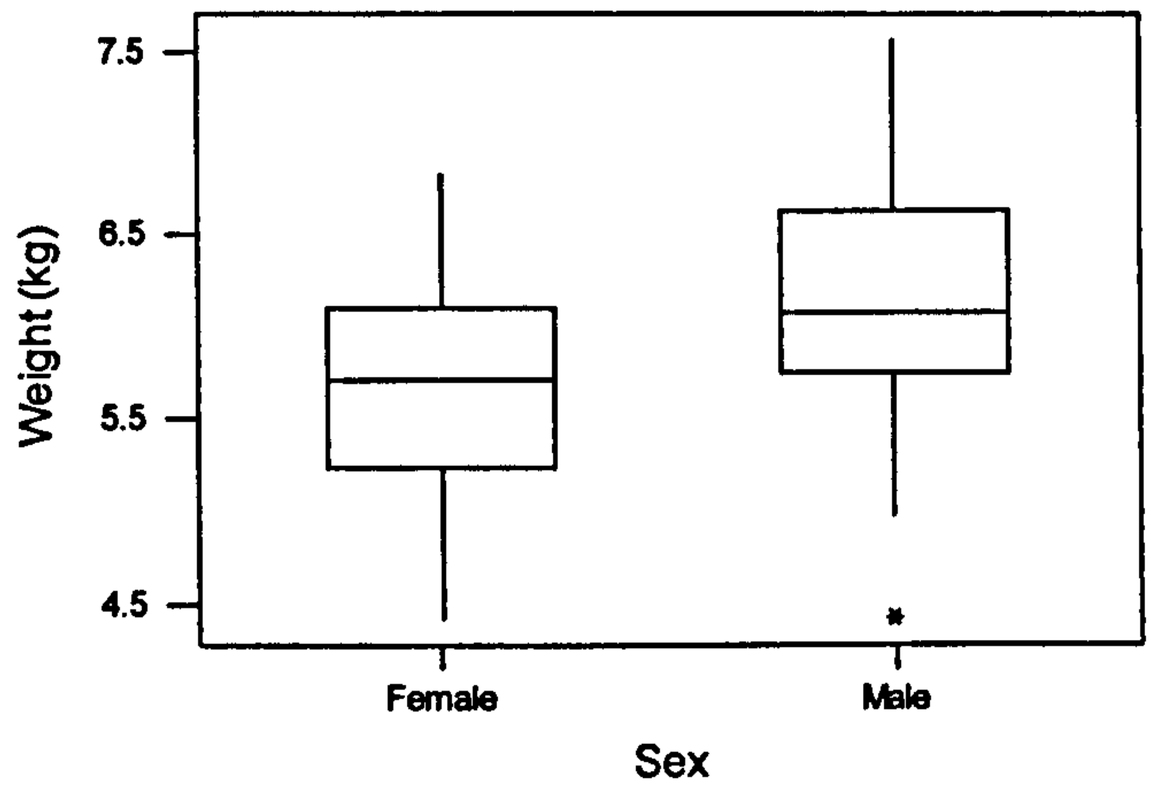
	Mean	Mean Female	Mean Male	P Value*
Age (days)	83.9 ± 6.77	84.0 ± 7.1	83.8 ± 6.3	0.88
Weight (kg)	5.93 ± 0.69	5.70 ± 0.61	6.18 ± 0.69	**0.001**
Length (cm)	60.5 ± 2.2	59.7 ± 2.1	61.3 ± 2.0	**0.001**
Head Circumference (cm)	40.6 ± 1.5	39.9 ± 1.4	41.3 ± 1.3	**0.000**

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

4.2.2 Body measurements

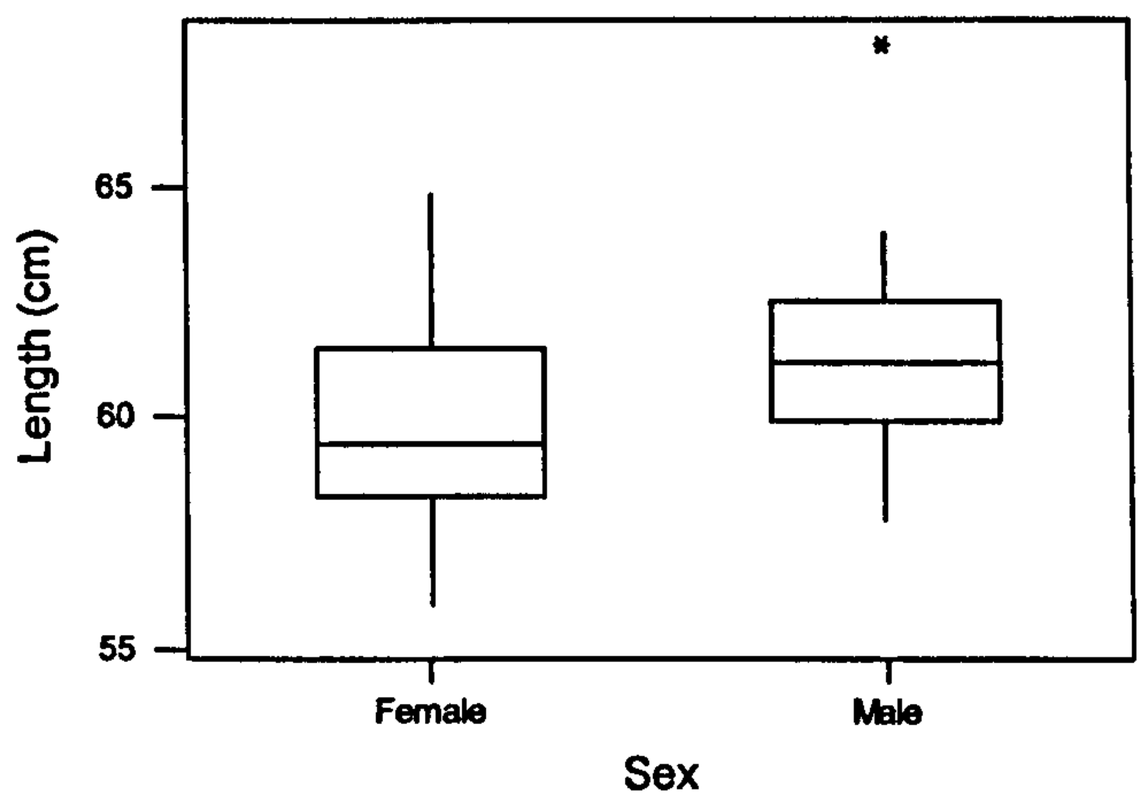
All of the body measurement data was normally distributed. The details are shown in Table 4.1 Overall the females were smaller than the males. The mean weight of all of the infants was 5.93 ± 0.69 kg. The mean weight of the females (5.70 ± 0.61 kg) was lower than the males (6.18 ± 0.69 kg). A t test showed this difference was significant with $p = 0.001$. This is illustrated in Figure 4.2.

Figure 4.2 Weight at 3 Months



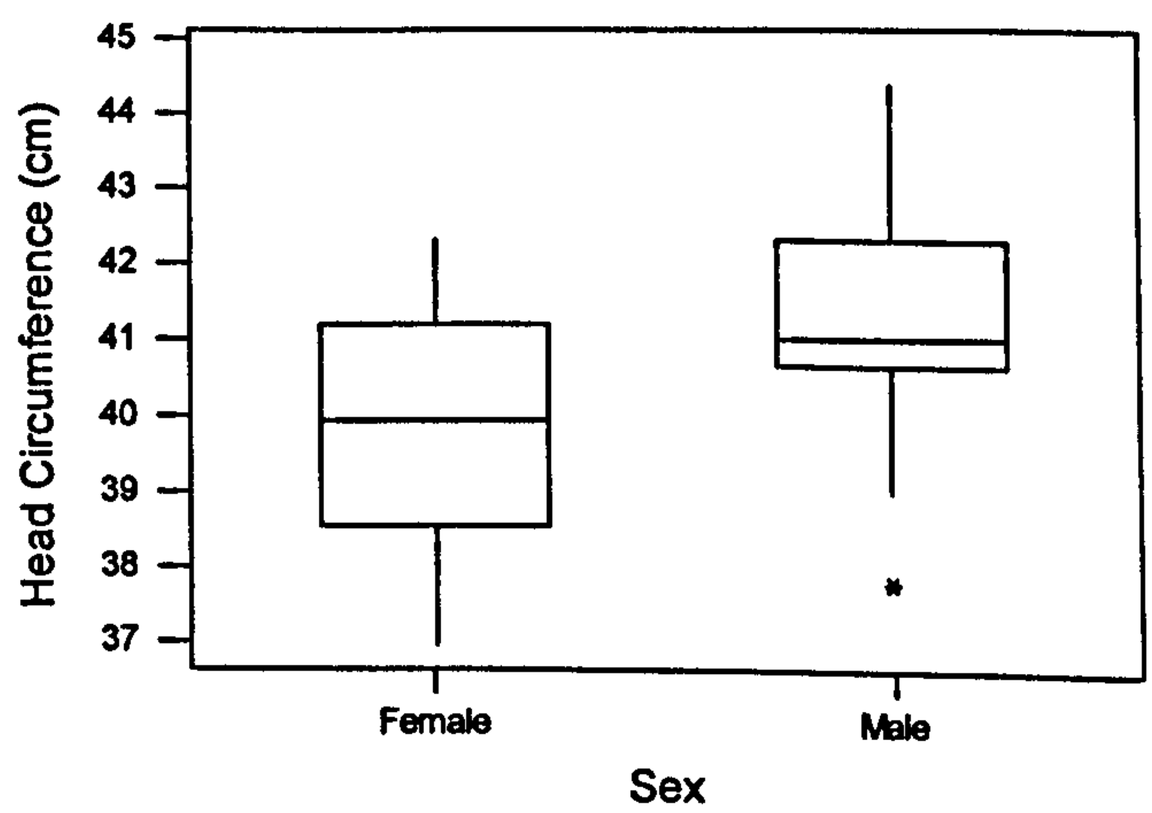
The mean length of all the infants was 60.5 ± 2.1 cm. The mean length of the females was 59.7 ± 2.1 cm and of the males 61.3 ± 2.0 cm. Two sample t tests showed this difference was significant with p = 0.001. This is illustrated in Figure 4.3.

Figure 4.3 Length at 3 Months



The mean head circumference of all the infants was 40.6 ± 1.5 cm. The female mean was 39.9 ± 1.4 cm and the male 41.3 ± 1.3 cm. Two sample t tests showed this difference was significant with p = 0.000. This is illustrated in Figure 4.4.

Figure 4.4 Head Circumference at 3 Months



4.2.3 Missing landmarks

Five of the landmarks were recorded as missing on some of the 3 month models. The details of the missing landmarks are shown in Table 4.2. The only landmarks to be missing were menton (me), which was under the chin, and the ear landmarks, otobasion superius right and left (obsR, obsL) and otobasion inferius (obiR, obiL). Menton was recorded as missing in the cases where an image could not be captured under the chin. This occurred in infants with little head control who could not be captured looking upwards. The main reason the ear landmarks were missing in the 3 month models was that the lighting around the ears was compromised if the face was not in a central position. The ear landmarks, especially otobasion superius, were also occasionally obscured by hair. Thirty one models were found to have one or more missing landmarks. The right ear landmarks were more frequently missing than the left.

Table 4.2 Missing Landmarks at 3 Months

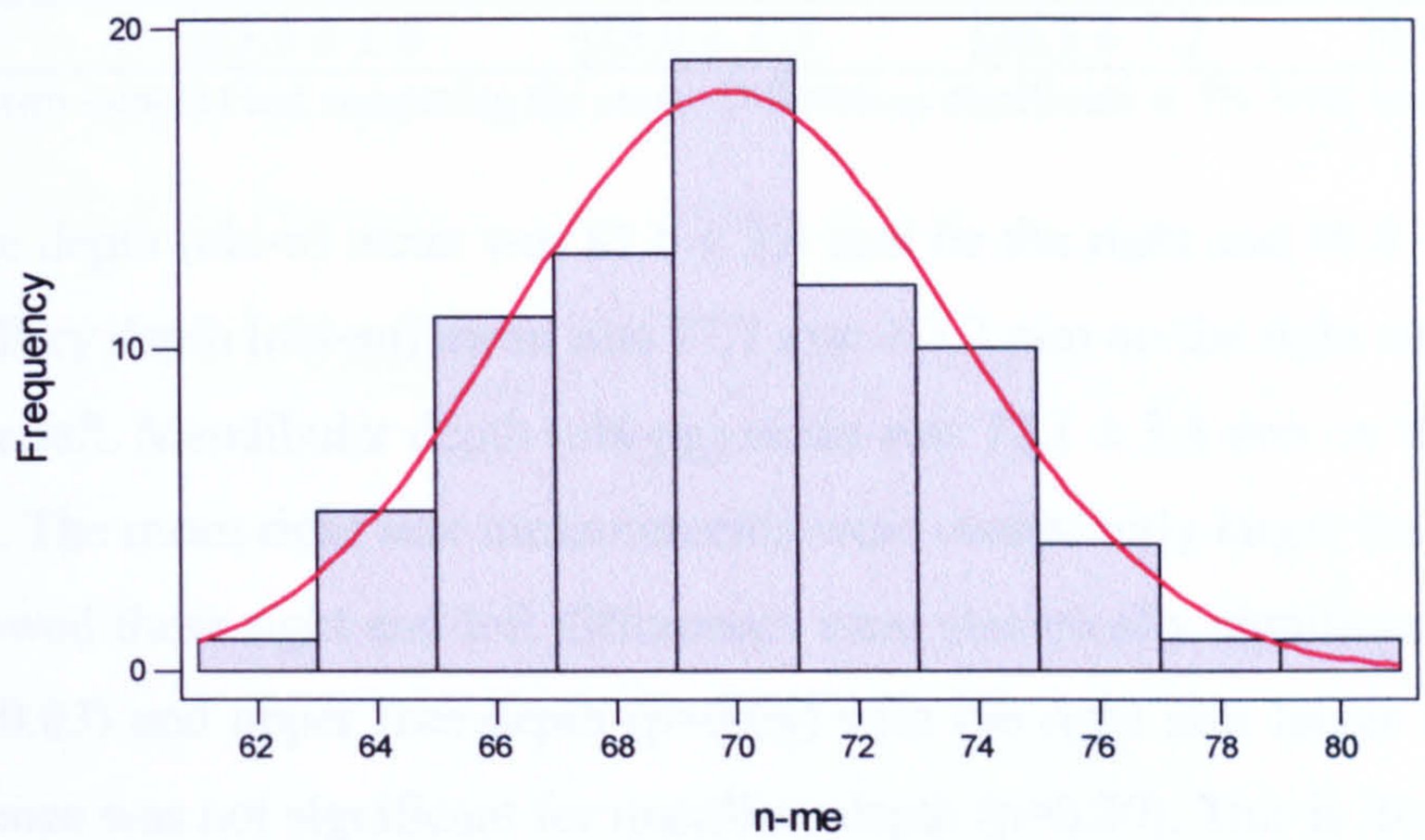
Landmark	Missing Frequency
me	6
obsR	16
obsL	6
obiR	16
obiL	15

4.2.4 Linear and Angular Measurements at 3 Months

The distributions of the linear and angular measurements were viewed as histograms to assess whether they were normally distributed. All the measurements were well approximated by a normal distribution. This is illustrated in Figure 4.5.

Any models with marked outliers were re-examined in the Facial Analysis Tool with the landmarks recalled. Landmarks were relocated if they were obviously misplaced and the measurement files were regenerated.

Figure 4.5 Histogram Showing Distribution of Total Face Height Measurements with a Normal Curve Superimposed



Means and standard deviations were calculated. Two sample t tests were used to determine whether there were significant differences between the sexes. These results are shown in Tables 4.3 to 4.7. Paired t tests were used on the paired measurements to assess whether there were any left or right side differences. Any significant side differences are described in the text but not in the tables.

4.2.4.1 Face Height, Width and Depth

The means and standard deviations of face heights, widths and depths at 3 months are shown in Table 4.3.

Table 4.3 Measurements of the Face at 3 Months in mm

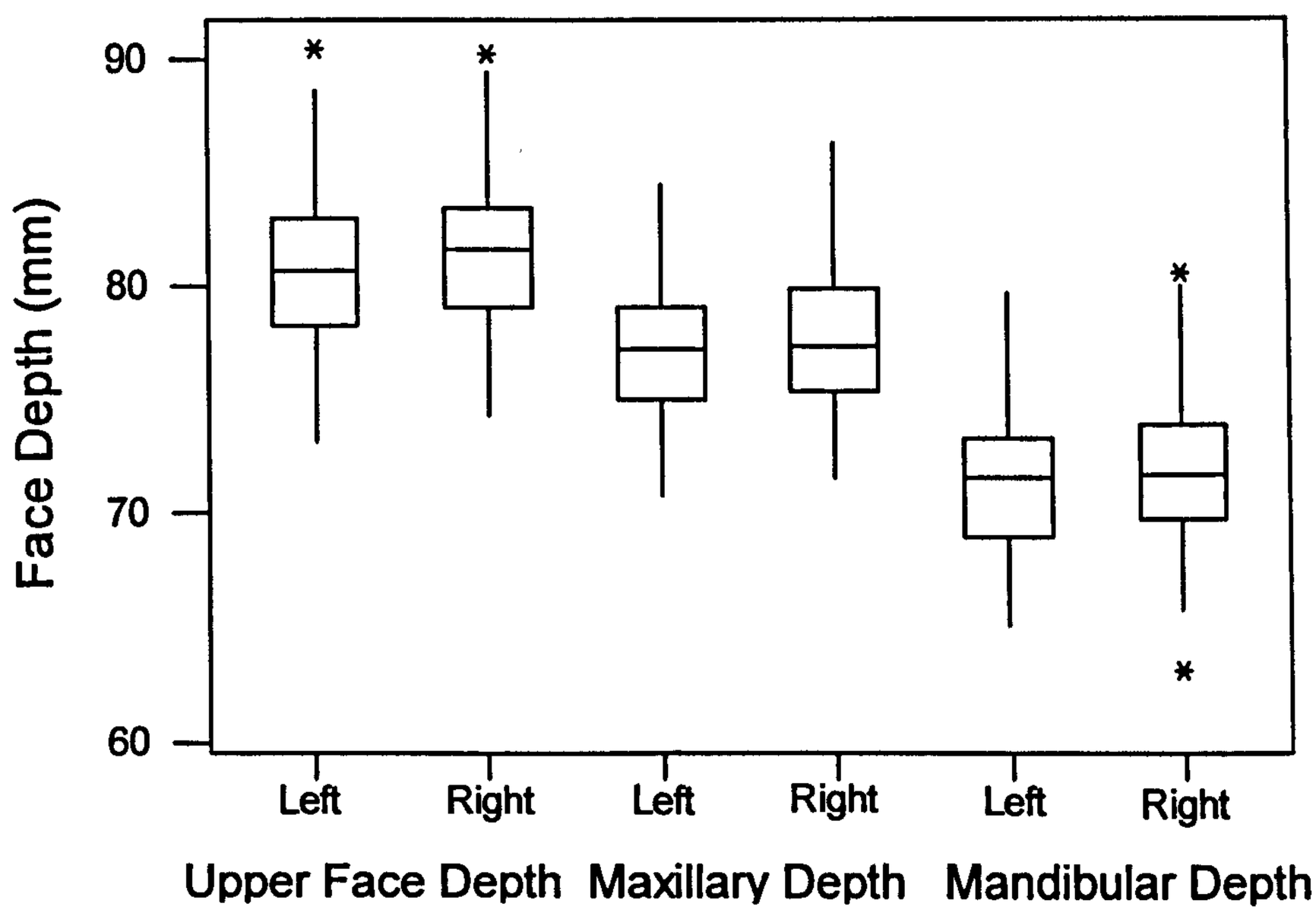
	Mean	Female Mean	Male Mean	P Value*
Face Depth				
obiL-n	80.8 ± 3.5	79.1 ± 2.9	82.1 ± 3.5	**0.000**
obiR-n	81.6 ± 3.4	80.3 ± 3.3	82.7 ± 3.2	**0.003**
obiL-sn	77.3 ± 3.2	75.6 ± 2.6	78.6 ± 3.0	**0.000**
obiR-sn	77.7 ± 3.2	76.3 ± 2.8	78.9 ± 3.0	**0.001**
obiL-pg	71.3 ± 3.2	70.1 ± 2.8	72.2 ±3.1	**0.006**
obiR-pg	72.1 ± 3.4	70.9 ± 3.2	73.1 ± 3.3	**0.007**
Face Width				
obsR-obsL	114.4 ± 4.5	113.0 ± 4.4	115.8 ± 4.3	**0.001**
obiR-obiL	93.9 ± 4.3	92.3 ± 3.6	95.0 ± 4.5	**0.013**

Face Height				
n-me	69.9 ± 3.7	68.8 ± 3.3	71.2 ± 3.7	**0.004**
sn-me	48.0 ± 3.0	47.2 ± 2.9	48.8 ± 3.0	**0.018**
n-sn	25.5 ± 1.6	25.0 ± 1.3	26.1 ± 1.7	**0.001**

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

Upper face depth (obi-n) mean was 81.6 ± 3.4 mm on the right and 80.8 ± 3.5 mm on the left. Maxillary depth (obi-sn) mean was 77.7 mm ± 3.2 mm on the right and 77.3 mm ± 3.2 mm on the left. Mandibular depth (obi-pg) mean was 72.1 ± 3.4 mm on the right and 71.3 ± 3.2 mm. The mean right side measurements were consistently larger than the left. Paired t tests showed these right and left differences were statistically significant for mandibular depth (p=0.03) and upper face depth (p=0.04) with the right side larger than the left, but the difference was not significant for maxillary depth (p=0.20). This is illustrated in Figure 4.6.

Figure 4.6 Right and Left Differences in Face Depth at 3 Months

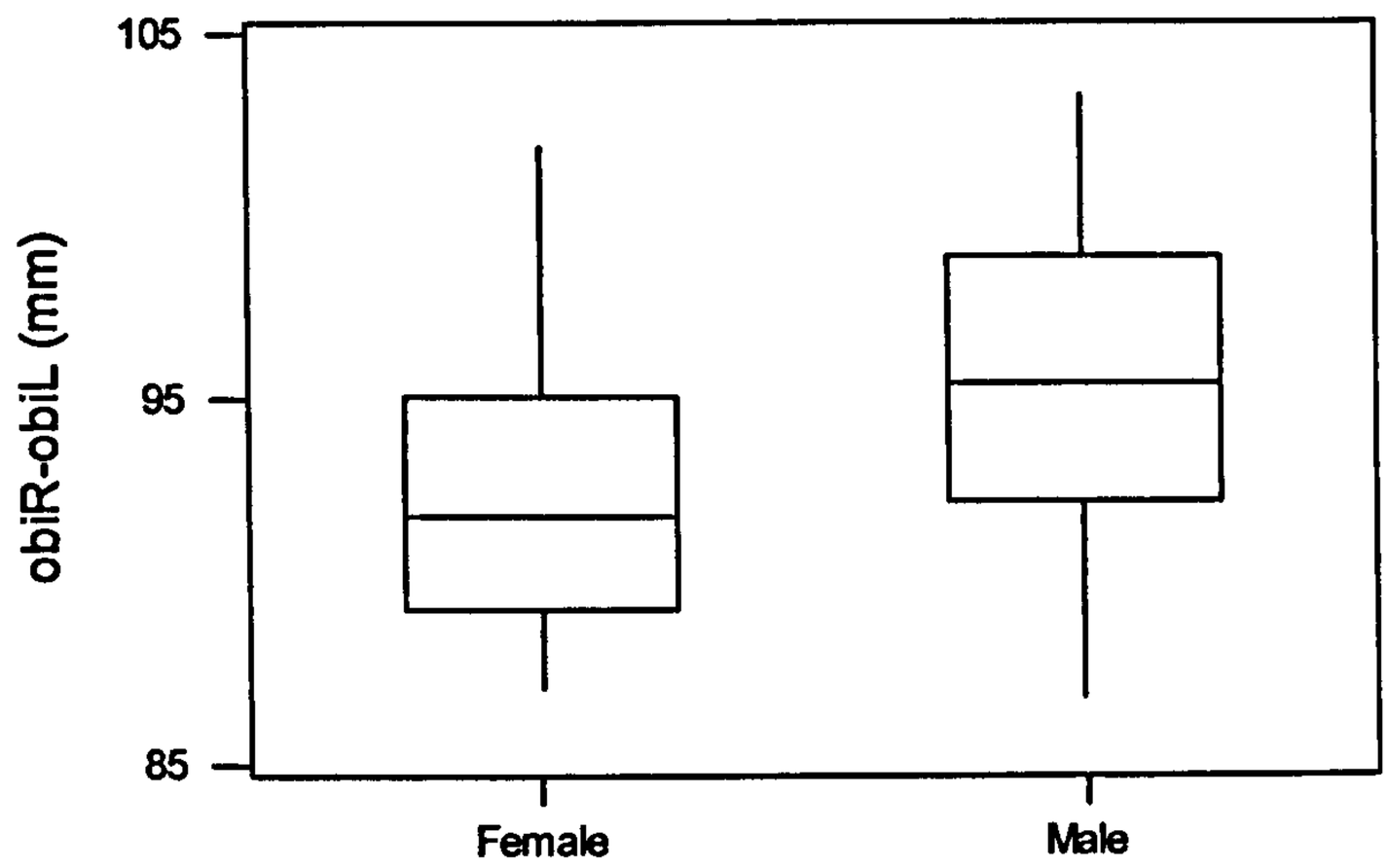


The males were statistically significantly larger than the females for all of the face depth measurements, with mean differences of 2.1 to 3.0 mm.

The mean total face height (n-me) was 69.6 ± 3.7 mm. Upper face height (n-sn) mean was 25.5 ±_1.6 mm and lower face height mean was 48.0 ± 3.0 mm. The male face height was statistically significantly greater than the females for all of these measurements, with mean differences of 1.1 to 2.4 mm.

The upper face width (obsR-obsL) had a mean of 114.4 ± 4.5 mm. The lower face width (obiR-obiL) mean was 93.9 ± 4.3 mm. The male face width was statistically significantly greater than the females for both of these measurements, with mean differences of 2.7 to 2.8 mm. This is illustrated in Figure 4.7. These results were based on the measurements of only 67 infants for upper face width and 59 infants for lower face width since the ear landmarks were frequently missing in these models.

Figure 4.7 Gender Differences in Lower Face Width at 3 Months



4.2.4.2 Eye Measurements

The means and standard deviations of the measurements around the eyes are shown in Table 4.4.

Table 4.4 Measurements of the Eyes at 3 Months in mm

	Mean	Female Mean	Male Mean	P Value*
Eyes				
exR-exL	66.1 ± 2.7	65.2 ± 2.4	67.0 ± 2.8	**0.002**
enL-enR	26.7 ± 1.7	26.2 ± 1.7	27.2 ± 1.6	**0.009**
exL-enL	20.4 ± 1.0	20.1 ± 0.8	20.6 ± 1.1	**0.035**
exR-enR	20.5 ± 1.1	20.3 ± 1.0	20.8 ± 1.2	0.086

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

The biocular width (exL-exR) mean was 66.1 ± 2.7 mm. The intercanthal width (enL-enR) mean was 26.7 ± 1.7 mm. Palpebral fissure width (ex-en) mean was 20.4 ± 1.0 mm on the left and 20.5 ± 1.1 mm on the right. Biocular and intercanthal widths were statistically significantly greater in males than females with mean differences of 1.0 to 1.8 mm. A

significant difference in palpebral fissure width between males and females was also found on the left side (p=0.035) although the mean difference was only 0.5 mm. This difference was not found to be significant on the right. A paired t test found a significant difference (p=0.043) between the left and right palpebral fissure widths with the right side being a mean of 0.19 mm larger.

4.2.4.3 Nose and Nostril Measurements

The means and standard deviations of the measurements around the nose and nostrils are shown in Table 4.5.

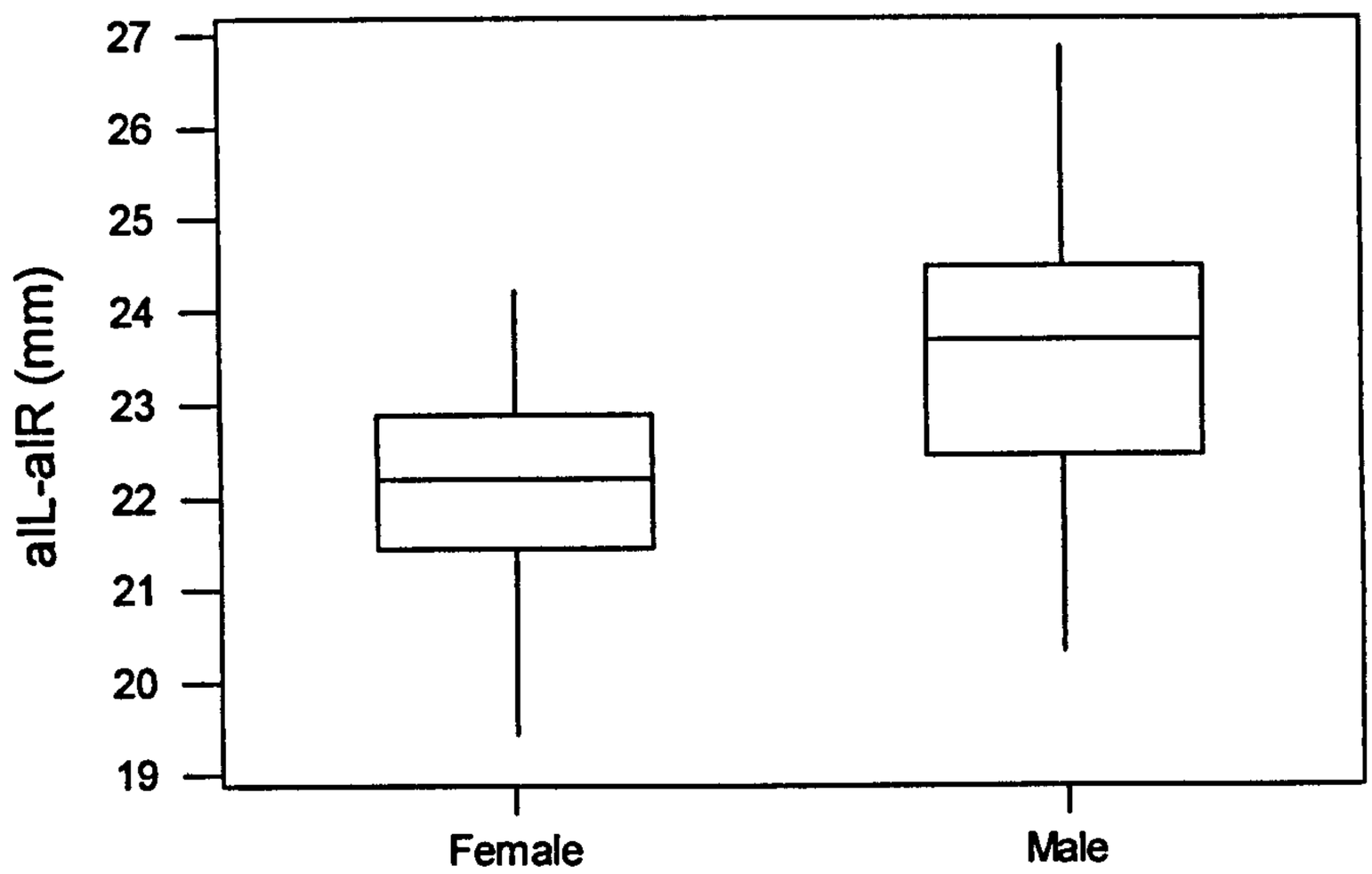
Table 4.5 Measurements of the Nose and Nostrils at 3 Months in mm

	Mean	Female Mean	Male Mean	P Value*
Nose				
acL-acR	25.2 ± 1.4	24.5 ±1.1	25.9 ± 1.3	**0.000**
alL-alR	22.9 ± 1.4	22.2 ± 1.0	23.6 ± 1.4	**0.000**
acL-prn	16.3 ± 1.1	15.9 ± 0.8	16.8 ± 1.2	**0.000**
acR-prn	17.1 ± 1.1	16.4 ± 0.8	17.7 ± 0.9	**0.000**
n-prn	20.4 ± 1.7	19.8 ± 1.5	21.1 ± 1.6	**0.000**
sn-prn	9.7 ± 0.9	9.5 ± 0.9	9.8 ± 1.0	0.079
Nostrils				
sbalL-cL	6.0 ± 0.7	5.8 ± 0.6	6.3 ± 0.7	**0.001**
sbalR-cR	5.7 ± 0.7	5.5 ± 0.6	6.0 ± 0.7	**0.001**
sn'L-al'iL	4.3 ± 0.7	4.1 ± 0.7	4.6 ± 0.6	**0.000**
sn'R-al'iR	4.7 ± 0.7	4.4 ± 0.6	5.0 ± 0.8	**0.001**
sn'R-sn'L	5.4 ± 0.9	5.3 ± 0.8	5.6 ± 0.9	0.12

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in bold.

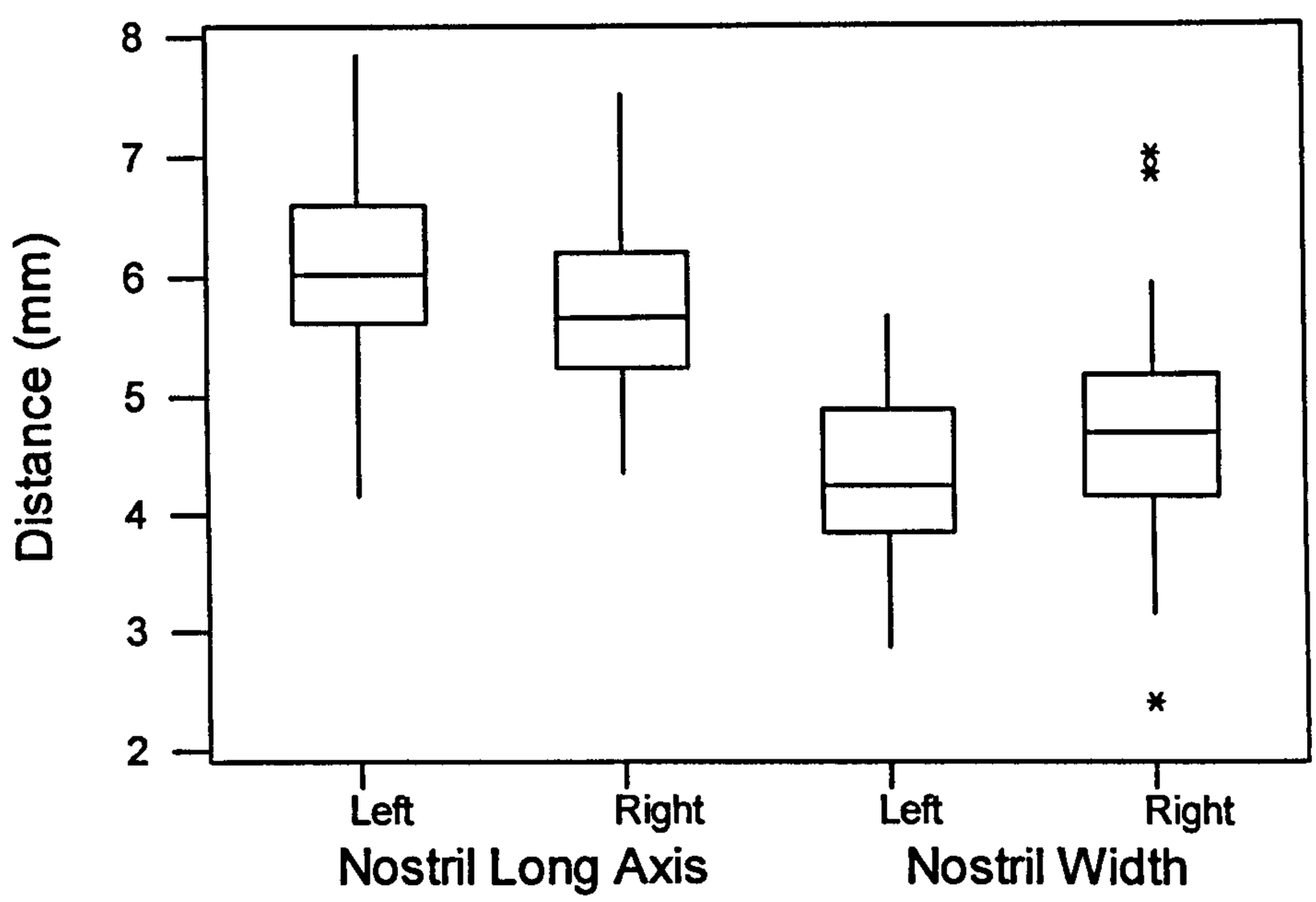
Anatomic nose width (acR-acL) and soft nose width (alR-alL) had means of 25.2 ± 1.4 mm and 22.9 ± 1.4 mm respectively. Nasal dorsum length (n-prn) mean was 20.4 ± 1.7 mm and nasal tip protrusion (sn-prn) mean was 9.7 ± 0.9 mm. All of the nose measurements were significantly greater in males than females except nasal tip protrusion. The difference in soft nose width is illustrated in Figure 4.8.

Figure 4.8 Gender Differences in Soft Nose Width at 3 Months



The nostril long axis (sbal-c) mean was 6.0 ± 0.7 mm on the left and 5.7 ± 0.7 mm on the right. Nostril width (sn'-al'i) mean was 4.3 ± 0.7 mm on the left and 4.7 ± 0.7 mm on the right. Paired t tests showed these right and left differences were statistically significant with the left nostril longer (p=0.000) and narrower (p=0.000) than the right. This is illustrated in Figure 4.9.

Figure 4.9 Right and Left Differences in Nostril Measurements at 3 Months



Nostril length and width were statistically significantly greater in males than females with mean differences of 0.5 to 0.6 mm. This difference was not found in columella width (sn'R-sn'L).

4.2.4.4 Upper and Lower Lip Measurements

The means and standard deviations of the measurements around the upper and lower lips are shown in Table 4.5.

Table 4.6 Measurements of the Upper and Lower Lips at 3 Months in mm

	Mean	Female Mean	Male Mean	P Value*
Upper Lip				
chR-chL	29.1 ± 2.7	28.5 ± 2.4	29.7 ± 2.9	0.052
cphL-chL	18.1 ± 1.8	17.9 ± 1.7	18.2 ± 2.0	0.51
cphR-chR	18.3 ± 1.8	18.0 ± 1.7	18.5 ± 1.8	0.18
cphR-cphL	6.7 ± 0.9	6.2 ± 0.8	7.2 ± 0.8	**0.000**
ls-sn	10.3 ± 1.4	10.0 ± 1.2	10.7 ± 1.4	**0.018**
ls-stos	5.4 ± 1.2	5.4 ± 1.0	5.3 ± 1.5	0.63
sn-stos	14.0 ± 1.4	13.7 ± 1.2	14.3 ± 1.5	**0.035**
sbalL-chL	23.1 ± 1.8	22.7 ± 1.8	23.5 ± 1.7	**0.038**
sbalR-chR	23.5 ± 1.9	23.1 ± 2.0	24.0 ± 1.8	**0.028**
Lower Lip				
chL-li	15.0 ± 1.5	14.7 ± 1.4	15.4 ± 1.6	**0.018**
chR-li	15.8 ± 1.5	15.4 ± 1.3	16.1 ± 1.6	**0.037**
li-stoi	5.6 ± 1.1	5.4 ± 1.2	5.8 ± 1.0	0.078
sl-li	6.6 ± 1.3	6.6 ± 1.2	6.6 ± 1.4	0.89
sl-stoi	10.8 ± 0.9	10.7 ± 0.9	10.8 ± 0.9	0.52

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

Mouth width (chR-chL) mean was 29.1 ± 2.7 mm. No statistically significant difference was found in this measurement between males and females although it was close to being significant (p=0.052). Philtrum width (cphL-cphR) mean was 6.7 ± 0.9 mm. This measurement was statistically significantly greater in males than females (p=0.000) with a mean difference of 1.0 mm.

Upper lip height measurements were all significantly greater in males than females except the upper cutaneous lip height (ls-stos). The lateral lip heights (sbalL-chL, sbalR-chR) had means of 23.1 ± 1.8 mm on the left and 23.5 ± 1.9 mm on the right. Paired t test showed this right and left difference was statistically significant (p=0.004). The lower vermilion lengths (chR-li, chL-li) were found to be statistically significantly greater in males than females. A paired t test found the lower vermilion length was significantly greater on the right (p=0.037) with a mean of 15.8 ± 1.5 mm on the right and 15.0 ± 1.5 mm on the left.

4.2.4.5 Angular Measurements

The means and standard deviations of the angular measurements are shown in Table 4.7.

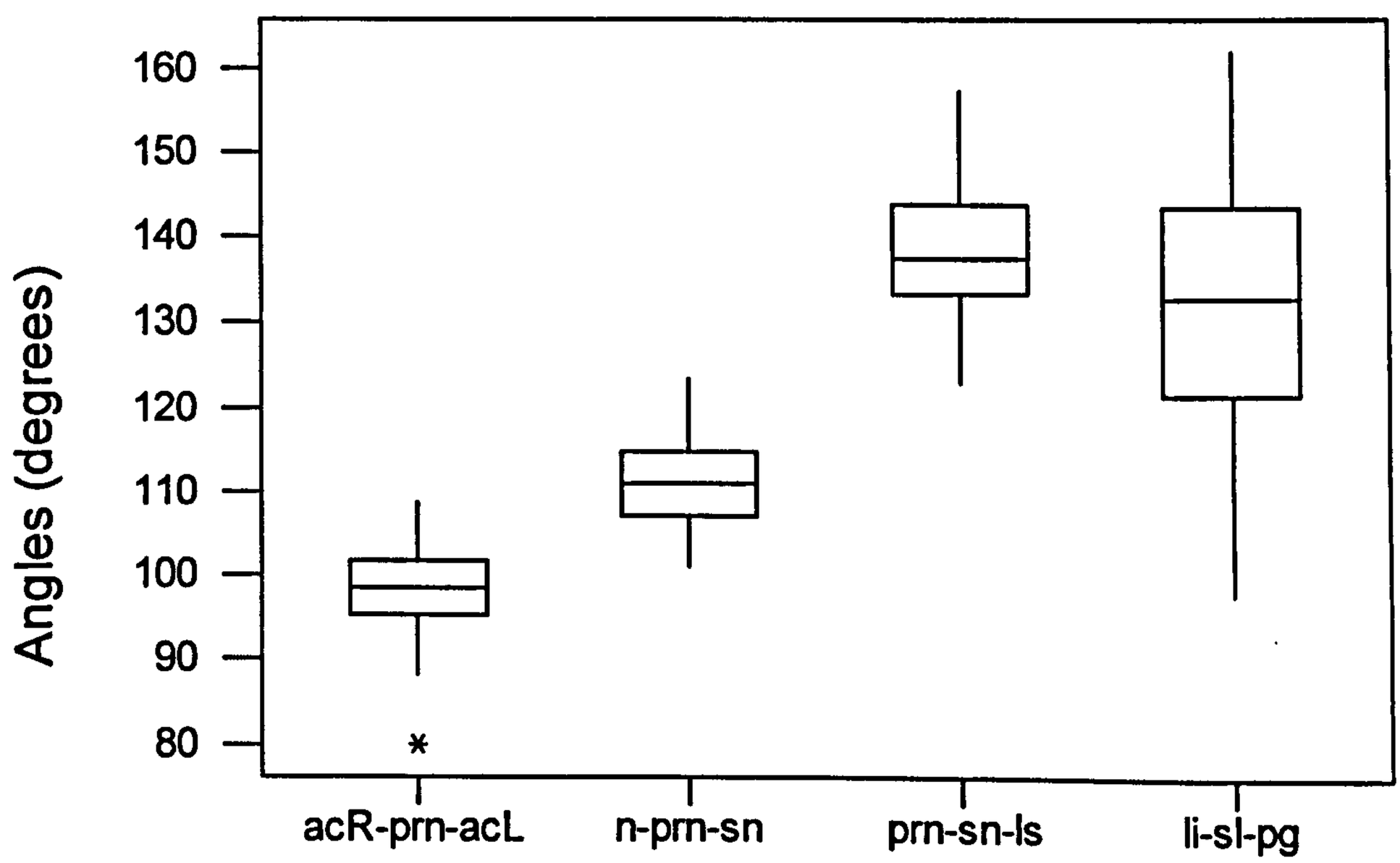
Table 4.7 Angles of the Face at 3 Months in degrees

	Mean	Female Mean	Male Mean	P Value*
Angles				
acR-prn-acL	98.5 ± 5.3	98.0 ± 4.7	98.9 ± 5.9	0.43
n-prn-sn	111.1 ± 4.7	110.7 ± 4.2	111.3 ± 5.1	0.55
prn-sn-ls	138.1 ± 7.3	138.0 ± 6.2	138.2 ± 8.3	0.91
li-sl-pg	133.1 ± 13.2	131.9 ± 12.4	134.3 ± 14.0	0.39

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in bold.

The nasal tip angle (n-prn-sn) mean was 111 ± 5°. The nasolabial angle (prn-sn-ls) mean was 138 ± 7°. The labiomental angle (li-sl-pg) mean was 133 ± 13°. The nasal tip horizontal displacement angle (acR-prn-acL) mean was 99 ± 5°. There were no significant male or female differences in these angles. The distribution of the angles is shown in Figure 4.10.

Figure 4.10 Angles of the Face at 3 Months



4.2.5 Correlations of Body and Face Measurements at 3 Months

4.2.5.1 Correlations of Body Measurements

Correlations of weight, length and head circumference at 3 months are shown in Table 4.8.

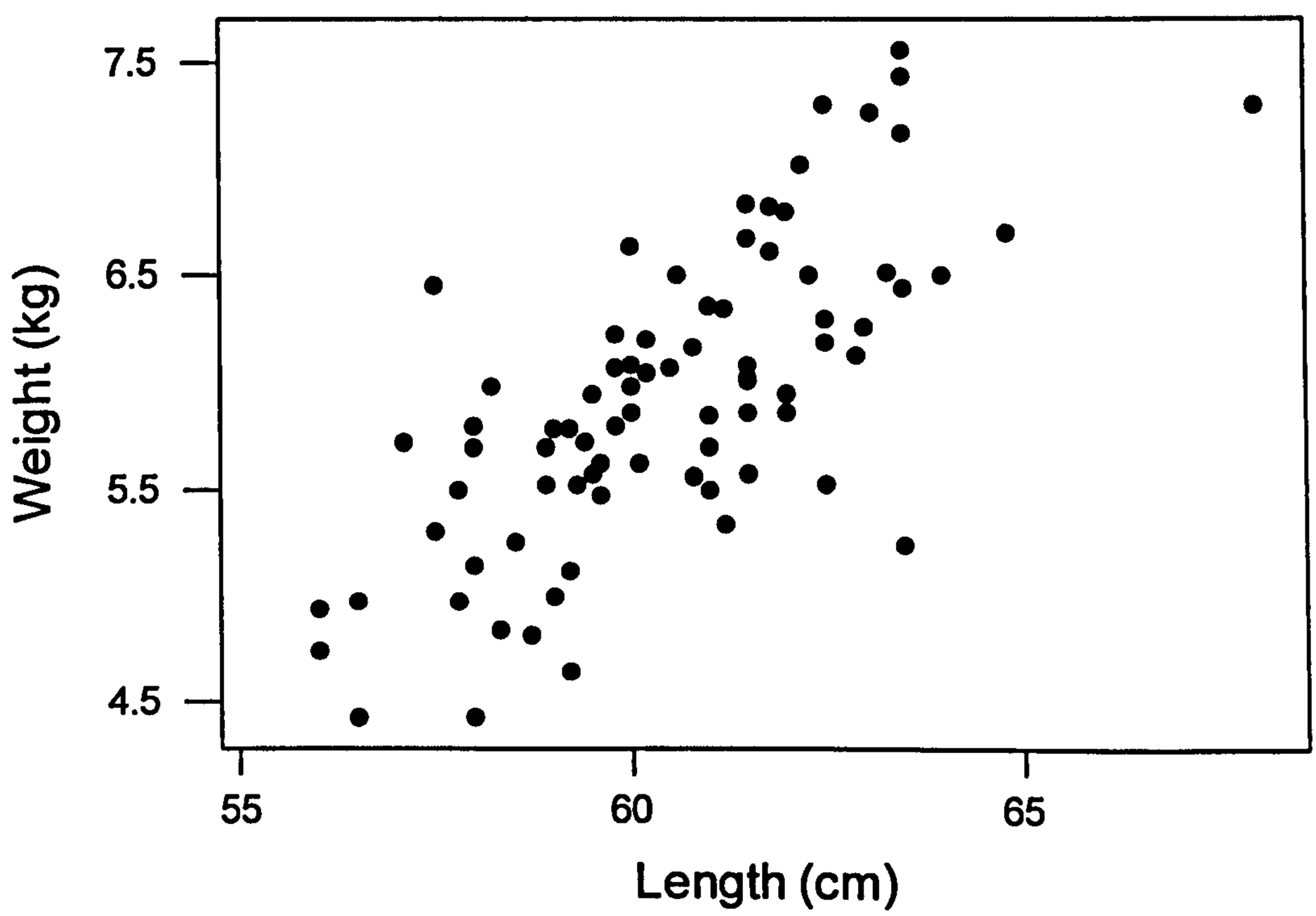
Table 4.8 Correlation of Body Measurements at 3 Months

	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Weight	0.72	**0.000**	0.48	**0.000**
Length			0.54	**0.000**

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

All of the correlations were statistically significant. The highest correlation was between weight and length with r = 0.72. This is illustrated in Figure 4.11.

Figure 4.11 Plot of Weight against Length at 3 Months



4.2.5.2 Correlations with Face Height, Width and Depth

The correlations of face heights, widths and depths with body weight, length and head circumference (body measurements) are shown in Table 4.9.

Table 4.9 Correlations of Body Measurements with Face Height, Width and Depth at 3 Months

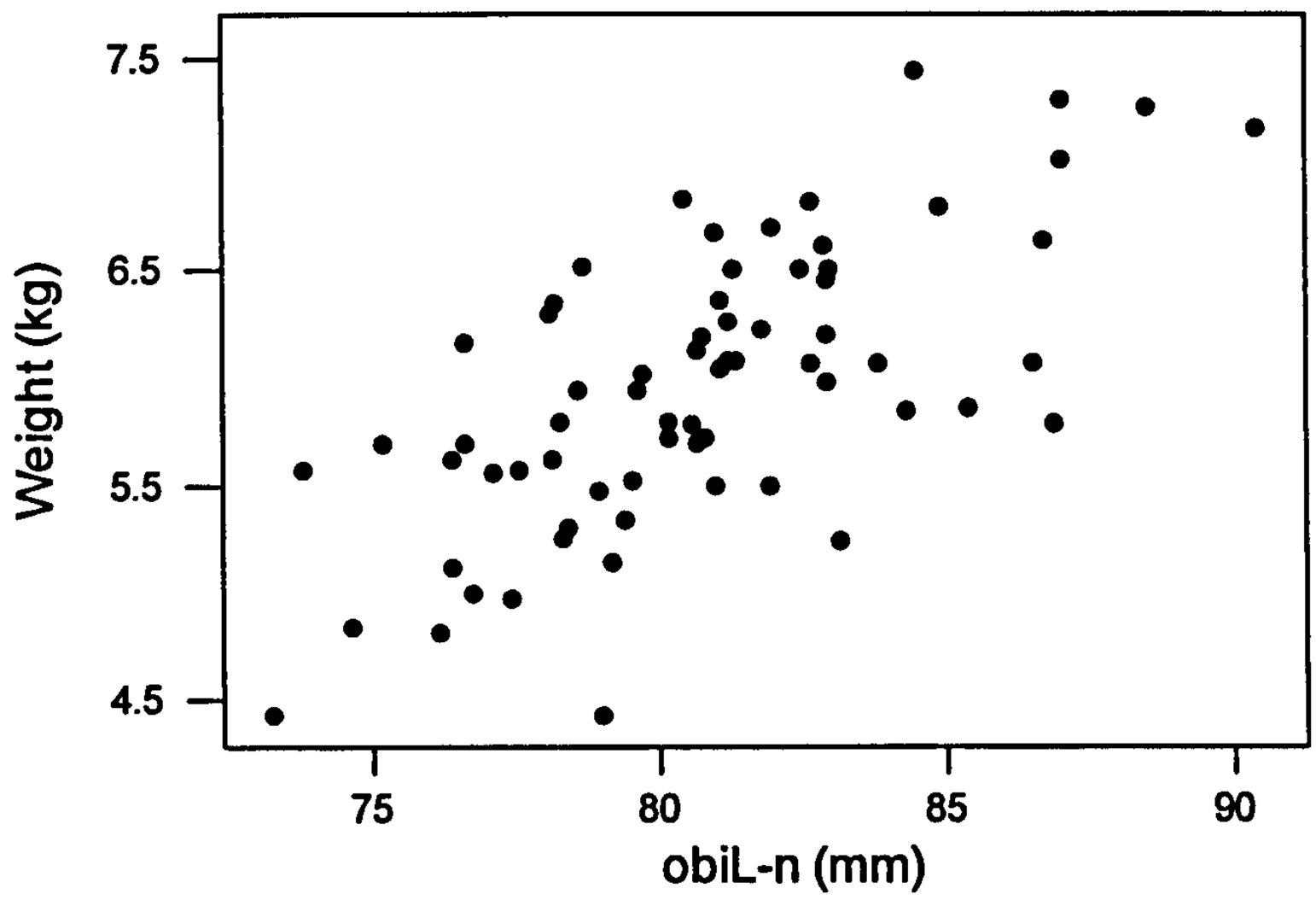
	Correlation with Weight*	P ** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Face Depth						
obiL-n	0.68	**0.000**	0.45	**0.000**	0.54	**0.000**
obiR-n	0.35	**0.004**	0.28	**0.020**	0.34	**0.005**
obiL-sn	0.66	**0.000**	0.45	**0.000**	0.45	**0.000**
obiR-sn	0.41	**0.001**	0.38	**0.002**	0.33	**0.007**
obiL-pg	0.63	**0.002**	0.38	**0.002**	0.27	**0.028**
obiR-pg	0.62	**0.000**	0.46	**0.000**	0.30	**0.014**
Face Width						
obsR-obsL	0.61	**0.000**	0.49	**0.000**	0.43	**0.000**
obiR-obiL	0.52	**0.000**	0.22	0.089	0.40	**0.002**
Face Height						
n-me	0.59	**0.000**	0.55	**0.000**	0.39	**0.000**
sn-me	0.44	**0.000**	0.43	**0.000**	0.27	**0.018**
n-sn	0.50	**0.000**	0.45	**0.000**	0.45	**0.000**

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

All but one of the face measurements were significantly correlated with the body measurements. The strongest correlations tended to be with weight. The highest correlation coefficient was 0.68 between upper left face depth and weight. This is illustrated in Figure 4.12. The lowest correlation was between lower face width and body length with an r value of 0.22, which was not significant (p=0.089).

Face depths and widths all correlated significantly with each other except the left mandibular depth with the right upper face and maxillary depths. Face heights correlated significantly with each other and with face depths but lower face width did not correlate with any of the face height measurements at 3 months.

Figure 4.12 Plot of Upper Left Face Depth against Weight at 3 Months



4.2.5.3 Correlations with Eye Measurements

Correlations of the eye measurements with the body measurements are shown in Table 4.10.

Table 4.10 Correlations of Body Measurements with Eye Measurements at 3 Months

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Eyes						
exR-exL	0.51	**0.000**	0.45	**0.000**	0.43	**0.000**
enL-enR	0.44	**0.000**	0.28	**0.011**	0.30	**0.011**
exL-enL	0.34	**0.001**	0.39	**0.000**	0.29	**0.009**
exR-enR	0.33	**0.002**	0.34	**0.002**	0.32	**0.003**

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

All of the eye measurements were significantly correlated with the body measurements. The highest correlation was between biocular width and weight with r= 0.51. The lowest correlation (r=0.28) was between intercanthal width and body length.

All of the eye measurements correlated significantly with each other except right and left palpebral fissure widths with intercanthal width (r=0.20, 0.21).

4.2.5.4 Correlations with Nose and Nostril Measurements

Correlations of the nose and nostril measurements with body measurements are shown in Table 4.11.

Table 4.11 Correlations of Body Measurements with Nose and Nostril Measurements at 3 Months

	Correlation with Weight*	P** Value	Correlation with Length*	P ** Value	Correlation with Head Circumference*	P** Value
Nose						
acL-acR	0.55	**0.000**	0.40	**0.000**	0.39	**0.000**
alL-alR	0.46	**0.000**	0.33	**0.002**	0.37	**0.001**
acL-prn	0.42	**0.000**	0.28	**0.010**	0.32	**0.004**
acR-prn	0.53	**0.000**	0.45	**0.000**	0.53	**0.000**
n-prn	0.52	**0.000**	0.47	**0.000**	0.43	**0.000**
sn-prn	0.22	**0.049**	0.15	0.164	0.24	**0.029**
Nostrils						
sbalL-cL	0.21	**0.050**	0.20	0.064	0.26	**0.018**
sbalR-cR	0.11	0.333	0.17	0.125	0.20	0.067
sn'L-al'iL	0.30	**0.006**	0.26	**0.020**	0.30	**0.006**
sn'R-al'iR	0.14	0.202	0.09	0.401	0.21	0.052
sn'R-sn'L	0.13	0.245	0.02	0.893	0.04	0.703

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in **bold**.

All of the nose measurements except nasal tip protrusion (sn-prn) were significantly correlated with body measurements with r values ranging from 0.28 to 0.55. Nasal tip protrusion was significantly but weakly correlated with weight (r=0.22) and head circumference (r=0.24) but not with length.

The nose measurements all correlated significantly with each other except nasal tip protrusion (sn-prn) with anatomic nose width (acR-acL) and nasal dorsum length (n-prn).

Very few of the nostril measurements were significantly correlated with body measurements. The strongest correlations were between left nostril width and body weight (r=0.30) and head circumference (r=0.30).

The nostril width and long axis were significantly correlated with each other but not with columella width. Columella width correlated with the nose width measurements but not with nasal tip protrusion (sn-prn) or nasal dorsum length (n-prn).

4.2.5.5 Correlations with Upper and Lower Lip Measurements

Correlations of upper and lower lip measurements with body measurements are shown in Table 4.12.

Table 4.12 Correlations of Body Measurements with Upper and Lower Lip Measurements at 3 Months

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Upper Lip						
chR-chL	0.30	**0.006**	0.27	**0.015**	0.25	**0.024**
cphL-chL	0.36	**0.001**	0.43	**0.000**	0.20	0.066
cphR-chR	0.34	**0.002**	0.40	**0.000**	0.24	**0.028**
cphR-cphL	0.33	**0.002**	0.31	**0.004**	0.26	**0.018**
ls-sn	0.21	0.060	0.12	0.287	0.10	0.374
ls-stos	-0.01	0.923	-0.03	0.817	-0.02	0.874
sn-stos	0.16	0.147	0.14	0.210	0.10	0.385
sbalL-chL	0.39	**0.000**	0.36	**0.000**	0.28	**0.010**
sbalR-chR	0.45	**0.000**	0.40	**0.000**	0.27	**0.014**
Lower Lip						
chL-li	0.37	**0.001**	0.31	**0.005**	0.23	**0.033**
chR-li	0.33	**0.002**	0.26	**0.019**	0.21	0.060
li-stoi	0.25	**0.023**	0.21	0.060	0.19	0.093
sl-li	-0.02	0.831	-0.01	0.916	0.03	0.768
sl-stoi	0.03	0.788	0.07	0.562	0.15	0.167

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

Mouth width, philtrum width and upper and lower vermilion lengths were all significantly but weakly correlated with body measurements with r values ranging from 0.20 to 0.43. They also all correlated significantly with each other.

Upper lateral lip heights were also significantly correlated with body measurements with r values of 0.27 to 0.45. None of remaining lip heights were significantly correlated with body measurements except for a weak correlation between lower vermilion height and body weight (r=0.25). Upper and lower lip heights did tend to correlate with each other however only the lateral lip heights correlated significantly with the upper vermilion lengths (r=0.55 to 0.74).

4.2.5.6 Correlations with Angular Measurements

Correlations of the angular measurements with body weight, length and head circumference are shown in Table 4.13.

Table 4.13 Correlations of Body Measurements with Angles of the Face at 3 Months

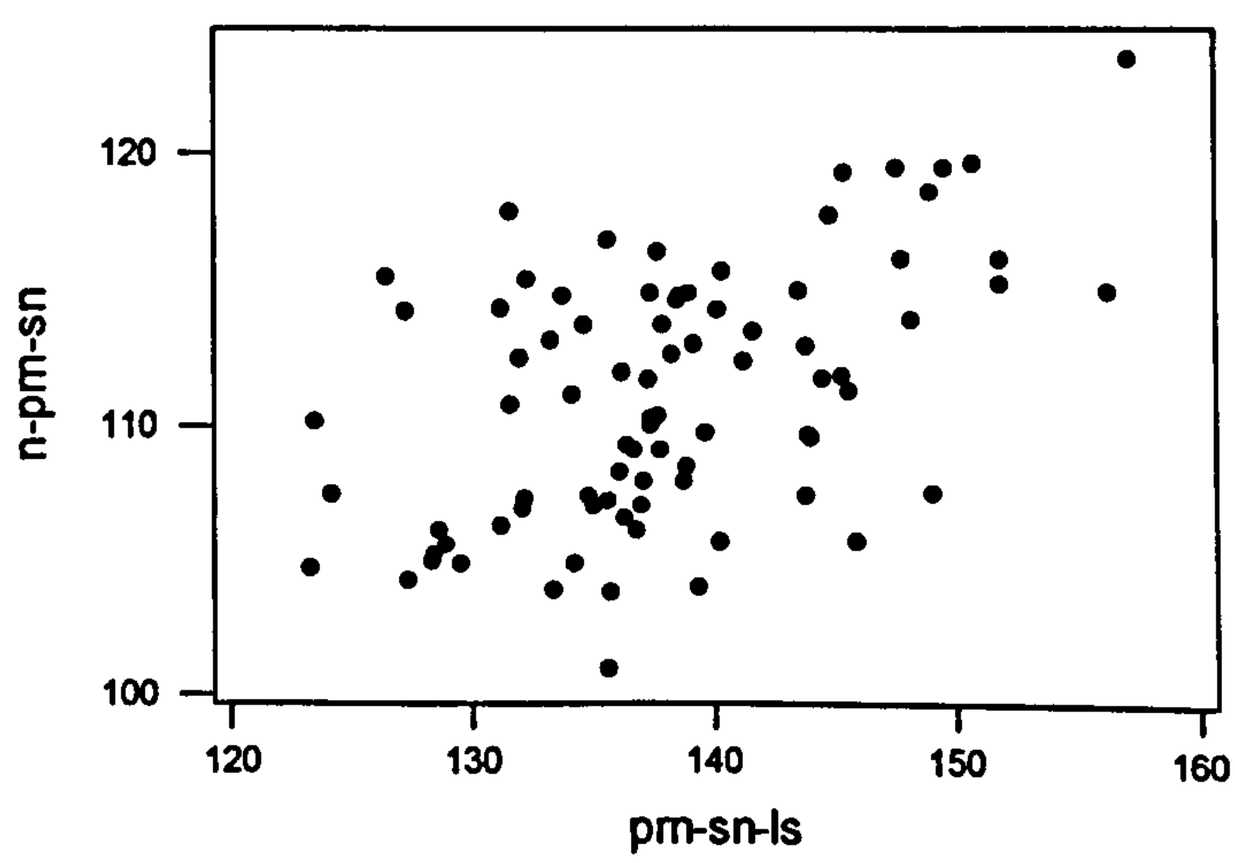
	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Angles						
acR-prn-acL	0.02	0.830	-0.02	0.882	-0.12	0.278
n-prn-sn	-0.22	**0.050**	-0.18	0.101	-0.16	0.160
prn-sn-ls	-0.38	**0.000**	-0.32	**0.004**	-0.12	0.287
li-sl-pg	-0.39	**0.000**	-0.19	0.089	-0.07	0.515

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

Only the nasal tip horizontal displacement angle (acR-prn-acL) appeared to be independent of body measurements. Nasal tip angle (n-prn-sn), nasolabial angle (prn-sn-ls) and labiomental angle (li-sl-pg) all had weak negative correlations with body weight with r values ranging from -0.22 to -0.39. Nasolabial angle also had a weak negative correlation with length but there were no other significant correlations between the angles and length or head circumference.

Nasal tip angle (n-prn-sn) correlated significantly with nasal tip horizontal displacement angle (acR-prn-acL), nasolabial angle (prn-sn-ls) (r=0.39, 0.51), and weakly (r=0.23) with labiomental angle (li-sl-pg). The strongest of these correlations is illustrated in Figure 4.13. Labiomental angle also correlated significantly but weakly with nasal tip horizontal displacement angle (r=0.25).

Figure 4.13 Plot of Nasal Tip Angle against Nasolabial Angle at 3 Months

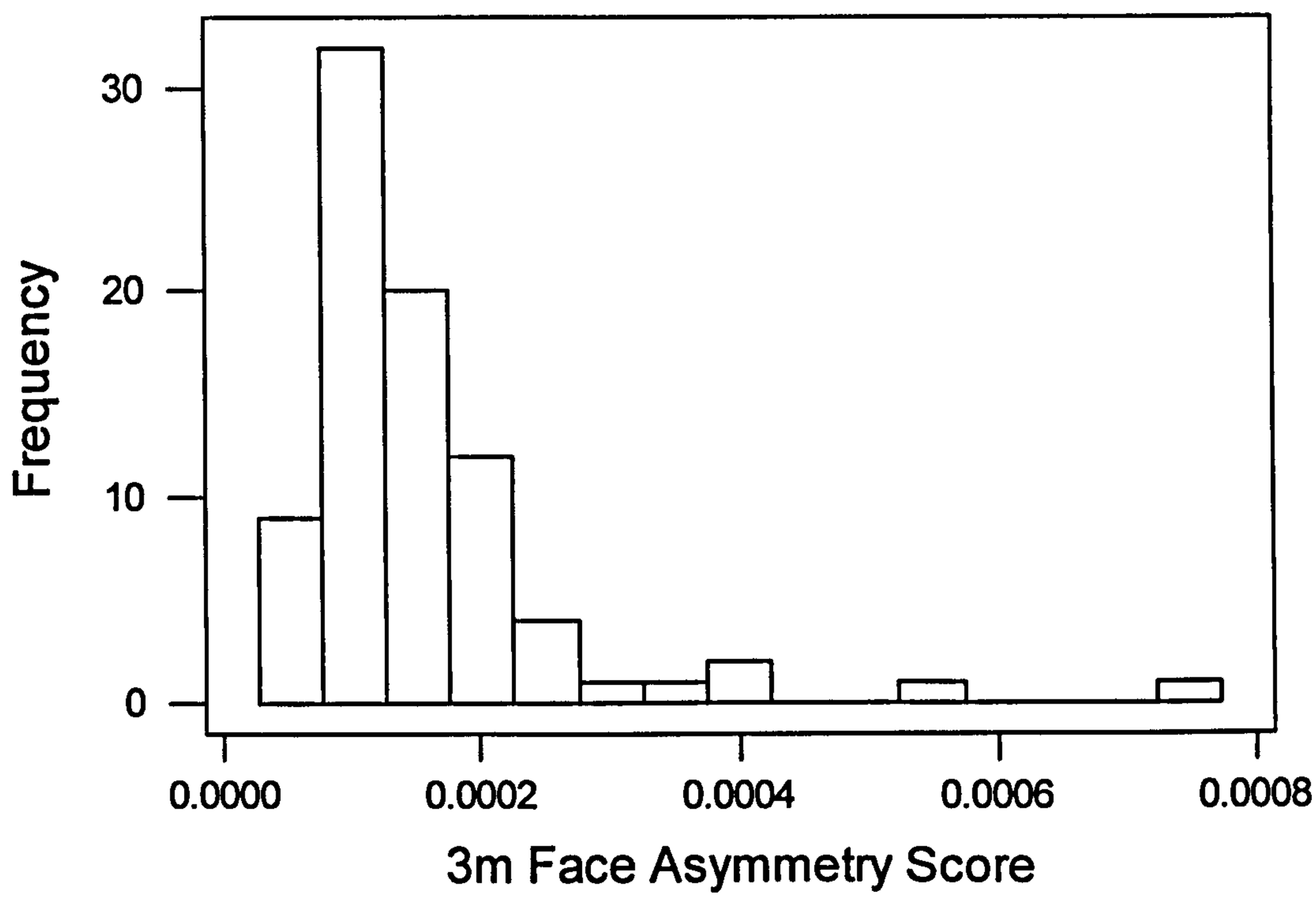


4.2.6 Asymmetry at 3 Months

4.2.6.1 Face

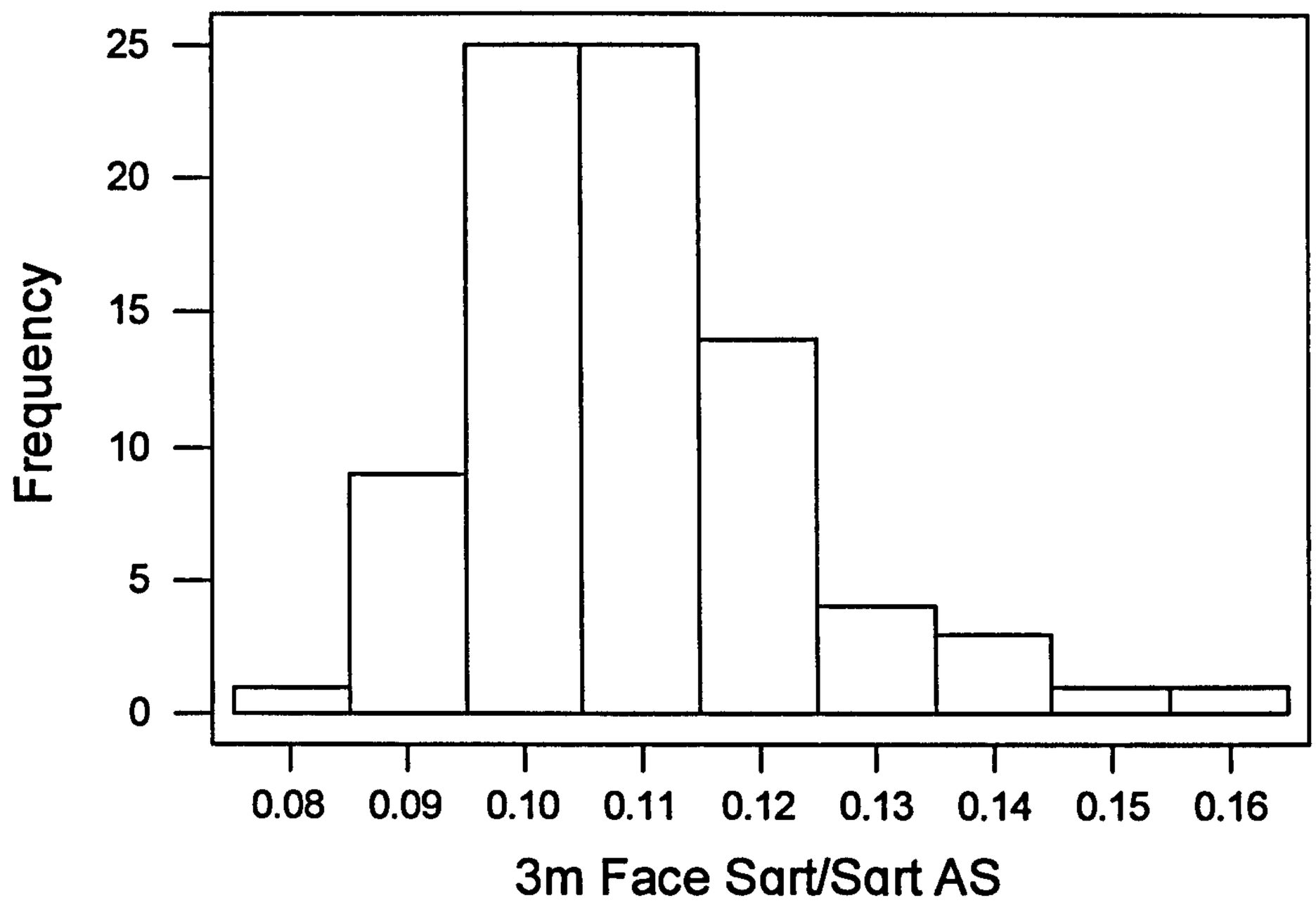
The distribution of the asymmetry scores for the face at 3 months is shown in Figure 4.13. This score incorporated all of the midface landmarks but not the ear, lower lip or chin landmarks (see section 2.4.1.2)

Figure 4.14 Distribution of Asymmetry Scores for the Face at 3 Months



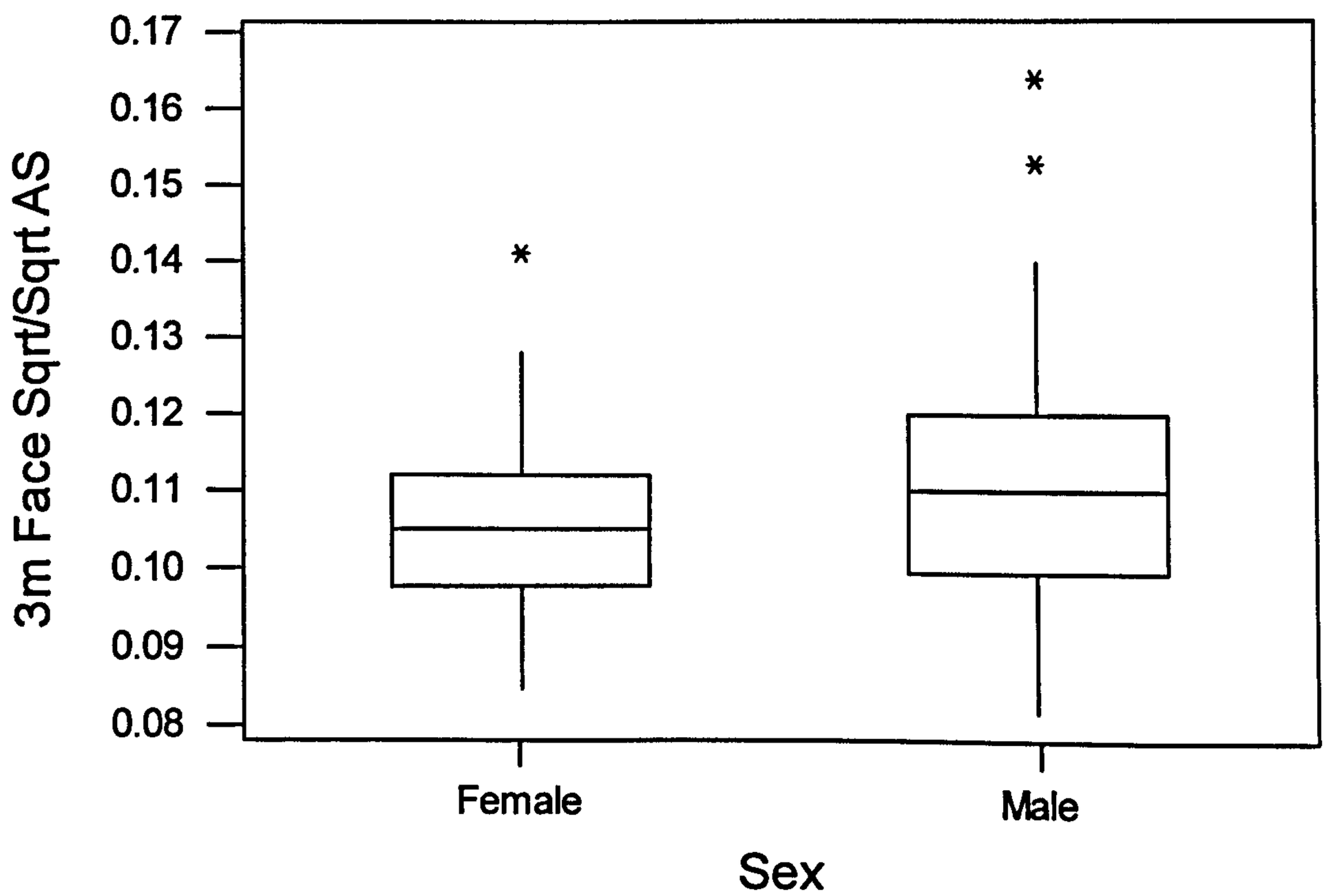
As shown in Figure 4.14, the raw asymmetry scores were not normally distributed. However, the fourth roots of the asymmetry scores (sqrt/sqrt AS) were well approximated by a normal distribution. This is shown in Figure 4.15. Standard parametric tests could therefore be applied to this transformed data. Taking the fourth root is a procedure that is recognised as a good way to deal with data that arises as sums of squared distances such as the raw asymmetry scores (Cressie 1995).

Figure 4.15 Distribution of the Sqrt/Sqrt AS for the Face at 3 Months



The mean fourth root of the asymmetry score (sqrt/sqrt AS) for the face was 0.109 ± 0.014. The mean sqrt/sqrt AS for the females was 0.106 ± 0.011 and for the males 0.112 ± 0.017. Two sample t test showed that this slight difference was not statistically significant (p=0.064). This is illustrated in Figure 4.16.

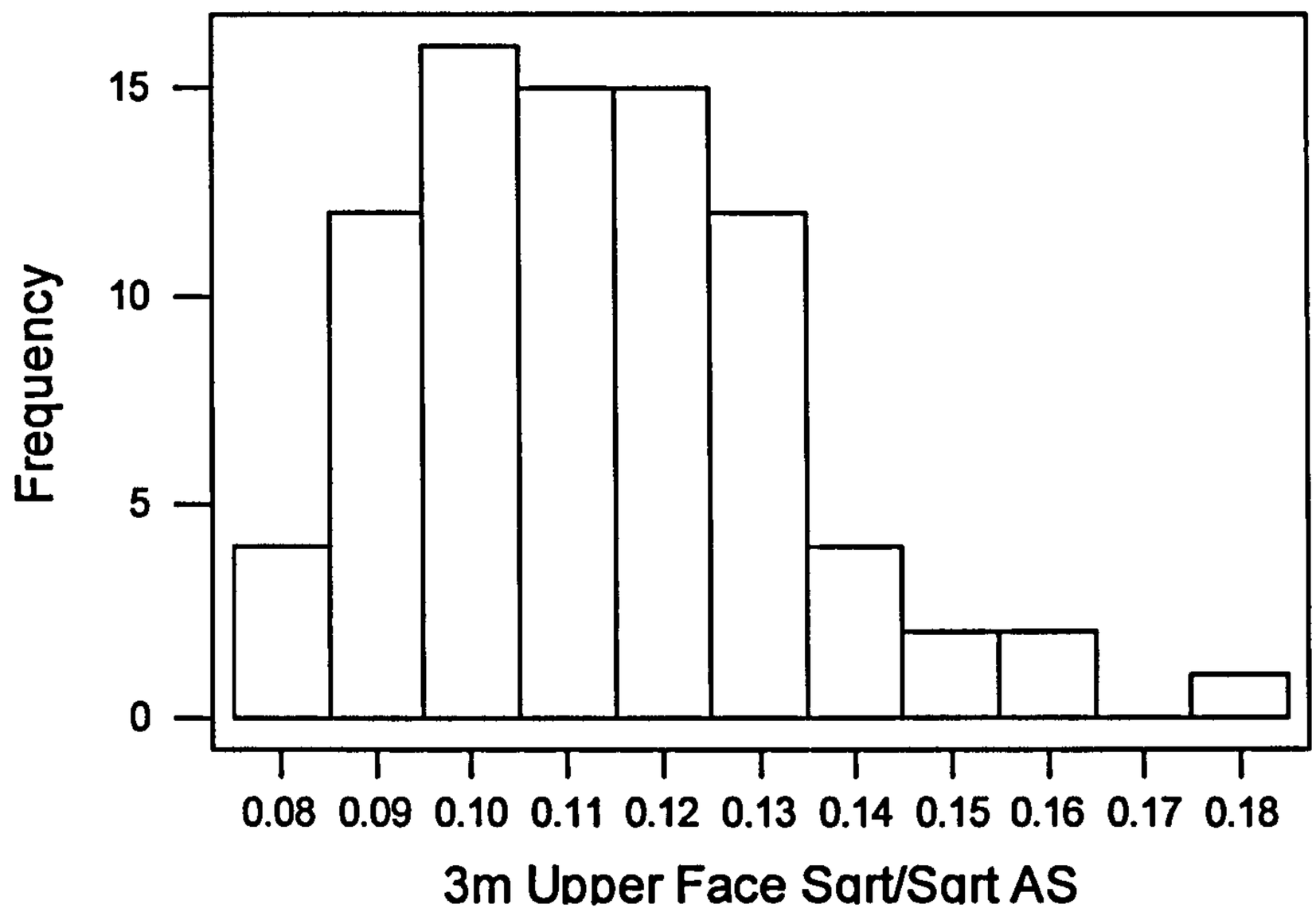
Figure 4.16 Sqrt/Sqrt AS for the Face of Males and Females at 3 Months



4.2.6.2 Upper Face

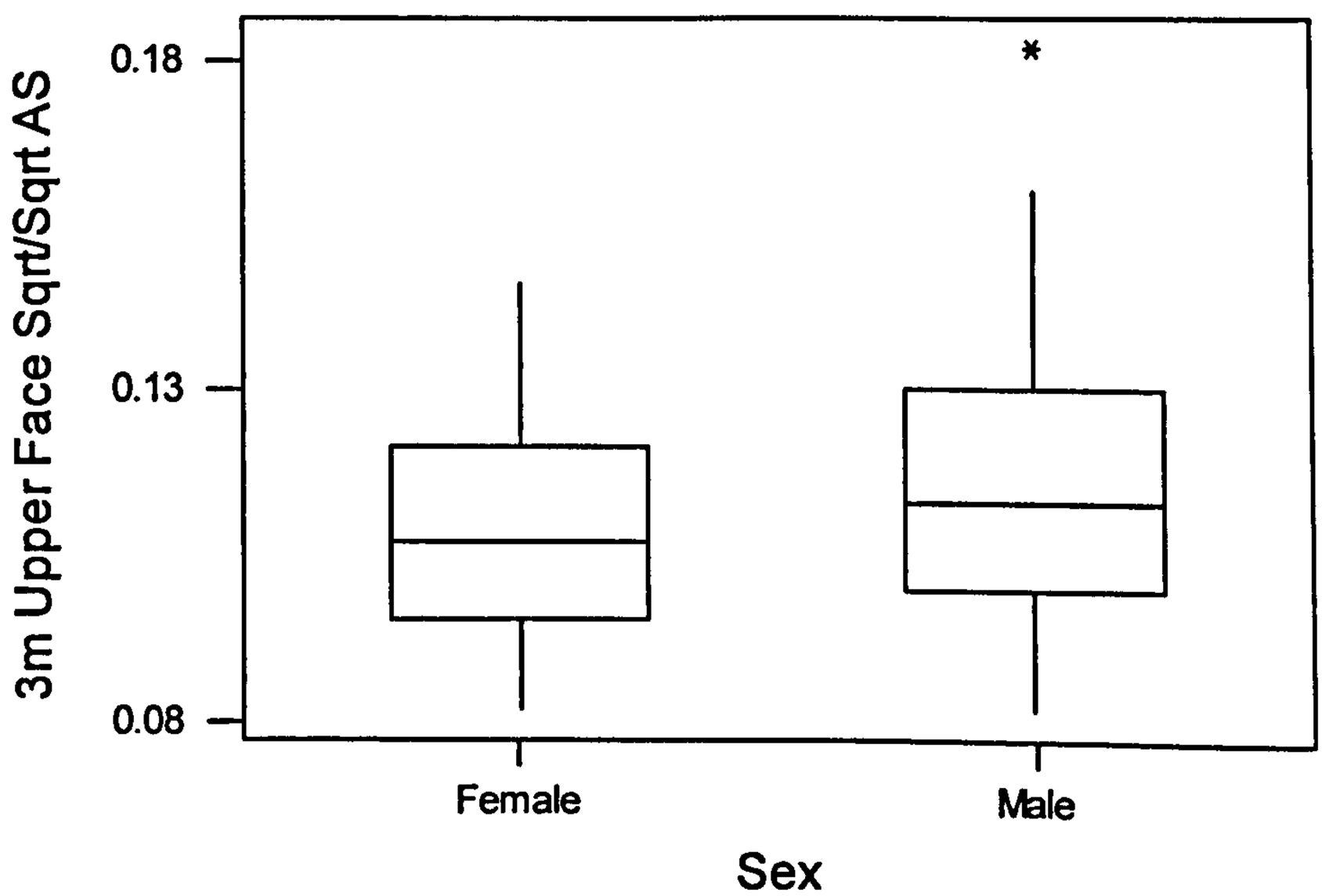
The distribution of the mean fourth root asymmetry scores (sqrt/sqrt AS) for the upper face is shown in Figure 4.17. The upper face asymmetry score incorporated the right and left endocanthion and exocanthion, and nasion.

Figure 4.17 Distribution of the Sqrt/Sqrt AS for the Upper Face at 3 Months



The mean sqrt/sqrt AS for the upper face was 0.113 ± 0.020. There was no statistically significant difference between the males and females (p=0.13). This is illustrated in Figure 4.18.

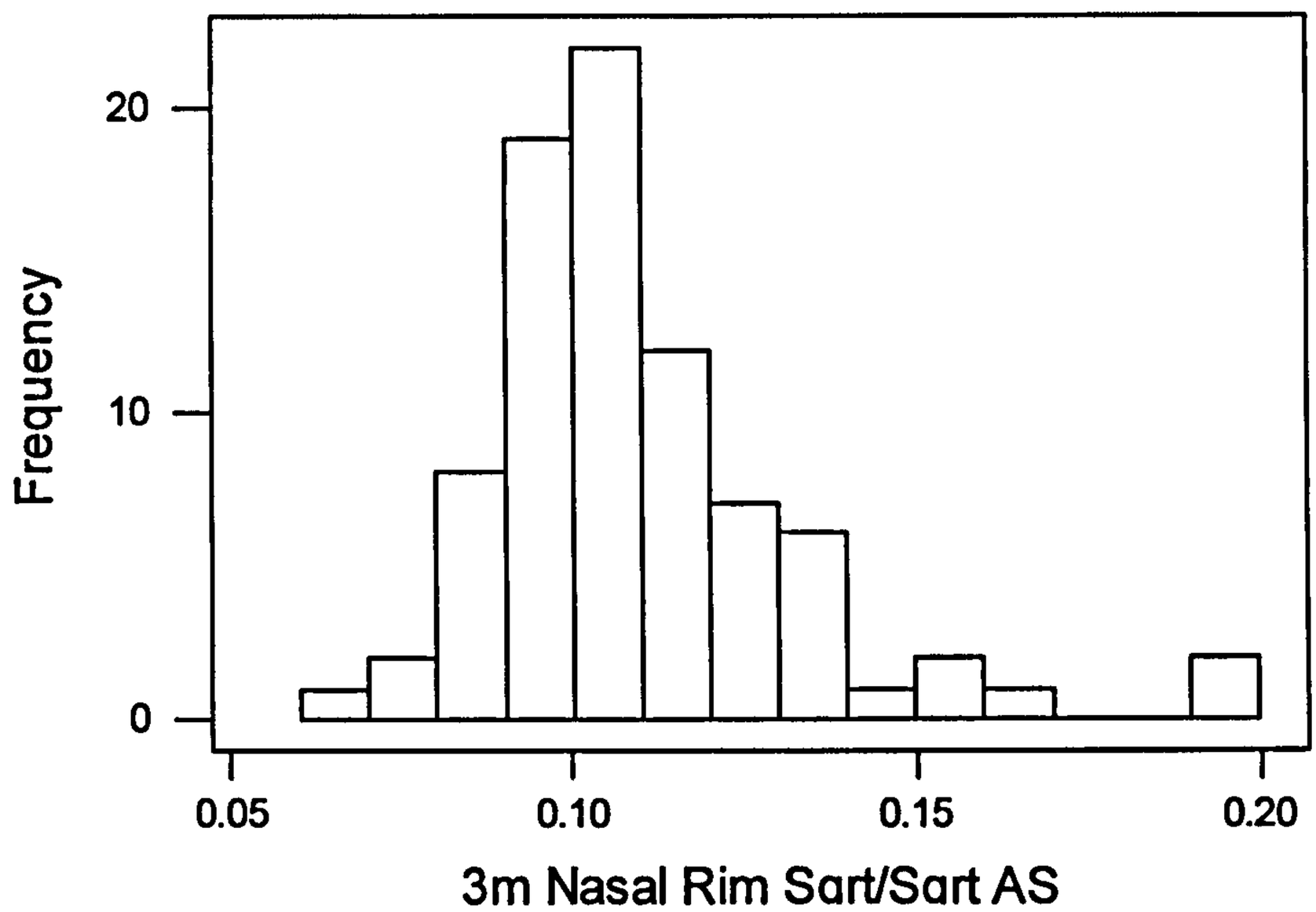
Figure 4.18 Sqrt/Sqrt AS for the Upper Face of Males and Females at 3 Months



4.2.6.3 Nasal Rim

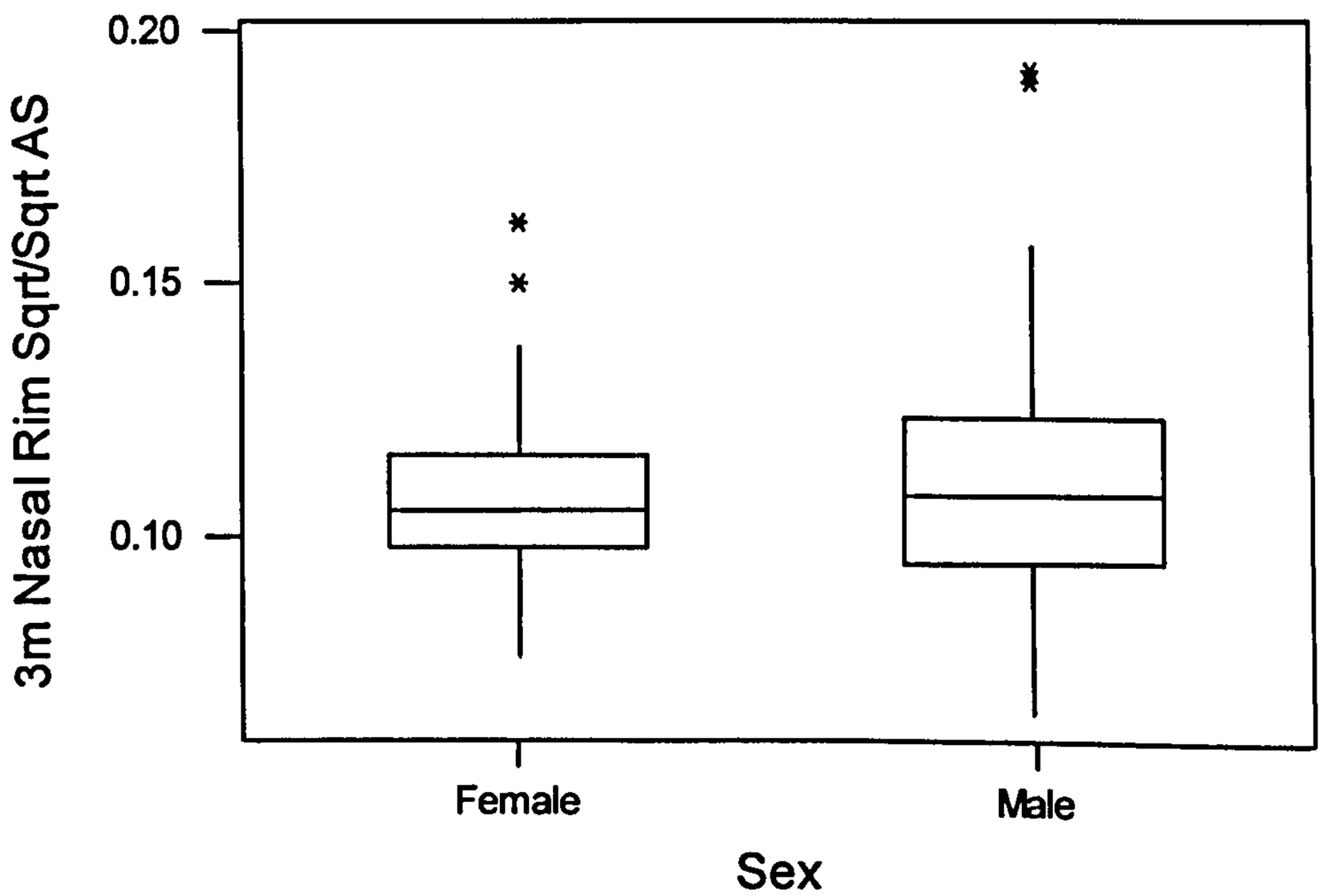
The distribution of the mean fourth roots of the asymmetry scores (sqrt/sqrt AS) for the nasal rim is shown in Figure 4.19. The landmarks incorporated in the nasal rim asymmetry score were the right and left alar crest, alare, alare' outer and pronasale.

Figure 4.19 Distribution of the Sqrt/Sqrt AS for the Nasal Rim at 3 Months



The mean sqrt/sqrt AS for the nasal rim was 0.109 ± 0.022. There was no statistically significant difference between the males and females (p=0.37). This is illustrated in Figure 4.20.

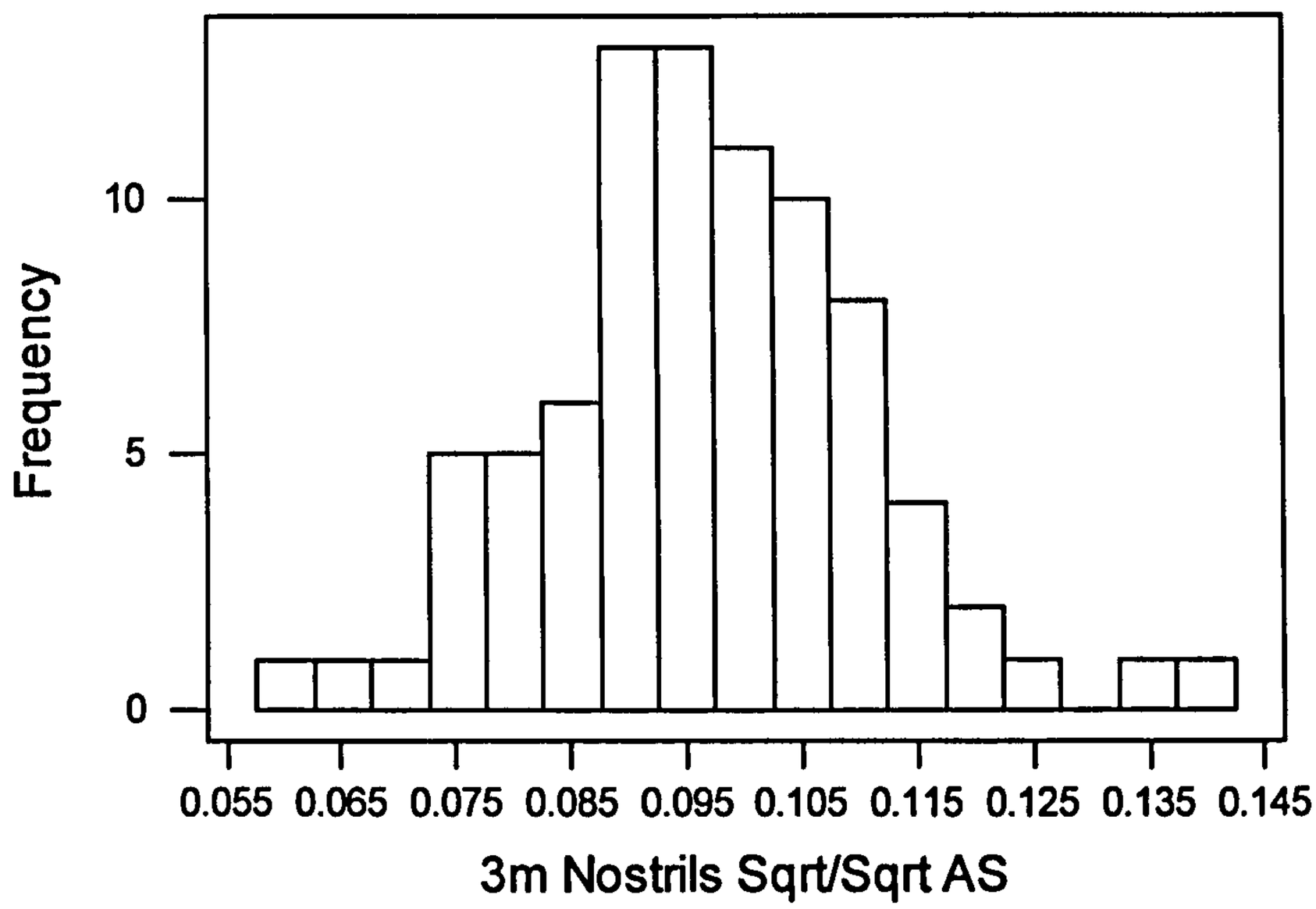
Figure 4.20 Sqrt/Sqrt AS for the Nasal Rim of Males and Females at 3 Months



4.2.6.4 Nostrils

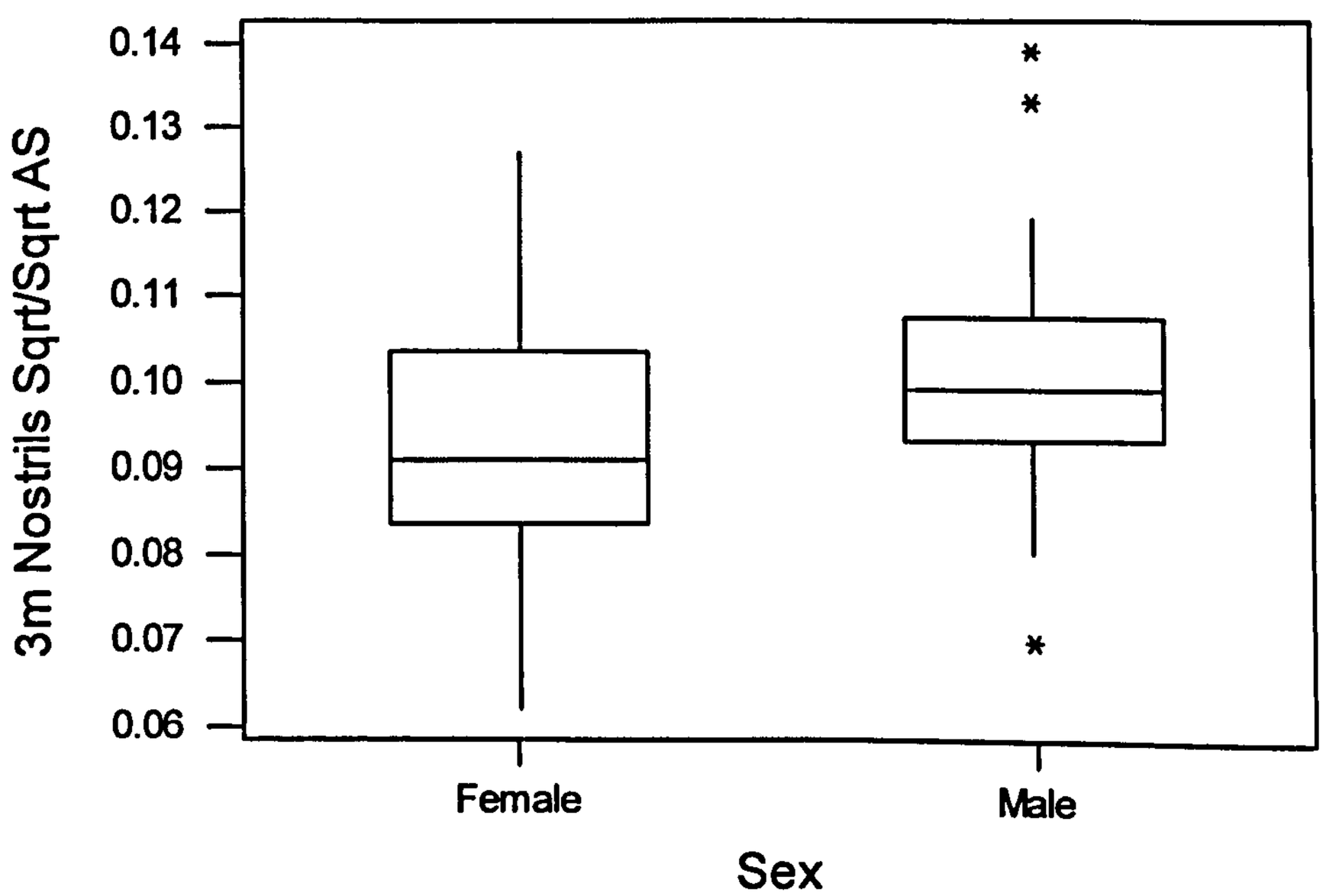
The distribution of the fourth root of the asymmetry scores (sqrt/sqrt AS) for the nostrils is shown in Figure 4.21. The landmarks incorporated in the nostril asymmetry score were the right and left subnasale', columella, alare' inner and subalare, and subnasale.

Figure 4.21 Distribution of the Sqrt/Sqrt Asymmetry Scores for the Nostrils at 3 Months



The mean sqrt/sqrt AS for the nostrils was 0.096 ± 0.014. The mean for the females was 0.093 ± 0.015 and for the males 0.100 ± 0.013. This slight difference was statistically significant (p=0.034). This is illustrated in Figure 4.22.

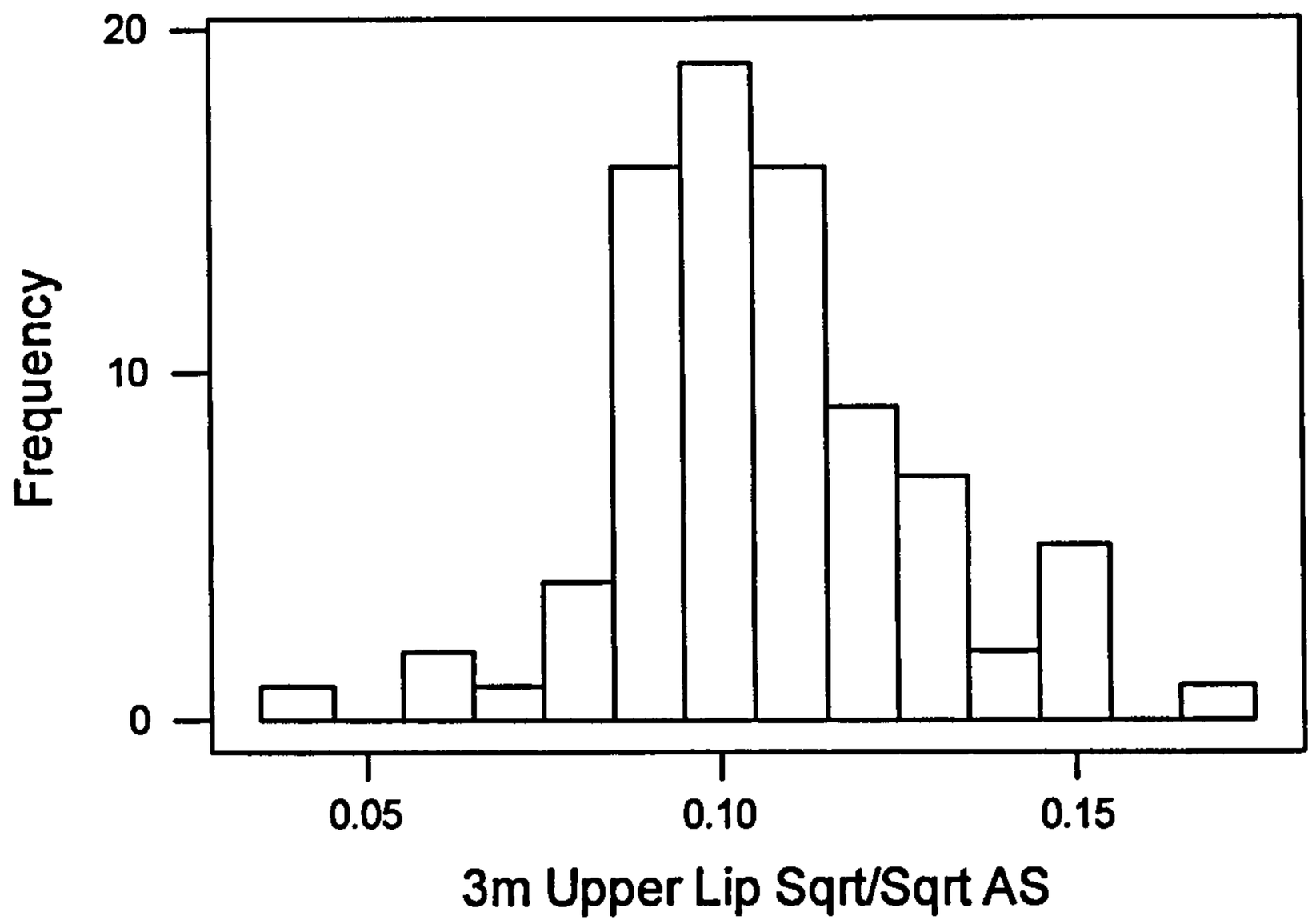
Figure 4.22 Gender Differences in Sqrt/Sqrt AS for the Nostrils at 3 Months



4.2.6.5 Upper Lip

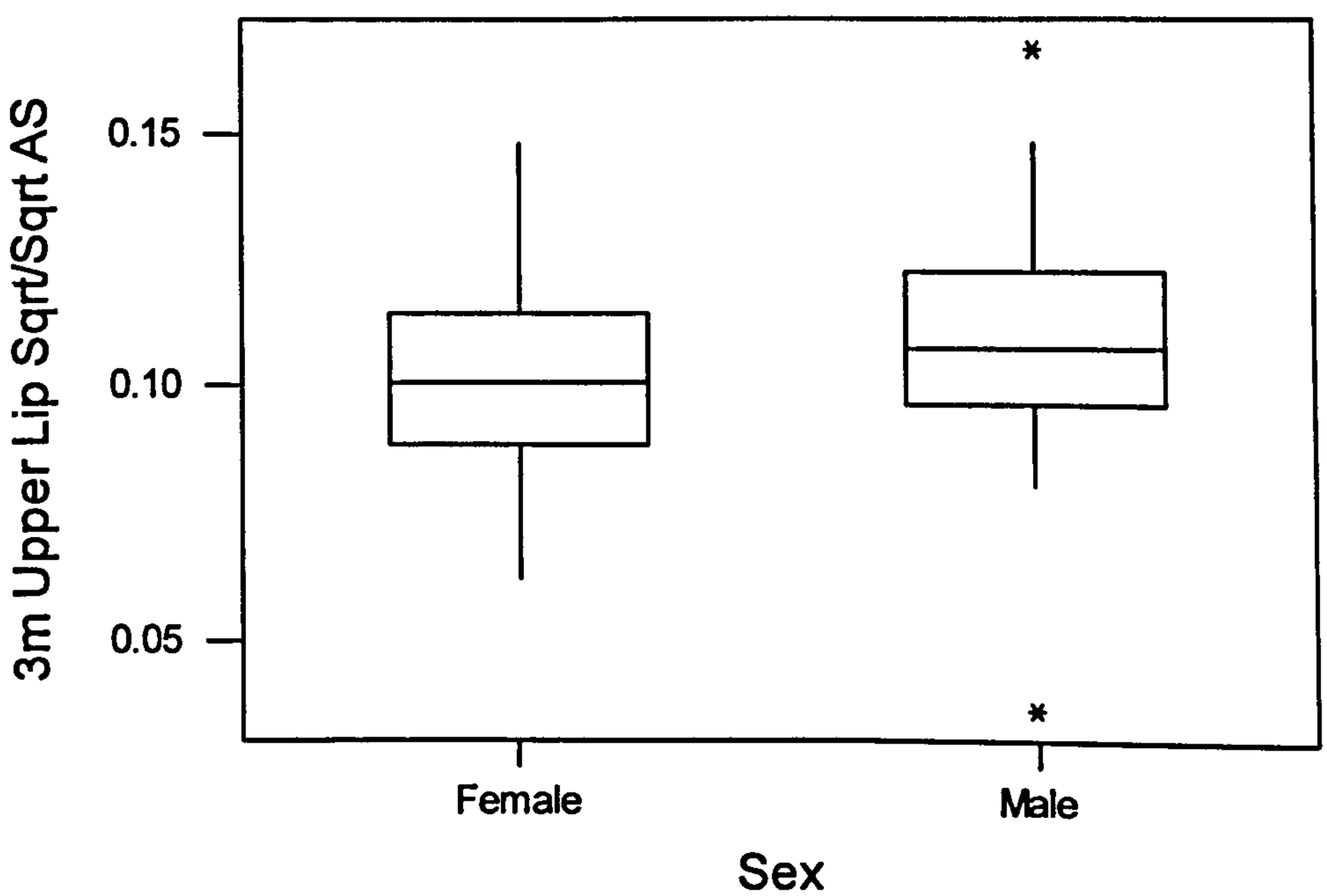
The distribution of the fourth roots of the asymmetry scores (sqrt/sqrt AS) for the upper lip is shown in Figure 4.23. The landmarks incorporated in the upper lip asymmetry score were the right and left cheilion and crista philtri, and labrale superius.

Figure 4.23 Distribution of the Sqrt/Sqrt Asymmetry Scores for the Upper Lip at 3 Months



The mean sqrt/sqrt AS for the upper lip was 0.105 ± 0.022. There was no statistically significant difference between the males and females (p=0.22). This is shown in Figure 4.24.

Figure 4.24 Sqrt/Sqrt AS for the Upper Lip of Males and Females at 3 Months



4.2.6.6 Comparisons of Asymmetry Scores at 3 Months

The asymmetry score for the face and for the individual features can be compared even though they are calculated from different number of landmarks because it is an average squared deviation across the landmarks involved. The face score is a weighted average of the individual feature scores so it will always occupy a central position with respect to the others. The result of comparing the asymmetry scores of the different regions of the face is illustrated in Figure 4.25.

Figure 4.25 Comparison of the Asymmetry of the Regions of the Face at 3 Months

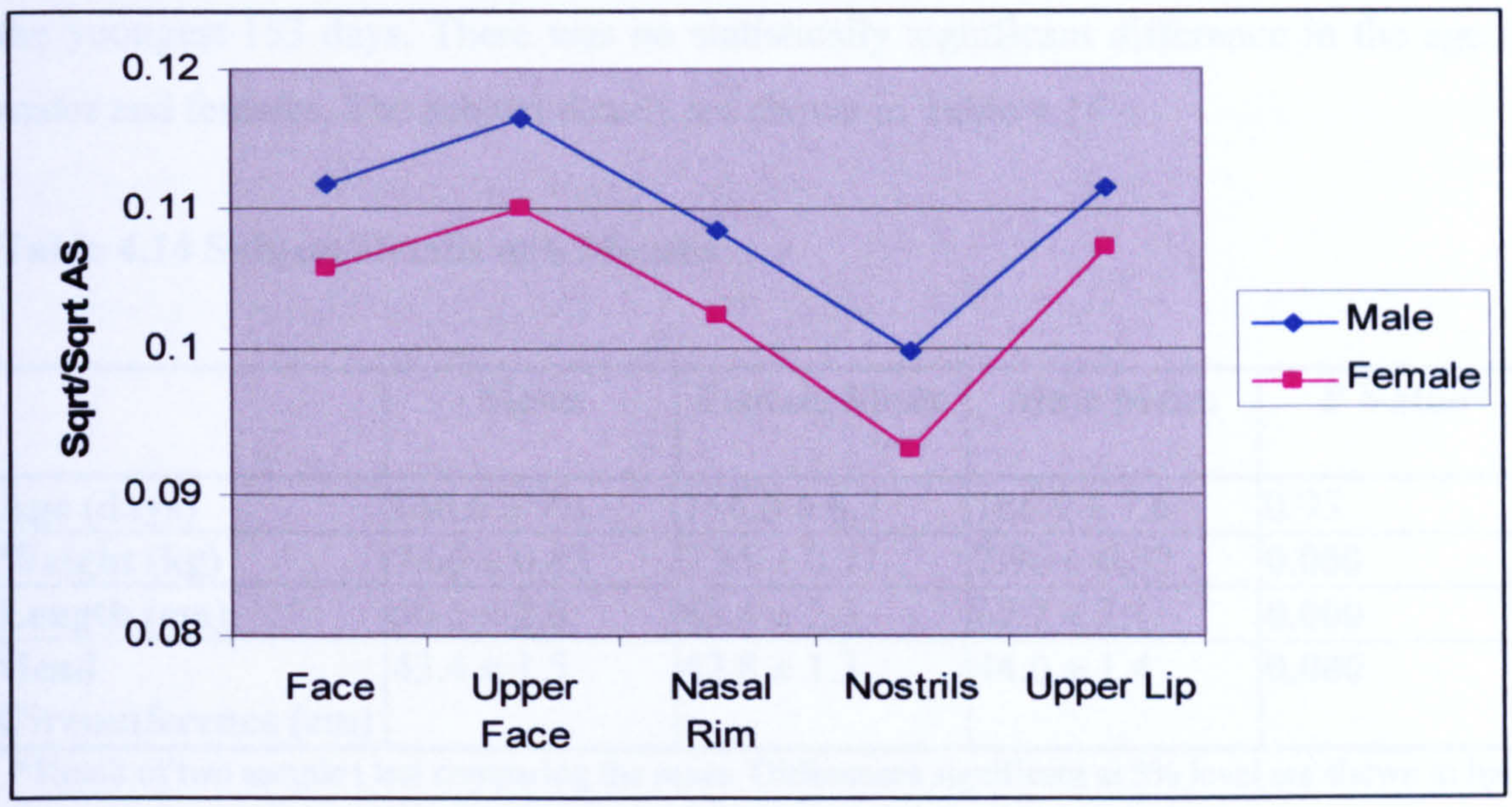


Figure 4.25 shows that the asymmetry scores for the females tended to be lower than the males although this difference was only significant for the nostril asymmetry score (p=0.034). Paired t tests showed that the sqrt/sqrt AS was significantly lower for the nostrils than for any of the other scores (p=0.000). Significant differences were also found between the upper face and face (p=0.009) and upper lip (p=0.005). The difference between the upper lip and face was close to being significant (p=0.058). The greatest asymmetry was in the upper face and the least in the nostrils.

4.2.6.7 Correlations of Asymmetry Scores at 3 Months

None of the asymmetry scores correlated significantly with the body measurements. As expected, the asymmetry score for the face correlated highly and significantly with the asymmetry scores for all of the individual regions of the face (r=0.56 to 0.89). All the individual asymmetry scores correlated weakly with each other (r=0.22 to 0.49).

4.3 Six Months

4.3.1 Subjects

Ninety seven infants attended at the 6 month stage. Ninety three infants, 49 males and 44 females were captured with a lips apart pose. A further 4 infants who attended at this stage could only be captured with a lips together pose and their results are not included in this analysis.

The mean age at the 6 month stage was 167 ± 7 days. The oldest child was 186 days and the youngest 153 days. There was no statistically significant difference in the age of the males and females. The subject details are shown in Table 4.14

Table 4.14 Subject Details at 6 Months

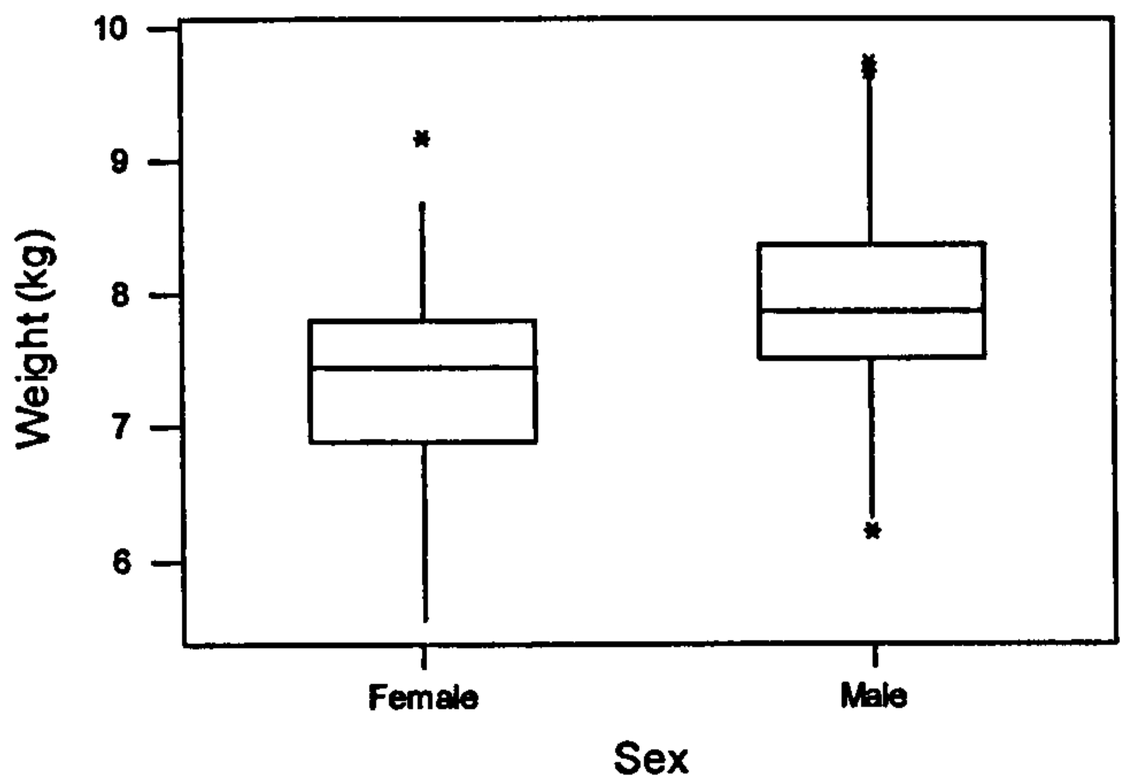
	Mean	Female Mean	Male Mean	P Value*
Age (days)	166.6 ± 7.1	166.6 ± 6.7	166.5 ± 7.6	0.95
Weight (kg)	7.66 ± 0.82	7.35 ± 0.71	7.95 ± 0.82	**0.000**
Length (cm)	66.5 ± 2.6	65.4 ± 2.5	67.7 ± 2.1	**0.000**
Head Circumference (cm)	43.4 ± 1.5	42.8 ± 1.3	44.0 ± 1.4	**0.000**

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in bold.

4.3.2 Body measurements

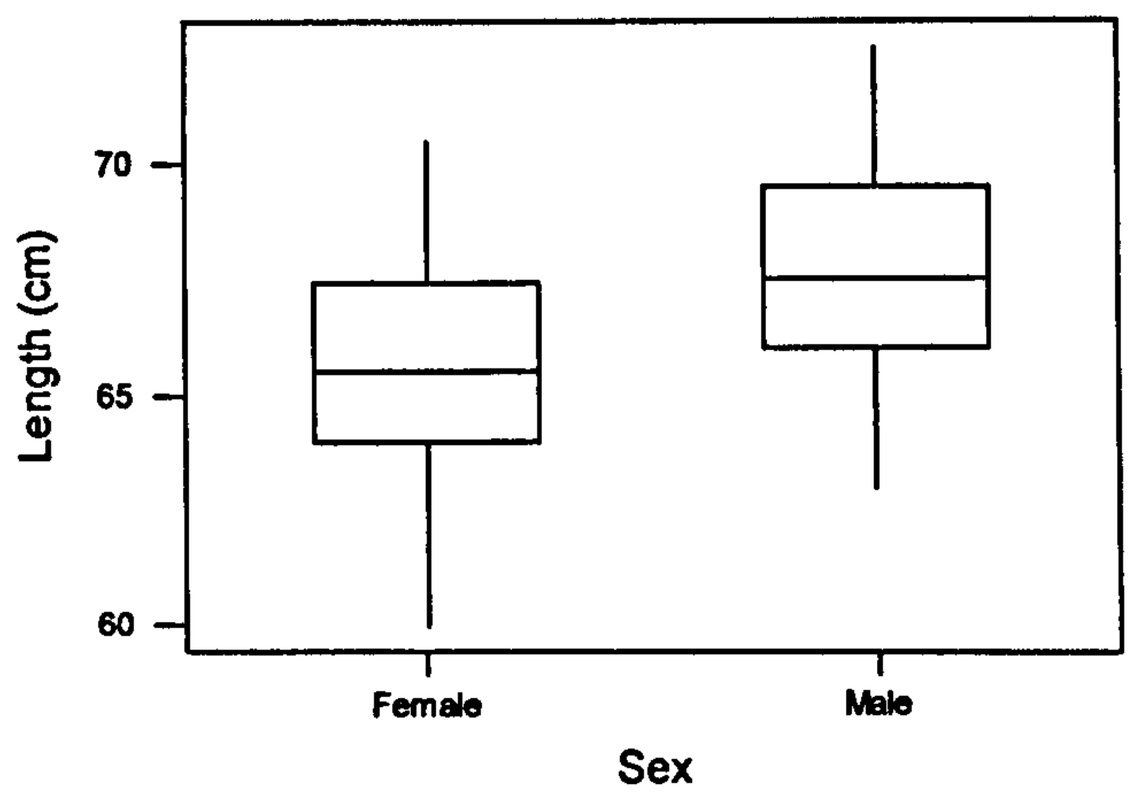
The body measurements at 6 months are shown in Table 4.14. The mean weight of the infants was 7.66 ± 0.82 kg. The mean weight of the females was 7.35 ± 0.71 kg and the males 7.95 ± 0.82 kg. Two sample t tests showed this difference was statistically significant (p=0.000). This is illustrated in Figure 4.26.

Figure 4.26 Weight at 6 Months



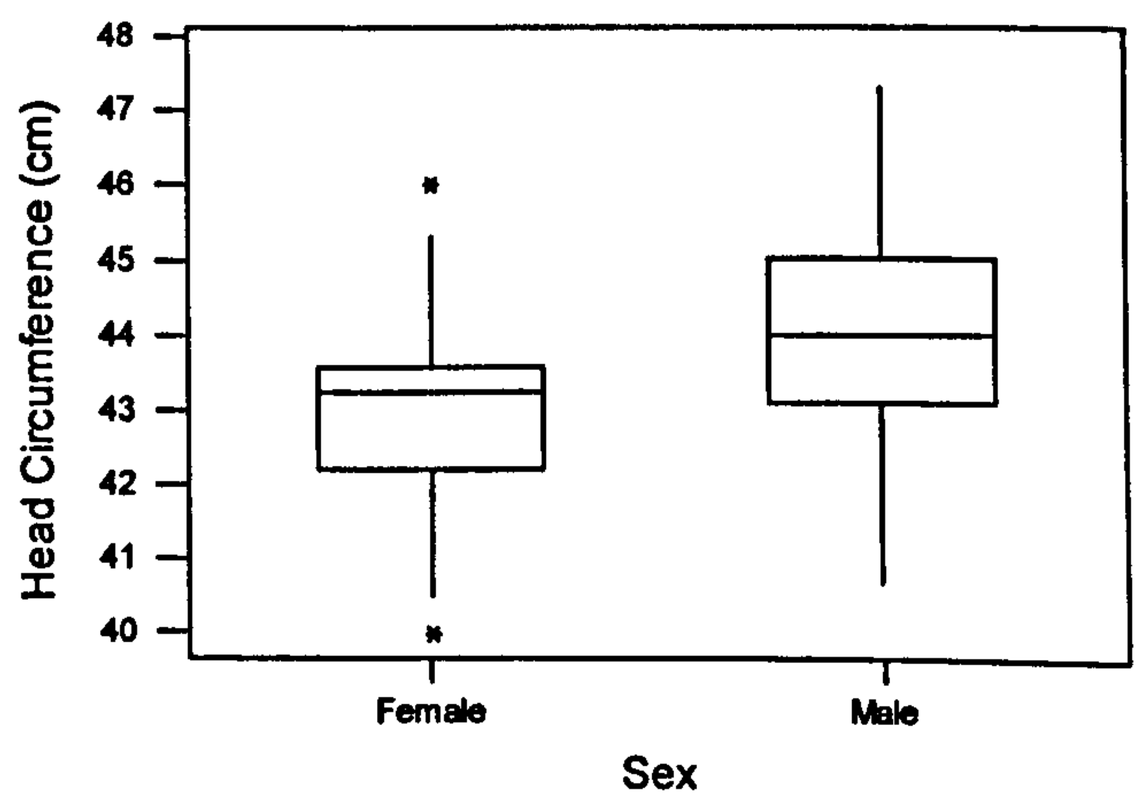
The mean length of all the infants was 66.5 ± 2.6 cm. The mean length of the females was 65.5 ± 2.5cm and of the males 67.7 ± 2.1 cm. This difference was also statistically significant (p=0.000). This is illustrated in Figure 4.27.

Figure 4.27 Length at 6 Months



The mean head circumference of all the infants was 43.4 ± 1.5cm. The female mean was 42.8 ± 1.3 cm and the male 44.1 ± 1.4 cm. This difference was also statistically significant (p=0.000). This is illustrated in Figure 4.28.

Figure 4.28 Head Circumference at 6 Months



4.3.3 Missing Landmarks

Five landmarks were found to be missing in some of the 6 months models. The missing landmark details are shown in Table 4.15. Menton was not missing in any of the 6 month models however pronasale (prn) was missing in one case where the face was too far forward during image capture and the tip of the nose was not captured. The other missing landmarks were around the ears. The right ear landmarks were again more frequently missing than the left. 10 models had one missing landmark and 8 had two missing landmarks.

Table 4.15 Missing Landmarks at 6 Months

Landmark	Missing Frequency
prn	1
obsR	11
obsL	4
obiR	6
obiL	4

4.3.4 Linear and Angular Measurements at 6 Months

4.3.4.1 Face Height, Width and Depth

The means and standard deviations of face heights, widths and depths at 3 months are shown in Table 4.16.

Table 4.16 Measurements of the Face at 6 Months in mm

	Mean	Female Mean	Male Mean	P Value*
Face Depth				
obiL-n	87.4 ± 3.3	85.9 ± 3.1	88.7 ± 3.0	**0.000**
obiR-n	87.8 ± 3.7	86.1 ± 3.2	89.3 ± 3.5	**0.000**
obiL-sn	83.4 ± 2.9	81.8 ± 2.6	84.7 ± 2.6	**0.000**
obiR-sn	83.6 ± 3.3	81.8 ± 2.7	85.2 ± 3.0	**0.000**
obiL-pg	77.3 ± 3.1	76.0 ± 2.8	78.4 ± 2.9	**0.000**
obiR-pg	78.0 ± 3.2	76.6 ± 2.6	79.2 ± 3.2	**0.000**
Face Width				
obsR-obsL	122.1 ± 5.3	120.0 ± 4.9	124.0 ± 4.8	**0.000**
obiR-obiL	99.5 ± 4.0	97.8 ± 3.4	101.0 ± 3.8	**0.000**

Face Height				
n-me	75.5 ± 3.8	73.7 ± 3.8	77.2 ± 2.9	**0.000**
sn-me	51.9 ± 3.1	50.6 ± 3.3	53.0 ± 2.4	**0.000**
n-sn	27.3 ± 1.6	26.5 ± 1.5	28.0 ± 1.4	**0.000**

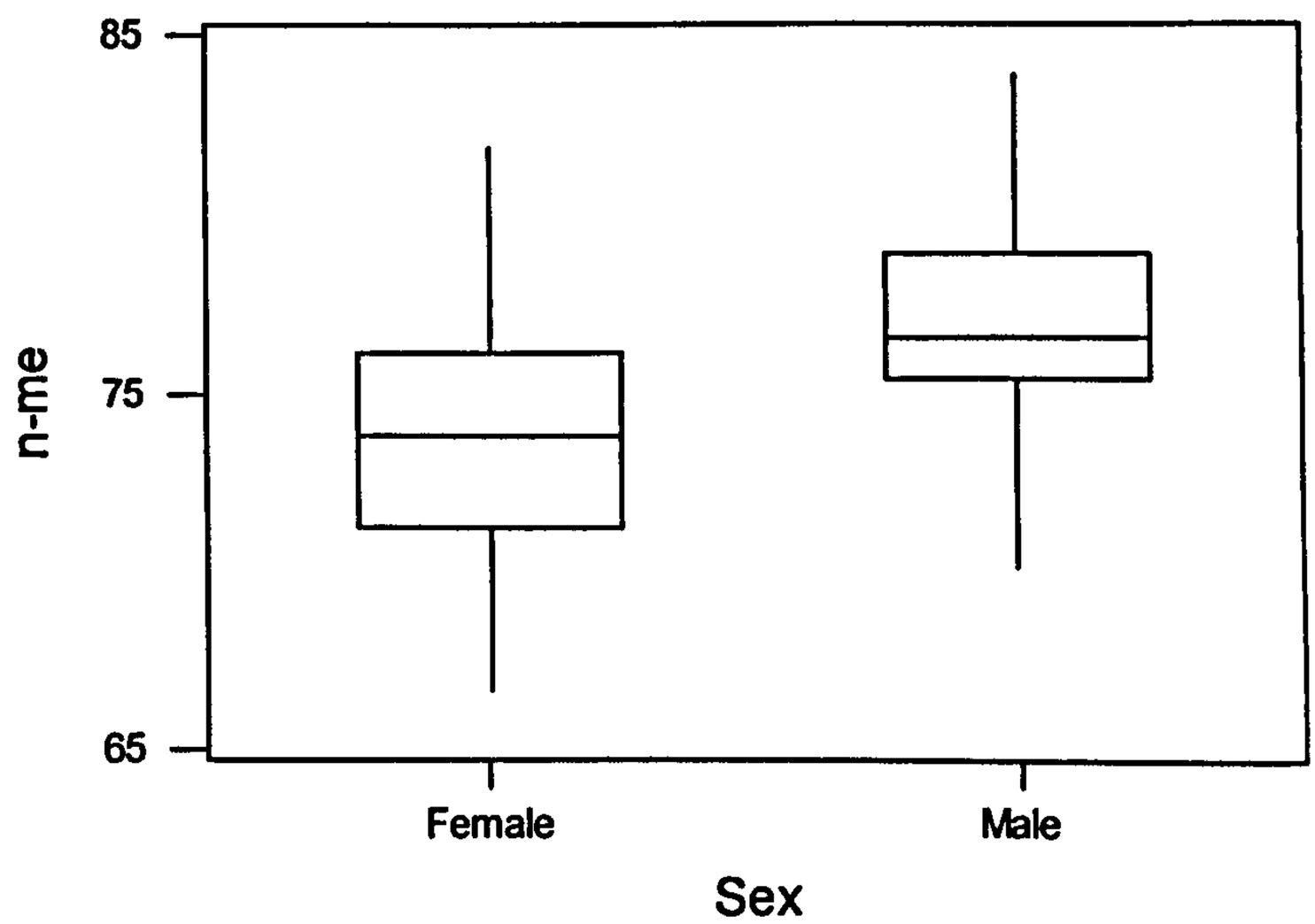
*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

Upper face depth (obi-n) mean was 87.8 ± 3.7 mm on the right and 87.4 ± 3.3 mm on the left. Maxillary depth (obi-sn) mean was 83.6 ± 3.3 mm on the right and 83.4 ± 2.9 mm on the left. Mandibular depth (obi-pg) mean was 77.3 ± 3.1 mm on the left and 78.0 ± 3.3 mm on the right. The right side measurements were consistently larger than the left but these differences were only statistically significant for mandibular depth (p=0.013). The males were also statistically significantly larger than the females for all of these measurements, with mean differences of 2.4 to 3.4 mm.

The upper face width (obsR-obsL) had a mean value of 122.1 ± 5.3 mm. The lower face width (obiR-obiL) mean was 99.5 ± 4.0 mm. The male face width was significantly greater than the females for both of these measurements, with mean differences of 3.2 to 4.0 mm.

The mean total face height (n-me) was 75.5 ± 3.8 mm. Upper face height (n-sn) mean was 27.3 ± 1.6 mm. Lower face height mean was 51.9 ± 3.1 mm. The male face height was statistically significantly greater than the females for all of these measurements, with mean differences of 1.5 to 3.5 mm. This is shown in Figure 4.29.

Figure 4.29 Gender Differences in Total Face Height at 6 Months



4.3.4.2 Eye Measurements

The means and standard deviations of the measurements around the eyes at 6 months are shown in Table 4.17.

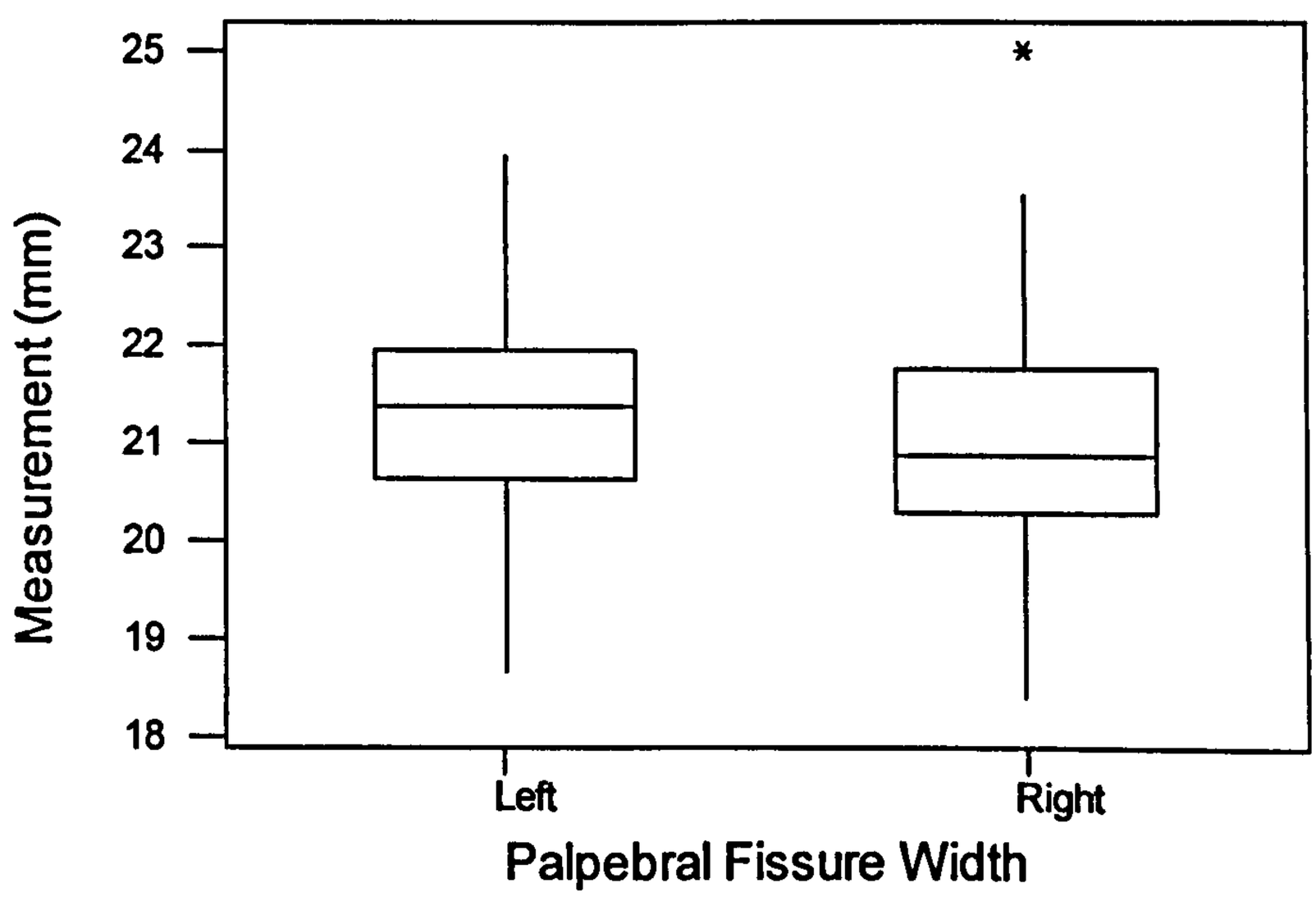
Table 4.17 Measurements of the Eyes at 6 Months in mm

	Mean	Female Mean	Male Mean	P Value*
Eyes				
exL-exR	68.9 ± 2.6	67.8 ± 2.0	69.8 ± 2.6	**0.000**
enL-enR	28.1 ± 1.8	27.6 ± 1.7	28.5 ± 1.9	**0.022**
exL-enL	21.3 ± 1.0	21.0 ± 0.9	21.6 ± 1.0	**0.002**
exR-enR	21.1 ± 1.1	20.7 ± 0.9	21.4 ± 1.2	**0.003**

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in bold.

The biocular width (exL-exR) mean was 68.9 ± 2.6 mm. The intercanthal width (enL-enR) mean was 28.1 ± 1.8 mm. Palpebral fissure width (ex-en) was 21.3 ± 1.0 mm on the left and 21.1 ± 1.1 mm on the right. All of these measurements were statistically significantly greater in males than females. A paired t test found that the palpebral fissure width was significantly greater on the left (p=0.003) with a mean difference of 0.23 mm. This is illustrated in Figure 4.30.

Figure 4.30 Left and Right Differences in Palpebral Fissure Width at 6 Months



4.3.4.3 Nose and Nostril Measurements

The means and standard deviations of the measurements around the nose and nostrils at 6 months are shown in Table 4.18.

Table 4.18 Measurements of the Nose and Nostrils at 6 Months in mm

	Mean	Female Mean	Male Mean	P Value*
Nose				
acL-acR	26.6 ± 1.5	26.0 ± 1.4	27.2 ± 1.4	**0.000**
alL-alR	23.9 ± 1.5	23.3 ± 1.3	24.5 ± 1.5	**0.000**
acL-prn	17.3 ± 1.3	16.8 ± 1.0	17.8 ± 1.3	**0.000**
acR-prn	17.9 ± 1.2	17.4 ± 0.9	18.4 ± 1.2	**0.000**
n-prn	21.9 ± 1.7	21.1 ± 1.5	22.6 ± 1.6	**0.000**
sn-prn	10.0 ± 1.0	9.9 ± 0.8	10.1 ± 1.2	0.45
Nostrils				
sbalL-cL	6.5 ± 0.8	6.2 ± 0.6	6.8 ± 0.8	**0.000**
sbalR-cR	6.3 ± 0.8	6.0 ± 0.5	6.5 ± 0.9	**0.000**
sn'L-al'iL	4.5 ± 0.8	4.3 ± 0.6	4.7 ± 0.8	**0.010**
sn'R-al'iR	4.9 ± 0.7	4.7 ± 0.7	5.1 ± 0.8	**0.018**
sn'R-sn'L	5.8 ± 0.8	5.6 ± 0.8	5.9 ± 0.8	0.070

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

Anatomic nose width (acR-acL) and soft nose width (alR-alL) means were 26.6 ± 1.5 mm and 23.9 ± 1.5 mm respectively. Nasal dorsum length (n-prn) mean was 21.9 ± 1.7mm and nasal tip protrusion (sn-prn) mean was 10.0 ± 1.0 mm. Paired t tests showed that the right alar length (acR-prn) was significantly greater than the left (p=0.000) with a mean difference of 0.59 mm. All of the nose measurements were significantly greater in males than females except nasal tip protrusion.

The nostril long axis (sbal-c) mean was 6.5 ± 0.8 mm on the left and 6.3 ± 0.8 mm on the right. Nostril width (sn'-al'i) mean was 4.5 ± 0.8 mm on the left and 4.9 ± 0.7 mm on the right. Paired t tests showed these right and left differences were statistically significant with the left nostril longer (p=0.000) and narrower (p=0.000) than the right. This is consistent with the findings at 3 months. Nostril length and width were significantly greater in males than females.

4.3.4.4 Upper and Lower Lip Measurements

The means and standard deviations of the measurements around the upper and lower lips at 6 months are shown in Table 4.19.

Table 4.19 Measurements of the Upper and Lower Lips at 6 Months in mm

	Mean	Female Mean	Male Mean	P Value*
Upper Lip				
chR-chL	31.1 ± 2.2	30.5 ± 2.1	31.6 ± 2.2	**0.019**
cphL-chL	19.9 ± 1.6	19.4 ± 1.7	20.2 ± 1.5	**0.023**
cphR-chR	20.2 ± 1.7	19.7 ± 1.7	20.7 ± 1.6	**0.005**
cphR-cphL	7.3 ± 1.1	6.8 ± 0.9	7.7 ± 1.2	**0.000**
ls-sn	10.7 ± 1.5	10.4 ± 1.5	10.9 ± 1.5	0.14
ls-stos	5.3 ± 1.3	5.1 ± 1.3	5.4 ± 1.3	0.34
sn-stos	14.4 ± 1.4	14.1 ± 1.4	14.8 ± 1.3	**0.013**
sbalL-chL	24.9 ± 1.7	24.5 ± 2.0	25.3 ± 1.3	**0.039**
sbalR-chR	25.4 ± 1.9	24.8 ± 2.0	26.0 ± 1.6	**0.002**
Lower Lip				
chL-li	16.4 ± 1.3	16.1 ± 1.3	16.8 ± 1.4	**0.016**
chR-li	17.1 ± 1.4	16.6 ± 1.3	17.5 ± 1.4	**0.004**
li-stoi	5.9 ± 1.3	5.6 ± 1.0	6.1 ± 1.4	0.053
sl-li	7.0 ± 1.2	7.1 ± 1.2	7.0 ± 1.2	0.75
sl-stoi	11.4 ± 1.0	11.3 ± 1.1	11.6 ± 1.0	0.16

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

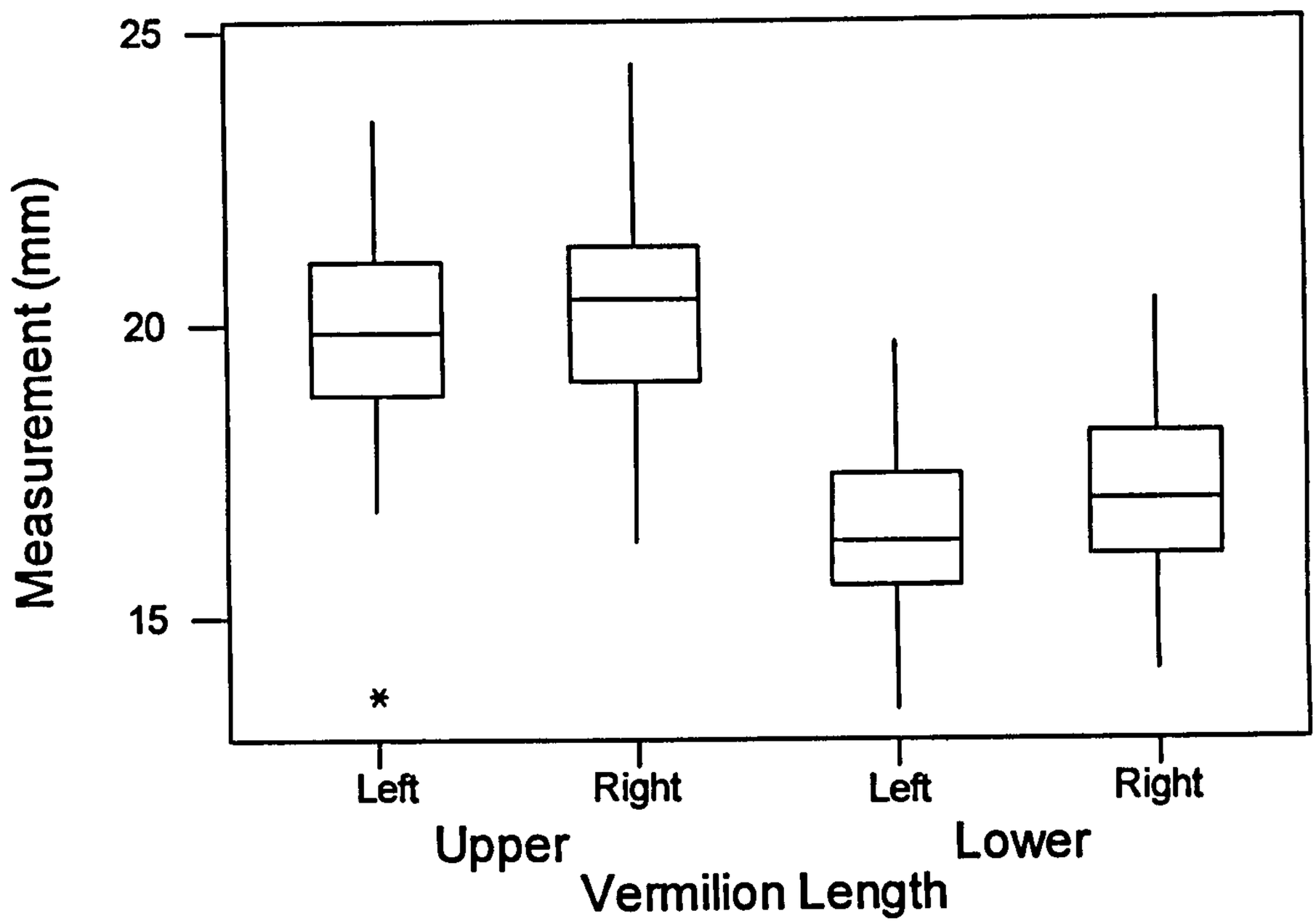
Mouth width (chR-chL) mean was 31.1 ± 2.2 mm. There was a statistically significant difference in this measurement between males and females with a mean difference of 1.1 mm. Philtrum width (cphL-cphR) mean was 7.3 ± 1.1 mm. This measurement was significantly greater in males than females with a mean difference of 0.9 mm. Upper vermilion lengths (cphR-chR, cphL-chL) were also significantly greater in males than females. Paired t test found that the right upper vermilion length was greater than the left (p=0.005) with a mean difference of 0.35 mm.

Upper lip height (sn-stos) mean was 14.4 ± 1.4mm. The lateral lip height (sbal-ch) mean was 24.9 ± 1.7 mm on the left and 25.4 ± 1.9 mm. A paired t test showed this right and left difference was statistically significant (p=0.000). Upper lip height (sn-stos) and lateral lip heights (sbalR-chR, sbalL-chL) were significantly greater in males than females.

Lower lip height (sl-stoi) mean was 11.4 ± 1.0 mm. Lower cutaneous lip height (sl-li) mean was 7.0 ± 1.2 mm. Lower vermilion height (li-stoi) mean was 5.9 ± 1.3 mm. None of these lower lip measurements were significantly different in males or females although the

difference in lower vermilion height was close to being significant (p=0.053). Only the lower lip vermilion lengths (chR-li, chL-li) were shown to be statistically significantly different in males and females. Paired t test showed that the lower vermilion length was significantly (p=0.000) greater on the right than the left with a mean difference of 0.62 mm. This is illustrated in Figure 4.31.

Figure 4.31 Left and Right Differences in Vermilion Lengths at 6 Months



4.3.4.5 Angular Measurements

The means and standard deviations of the angular measurements of the face at 6 months are shown in Table 4.20.

Table 4.20 Angles of the Face at 6 Months in degrees

	Mean	Female Mean	Male Mean	P Value*
Angles				
acR-prn-acL	98.3 ± 5.1	99.3 ± 4.4	97.3 ± 5.5	0.059
n-prn-sn	112.3 ± 6.1	112.2 ± 5.1	112.4 ± 7.0	0.88
prn-sn-ls	136.2 ± 7.0	135.6 ± 6.3	136.7 ± 7.7	0.48
li-sl-pg	135.7 ± 12.1	136.2 ± 12.0	135.3 ± 12.3	0.74

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in bold.

The nasal tip angle (n-prn-sn) mean was 112 ± 6°. The nasolabial angle (prn-sn-ls) mean was 136 ± 7°. The labiomental angle (li-sl-pg) mean was 136 ± 12°. The nasal tip

horizontal displacement angle (acR-prn-acL) mean was 98 ± 5°. There was no significant male or female difference in any of these angles although the difference in the nasal tip horizontal displacement angle was close to being significant (p=0.059).

4.3.5 Correlations of Body and Face Measurements at 6 Months

4.3.5.1 Correlations of Body Measurements

Correlations of weight, length and head circumference at 6 months are shown in Table 4.21.

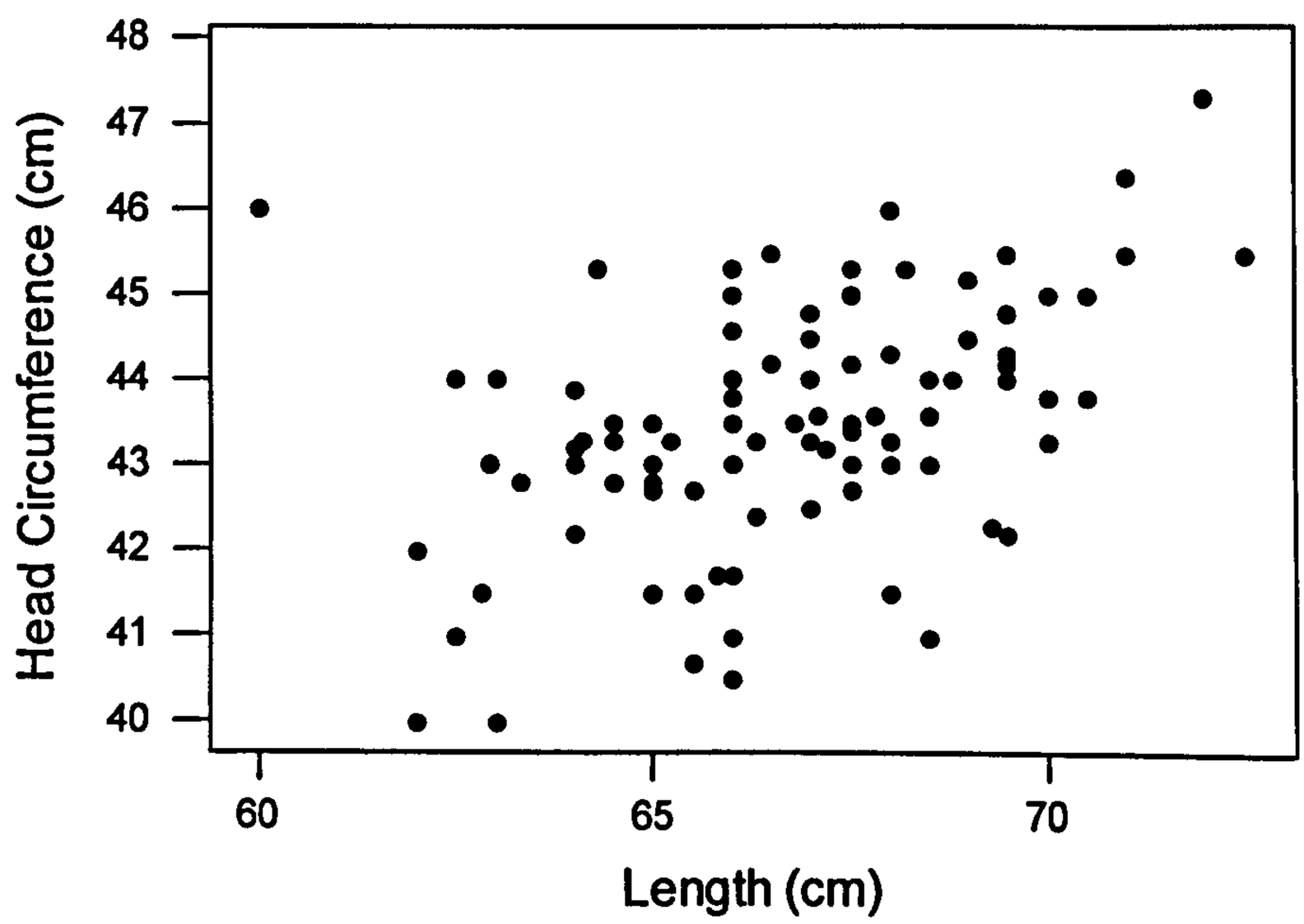
Table 4.21 Correlation of Body Measurements at 6 Months

	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Weight	0.65	**0.000**	0.46	**0.000**
Length			0.44	**0.000**

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

All of the correlations were statistically significant. The highest correlation was between weight and length with an r value of 0.65. This is illustrated in Figure 4.32.

Figure 4.32 Plot of Length against Head Circumference at 6 Months



4.3.5.2 Correlations with Face Height, Width and Depth

Correlations of face heights, widths and depths with body measurements at 6 months are shown in Table 4.22.

Table 4.22 Correlations of Body Measurements with Face Height, Width and Depth at 6 Months

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Face Depth						
obiL-n	0.62	**0.000**	0.40	**0.000**	0.54	**0.000**
obiR-n	0.69	**0.000**	0.48	**0.000**	0.58	**0.000**
obiL-sn	0.60	**0.000**	0.43	**0.000**	0.49	**0.000**
obiR-sn	0.66	**0.000**	0.50	**0.000**	0.56	**0.000**
obiL-pg	0.58	**0.000**	0.44	**0.000**	0.31	**0.004**
obiR-pg	0.62	**0.000**	0.48	**0.000**	0.38	**0.000**
Face Width						
obsR-obsL	0.53	**0.000**	0.45	**0.000**	0.49	**0.000**
obiR-obiL	0.56	**0.000**	0.34	**0.002**	0.33	**0.002**
Face Height						
n-me	0.48	**0.000**	0.39	**0.000**	0.46	**0.000**
sn-me	0.37	**0.000**	0.29	**0.005**	0.39	**0.000**
n-sn	0.35	**0.001**	0.40	**0.000**	0.41	**0.000**

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in **bold**.

All of the face measurements were significantly correlated with the body measurements. The strongest correlations tended to be with weight. The highest r value was 0.69 between upper right face depth and weight. The lowest correlation was between left mandibular depth and head circumference with r = 0.31.

All of the face depth, width and height measurements correlated significantly with each other.

4.3.5.3 Correlations with Eye Measurements

Correlations of body measurements with measurements around the eyes at 6 months are shown in Table 4.23.

Table 4.23 Correlations of Body Measurements with Eye Measurements at 6 Months

	Correlation with Weight*	P** Value	Correlation with Length*	P* Value	Correlation with Head Circumference*	P** Value
Eyes						
exR-exL	0.54	**0.000**	0.53	**0.000**	0.49	**0.000**
enL-enR	0.41	**0.000**	0.26	**0.012**	0.39	**0.000**
exL-enL	0.41	**0.000**	0.50	**0.000**	0.31	**0.002**
exR-enR	0.30	**0.004**	0.45	**0.000**	0.22	**0.032**

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

All of the eye measurements were significantly correlated with the body measurements. The highest correlation was between biocular width and body weight with r = 0.54. The lowest correlation (r=0.22) was between left palpebral fissure width and head circumference. Biocular width correlated significantly with intercanthal width and left and right palpebral fissure widths (r=0.66-0.70). The left and right palpebral fissure widths correlated significantly with each other (r=0.76) but did not correlate with the intercanthal width.

4.3.5.4 Correlations with Nose and Nostril Measurements

Correlations of body measurements with nose and nostril measurements at 6 months are shown in Table 4.24.

Table 4.24 Correlations of Body Measurements with Nose and Nostril Measurements at 6 Months

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Nose						
acL-acR	0.45	**0.000**	0.45	**0.000**	0.27	**0.009**
alL-alR	0.46	**0.000**	0.42	**0.000**	0.29	**0.005**
acL-prn	0.41	**0.000**	0.42	**0.000**	0.29	**0.006**
acR-prn	0.44	**0.000**	0.46	**0.000**	0.33	**0.001**
n-prn	0.31	**0.002**	0.36	**0.000**	0.37	**0.000**
sn-prn	0.20	0.052	0.15	0.166	0.13	0.221
Nostrils						
sbalL-cL	0.25	**0.014**	0.33	**0.001**	0.24	**0.024**
sbalR-cR	0.22	**0.033**	0.26	**0.012**	0.08	0.437
sn'L-al'iL	0.18	0.087	0.16	0.131	0.11	0.288
sn'R-al'iR	0.14	0.180	0.15	0.146	0.20	0.059
sn'R-sn'L	0.21	**0.043**	0.05	0.600	0.17	0.107

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

All of the nose measurements except nasal tip protrusion were significantly correlated with body measurements with r values ranging from 0.27 to 0.46. All of the nose measurements correlated significantly with each other except nasal tip protrusion and nasal dorsum length (r=0.07).

A few of the nostril measurements were significantly but weakly correlated with body measurements at 6 months. The strongest correlations were between nostril long axis and body length (r=0.33, 0.26). Nostril long axis and widths all correlated significantly with each other but columella width did not correlate with any of the nostril measurements. Columella width did correlate with all of the nose measurements except nasal tip protrusion.

4.3.5.5 Correlations with Upper and Lower Lip Measurements

Correlations of upper and lower lip measurements with body measurements at 6 months are shown in Table 4.25.

Table 4.25 Correlations of Body Measurements with Upper and Lower Lip Measurements at 6 Months

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Upper Lip						
chR-chL	0.40	**0.000**	0.36	**0.000**	0.27	**0.008**
cphL-chL	0.40	**0.000**	0.39	**0.000**	0.37	**0.000**
cphR-chR	0.41	**0.000**	0.43	**0.000**	0.39	**0.000**
cphR-cphL	0.23	**0.026**	0.36	**0.000**	0.24	**0.020**
ls-sn	0.03	0.772	-0.15	0.162	0.10	0.343
ls-stos	0.09	0.394	0.16	0.129	-0.09	0.385
sn-stos	0.11	0.316	0.02	0.821	0.05	0.615
sbalL-chL	0.32	**0.002**	0.22	**0.032**	0.35	**0.001**
sbalR-chR	0.35	**0.001**	0.27	**0.009**	0.43	**0.000**
Lower Lip						
chL-li	0.34	**0.001**	0.33	**0.001**	0.25	**0.017**
chR-li	0.30	**0.004**	0.32	**0.002**	0.32	**0.002**
li-stoi	0.27	**0.009**	0.15	0.161	0.17	0.095
sl-li	-0.02	0.836	-0.13	0.902	-0.07	0.505
sl-stoi	0.22	**0.035**	0.20	0.052	0.07	0.492

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

Mouth width, philtrum width and upper and lower vermilion lengths were all significantly but weakly correlated with body measurements with r values ranging from 0.23 to 0.43. They were also all significantly correlated with each other.

Upper lateral lip heights were significantly correlated with body measurements with r values of 0.22 to 0.43. None of remaining upper lip heights was significantly correlated with body measurements. There were weak correlations between lower vermilion height) and lower lip height with body weight (r=0.22.0.27) but not with body length or head circumference. Upper lip height correlated with lateral lip heights but not with vermilion lengths or mouth width.

4.3.5.6 Correlations with Angular Measurements

Correlations of body measurements with angular measurements of the face at 6 months are shown in Table 4.26.

Table 4.26 Correlations of Body Measurements with Angles of the Face at 6 Months

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Angles						
acR-prn-acL	-0.06	0.530	-0.10	0.355	-0.15	0.158
n-prn-sn	-0.08	0.424	-0.02	0.846	-0.04	0.704
prn-sn-ls	-0.26	**0.012**	-0.17	0.103	-0.11	0.280
li-sl-pg	-0.18	0.082	-0.13	0.211	-0.01	0.960

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

Only the nasal tip angle (prn-sn-ls) had a significant but weak negative correlation with body weight. All the other angles appeared to be independent of body measurements except labiomental angle which had a weak negative correlation with weight with a p value that was close to being significant (p=0.082).

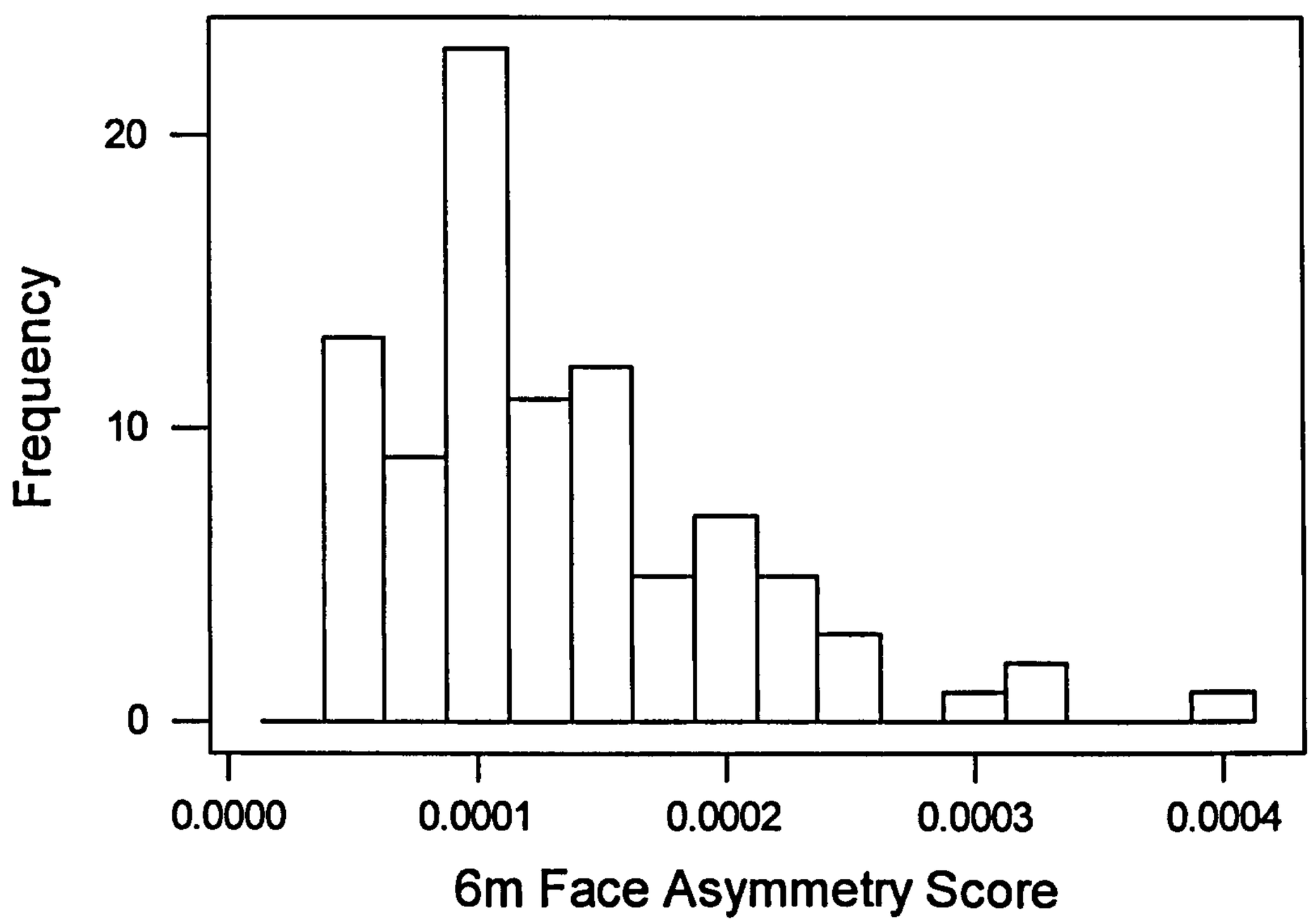
Nasal tip angle (n-prn-sn) correlated significantly with both nasal tip horizontal displacement angle (acR-prn-acL) and nasolabial angle (prn-sn-ls). None of the other angles were correlated with each other.

4.3.6 Asymmetry at 6 Months

4.3.6.1 Face

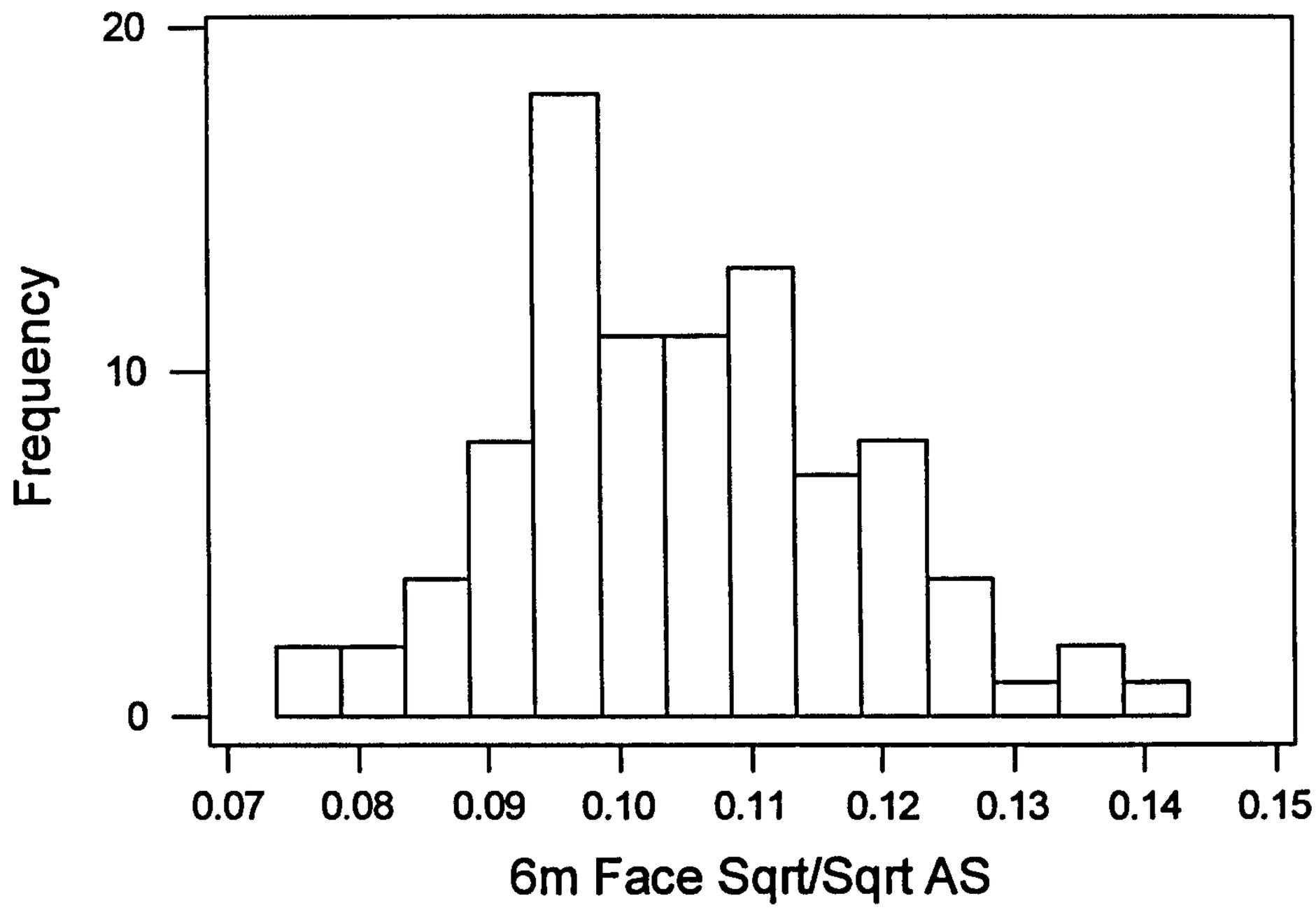
The distribution of the asymmetry scores for the face at 6 months is shown in Figure 4.33. All of the asymmetry scores were based on the landmarks in the midface, excluding the ear, lower lip and chin landmarks.

Figure 4.33 Distribution of Asymmetry Scores for the Face at 6 Months



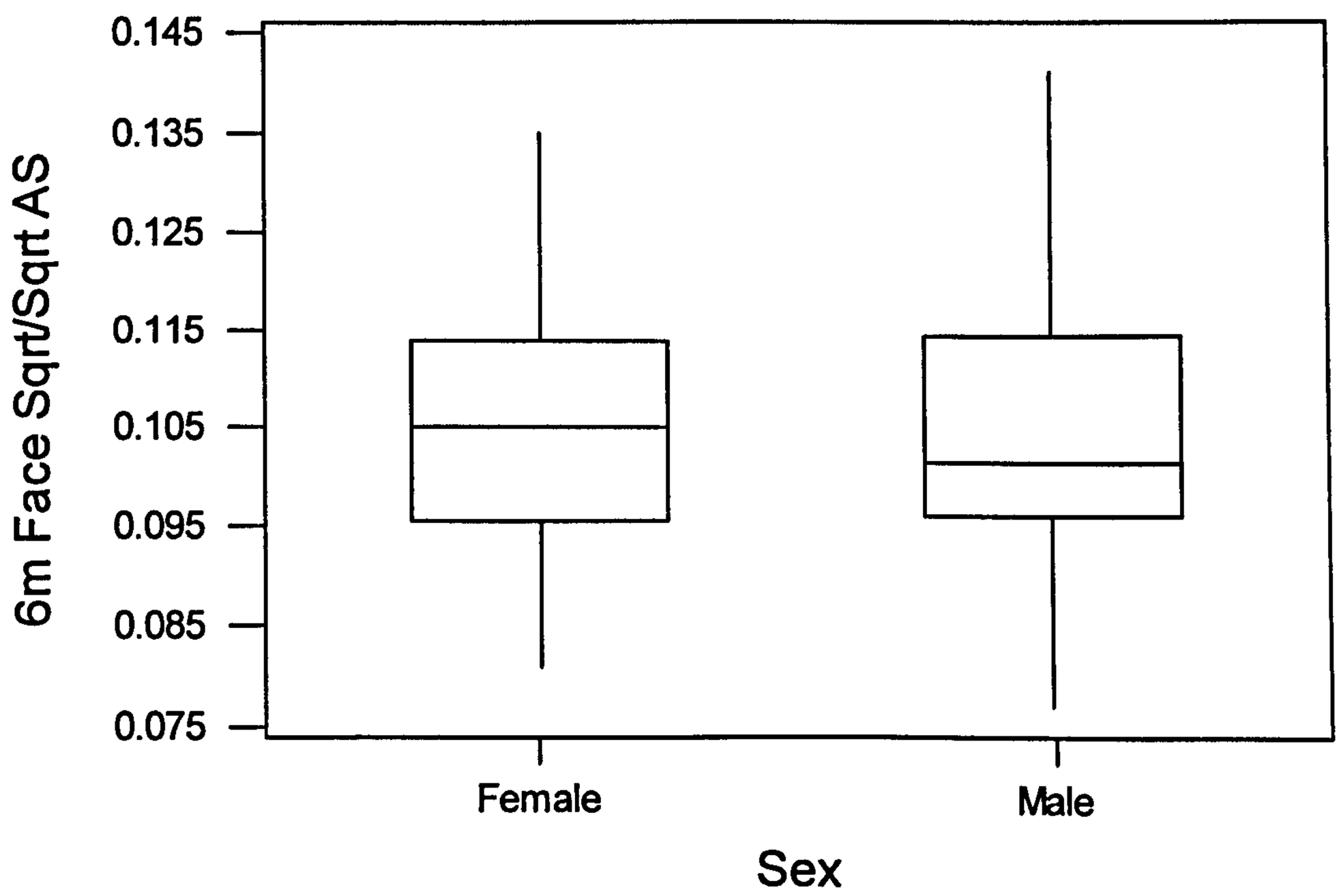
As was found at 3 months, the raw asymmetry scores were not normally distributed. Once again the fourth roots of the asymmetry scores (sqrt/sqrt AS) were well approximated by a normal distribution, as shown in Figure 4.34. Standard parametric tests were therefore applied to this transformed data.

Figure 4.34 Distribution of the Sqrt/Sqrt AS for the Face at 6 Months



The mean sqrt/sqrt AS for the face was 0.105 + 0.013. The mean sqrt/sqrt AS for the females was 0.106 + 0.013 and for the males 0.104 + 0.014. Two sample t test showed this difference was not statistically significant (p=0.58). This is illustrated in Figure 4.35.

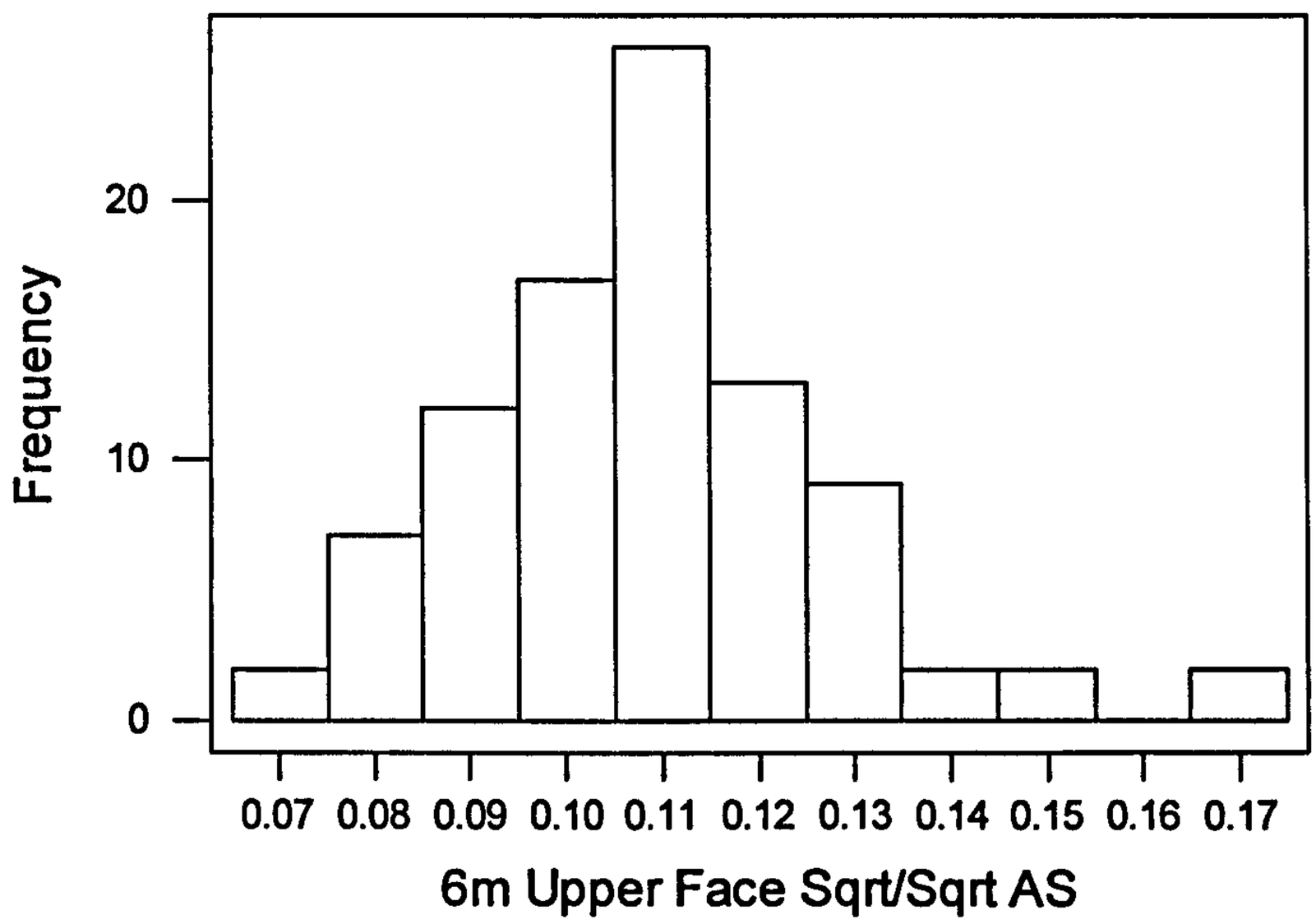
Figure 4.35 Sqrt/Sqrt AS for the Face of Males and Females at 6 Months



4.3.6.2 Upper Face

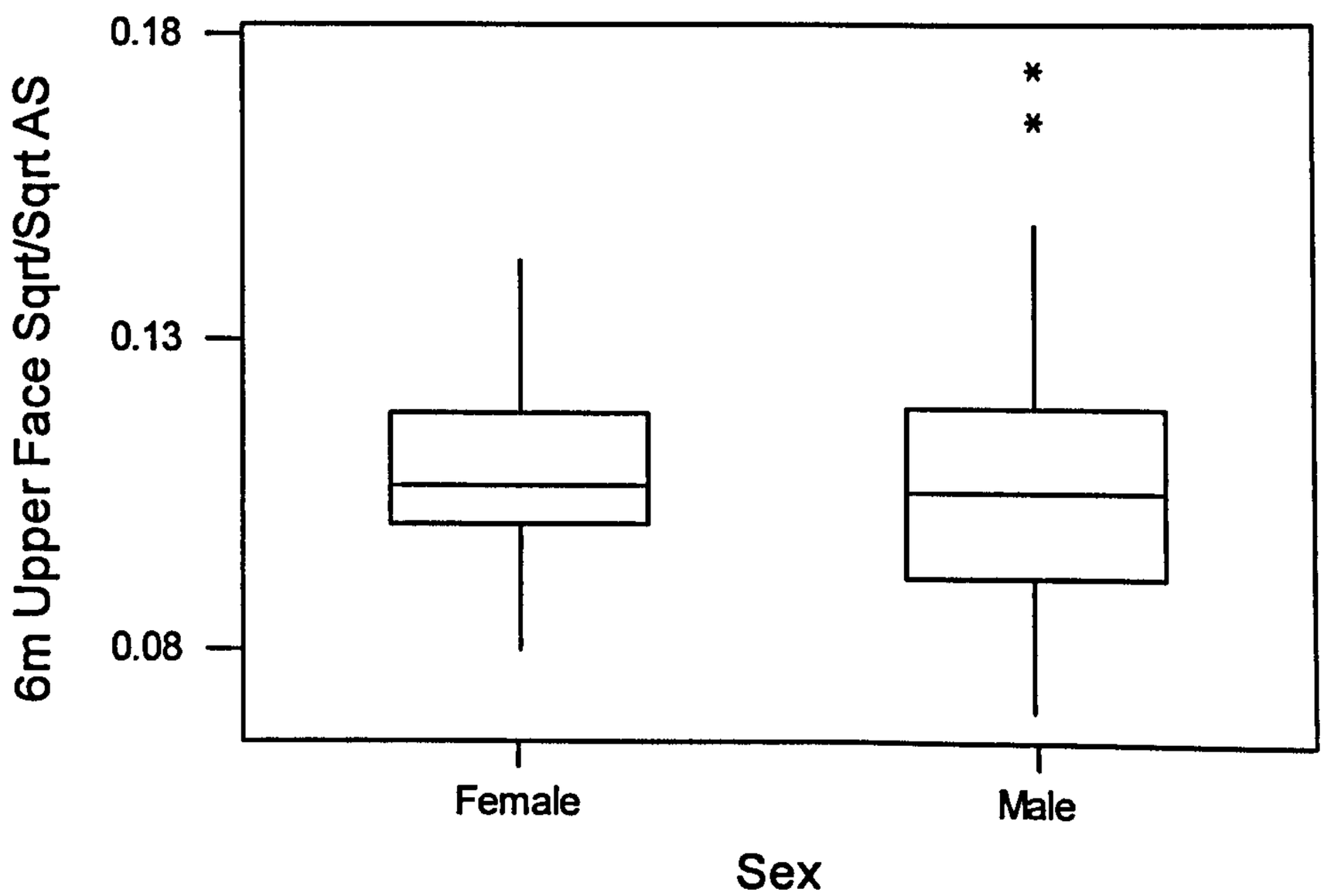
The distribution of the sqrt/sqrt AS for the upper face at 6 months is shown in Figure 4.36. The upper face asymmetry score included the endocanthion, exocanthion and nasion landmarks.

Figure 4.36 Distribution of the Sqrt/Sqrt AS for the Upper Face at 6 Months



The mean sqrt/sqrt AS for the upper face was 0.108 ± 0.019. There was no statistically significant difference between the males and females (p=0.60). This is shown in Figure 4.37.

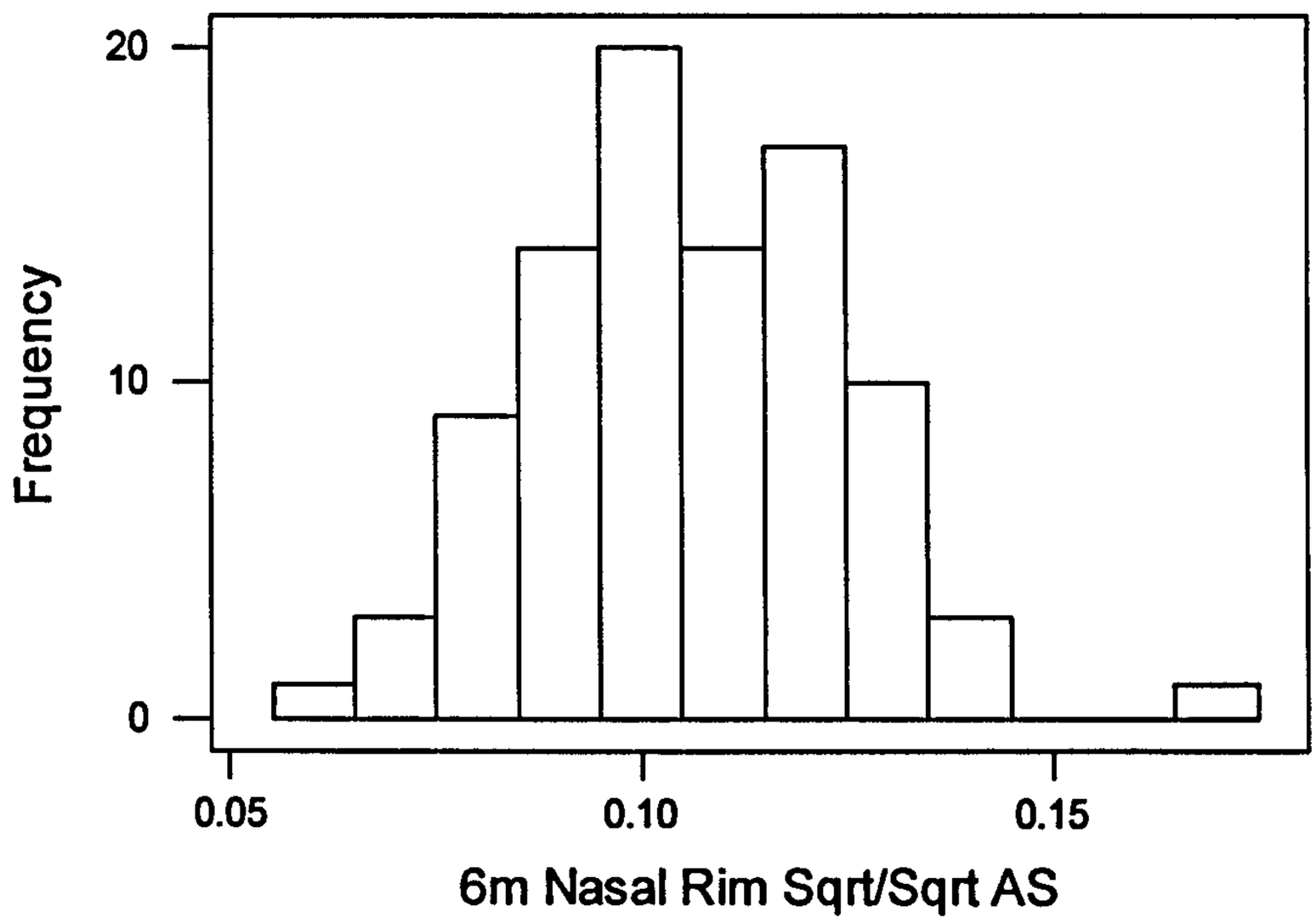
Figure 4.37 Sqrt/Sqrt AS for the Upper Face of Males and Females at 6 Months



4.3.6.3 Nasal Rim

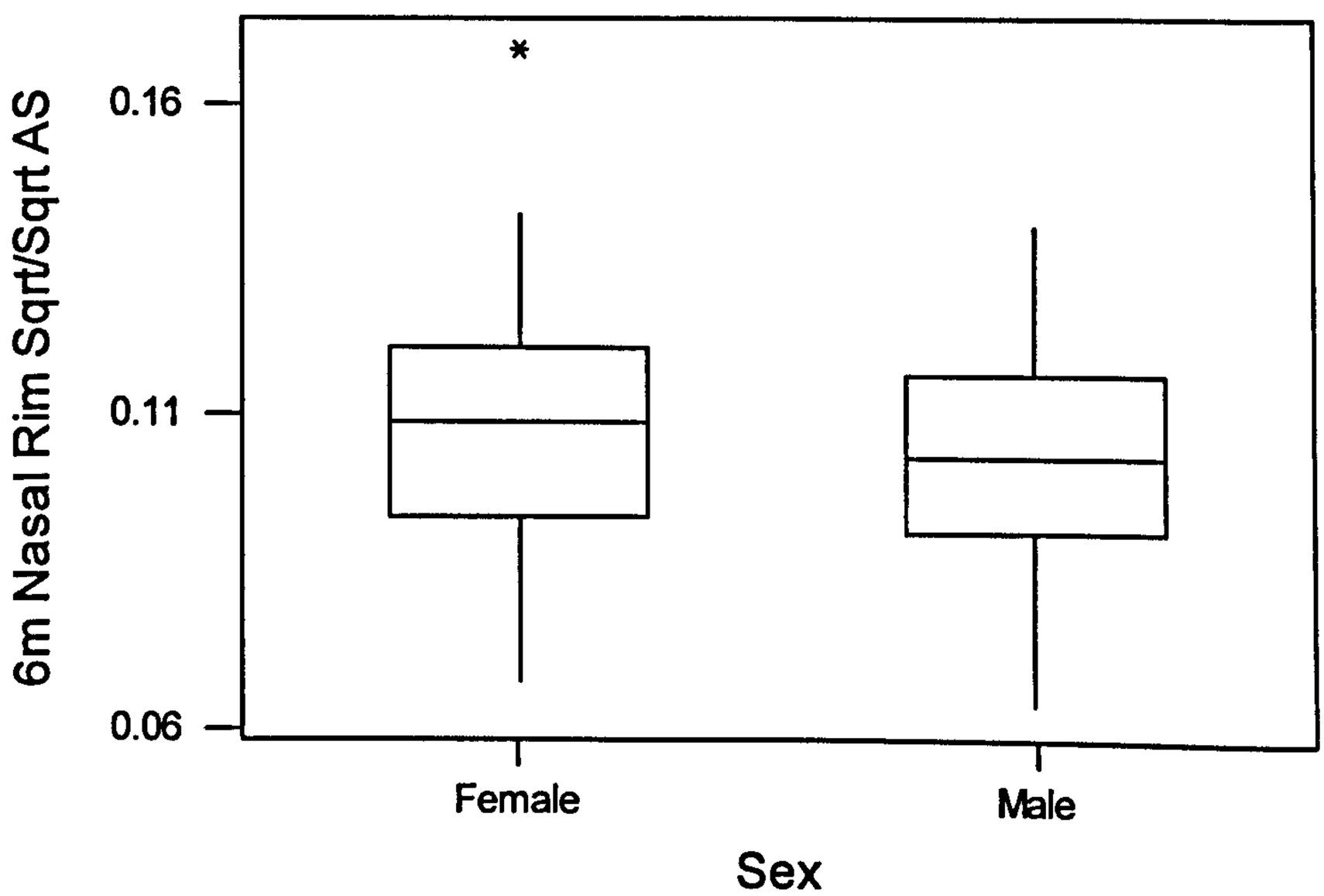
The distribution of the sqrt/sqrt AS for the nasal rim at 6 months is shown in Figure 4.38. The asymmetry score for the nasal rim incorporated the alar crest, alare, alare' outer and pronasale landmarks.

Figure 4.38 Distribution of the Sqrt/Sqrt AS for the Nasal Rim at 6 Months



The mean sqrt/sqrt AS for the nasal rim was 0.105 + 0.019. There was no statistically significant difference between the males and females (p=0.39). This is shown in Figure 4.39.

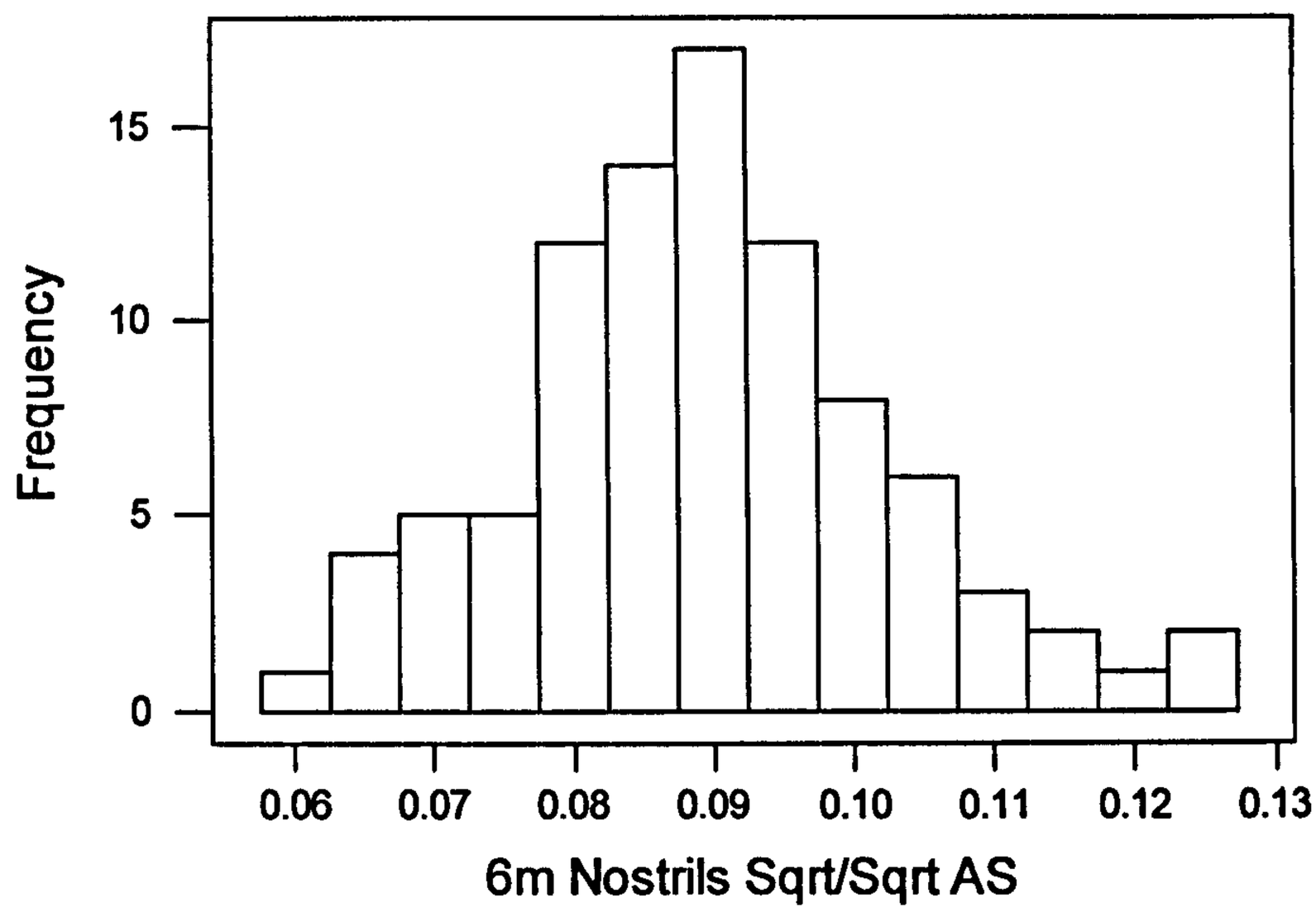
Figure 4.39 Sqrt/Sqrt AS for the Nasal Rim of Males and Females at 6 Months



4.3.6.4 Nostrils

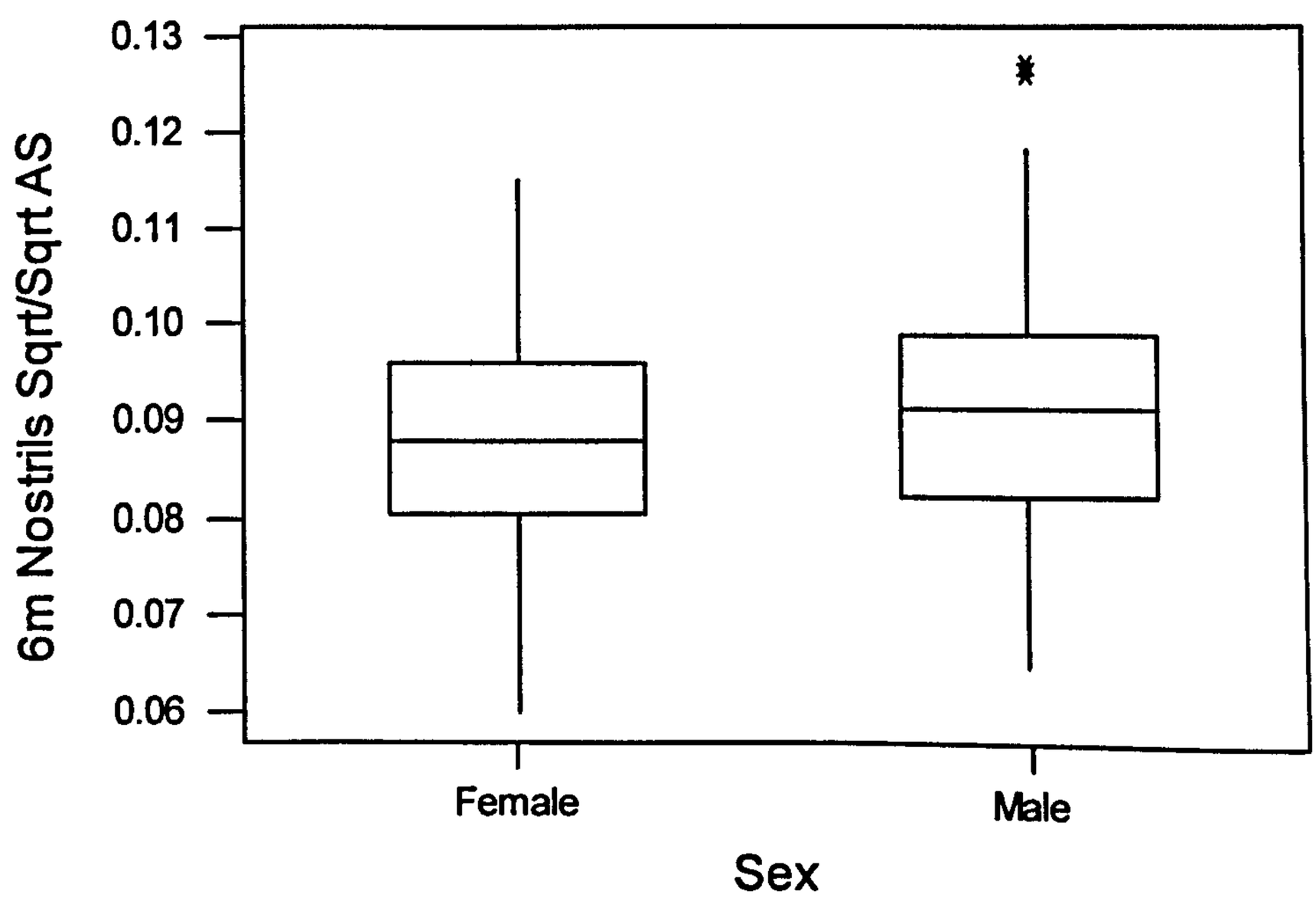
The distribution of the sqrt/sqrt AS for the nostrils at 6 months is shown in Figure 4.40. The landmarks included in this asymmetry score were subalare, alare' inner, columella, subnasale' and subnasale.

Figure 4.40 Distribution of the Sqrt/Sqrt AS for the Nostrils at 6 Months



The mean sqrt/sqrt AS for the nostrils was 0.090 ± 0.013. Contrary to the findings at 3 months, there was no statistically significant difference (p=0.25) between the asymmetry of the nostrils of males and females at 6 months. This is shown in Figure 4.41.

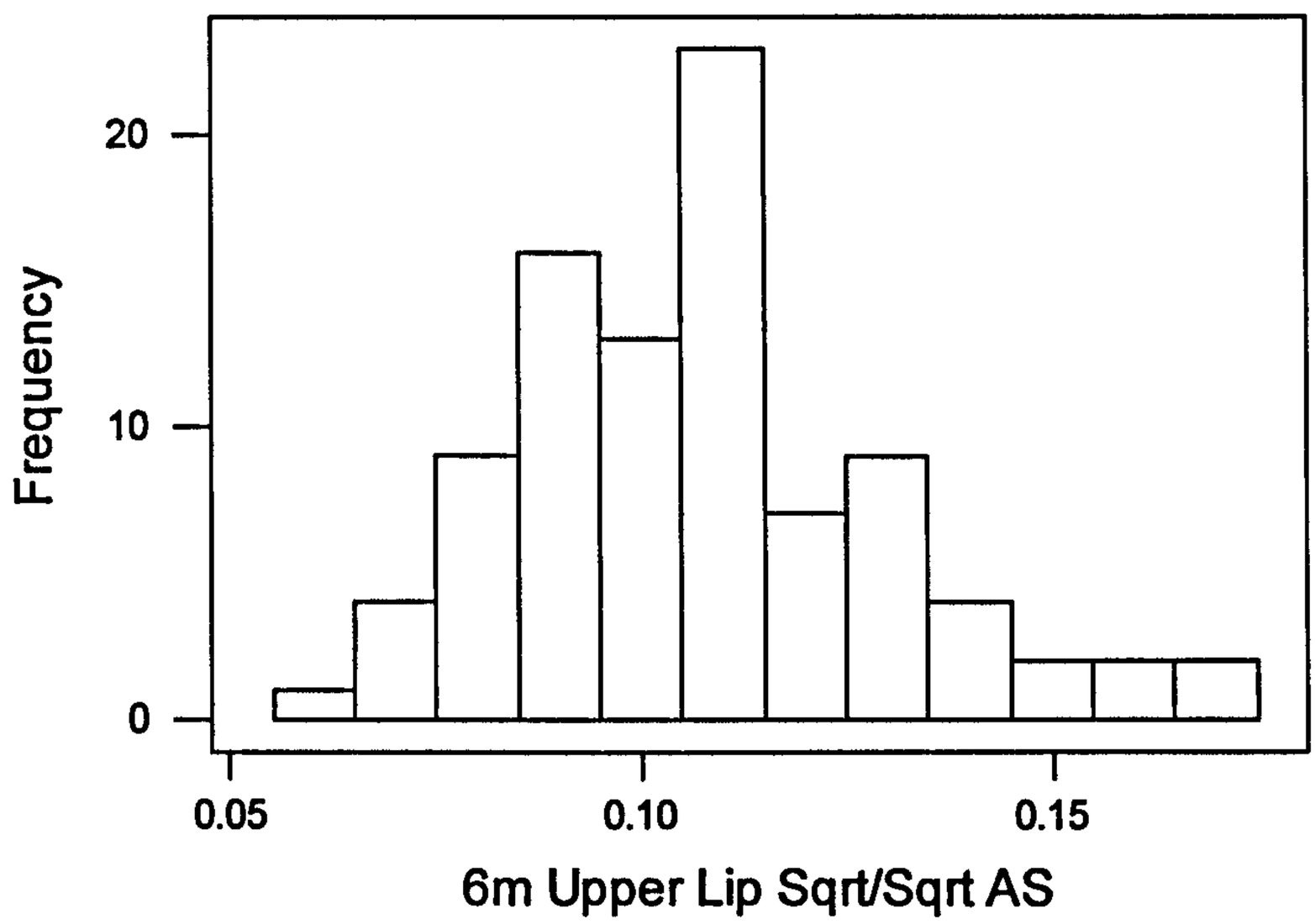
Figure 4.41 Sqrt/Sqrt AS for the Nostrils of Males and Females at 6 Months



4.3.6.5 Upper Lip

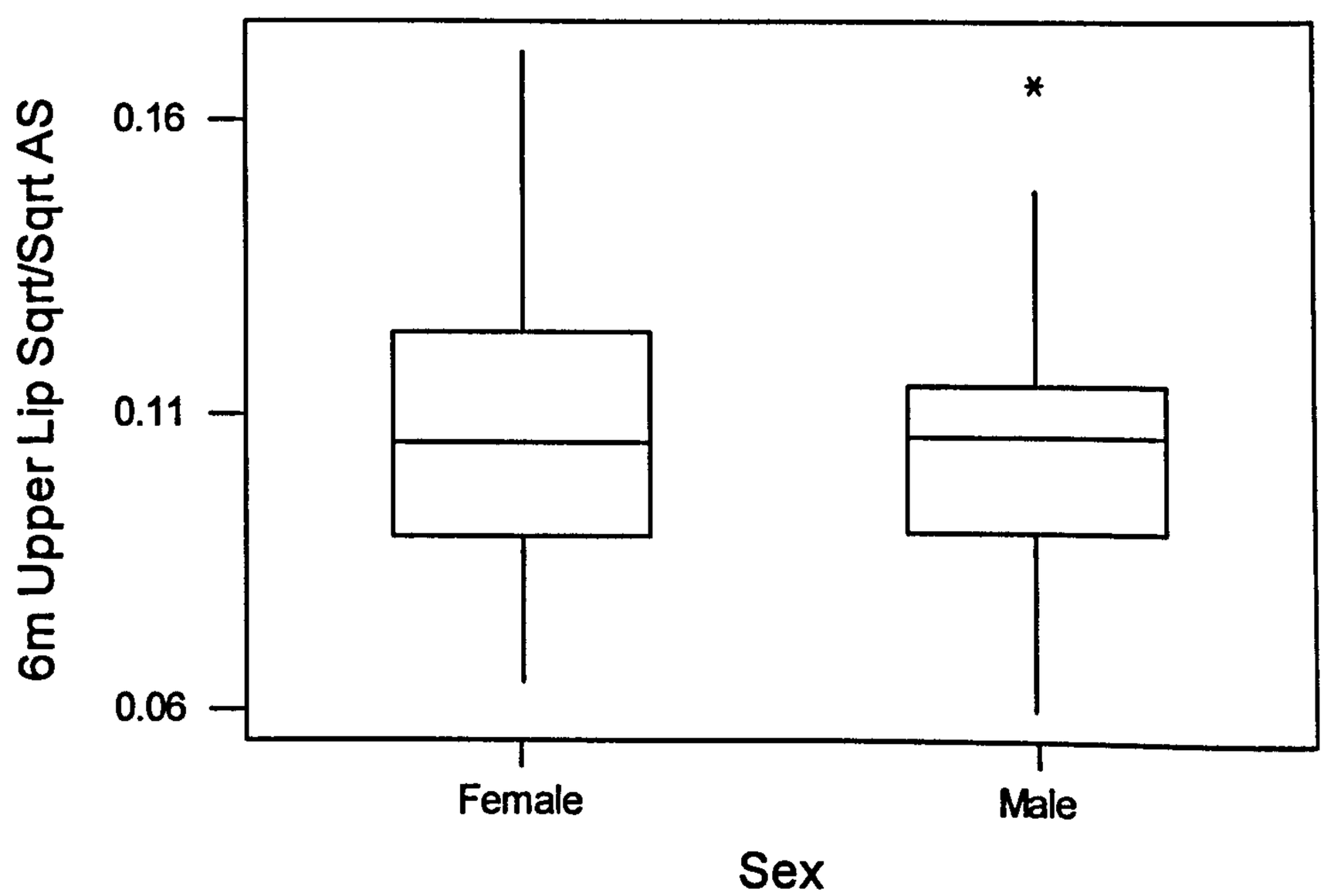
The distribution of the sqrt/sqrt AS for the upper lip at 6 months is shown in Figure 4.42. The landmarks included in this asymmetry score were cheilion, crista philtri and labrale superius.

Figure 4.42 Distribution of the Sqrt/Sqrt AS for the Upper Lip at 6 Months



The mean sqrt/sqrt AS for the upper lip was 0.106 ± 0.023. There was no statistically significant difference between the males and females (p=0.62). This is illustrated in Figure 4.43.

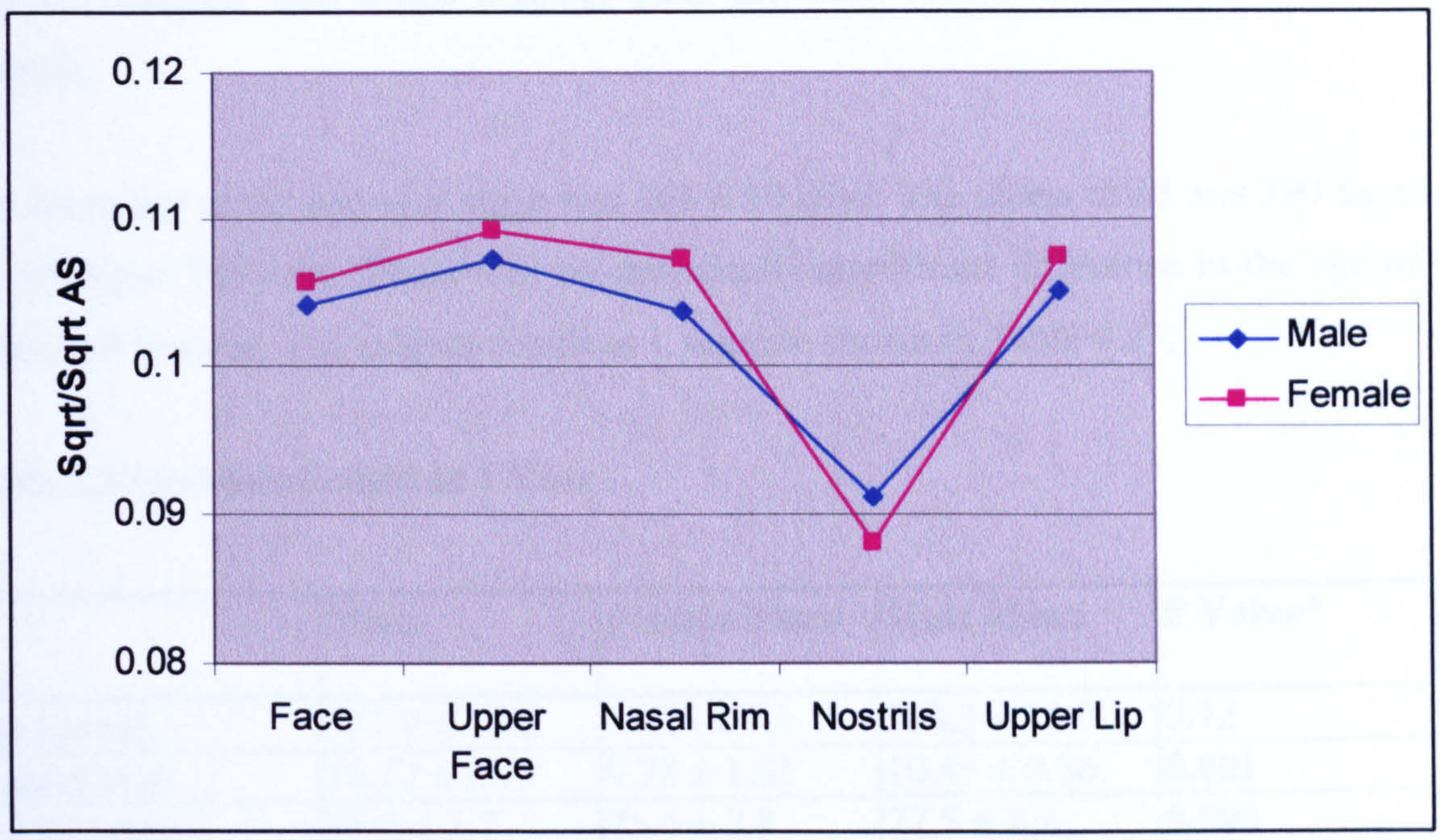
Figure 4.43 Sqrt/Sqrt AS for the Upper Lip of Males and Females at 6 Months



4.3.6.6 Comparisons of Asymmetry Scores at 6 Months

The result of comparing the asymmetry scores of the different regions of the face is illustrated in Figure 4.44.

Figure 4.44 Comparison of the Asymmetry of the Regions of the Face at 6 Months



Unlike the other ages, there was a tendency for the asymmetry scores of the females to be higher than the males at 6 months, but these differences were not significant. Paired t tests showed that the sqrt/sqrt AS of the nostrils was significantly lower than for any of the other scores (p=0.000). The only other significant difference was between the face and the upper face score (p=0.025). Once again the greatest asymmetry was in the upper face and the least in the nostrils.

4.3.6.7 Correlations of Asymmetry Scores at 6 Months

None of the asymmetry scores correlated highly with the body measurements although there were weak but significant negative correlations between body weight and head circumference and face and upper lip asymmetry (r=-0.21 to -0.26). The asymmetry score for the face correlated highly and significantly with the asymmetry scores for all of the individual regions of the face (r=0.50-0.72). All the individual asymmetry scores correlated weakly with each other (r=0.21-0.34) except upper lip with nostril asymmetry (r=0.18, p=0.08).

4.4 One Year

4.4.1 Subjects

Ninety seven infants were captured at 1 year. Ninety one infants, 48 males and 43 females were captured with a lips apart pose. The other 6 infants who attended at this stage could only be captured with a lips together pose and their results were not included in the analysis.

The mean age at the one year stage was 368 ± 10 days. The oldest child was 390 days and the youngest 348 days. There was no statistically significant difference in the age of the males and females. The subject details at 1 year are shown in Table 4.27.

Table 4.27 Subject Details at 1 Year

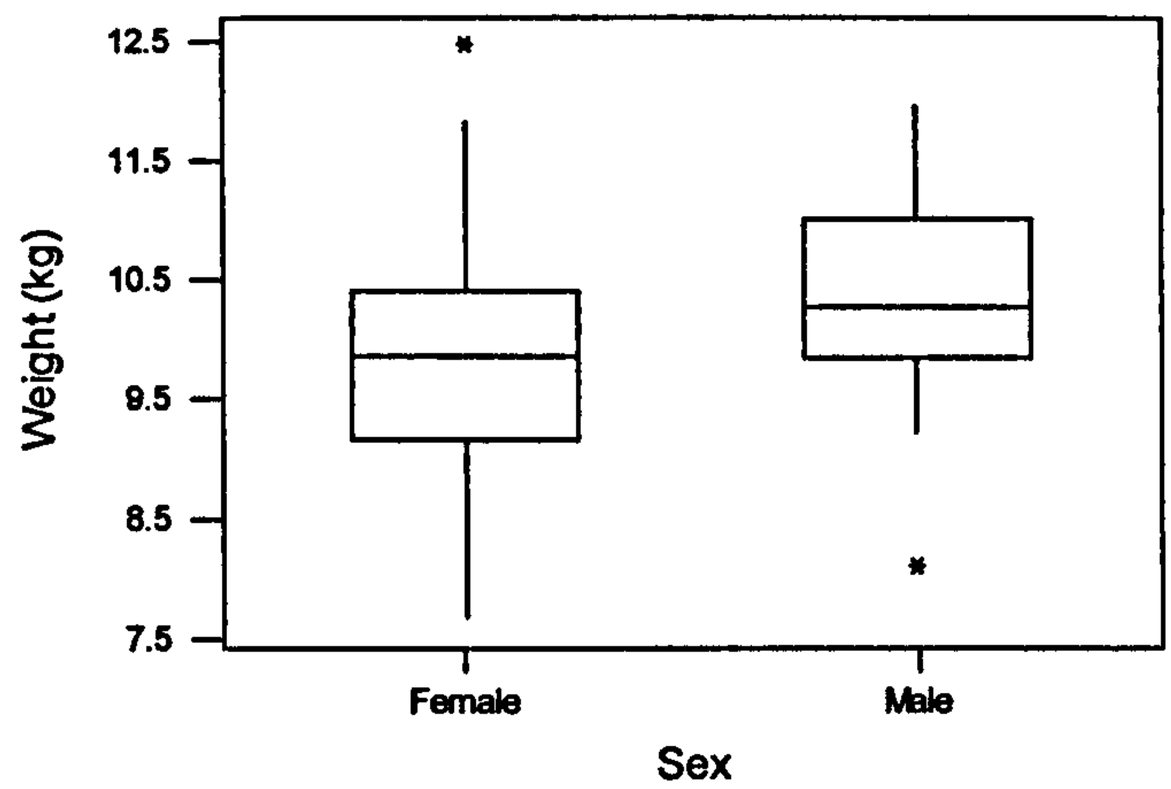
	Mean	**Female Mean**	**Male Mean**	**P Value***
Age (days)	367.9 ± 10.6	367.5 ± 9.1	368.3 ± 12.0	0.72
Weight (kg)	10.12 ± 0.99	9.78 ± 1.01	10.45 ± 0.86	**0.001**
Height (cm)	76.5 ± 2.7	75.4 ± 2.8	77.5 ± 2.2	**0.000**
Head Circumference (cm)	46.4 ± 1.6	45.6 ± 1.4	47.1 ± 1.3	**0.000**

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in bold.

4.4.2 Body measurements

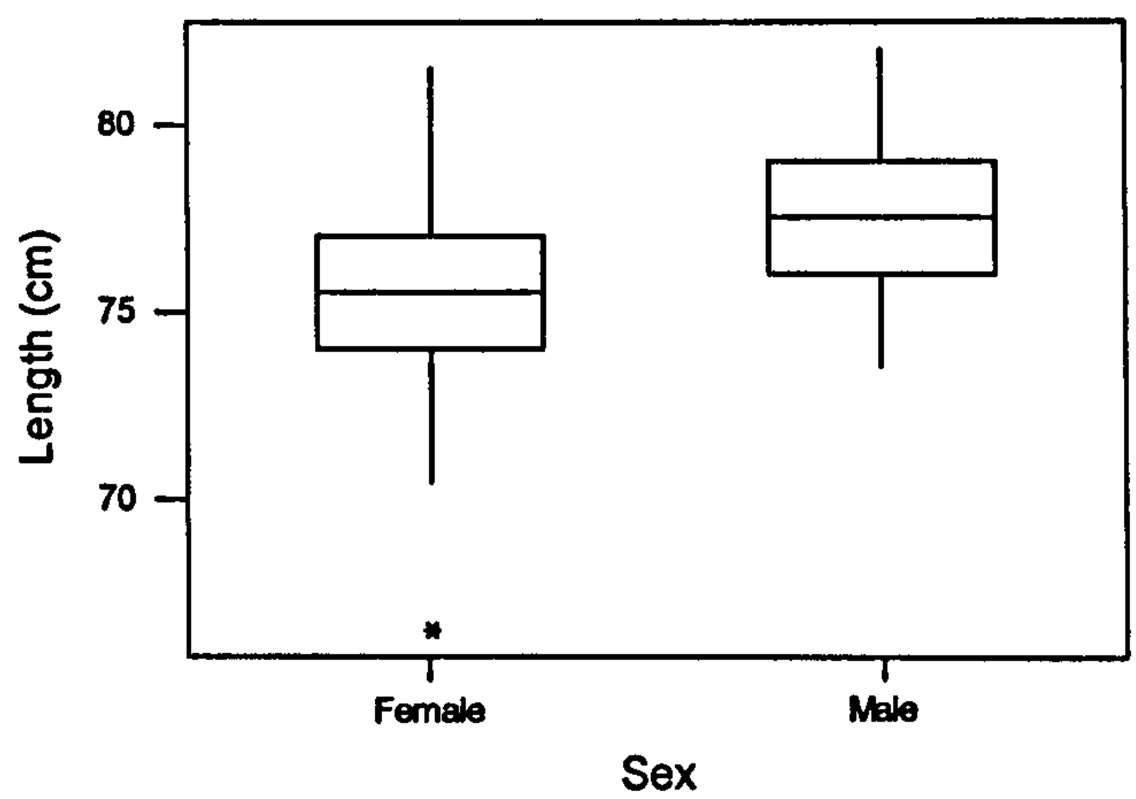
The means and standard deviations of the body measurements at 1 year are shown in Table 4.27. The mean weight of the infants was 10.12 ± 0.99 kg. The mean weight of the females was 9.78 ± 1.01 kg and the males 10.45 ± 0.86 kg. This difference was statistically significant (p=0.001) and is illustrated in Figure 4.45.

Figure 4.45 Weight at 1 Year



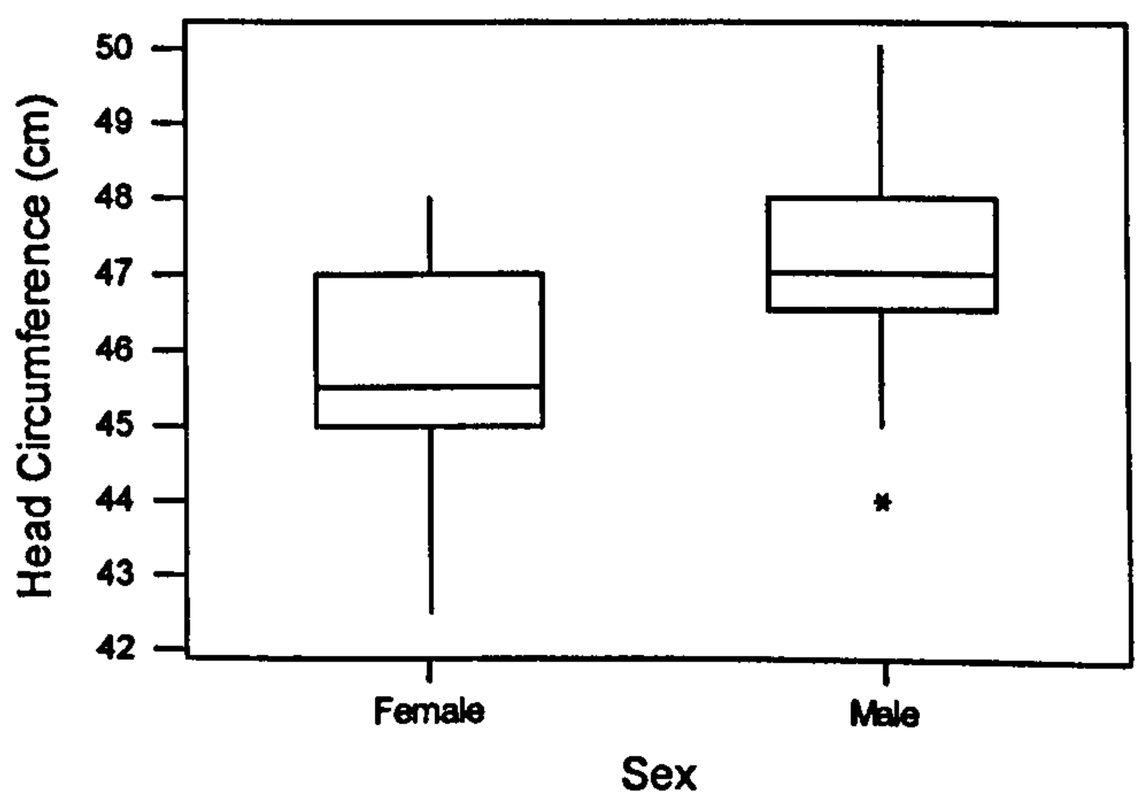
The mean length of all the infants was 76.5 ± 2.7 cm. The mean length of the females was 75.4 ± 2.8 cm and of the males 77.5 ± 2.2 cm. This difference was also statistically significant (p=0.000). This is illustrated in Figure 4.46.

Figure 4.46 Length at 1 Year



The mean head circumference of all the infants was 46.4 ± 1.6 cm. The female mean was 45.6 ± 1.4 cm and the male 47.1 ± 1.3 cm. This difference was statistically significant (p=0.000). This is illustrated in Figure 4.47.

Figure 4.47 Head Circumference at 1 Year



4.4.3 Missing Landmarks

Four landmarks were found to be missing on some of the 1 year models. The most frequently missing landmarks were otobasion superius left and right which were often obscured by hair in this age group. 13 models had one missing landmark and 12 had two missing landmarks. 11 of the models with two missing landmarks were missing both otobasion superius right and left.

Table 4.28 Missing Landmarks at 1 Year

Landmark	Missing Frequency
me	2
obsR	16
obsL	17
obiR	2
obiL	0

4.4.4 Linear and Angular Measurements at 1 Year

4.4.4.1 Face Height, Width and Depth

The means and standard deviations of face heights, width and depths at 1 year are shown in Table 4.29.

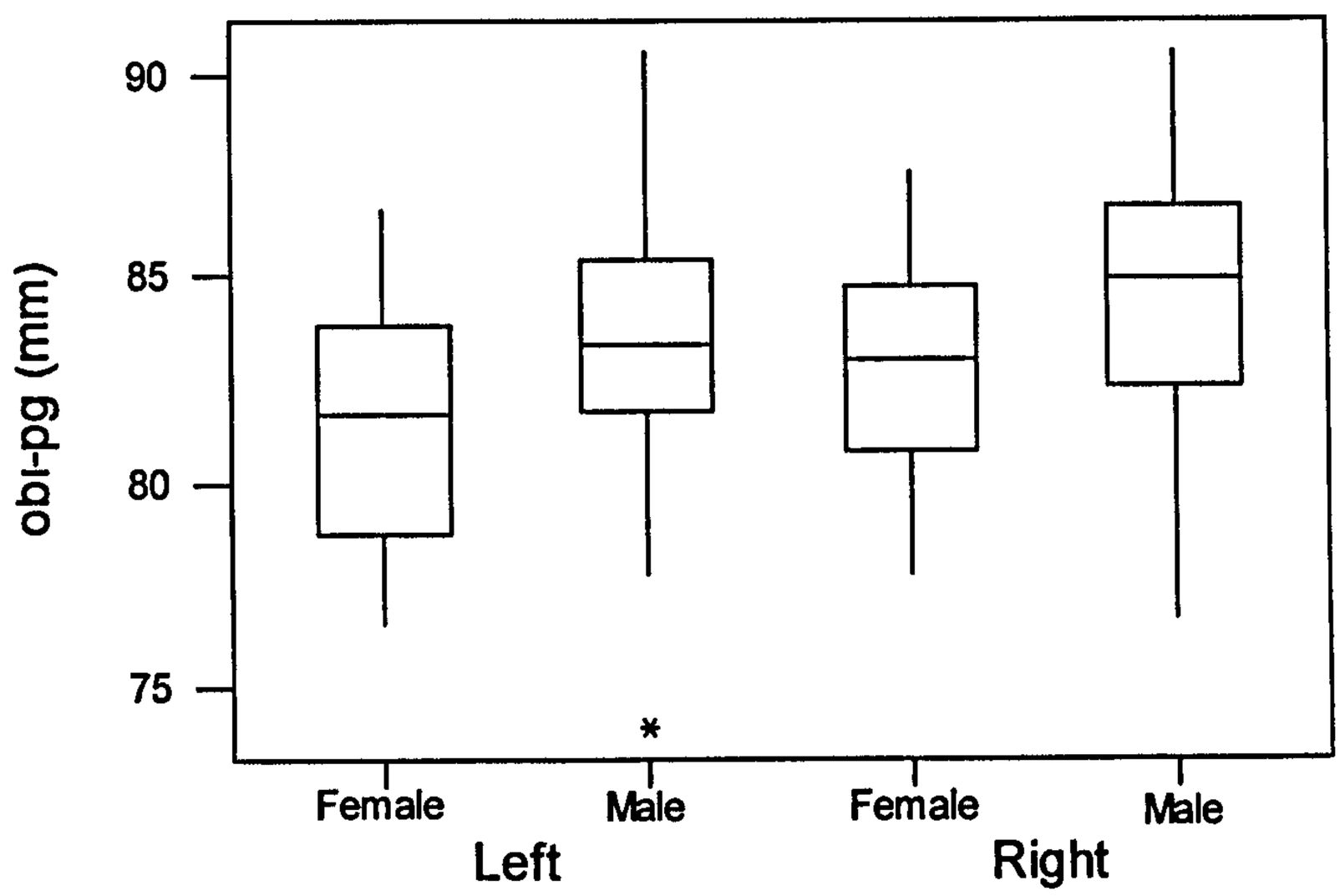
Table 4.29 Measurements of the Face at 1 Year in mm

	Mean	Female Mean	Male Mean	P Value*
Face Depth				
obiL-n	92.6 ± 3.5	91.2 ± 3.2	93.8 ± 3.3	**0.000**
obiR-n	93.6 ± 3.6	92.1 ± 3.1	95.0 ± 3.4	**0.000**
obiL-sn	88.1 ± 3.2	86.8 ± 2.7	89.4 ± 3.0	**0.000**
obiR-sn	88.9 ± 3.1	87.4 ± 2.5	90.3 ± 2.9	**0.000**
obiL-pg	82.6 ± 3.1	81.6 ± 2.9	83.6 ± 3.1	**0.002**
obiR-pg	83.8 ± 3.0	82.9 ± 2.6	84.6 ± 3.1	**0.007**
Face Width				
obsR-obsL	127.8 ± 4.6	125.9 ± 4.4	129.1 ± 4.4	**0.005**
obiR-obiL	104.1 ± 4.1	103.0 ± 3.6	105.0 ± 4.3	**0.021**
Face Height				
n-me	79.7 ± 4.3	77.8 ± 4.1	81.4 ± 3.7	**0.000**
sn-me	54.3 ± 3.9	52.7 ± 4.0	55.6 ± 3.4	**0.001**
n-sn	28.9 ± 1.6	28.2 ± 1.4	29.4 ± 1.6	**0.000**

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

Upper face depth (obi-n) mean was 93.6 ± 3.6 mm on the right and 92.6 ± 3.5 mm on the left. Maxillary depth (obi-sn) mean was 88.9 ± 3.1 mm on the right and 88.1 ± 3.2 mm on the left. Mandibular depth (obi-pg) mean was 83.8 ± 3.0 mm on the right and 82.6 ± 3.1 mm on the left. These differences between the right and left sides were all statistically significant (p=0.000) with the right side consistently larger than the left with mean differences of 0.75 to 1.21 mm. The males were also statistically significantly larger than the females for all of these measurements, with mean difference of 2.0 to 2.9 mm. This is illustrated in Figure 4.48.

Figure 4.48 Left and Right and Gender Differences in Mandibular Depth at 1 Year



The upper face width (obsR-obsL) had a mean value of 127.8 ± 4.6 mm. The lower face width (obiR-obiL) mean was 104.1 ± 4.1 mm. The male face width was statistically significantly greater than the females for both of these measurements, with mean differences of 2.0 to 3.2 mm. Upper face width measurements were based on data from only 28 females and 48 males since the upper ear landmarks were frequently missing in these models.

The mean total face height (n-me) was 79.7 ± 4.3 mm. Upper face height (n-sn) mean was 28.9 ± 1.6 mm. Lower face height (sn-me) mean was 54.3 ± 3.9 mm. The male face height was statistically significantly greater than the females for all of these measurements, with mean differences of 1.2 to 3.6mm.

4.4.4.2 Eye Measurements

Means and standard deviations of the measurements around the eyes at 1 year are shown in Table 4.30.

Table 4.30 Measurements of the Eyes at 1 Year in mm

	Mean	Female Mean	Male Mean	P Value*
Eyes				
exL-exR	71.7 ± 2.9	71.0 ± 2.6	72.4 ± 3.0	**0.021**
enL-enR	28.6 ± 1.8	28.3 ± 1.7	28.9 ± 1.9	0.15
exL-enL	22.4 ± 1.1	22.1 ± 1.0	22.6 ± 1.1	**0.024**
exR-enR	22.4 ± 1.0	22.2 ± 0.9	22.6 ± 1.1	**0.046**

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

The biocular width (exL-exR) mean was 71.7 ± 2.9 mm. The intercanthal width (enL-enR) mean was 28.6 ± 1.8 mm. The mean palpebral fissure width (ex-en) was 22.4 ± 1.0 mm on both sides. All of these measurements except intercanthal width were statistically significantly greater in males than females. The mean differences in palpebral fissure width between the males and females were only 0.4 to 0.5 mm.

4.4.4.3 Nose and Nostril Measurements

The means and standard deviations of the measurements around the nose and nostrils at 1 year are shown in Table 4.31.

Table 4.31 Measurements of the Nose and Nostrils at 1 Year in mm

	Mean	Female Mean	Male Mean	P Value*
Nose				
acL-acR	27.6 ± 1.6	27.0 ± 1.5	28.0 ± 1.7	**0.003**
alL-alR	24.9 ± 1.6	24.5 ± 1.2	25.4 ± 1.9	**0.007**
acL-prn	18.3 ± 1.2	17.8 ± 1.1	18.8 ± 1.2	**0.000**
acR-prn	19.0 ± 1.2	18.5 ± 1.0	19.5 ± 1.2	**0.000**
n-prn	22.9 ± 1.5	22.2 ± 1.4	23.4 ± 1.4	**0.002**
sn-prn	10.8 ± 1.0	10.7 ± 0.8	11.0 ± 1.1	0.17
Nostrils				
sbalL-cL	6.5 ± 0.9	6.1 ± 0.7	6.9 ± 0.9	**0.000**
sbalR-cR	6.3 ± 0.9	5.9 ± 0.6	6.7 ± 0.9	**0.000**
sn'L-al'iL	4.7 ± 0.9	4.5 ± 0.8	4.9 ± 0.9	**0.013**
sn'R-al'iR	5.1 ± 0.9	4.9 ± 0.9	5.3 ± 0.9	0.093
sn'R-sn'L	5.8 ± 1.0	5.8 ± 0.9	5.8 ± 1.0	1.0

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

Anatomic nose width (acR-acL) and soft nose width (alR-alL) means were 27.6 ± 1.6 mm and 24.9 ± 1.6 mm respectively. Nasal dorsum length (n-prn) mean was 22.9 ± 1.5 mm and nasal tip protrusion (sn-prn) mean was 10.8 ± 1.0 mm. All of the nose measurements were significantly greater in males than females except nasal tip protrusion.

The nostril long axis (sbal-c) mean was 6.5 ± 0.9 mm on the left and 6.3± 0.9 mm on the right. Nostril width (sn'-al'i) mean was 4.7 ± 0.9 mm on the left and 5.1 ± 0.9 mm on the right. These right and left differences were statistically significant with the left nostril longer (p=0.013) and narrower (p=0.000) than the right. This was consistent with the findings at 3 and 6 months. Nostril length was statistically significantly greater in males than females with a mean difference of 0.8 mm. The left nostril width was significantly greater in males but no significant difference was shown on the right although the p value was close to significance (p=0.093).

4.4.4.4 Upper and Lower Lip Measurements

The means and standard deviations of the upper and lower lip measurements at 1 year are shown in Table 4.32.

Table 4.32 Measurements of the Upper and Lower Lips at 1 Year in mm

	Mean	Female Mean	Male Mean	P Value*
Upper Lip				
chR-chL	33.4 ± 2.4	33.2 ± 2.5	33.5 ± 2.3	0.50
cphL-chL	21.4 ± 1.6	21.0 ± 1.7	21.7 ± 1.5	**0.044**
cphR-chR	21.6 ± 1.8	21.0 ± 1.9	22.1 ± 1.5	**0.004**
cphR-cphL	7.8 ± 1.1	7.5 ± 1.0	8.1 ± 1.1	**0.004**
ls-sn	10.9 ± 1.8	10.7 ± 1.7	11.1 ± 1.8	0.31
ls-stos	5.6 ± 1.2	5.5 ± 1.1	5.7 ± 1.3	0.55
sn-stos	14.8 ± 1.4	14.6 ± 1.5	15.1 ± 1.4	0.089
sbalL-chL	26.0 ± 1.9	25.4 ± 1.8	26.5 ± 1.9	**0.010**
sbalR-chR	26.5 ± 2.0	25.8 ± 2.0	27.1 ± 1.8	**0.002**
Lower Lip				
chL-li	17.9 ± 1.4	17.7 ± 1.4	18.0 ± 1.4	0.34
chR-li	18.5 ± 1.3	18.3 ± 1.4	18.6 ± 1.3	0.30
li-stoi	6.7 ± 1.3	6.5 ± 1.3	6.9 ± 1.2	0.17
sl-li	6.9 ± 1.4	7.0 ± 1.4	6.9 ± 1.5	0.77
sl-stoi	11.9 ± 1.0	12.0 ± 1.0	11.9 ± 1.0	0.58

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in bold.

Mouth width (chR-chL) mean was 33.4 ± 2.4 mm. There was no statistically significant difference in this measurement between males and females. Philtrum width (cphL-cphR) mean was 7.8 ± 1.1 mm. This measurement was statistically significantly greater in males than females although the mean difference was only 0.6 mm. Upper vermilion lengths (cphR-chR, cphL-chL) were significantly greater in males than females with mean differences of 0.7 to 1.1 mm.

Upper lip height (sn-stos) mean was 14.8 ± 1.4 mm. The lateral lip height (sbal-ch) mean was 26.0 ± 1.9 mm on the left and 26.5 ± 2.0 mm on the right. Paired t test showed this right and left difference was statistically significant (p=0.000). Upper lip height measurements were not significantly greater in males than females except the lateral lip height.

Lower lip height (sl-stoi) mean was 11.9 ± 1.0 mm. None of the lower lip measurements were shown to be statistically significantly different in males and females. Paired t test showed the right lower vermilion length (cphR-chR) was statistically significantly greater than the left (p=0.000) with a mean difference of 0.56 mm.

4.4.4.5 Angular Measurements

The means and standard deviations of the angular measurements at 1 year are shown in Table 4.33.

Table 4.33 Angles of the Face at 1 Year in degrees

	Mean	Female Mean	Male Mean	P Value*
Angles				
acR-prn-acL	95.3 ± 4.6	96.3 ± 4.4	94.3 ± 4.7	**0.041**
n-prn-sn	112.9 ± 4.9	113.3 ± 4.4	112.6 ± 5.4	0.46
prn-sn-ls	130.1 ± 6.0	130.2 ± 5.2	130.1 ± 6.7	0.91
li-sl-pg	135.2 ± 11.6	137.6 ± 11.7	133.1 ± 11.2	0.065

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in bold.

The nasal tip angle (n-prn-sn) mean was 113 ± 5°. The nasolabial angle (prn-sn-ls) mean was 130 ± 6° and the mean labiomental angle (li-sl-pg) was 135 ± 12°. There was no significant gender difference in these angles although the mean difference of 4.5° was close to being significant for the labiomental angle (p=0.065). The nasal tip horizontal displacement angle (acR-prn-acL) mean was 95 ± 5°. This angle was significantly greater in females than males but with a mean difference of only 2°.

4.4.5 Correlations of Body and Face Measurements at 1 Year

4.4.5.1 Correlations of Body Measurements

Correlations of weight, length and head circumference at 1 year are shown in Table 4.34.

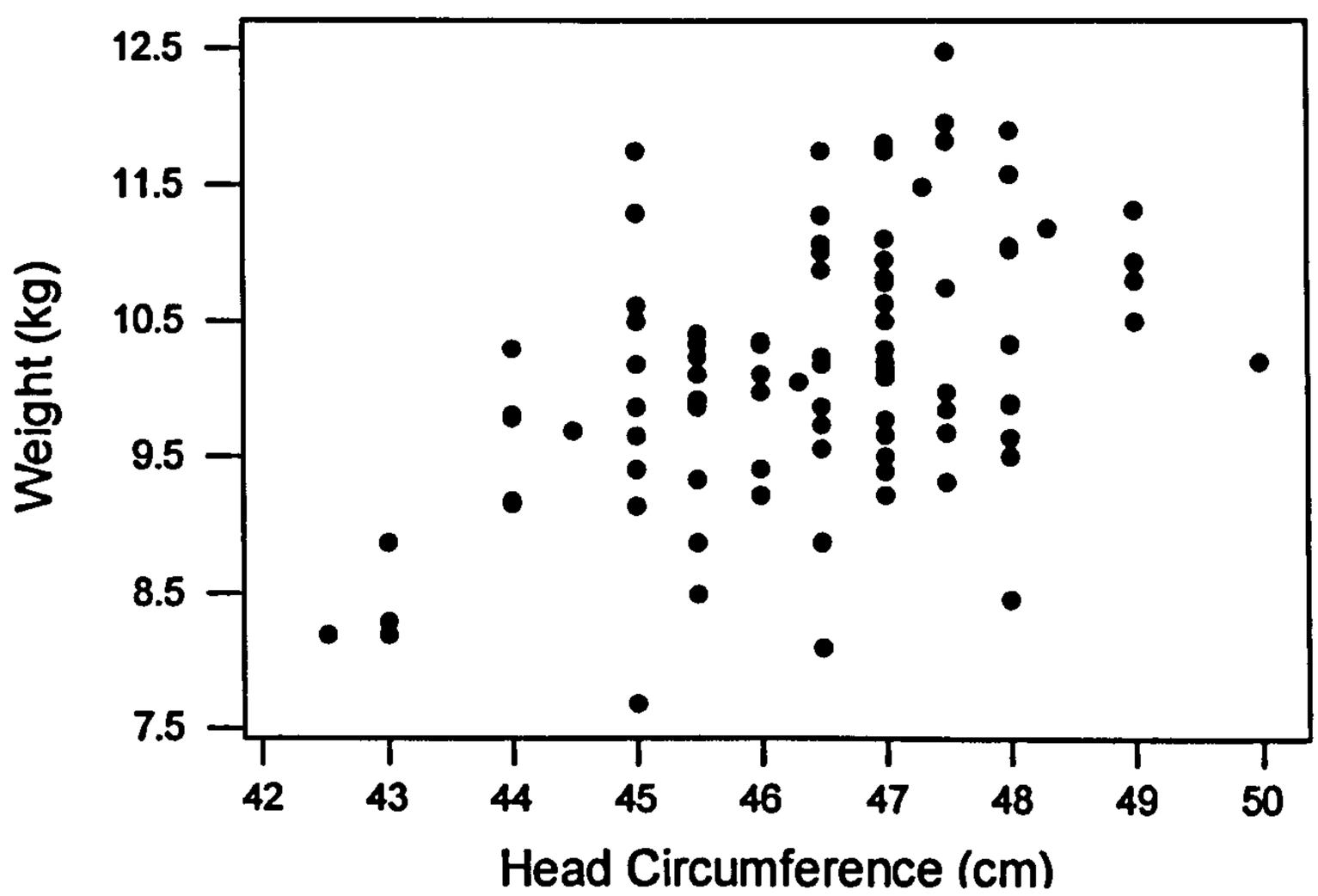
Table 4.34 Correlation of Body Measurements at 1 Year

	Correlation with Length*	P Value**	Correlation with Head Circumference*	P Value**
Weight	0.65	**0.000**	0.46	**0.000**
Length			0.44	**0.000**

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in **bold.**

All of the correlations were statistically significant. The highest correlation was between weight and length with an r value of 0.65. The correlation between head circumference and weight is illustrated in Figure 4.49.

Figure 4.49 Plot of Head Circumference against Weight at 1 Year



4.4.5.2 Correlations with Face Height, Width and Depth

Correlation of face heights, widths and depths with body measurements at 1 year are shown in Table 4.35.

Table 4.35 Correlations of Body Measurements with Face Height, Width and Depth at 1 Year

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Face Depth						
obiL-n	0.60	**0.000**	0.35	**0.001**	0.53	**0.000**
obiR-n	0.63	**0.000**	0.40	**0.000**	0.53	**0.000**
obiL-sn	0.58	**0.000**	0.38	**0.000**	0.44	**0.000**
obiR-sn	0.62	**0.000**	0.40	**0.000**	0.47	**0.000**
obiL-pg	0.52	**0.000**	0.37	**0.000**	0.34	**0.001**
obiR-pg	0.56	**0.000**	0.36	**0.001**	0.37	**0.000**
Face Width						
obsR-obsL	0.37	**0.002**	0.40	**0.001**	0.63	**0.000**
obiR-obiL	0.54	**0.000**	0.19	0.074	0.27	**0.010**
Face Height						
n-me	0.56	**0.000**	0.33	**0.002**	0.35	**0.001**
sn-me	0.49	**0.000**	0.24	**0.022**	0.23	**0.033**
n-sn	0.30	**0.004**	0.27	**0.011**	0.38	**0.000**

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in **bold**.

All of the face measurements were significantly correlated with the body measurements except lower face width and body length. The strongest correlations tended to be with weight. The highest r values of 0.63 were between upper right face depth and weight, and between upper face width and head circumference.

All of the face depth, width and height measurements correlated significantly with each other except total and lower face height with upper face width (r=0.16, 0.05), and upper face height with lower face width (r=0.17). The correlations of upper and lower face heights with left mandibular depth were weak (r=0.20).

4.4.5.3 Correlations with Eye Measurements

The correlations of body measurements with measurements around the eyes at 1 year are shown in Table 4.36.

Table 4.36 Correlations of Body Measurements with Eye Measurements at 1 Year

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Eyes						
exR-exL	0.47	**0.000**	0.46	**0.000**	0.55	**0.000**
enL-enR	0.41	**0.000**	0.28	**0.007**	0.42	**0.000**
exL-enL	0.40	**0.000**	0.44	**0.000**	0.40	**0.000**
exR-enR	0.33	**0.001**	0.40	**0.000**	0.42	**0.000**

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in **bold**.

All of the eye measurements were significantly correlated with the body measurements. The highest correlation was between biocular width and head circumference with r = 0.55. The lowest correlation (r=0.28) was between intercanthal width and body length. All of the eye measurements were significantly correlated although palpebral fissure widths were only very weakly correlated with intercanthal width (r=0.23, 0.25).

4.4.5.4 Correlations with Nose and Nostril Measurements

The correlations of nose and nostril measurements with body measurements at 1 year are shown in Table 4.37.

Table 4.37 Correlations of Body Measurements with Nose and Nostril Measurements at 1 Year

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Nose						
acL-acR	0.39	**0.000**	0.35	**0.001**	0.36	**0.000**
alL-alR	0.37	**0.000**	0.30	**0.004**	0.41	**0.000**
acL-prn	0.44	**0.000**	0.47	**0.000**	0.37	**0.000**
acR-prn	0.38	**0.000**	0.42	**0.000**	0.35	**0.001**
n-prn	0.29	**0.006**	0.32	**0.002**	0.33	**0.002**
sn-prn	0.24	**0.021**	0.17	0.111	0.27	**0.010**
Nostrils						
sbalL-cL	0.14	0.194	0.23	**0.032**	0.25	**0.017**
sbalR-cR	0.15	0.148	0.18	0.085	0.12	0.257
sn'L-al'iL	0.13	0.239	0.18	0.083	0.15	0.145
sn'R-al'iR	0.10	0.333	0.14	0.194	0.17	0.112
sn'R-sn'L	0.16	0.125	0.11	0.293	0.15	0.159

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in **bold**.

All of the nose measurements except nasal tip protrusion were significantly correlated with all of the body measurements with r values ranging from 0.28 to 0.55. Nasal tip protrusion was significantly but weakly correlated with weight (r=0.24) and head circumference (r=0.27) but not with length. All of the nose measurements were significantly correlated with each other except nasal dorsum length with anatomic and soft nose widths.

Very few of the nostril measurements were significantly correlated with body measurements. The only correlations were between left nostril long axis and body length (r=0.23) and head circumference (r=0.25). The nostril long axis and width were significantly correlated with each other but not with columella width. Columella width was correlated with all the nose measurements except nasal dorsum length and nasal tip protrusion.

4.4.5.5 Correlations with Upper and Lower Lip Measurements

Correlations of body measurements with upper and lower lip measurements at 1 year are shown in Table 4.38.

Table 4.38 Correlations of Body Measurements with Upper and Lower Lip Measurements at 1 Year

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Upper Lip						
chR-chL	0.18	0.093	0.32	**0.002**	0.35	**0.001**
cphL-chL	0.32	**0.002**	0.29	**0.005**	0.26	**0.014**
cphR-chR	0.31	**0.003**	0.33	**0.002**	0.26	**0.015**
cphR-cphL	0.22	**0.035**	0.31	**0.003**	0.16	0.119
ls-sn	0.20	0.058	0.02	0.838	0.15	0.163
ls-stos	0.09	0.422	0.03	0.774	-0.06	0.552
sn-stos	0.29	**0.005**	0.12	0.263	0.15	0.163
sbalL-chL	0.41	**0.000**	0.22	**0.040**	0.34	**0.001**
sbalR-chR	0.36	**0.001**	0.28	**0.006**	0.31	**0.003**
Lower Lip						
chL-li	0.17	0.105	0.28	**0.008**	0.31	**0.003**
chR-li	0.22	**0.036**	0.29	**0.006**	0.36	**0.000**
li-stoi	0.23	**0.026**	0.23	**0.030**	0.10	0.341
sl-li	0.15	0.164	0.05	0.641	-0.02	0.858
sl-stoi	0.26	**0.015**	0.18	0.085	-0.03	0.818

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

Mouth width, philtrum width and upper and lower vermilion lengths were significantly but weakly correlated with most body measurements with r values ranging from 0.22 to 0.35. Mouth width was not significantly correlated with body weight, philtrum width was not significantly correlated with head circumference, and lower left vermilion length was not significantly correlated with weight. Upper and lower vermilion lengths, mouth and philtrum widths were all significantly correlated with each other.

Upper lateral lip heights were also significantly correlated with body measurements with r values of 0.22 to 0.41. A few of the remaining lip heights were significantly correlated with body measurements including upper and lower lip heights with body weight. Lip heights were mostly significantly correlated with each other, including upper and lower lip heights. Lateral lip heights were significantly correlated with upper vermilion lengths (r=0.53 to 0.69) however the midline lip heights (ls-sn, sn-stos, ls-stos) were not.

4.4.5.6 Correlations with Angular Measurements

Correlations of angular measurements with body measurements 1 year are shown in Table 4.39.

Table 4.39 Correlations of Body Measurements with Angles of the Face at 1 Year

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Angles						
acR-prn-acL	-0.08	0.405	-0.22	**0.033**	-0.04	0.699
n-prn-sn	-0.13	0.217	-0.21	**0.046**	-0.06	0.555
prn-sn-ls	-0.21	**0.043**	-0.16	0.131	-0.05	0.658
li-sl-pg	-0.12	0.252	-0.17	0.108	-0.08	0.450

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

The nasal horizontal displacement angle (acR-prn-acL), nasal tip angle (n-prn-sn) and nasolabial angle (prn-sn-ls) only had weak negative correlations with one of the body measurements with r values of -0.21 to -0.22. Labiomental angle was not significantly correlated with any of the body measurements at 1 year.

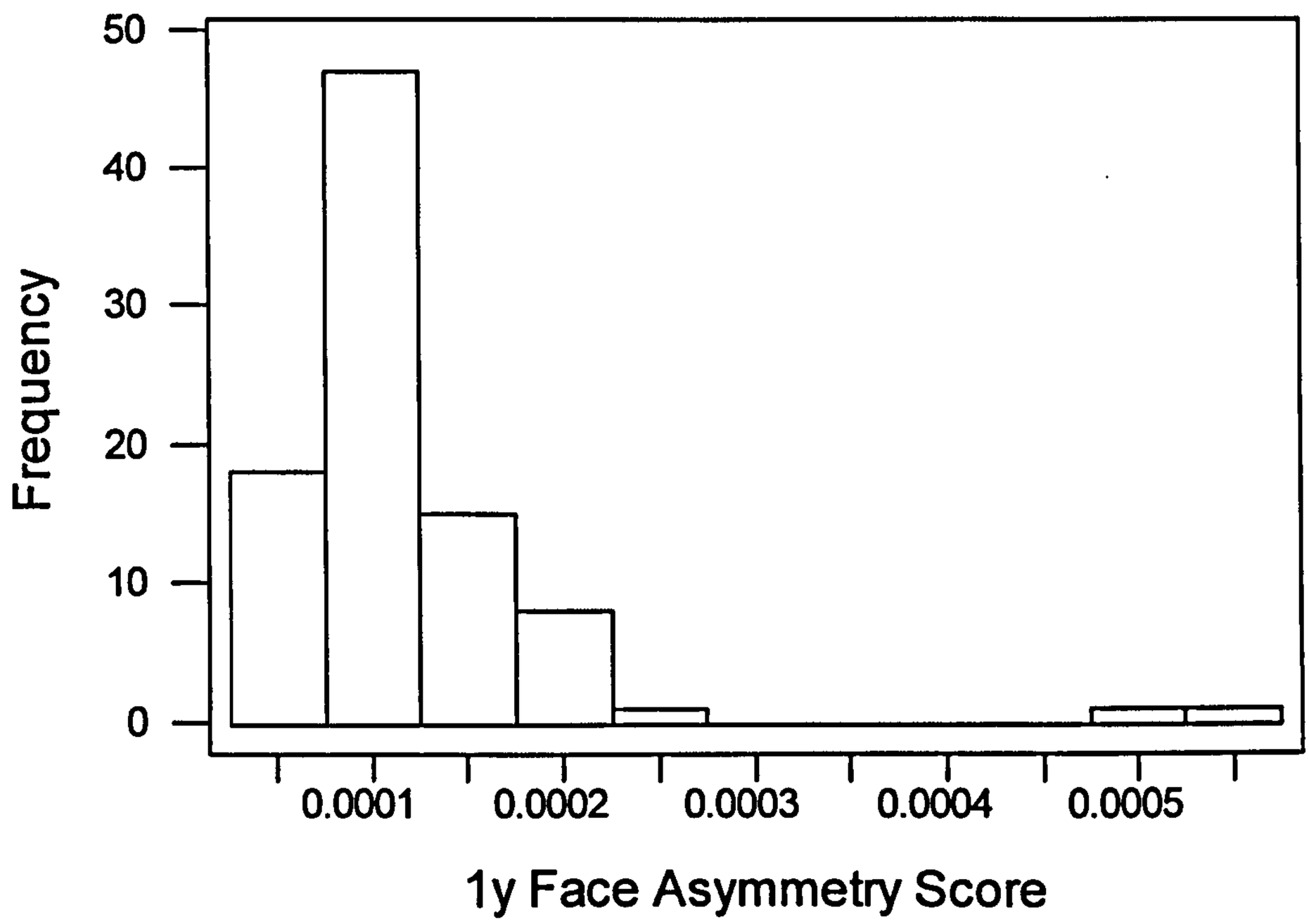
Nasal tip angle (n-prn-sn) correlated significantly with both nasal tip horizontal displacement angle (acR-prn-acL) and nasolabial angle (prn-sn-ls) consistent with the findings at 3 and 6 months. None of the other angles were correlated with each other.

4.4.6 Asymmetry at 1 Year

4.4.6.1 Face

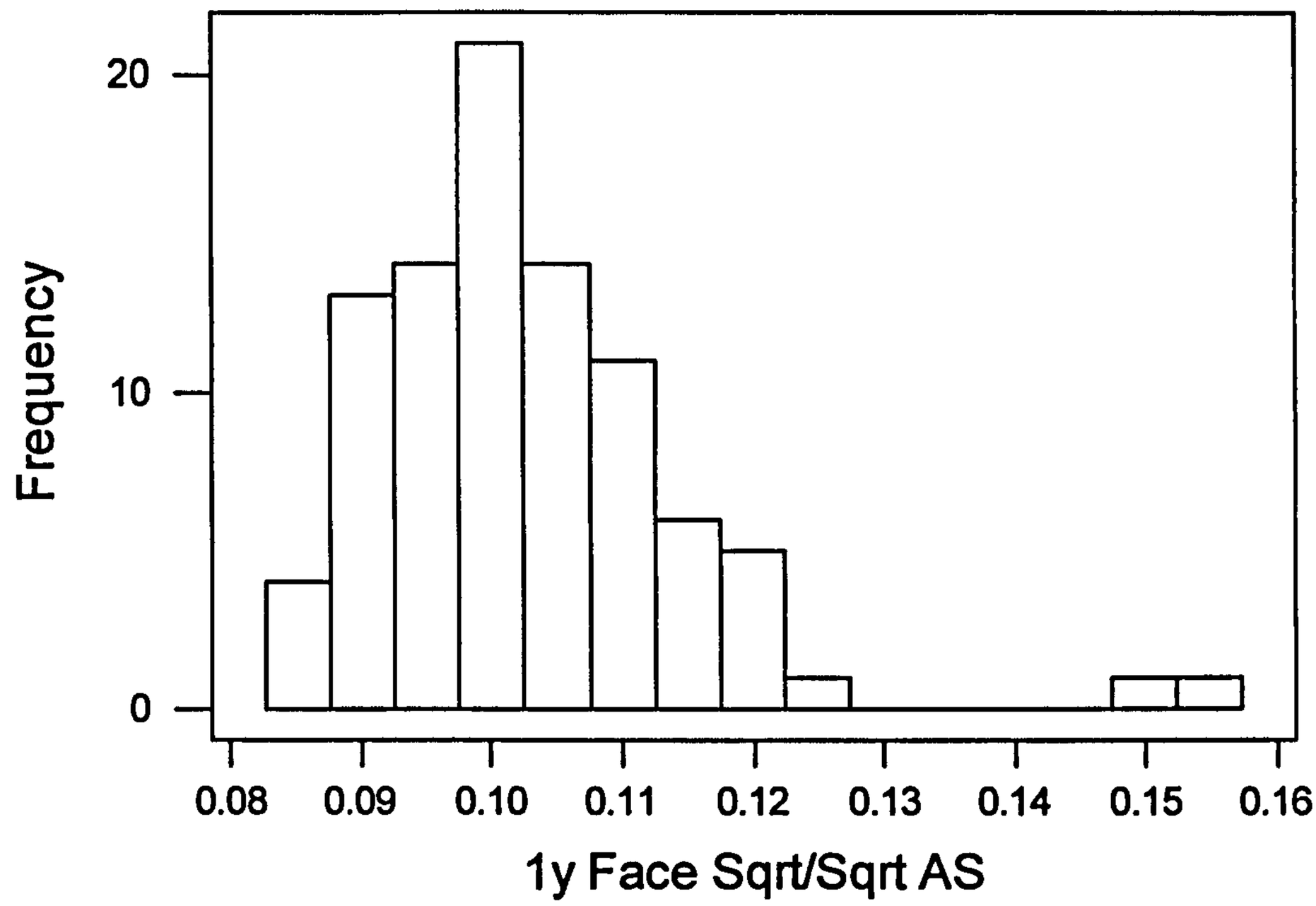
The distribution of the asymmetry scores for the face at 1 year is shown in Figure 4.50. All of the asymmetry scores were based on the landmarks in the midface, excluding the ear, lower lip and chin landmarks.

Figure 4.50 Distribution of Asymmetry Scores for the Face at 1 Year



As shown in Figure 4.49, the raw asymmetry scores were not normally distributed. However, the fourth roots of the asymmetry scores (sqrt/sqrt AS) were well approximated by a normal distribution, as shown in Figure 4.51. Standard parametric tests were therefore applied to this transformed data.

Figure 4.51 Distribution of the Sqrt/Sqrt AS for the Face at 1 Year



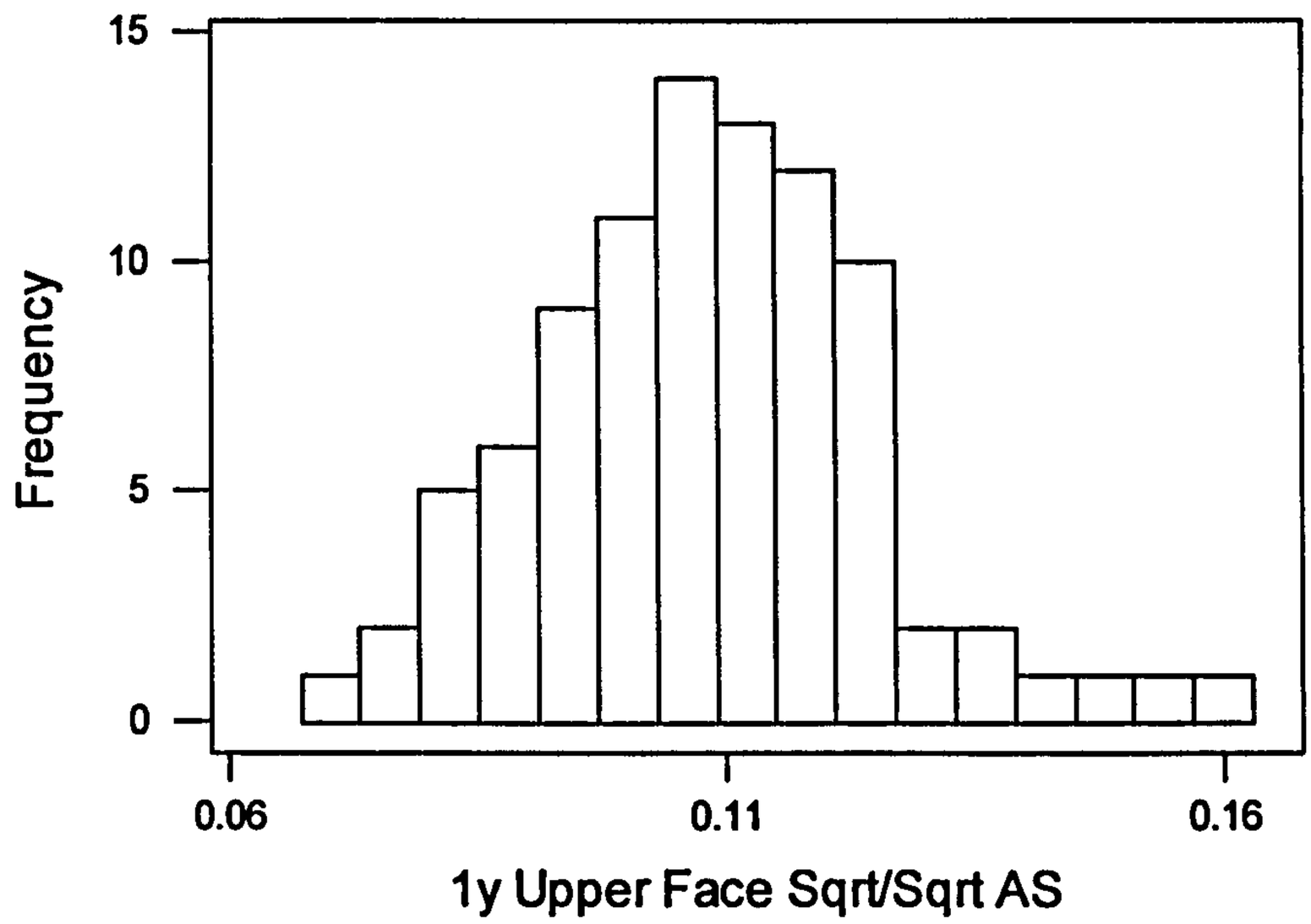
The mean sqrt/sqrt AS for the face was 0.103 ± 0.012. The mean sqrt/sqrt AS for the females was 0.100 ± 0.012 and for the males 0.105 ± 0.012. Two sample t test showed that this slight difference was not statistically significant (p=0.078). This is illustrated in Figure 4.52.

Figure 4.52 Sqrt/Sqrt AS for the Face of Males and Females at 1 Year

4.4.6.2 Upper Face

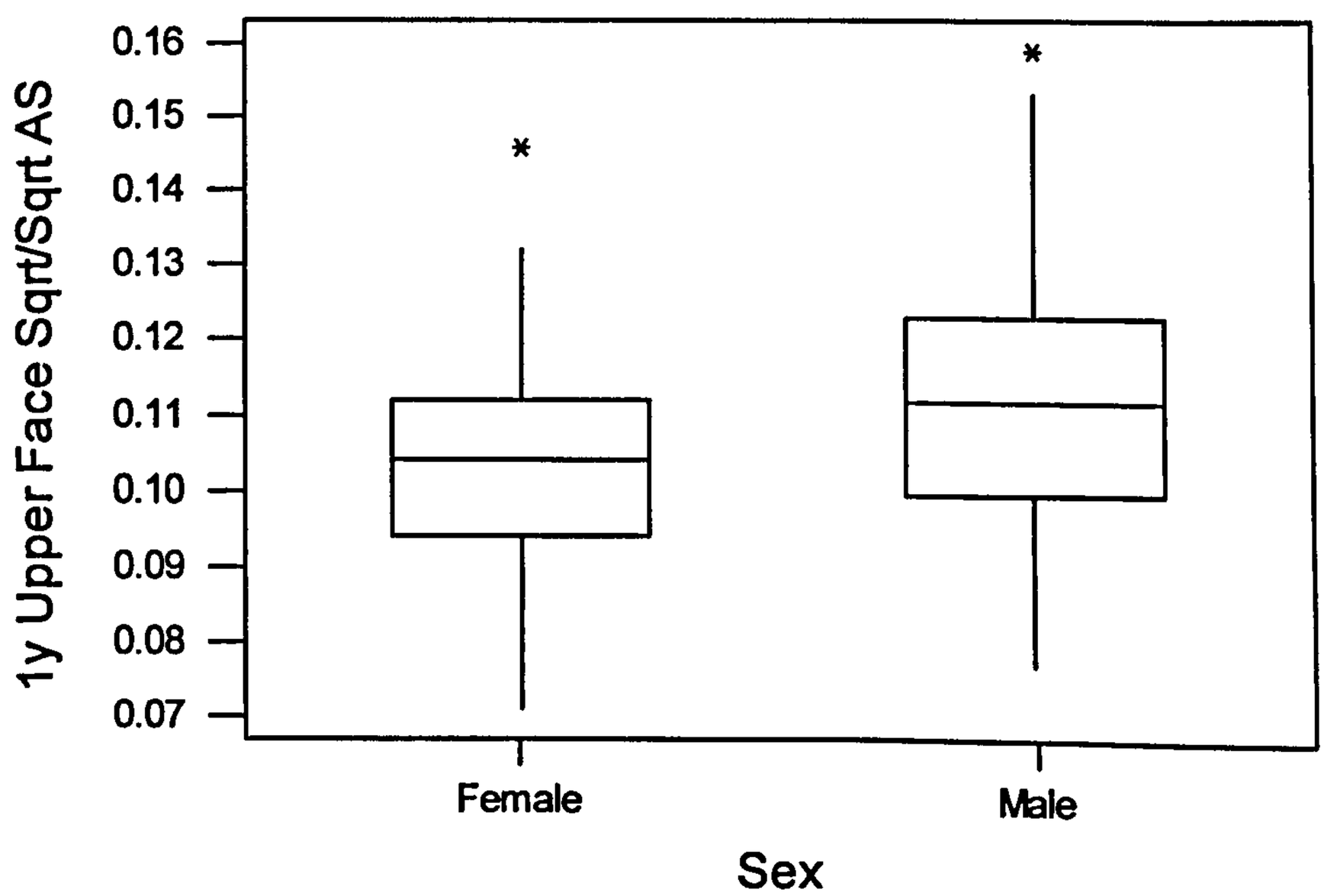
The distribution of the sqrt/sqrt AS for the upper face at 1 year is shown in Figure 4.53. The upper face asymmetry score was based on the endocanthion, exocanthion and nasion landmarks.

Figure 4.53 Distribution of the Sqrt/Sqrt AS for the Upper Face at 1 Year



The mean sqrt/sqrt AS for the upper face was 0.108 ± 0.017. The mean sqrt/sqrt AS for the females was 0.103 ± 0.015 and for the males 0.112 ± 0.017. Two sample t test showed that this slight difference was statistically significant (p=0.015). This is illustrated in Figure 4.54.

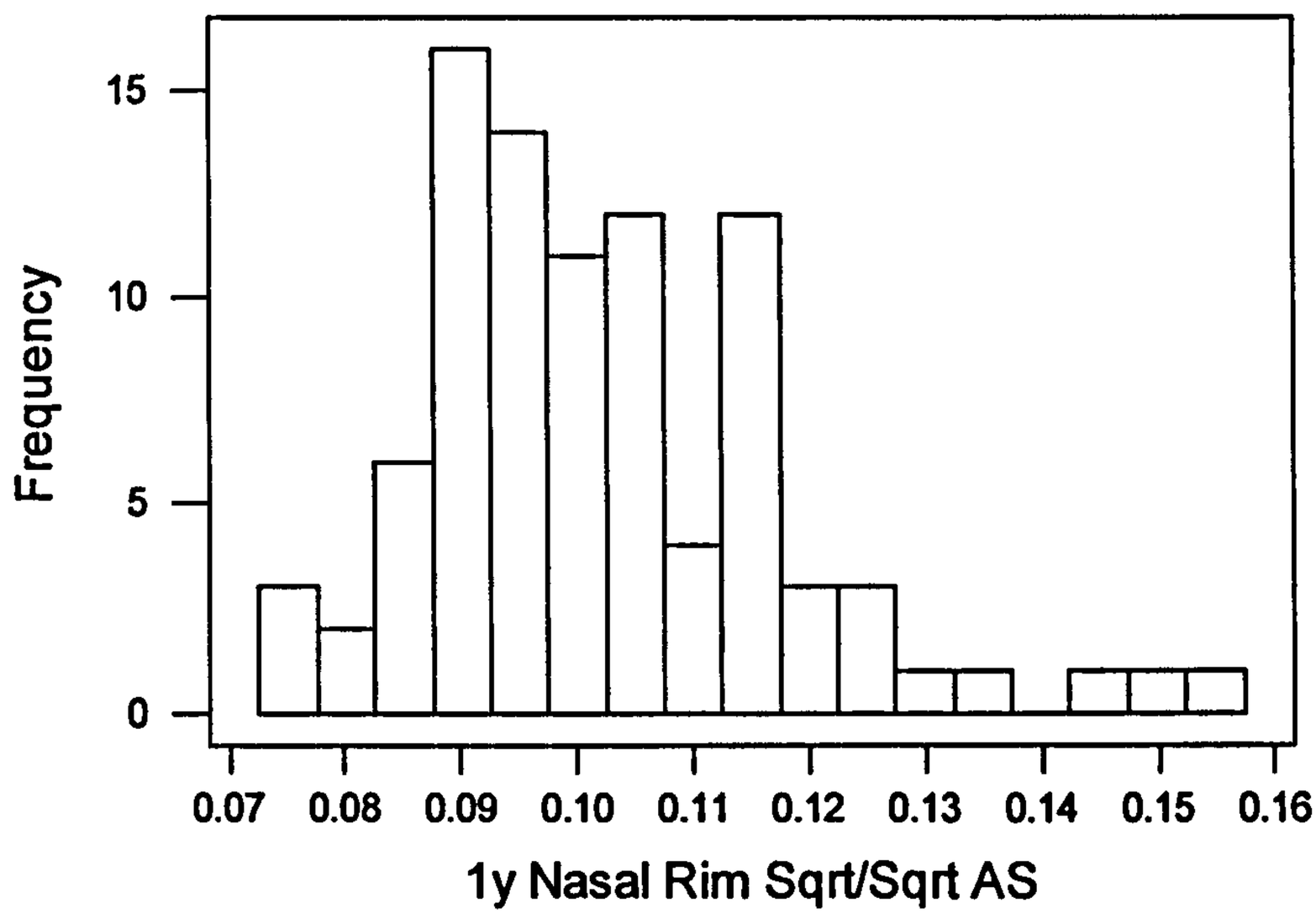
Figure 4.54 Gender Differences in Sqrt/Sqrt AS for the Upper Face at 1 Year



4.4.6.3 Nasal Rim

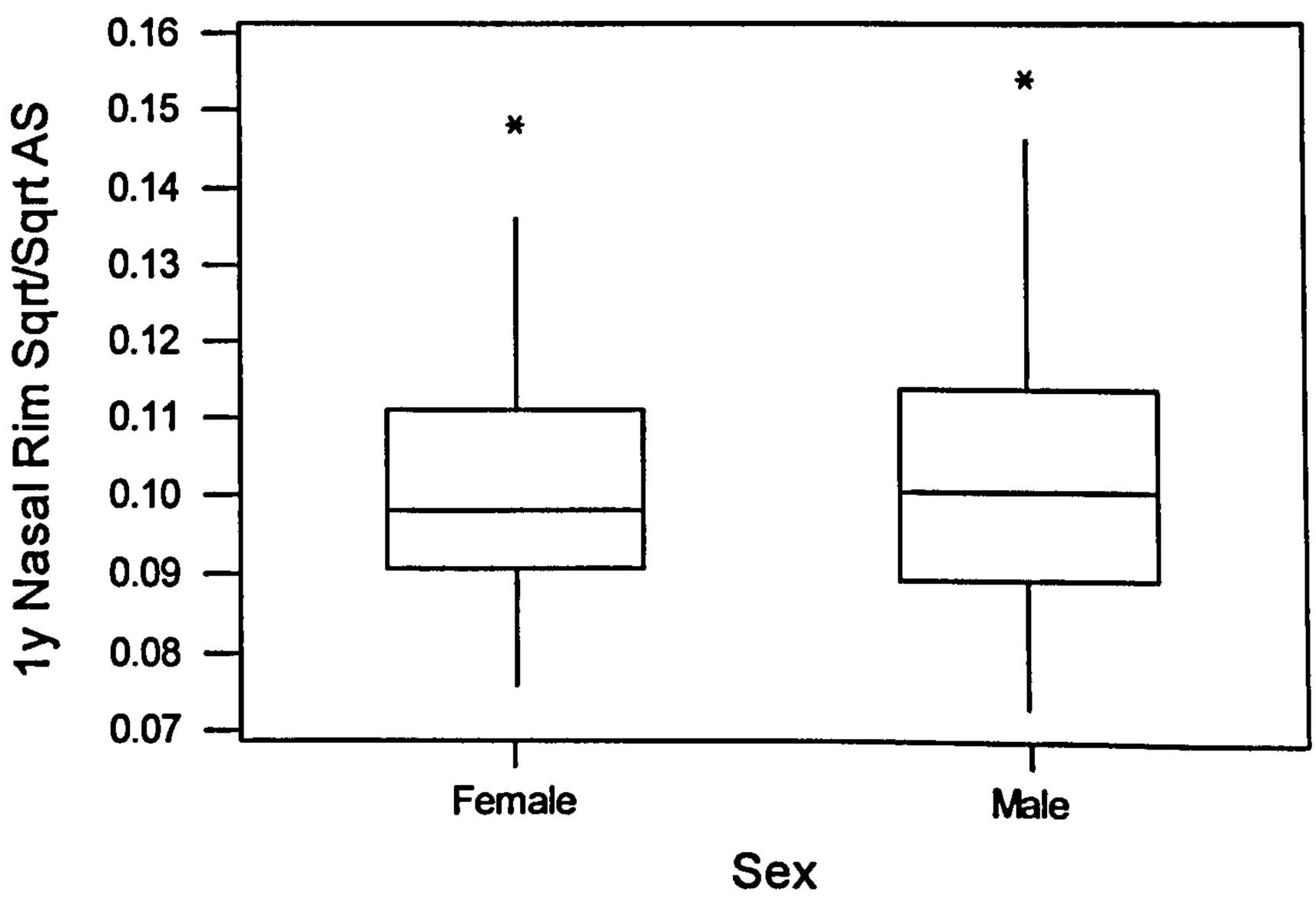
The distribution of the sqrt/sqrt AS for the nasal rim at 1 year is shown in Figure 4.55. The asymmetry score for the nasal rim incorporated the alar crest, alare, alare' outer and pronasale landmarks.

Figure 4.55 Distribution of the Sqrt/Sqrt AS for the Nasal Rim at 1 Year



The mean sqrt/sqrt AS for the nasal rim was 0.102 + 0.016. There was no statistically significant difference between the males and females (p=0.48). This is shown in Figure 4.56.

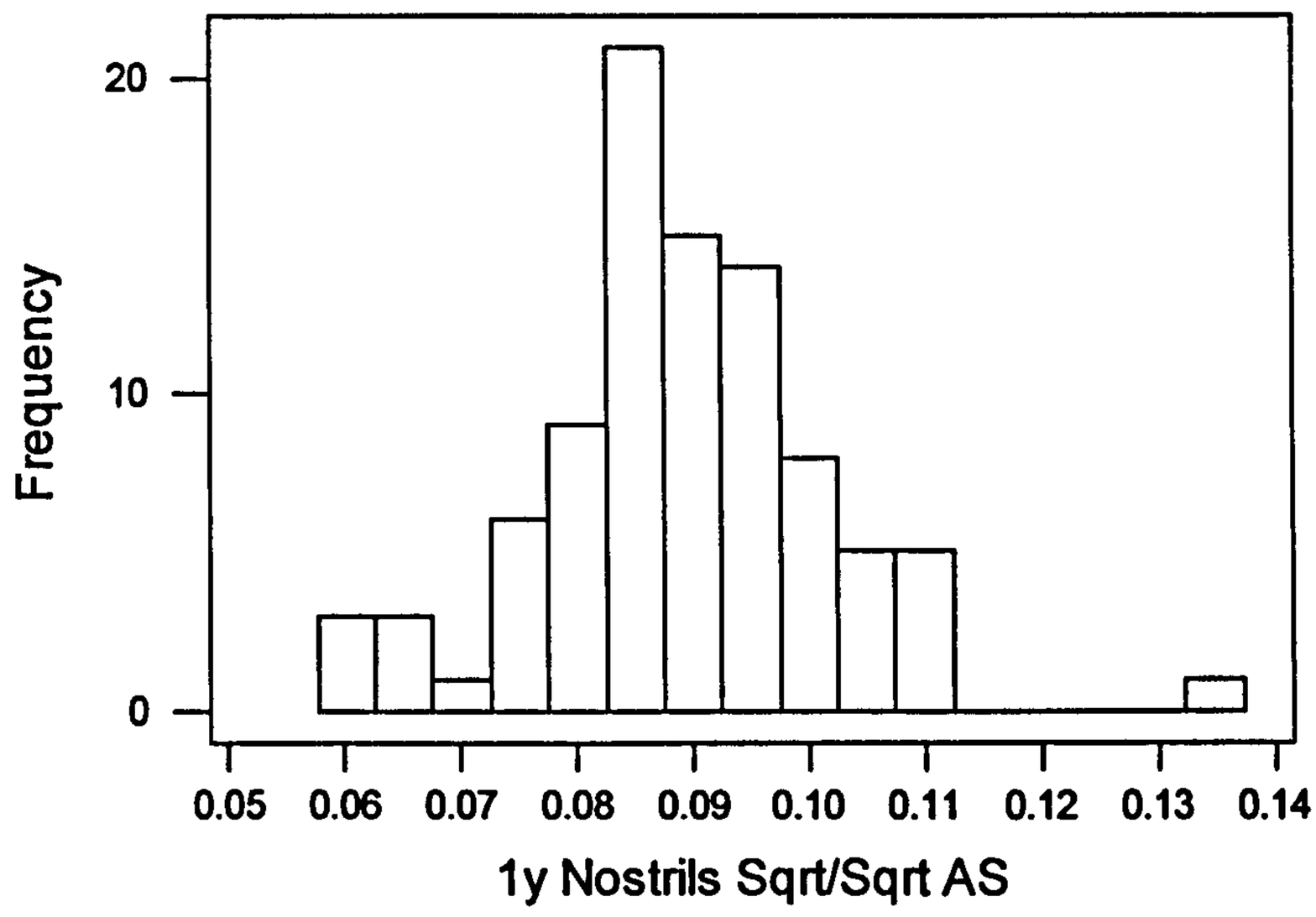
Figure 4.56 Sqrt/Sqrt AS for the Nasal Rim of Males and Females at 1 Year



4.4.6.4 Nostrils

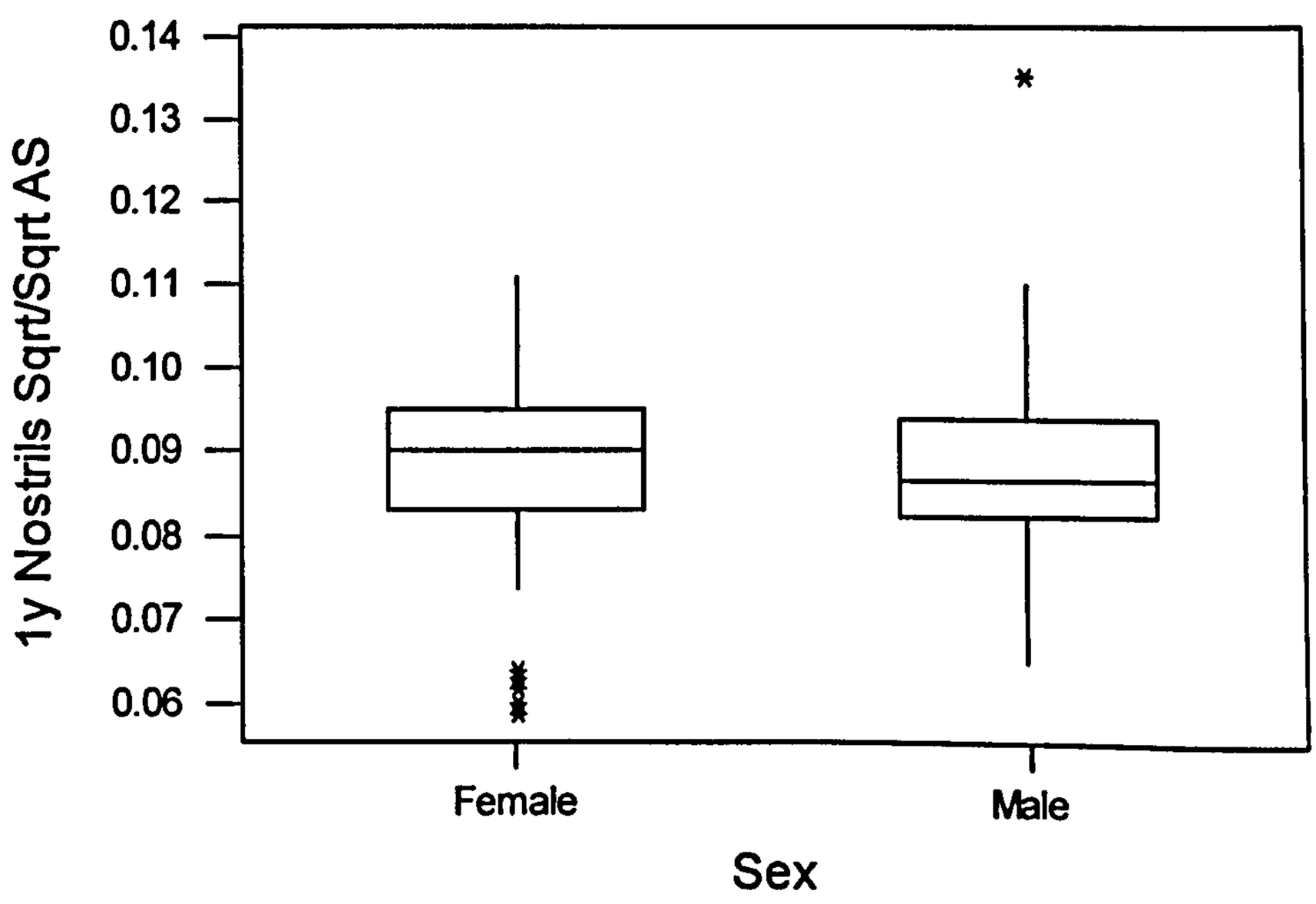
The distribution of the sqrt/sqrt AS for the nostrils at 1 year is shown in Figure 4.57. The landmarks included in this asymmetry score were subalare, alare' inner, columella, subnasale' and subnasale.

Figure 4.57 Distribution of the Sqrt/Sqrt AS for the Nostrils at 1 Year



The mean sqrt/sqrt AS for the nostrils was 0.089 ± 0.013. There was no statistically significant difference between the males and females (p=0.66). This is shown in Figure 4.58.

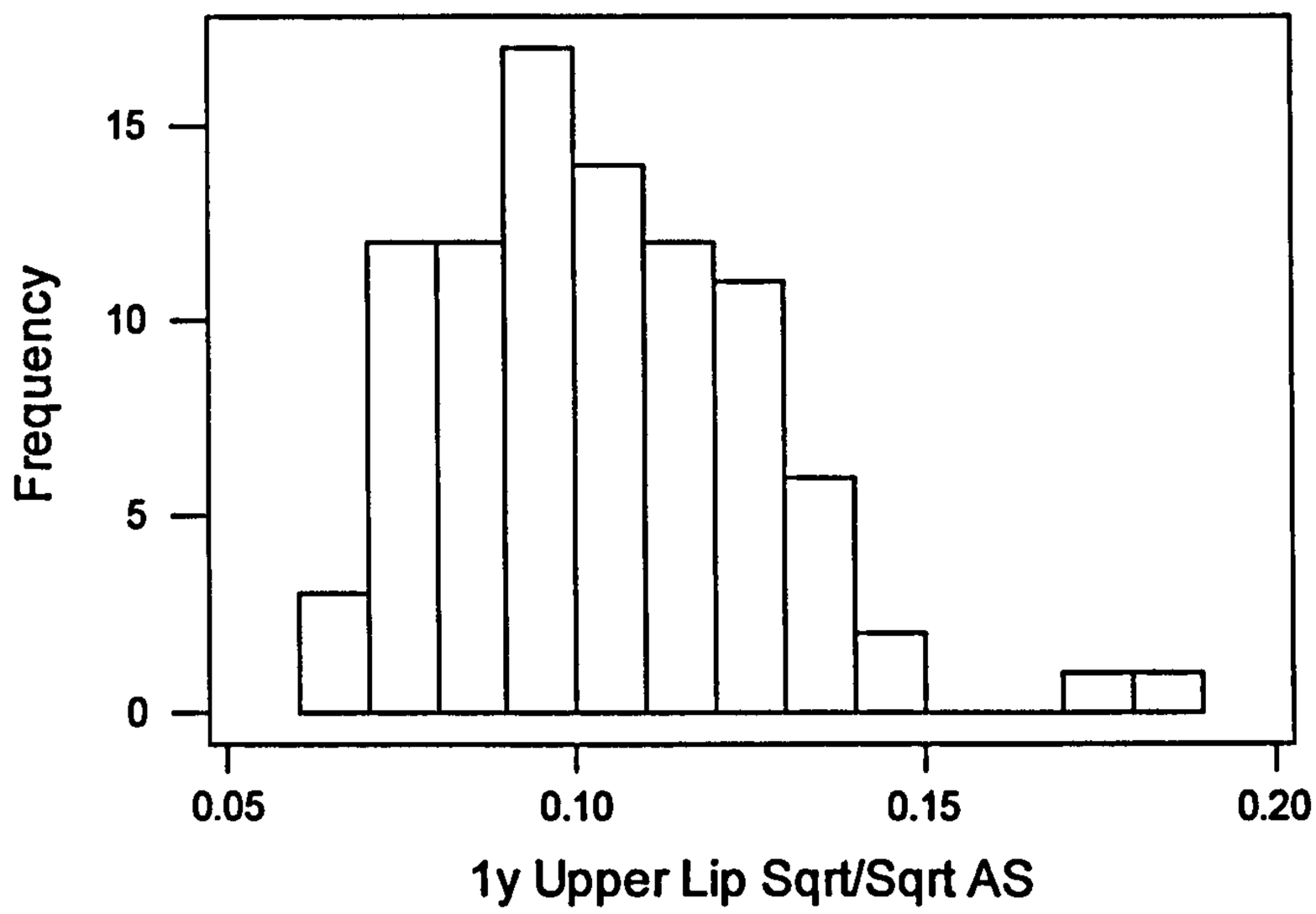
Figure 4.58 Sqrt/Sqrt AS for the Nostrils of Males and Females at 1 Year



4.4.6.5 Upper Lip

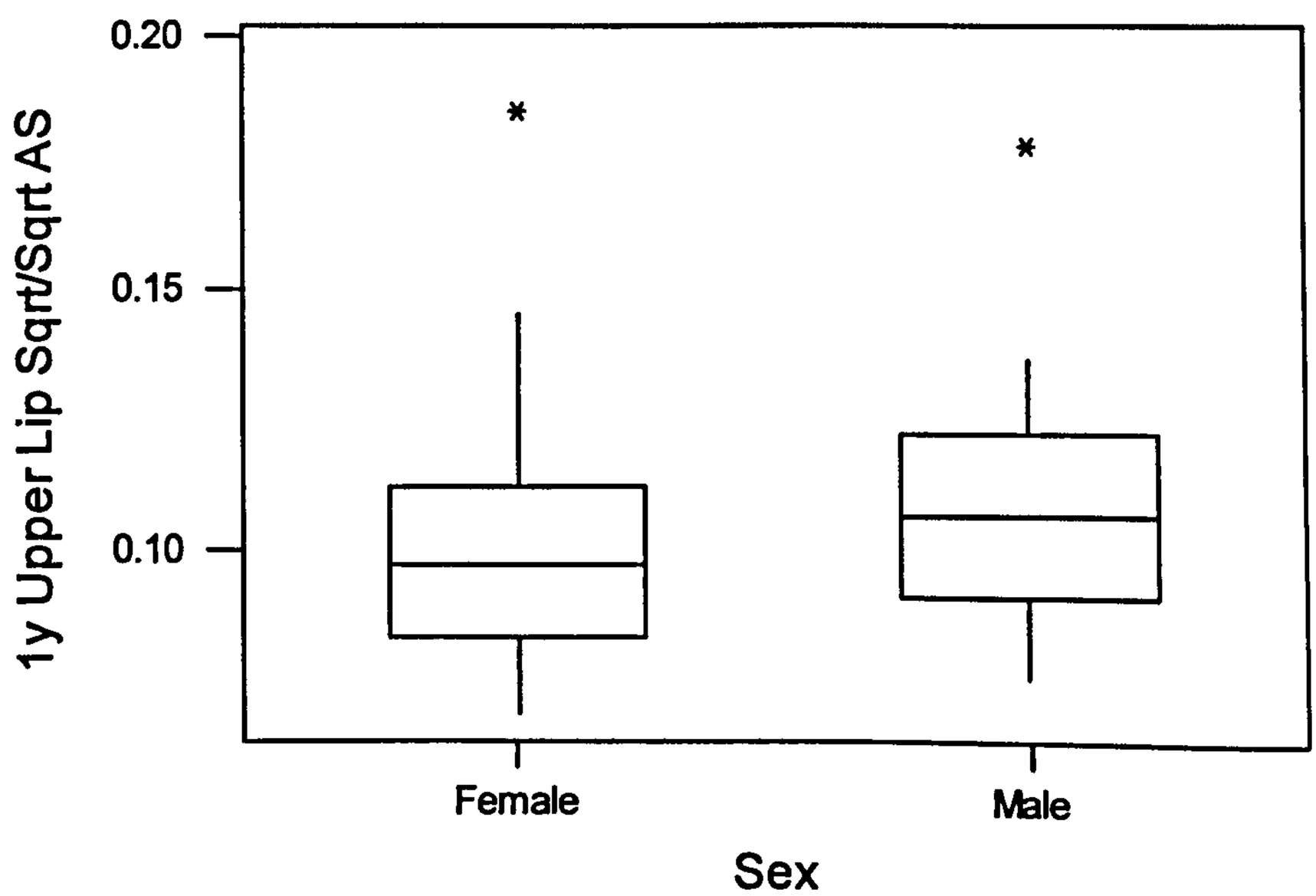
The distribution of the sqrt/sqrt AS for the upper lip at 1 year is shown in Figure 4.59. The landmarks included in this asymmetry score were cheilion, crista philtri and labrale superius.

Figure 4.59 Distribution of the Sqrt/Sqrt AS for the Upper Lip at 1 Year



The mean sqrt/sqrt AS for the upper lip was 0.105 ± 0.022. There was no statistically significant difference between the males and females (p=0.22). This is shown in Figure 4.60.

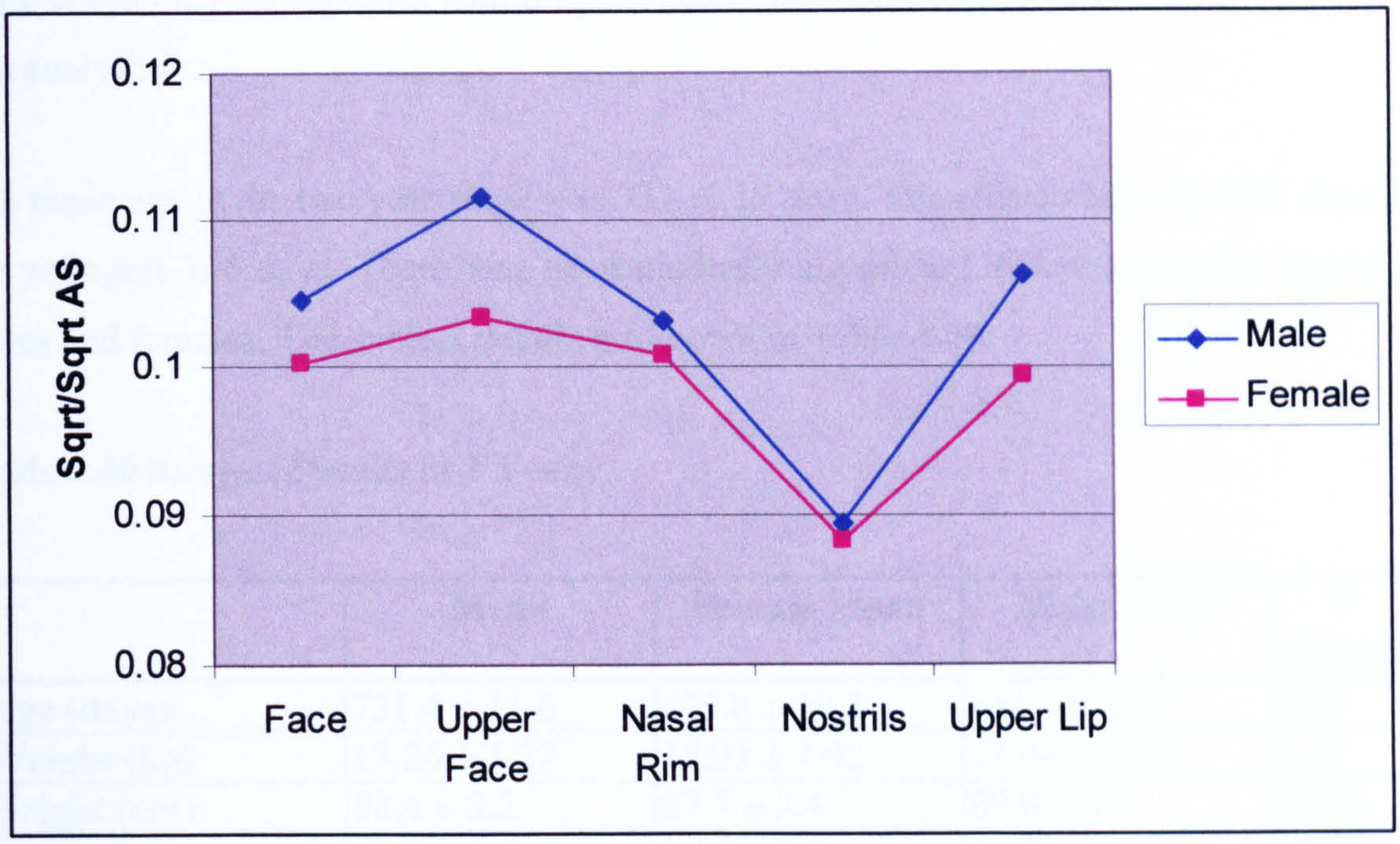
Figure 4.60 Sqrt/Sqrt AS for the Upper Lip of Males and Females at 1 Year



4.4.6.6 Comparisons of Asymmetry Scores at 1 Year

The results of comparing the asymmetry scores of the different regions of the face at 1 year are illustrated in Figure 4.61.

Figure 4.61 Comparison of the Asymmetry of the Regions of the Face at 1 Year



Once again there was a tendency for the asymmetry scores of the females to be lower than the males but this difference was only significant for the upper face (p=0.015). Paired t tests showed that the sqrt/sqrt AS of the nostrils was significantly lower than for any of the other scores (p=0.000). The only other significant differences were between the face and the upper face and the upper lip (p=0.000), and between the upper face and nasal rim score (p=0.01). As found at 3 and 6 months, the greatest asymmetry was in the upper face and the least in the nostrils.

4.4.6.7 Correlations of Asymmetry Scores at 1 Year

None of the asymmetry scores correlated significantly with the body measurements. As found at the other ages, the asymmetry score for the face correlated highly and significantly with the asymmetry scores for all of the individual regions of the face (r=0.51-0.80). All the individual asymmetry scores correlated weakly with each other (r=0.30-0.42), except the nasal rim asymmetry with the upper face and nostril asymmetry.

4.5 Two Years

4.5.1 Subjects

Ninety five infants were captured at the two year stage. Ninety two infants, 47 males and 45 females were captured with a lips apart pose. The further 3 infants who attended at this stage could only be captured with a lips together pose and their results are not included in this analysis.

The mean age at the two year stage was 731 ± 12 days. The oldest child was 761 days and the youngest 706 days. There was no statistically significant difference in the age of the males and females. The subject details are shown in Table 4.40.

Table 4.40 Subject Details at 2 Years

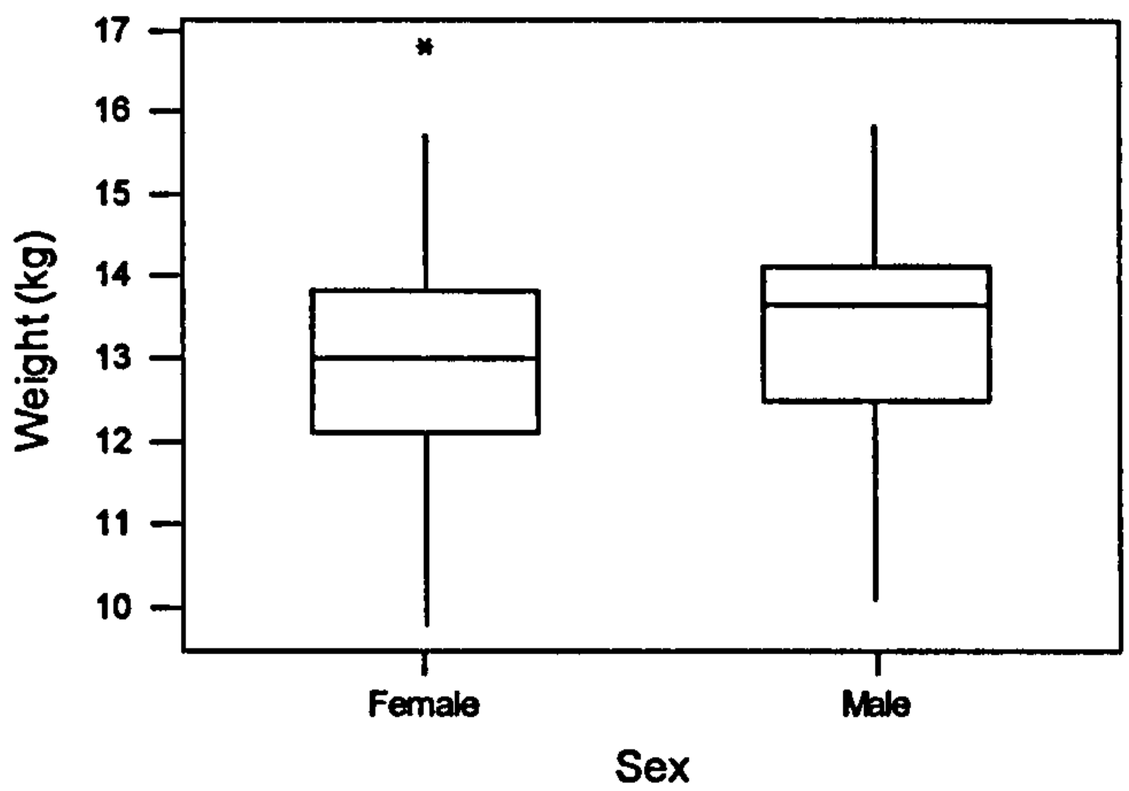
	Mean	Female Mean	Male Mean	P Value*
Age (days)	731.4 ± 11.6	731.8 ± 10.5	731.1 ± 12.7	0.79
Weight (kg)	13.26 ± 1.27	13.07 ± 1.42	13.44 ± 1.10	0.17
Height (cm)	88.4 ± 3.2	87.7 ± 3.4	89.0 ± 2.9	**0.046**
Head Circumference (cm)	48.9 ± 1.5	48.4 ± 1.2	49.4 ± 1.5	**0.001**

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in bold.

4.5.2 Body measurements

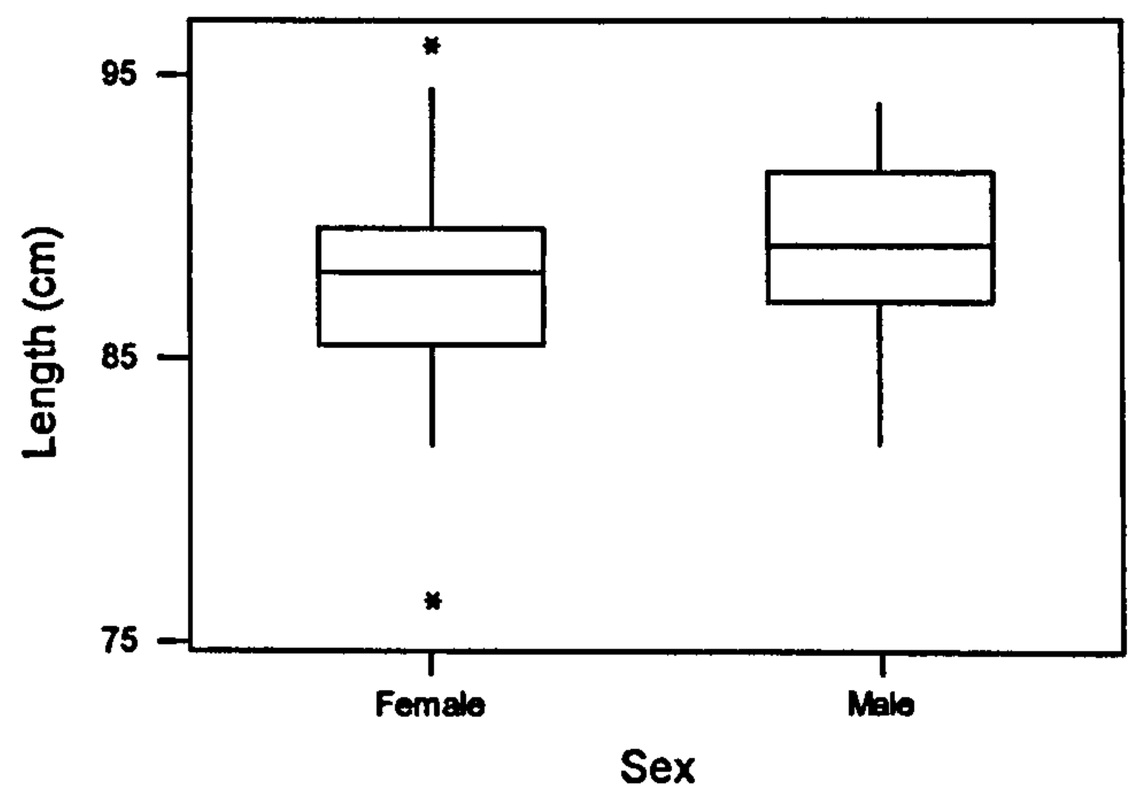
The means and standard deviations of the body measurements at 2 years are shown in Table 4.40. The mean weight of the children was 13.26 ± 1.27 kg. The mean weight of the females was 13.07 ± 1.42 kg and the males 13.44 ± 1.10 kg. Although there was a mean difference of 0.37 kg this was not statistically significant (p=0.17). This was contrary to the findings from 3 months to 1 year. This is illustrated in Figure 4.62.

Figure 4.62 Weight at 2 Years



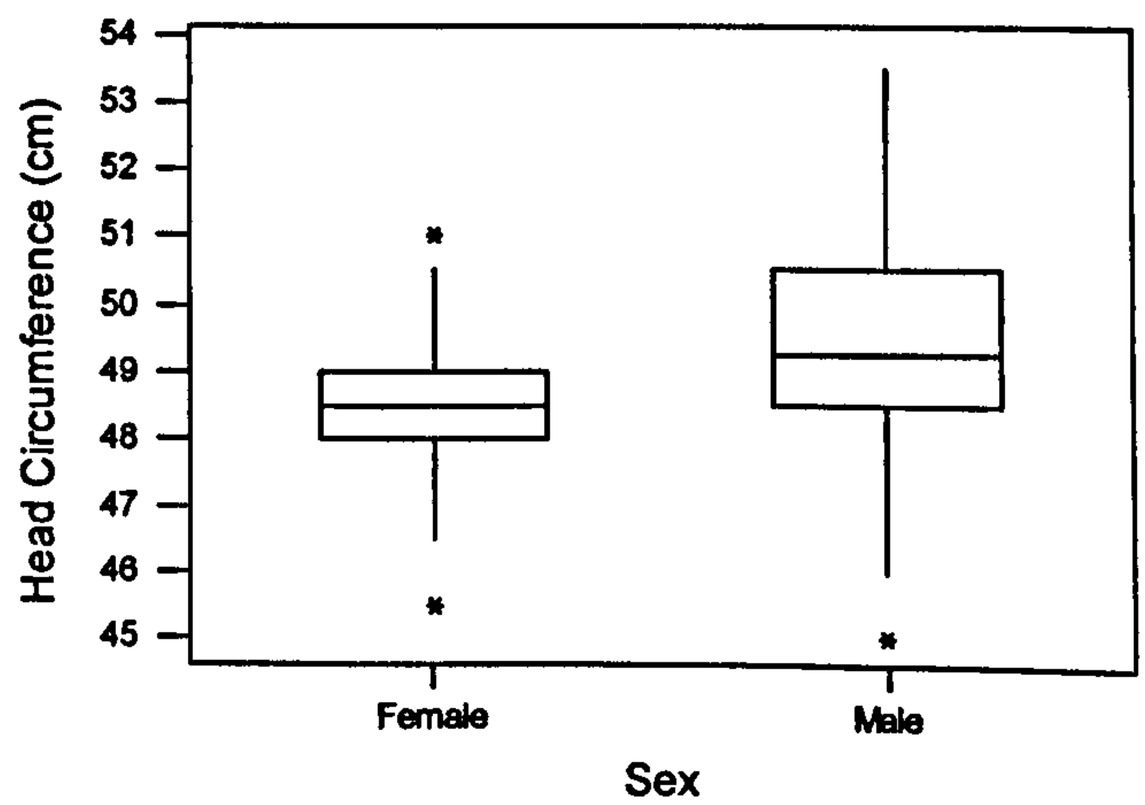
The mean length of all the children was 88.4± 3.2 cm. The mean length of the females was 87.7 ± 3.4 cm and of the males 89.0 ± 2.9 cm. This difference was statistically significant (p=0.046) but not as highly as in the previous ages. This is shown in Figure 4.63.

Figure 4.63 Length at 2 Years



The mean head circumference of all the children was 48.9 ± 1.5 cm. The female mean was 48.4 ± 1.2 cm and the male 49.4 ± 1.5 cm. This difference was also statistically significant (p=0.001). This is shown in Figure 4.64.

Figure 4.64 Head Circumference at 2 Years



4.5.3 Missing Landmarks

The details of the missing landmarks are shown in Table 4.41. Five landmarks were recorded as missing in some of the 2 year models. Otobasion superius right and left were frequently obscured by hair and were missing on both sides in 25 cases and on one side in a further 18 cases. Menton was recorded as missing on 9 models when the child was not positioned well enough to capture an image under the chin.

Table 4.41 Missing Landmarks at 2 Years

Landmark	Missing Frequency
me	9
obsR	30
obsL	38
obiR	2
obiL	5

4.5.4 Linear and Angular Measurements at 2 Years

4.5.4.1 Face Height, Width and Depth

The means and standard deviations of face heights, width and depths at 2 years are shown in Table 4.42.

Table 4.42 Measurements of Face Height, Width and Depth at 2 Years in mm

	Mean	Female Mean	Male Mean	P Value*
Face Depth				
obiL-n	96.8 ± 3.6	95.6 ± 2.9	97.8 ± 3.9	**0.003**
obiR-n	97.7 ± 3.6	96.3 ± 3.1	98.9 ± 3.6	**0.001**
obiL-sn	91.9 ± 3.1	92.0 ± 3.5	91.8 ± 2.8	0.72
obiR-sn	92.6 ± 3.0	92.7 ± 3.2	92.6 ± 2.8	0.86
obiL-pg	87.3 ± 3.6	86.6 ± 3.4	88.0 ± 3.6	0.065
obiR-pg	88.6 ± 3.4	87.7 ± 3.1	89.4 ± 3.5	**0.014**
Face Width				
obsR-obsL	133.5 ± 5.0	133.3 ± 5.3	133.6 ± 4.9	0.89
obiR-obiL	107.5 ± 4.4	106.2 ± 4.0	108.6 ± 4.6	**0.011**
Face Height				
n-me	84.7 ± 3.8	83.2 ± 3.3	86.1 ± 3.8	**0.000**
sn-me	56.9 ± 3.4	55.8 ± 3.0	58.0 ± 3.4	**0.003**
n-sn	31.0 ± 1.7	30.6 ± 1.5	31.4 ± 1.8	**0.022**

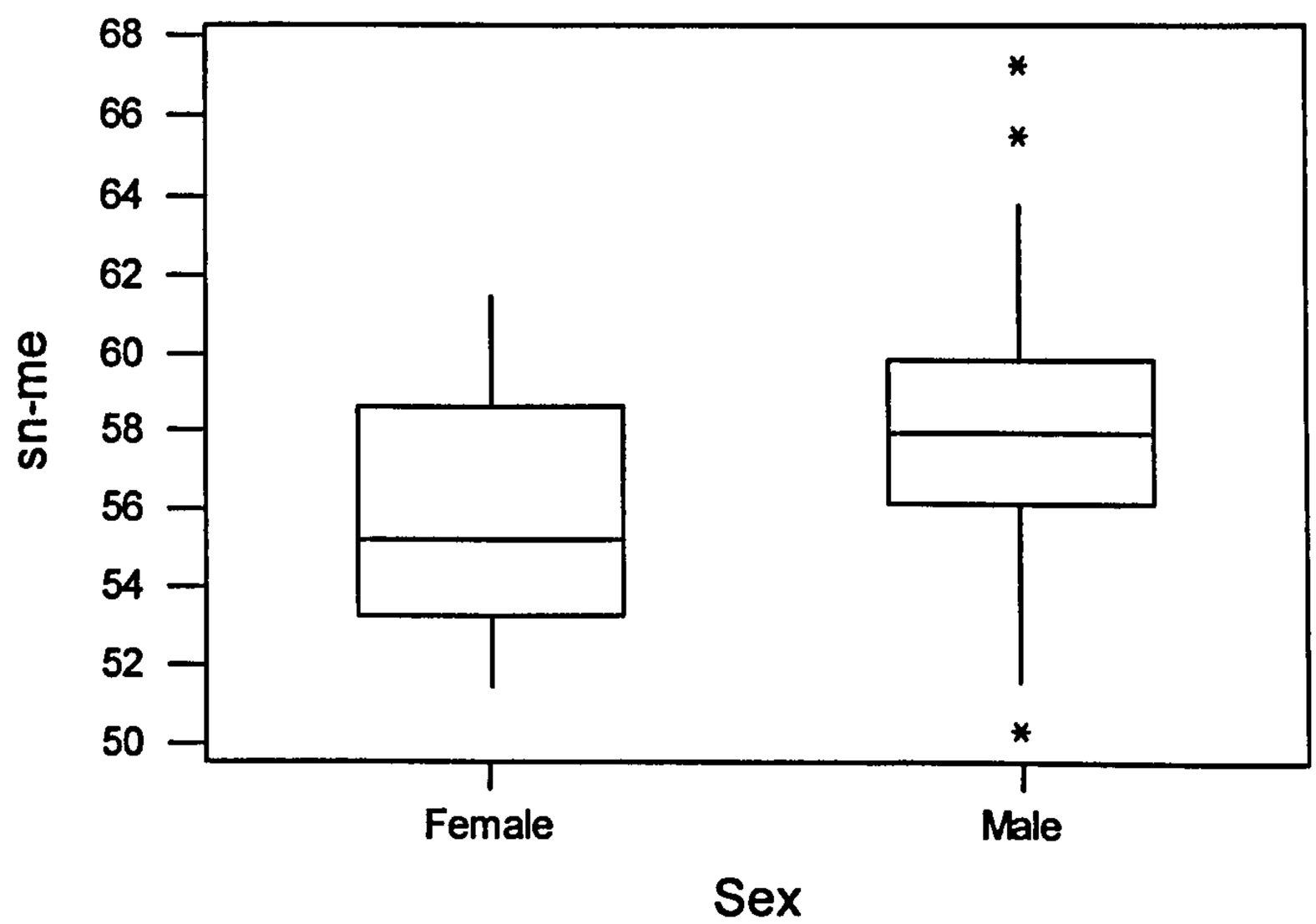
*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

Upper face depth (obi-n) mean was 97.7 ± 3.6 mm on the right and 96.8 ± 3.6 mm on the left. Maxillary depth (obi-sn) mean was 92.6 ± 3.0 mm on the right and 91.9 ± 3.1 mm on the left. Mandibular depth (obi-pg) mean was 88.6 ± 3.4 mm on the right and 87.3 ± 3.6 mm on the left. Paired t tests showed these right and left differences were all statistically significant (p=0.000) with the right side consistently larger than the left and similar to the results at the earlier ages. The males were only statistically significantly larger than the females for upper face depth (obi-n) and right mandibular depth (obiR-pg) although left mandibular length differences were approaching significance (p=0.065).

The upper face width (obsR-obsL) had a mean value of 133.5 ± 5.0 mm. Upper face width measurements were only based on data from 21 females and 28 males since the upper ear landmarks were frequently missing in these models. The lower face width (obiR-obiL) mean was 107.5 ± 4.4 mm. The male lower face width was statistically significantly greater than the females with a mean difference of 2.0 mm.

The mean total face height (n-me) was 84.7 ± 3.8 mm. Upper face height (n-sn) mean was 31.0 ± 1.7 mm. Lower face height (sn-me) mean was 56.9 ± 3.4 mm. The male face height was statistically significantly greater than the females for all of these measurements, with mean differences of 0.8 to 2.9 mm. This is illustrated in Figure 4.65.

Figure 4.65 Gender Differences in Lower Face Height at 2 Years



4.5.4.2 Eye Measurements

The means and standard deviations of the measurements around the eyes at 2 years are shown in Table 4.43.

Table 4.43 Measurements of the Eyes at 2 Years in mm

	Mean	Female Mean	Male Mean	P Value*
Eyes				
exL-exR	74.2 ± 3.0	73.4 ± 2.5	74.8 ± 3.3	**0.025**
enL-enR	29.0 ± 2.1	28.6 ± 1.9	29.4 ± 2.1	**0.041**
enL-exL	23.4 ± 1.1	23.2 ± 1.0	23.5 ± 1.2	0.15
exR-enR	23.4 ± 1.2	23.3 ± 1.0	23.5 ± 1.4	0.37

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in bold.

The biocular width (exL-exR) mean was 74.2 ± 3.0 mm. The intercanthal width (enL-enR) mean was 29.0 ± 2.1 mm. Palpebral fissure width (ex-en) means were 23.4 ± 1.1 mm on the left and 23.4 ± 1.2 mm on the right. Biocular and intercanthal widths were statistically significantly greater in males than females with mean differences of 0.8 to1.4 mm. This was consistent with the findings at 3 and 6 months although at 1 year intercanthal width was not significantly larger in males.

4.5.4.3 Nose and Nostril Measurements

The means and standard deviations of the measurements around the nose and nostrils at 2 years are shown in Table 4.44.

Table 4.44 Measurements of the Nose and Nostrils at 2 Years in mm

	Mean	Female Mean	Male Mean	P Value*
Nose				
acL-acR	28.6 ± 1.6	28.2 ± 1.5	29.0 ± 1.6	**0.016**
alL-alR	26.0 ± 1.6	25.6 ± 1.5	26.4 ± 1.6	**0.021**
acL-prn	19.8 ± 1.3	19.4 ± 1.0	20.1 ± 1.5	**0.010**
acR-prn	20.4 ± 1.2	20.0 ± 1.0	20.8 ± 1.3	**0.001**
n-prn	24.7 ± 1.8	24.3 ± 1.7	25.1 ± 1.9	**0.035**
sn-prn	11.8 ± 1.0	11.7 ± 0.8	11.9 ± 1.1	0.45

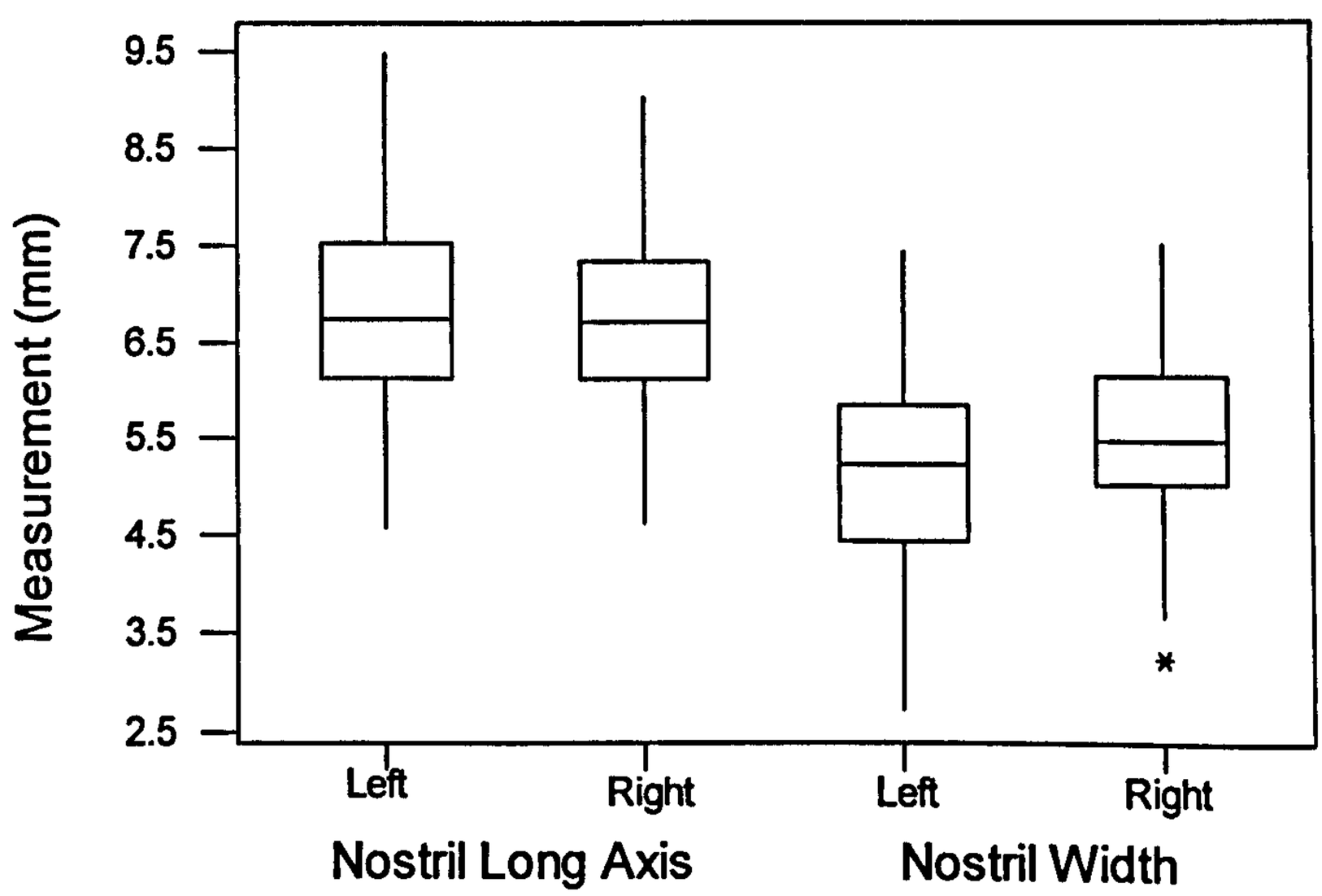
Nostrils				
sbalL-cL	6.8 ± 1.0	6.5 ± 0.8	7.2 ± 1.0	**0.001**
sbalR-cR	6.7 ± 0.9	6.3 ± 0.7	7.1 ± 0.9	**0.000**
sn'L-al'iL	5.2 ± 0.9	5.0 ± 0.9	5.4 ± 0.9	**0.032**
sn'R-al'iR	5.6 ± 0.9	5.4 ± 0.9	5.8 ± 0.9	**0.013**
sn'R-sn'L	5.9 ± 0.8	5.9 ± 0.9	6.0 ± 0.8	0.44

***Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in bold.**

Anatomic nose width (acR-acL) and soft nose width (alR-alL) mean were 28.6 ± 1.6 mm and 26.0 ± 1.6 mm respectively. Nasal dorsum length (n-prn) mean was 24.7 ± 1.8 mm and nasal tip protrusion (sn-prn) mean was 11.8 ± 1.0 mm. All of the nasal measurements were significantly greater in males than females except nasal tip protrusion, the same as at 1 year. Right alar length (acR-prn) was significantly greater than the left (p=0.000) with a mean difference of 0.64 mm. This was not found at any other age.

The nostril long axis (sbal-c) mean was 6.8 ± 1.0 mm on the left and 6.7 ± 0.9 mm on the right. Nostril width (sn'-al'i) mean was 5.2 ± 0.9 mm on the left and 5.6 ± 0.9 mm on the right. This right and left difference in nostril width was statistically significant with the left nostril narrower (p=0.00) than the right. This is illustrated in Figure 4.66. This is consistent with the findings from 3 months to 1 year although the difference in nostril long axis was also significant at the earlier stages. Nostril length and width were statistically significantly greater in males than females with mean differences of 0.4 to 0.8 mm.

Figure 4.66 Left and Right Differences in Nostril Long Axis and Width at 2 Years



4.5.4.4 Upper and Lower Lip Measurements

The means and standard deviations of the upper and lower lip measurements at 2 years are shown in Table 4.45.

Table 4.45 Measurements of the Upper and Lower Lips at 2 Years in mm

	Mean	Female Mean	Male Mean	P Value*
Upper Lip				
chR-chL	34.9 ± 2.8	34.6 ± 2.7	35.3 ± 3.0	0.23
cphL-chL	22.4 ± 1.8	22.0 ± 1.8	22.9 ± 1.6	**0.015**
cphR-chR	22.8 ± 1.9	22.5 ± 1.9	23.1 ± 1.8	0.15
cphR-cphL	8.2 ± 0.9	8.0 ± 0.8	8.5 ± 1.0	**0.013**
ls-sn	11.3 ± 1.8	11.0 ± 1.7	11.5 ± 1.9	0.28
ls-stos	6.2 ± 1.2	6.3 ± 1.2	6.1 ± 1.3	0.28
sn-stos	15.7 ± 1.3	15.4 ± 1.3	15.9 ± 1.4	0.077
sbalL-chL	27.2 ± 1.8	26.6 ± 1.8	27.6 ± 1.6	**0.006**
sbalR-chR	27.4 ± 1.8	27.1 ± 1.8	27.7 ± 1.7	0.12
Lower Lip				
chL-li	19.0 ± 1.6	18.7 ± 1.6	19.3 ± 1.6	0.08
chR-li	19.7 ± 1.6	19.5 ± 1.7	20.0 ± 1.6	0.21
li-stoi	7.8 ± 1.3	7.7 ± 1.3	7.9 ± 1.3	0.40
sl-li	7.2 ± 1.5	7.2 ± 1.5	7.2 ± 1.5	0.98
sl-stoi	12.6 ± 1.1	12.6 ± 1.1	12.7 ± 1.2	0.63

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

Mouth width (chR-chL) mean was 34.9 ± 2.8mm. There was no statistically significant difference in this measurement between males and females. Philtrum width (cphL-cphR) mean was 8.2 ± 0.9 mm. This measurement was statistically significantly greater in males than females although the mean difference was only 0.5 mm. Left upper vermilion length (cphL-chL) was significantly greater in boys than girls. Paired t tests showed that the right upper vermilion length was significantly greater than the left (p=0.000) with a mean difference of 0.37 mm

Upper lip height (sn-stos) mean was 15.7 ± 1.3 mm. The lateral lip height (sbal-ch) mean was 27.2 ± 1.8 mm on the left and 27.4 ± 1.8 mm on the right. Upper lip height measurements were not significantly greater in males than females except the left lateral lip height. Paired t tests showed the right lateral lip height was significantly greater than the left (p=0.018) with a mean difference of 0.26 mm.

Lower lip height (sl-stoi) mean was 12.6 ± 1.1 mm. None of the lower lip measurements were shown to be statistically significantly different in males and females. Lower

vermilion length was 19.7 ± 1.6 mm on the right and 19.0 ± 1.6 mm on the left. Paired t test showed this difference was statistically significant (p=0.000) with a mean difference of 0.69 mm.

4.5.4.5 Angular Measurements

The means and standard deviations of the angular measurements at 2 years are shown in Table 4.46.

Table 4.46 Angles of the Face at 2 Years in degrees

	Mean	Female Mean	Male Mean	P Value*
Angles				
acR-prn-acL	90.8 ± 4.7	91.3 ± 3.8	90.3 ± 5.4	0.30
n-prn-sn	111.5 ± 4.7	111.5 ± 4.9	111.4 ± 4.6	0.93
prn-sn-ls	127.7 ± 6.8	127.4 ± 6.8	128.1 ± 6.9	0.65
li-sl-pg	136.3 ± 10.7	137.2 ± 9.6	135.4 ± 11.6	0.43

*Result of two sample t test comparing the sexes. Differences significant at 5% level are shown in **bold**.

The nasal tip angle (n-prn-sn) mean was 112 ± 5°. The nasolabial angle (prn-sn-ls) mean was 128 ± 7°. The labiomental angle (li-sl-pg) mean was 136 ± 11°. There were no significant gender differences in any of these angles.

4.5.5 Correlations of Body and Face Measurements at 2 Years

4.5.5.1 Correlations of Body Measurements

Correlations of weight, length and head circumference at 2 years are shown in Table 4.47.

Table 4.47 Correlations of Body Measurements at 2 Years

	Correlation with Length*	P Value**	Correlation with Head Circumference*	P Value**
Weight	0.71	**0.000**	0.44	**0.000**
Length			0.36	**0.000**

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in **bold**.

All of the correlations between the body measurements were statistically significant. The highest correlation was between weight and length with r = 0.71.

4.5.5.2 Correlations with Face Height, Width and Depth

Correlation of face heights, widths and depths with body measurements at 2 years are shown in Table 4.48.

Table 4.48 Correlations of Body Measurements with Face Height, Width and Depth at 2 Years

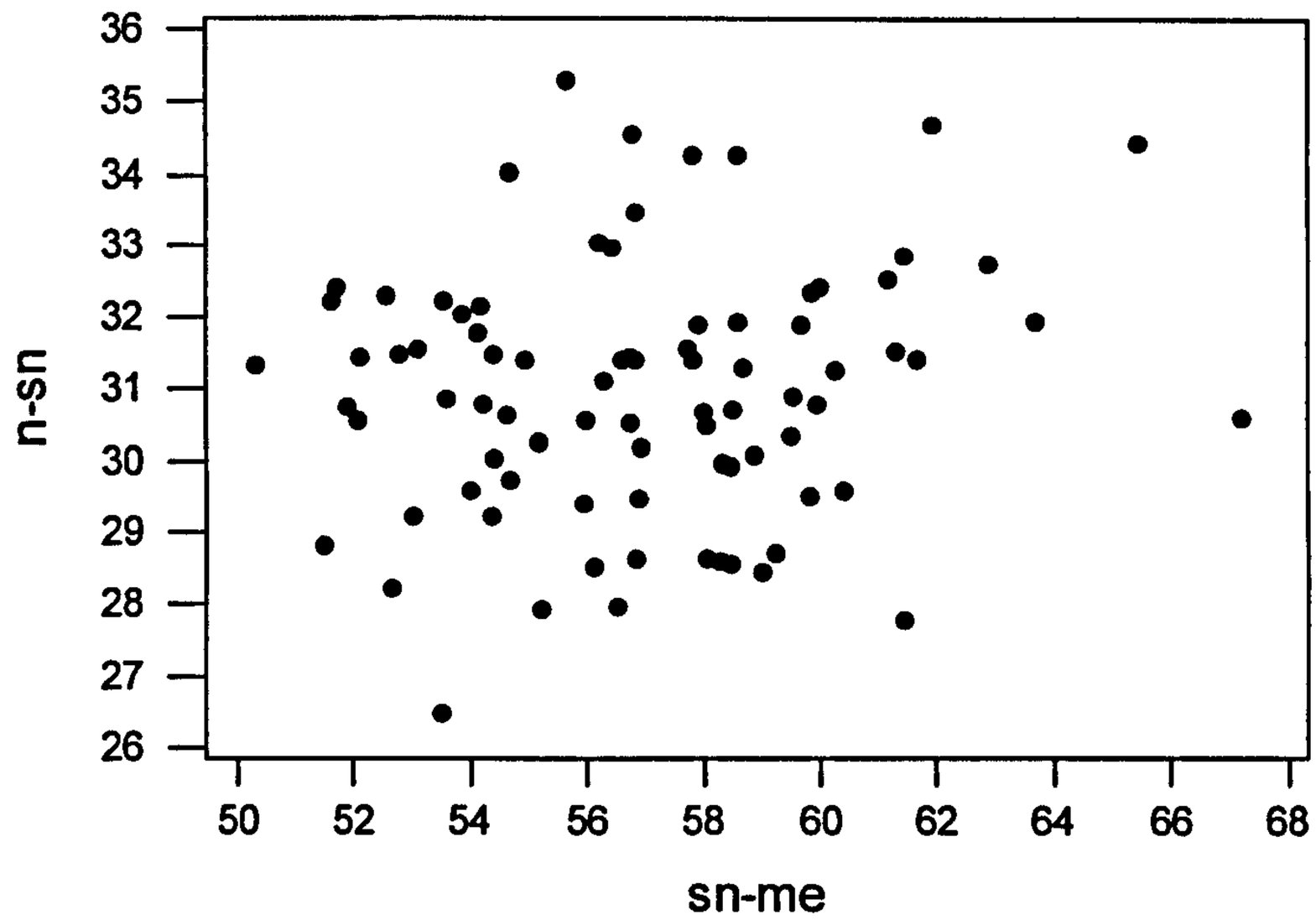
	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Face Depth						
obiL-n	0.48	**0.000**	0.29	**0.006**	0.58	**0.000**
obiR-n	0.54	**0.000**	0.37	**0.000**	0.61	**0.000**
obiL-sn	0.37	**0.001**	0.22	**0.049**	0.09	0.413
obiR-sn	0.27	**0.012**	0.22	**0.037**	0.10	0.371
obiL-pg	0.48	**0.000**	0.31	**0.004**	0.33	**0.002**
obiR-pg	0.58	**0.000**	0.42	**0.000**	0.40	**0.000**
Face Width						
obsR-obsL	0.37	**0.006**	0.38	**0.007**	0.44	**0.001**
obiR-obiL	0.48	**0.000**	0.22	**0.042**	0.25	**0.019**
Face Height						
n-me	0.41	**0.000**	0.41	**0.000**	0.29	**0.009**
sn-me	0.41	**0.000**	0.37	**0.001**	0.08	0.451
n-sn	0.10	0.342	0.24	**0.024**	0.39	**0.000**

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in **bold**.

All of the face measurements were significantly correlated with two or more of the body measurements. The strongest correlations tended to be with weight. The highest r value was 0.61 between upper left face depth and head circumference. The lowest significant correlation was between lower face width and body length with r = 0.22. Maxillary depths did not correlate with head circumference and nasal dorsum length did not correlate with weight.

Most of the face depths correlated significantly with each other. Right maxillary depth did not correlate with right or left mandibular depths (r=0.07, 0.08) or upper face depths (r=0.01, -0.01). Left maxillary depth did not correlate with right upper face depth (r=0.15). Face widths correlated significantly with each other (r=0.50). Total face height correlated significantly with lower and upper face heights (r=0.90, 0.53) but there was no correlation between upper and lower face heights at this age (r=0.14). This is illustrated in Figure 4.67. Total and lower face height correlated with lower face width (r=0.32, 0.35) but not with upper face width.

Figure 4.67 Plot of Upper Face Height against Lower Face Height at 2 Years



4.5.5.3 Correlations with Eye Measurements

Correlations of body measurements with measurements around the eyes at 2 years are shown in Table 4.49.

Table 4.49 Correlations of Body Measurements with Eye Measurements at 2 Years

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Eyes						
exR-exL	0.47	**0.000**	0.47	**0.000**	0.56	**0.000**
enL-enR	0.33	**0.001**	0.19	0.071	0.37	**0.000**
exL-enL	0.37	**0.001**	0.51	**0.000**	0.39	**0.000**
exR-enR	0.35	**0.001**	0.42	**0.000**	0.44	**0.000**

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in bold.

All of the eye measurements were significantly correlated with the body measurements except intercanthal width and body length. The highest correlation was between biocular width and head circumference with an r value of 0.56. Once again all the eye measurements were significantly correlated with each other except right and left palpebral fissure widths with intercanthal width.

4.5.5.4 Correlations with Nose and Nostril Measurements

Correlation of body measurements with measurements around the nose and nostrils at 2 years are shown in Table 4.50.

Table 4.50 Correlations of Body Measurements with Nose and Nostril Measurements at 2 Years

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Nose						
acL-acR	0.41	**0.000**	0.39	**0.000**	0.40	**0.000**
alL-alR	0.45	**0.000**	0.40	**0.002**	0.44	**0.000**
acL-prn	0.41	**0.000**	0.44	**0.010**	0.42	**0.000**
acR-prn	0.38	**0.000**	0.41	**0.000**	0.44	**0.000**
n-prn	0.08	0.419	0.21	**0.050**	0.30	**0.003**
sn-prn	0.23	**0.027**	0.19	0.067	0.32	**0.002**
Nostrils						
sbalL-cL	0.11	0.308	0.11	0.284	0.22	**0.039**
sbalR-cR	0.18	0.096	0.16	0.118	0.30	**0.004**
sn'L-al'iL	0.18	0.094	0.19	0.066	0.31	**0.003**
sn'R-al'iR	0.10	0.362	0.21	**0.047**	0.32	**0.002**
sn'R-sn'L	0.16	0.131	0.06	0.601	0.16	0.131

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in **bold**.

All of the nose measurements were significantly correlated with body measurements with r values ranging from 0.21 to 0.45. Nasal tip protrusion was significantly but weakly correlated with weight (r=0.22) and head circumference (r=0.24) but not with length. Nasal dorsum length was not significantly correlated with weight. All of the nose measurements were significantly correlated with each other except nasal dorsum length with anatomic and soft nose widths and nasal tip protrusion.

None of the nostril measurements were significantly correlated with body weight. Nostril widths and nostril long axis correlated weakly but significantly with head circumference. Right nostril width also correlated weakly but significantly with body length. Nostril long axis and width correlated with each other but not with columella width. Columella width did correlate with all the nose measurements except nasal tip protrusion and nasal dorsum length.

4.5.5.5 Correlations with Upper and Lower Lip Measurements

Correlation of body measurements with upper and lower lip measurements at 2 years are shown in Table 4.51.

Table 4.51 Correlations of Body Measurements with Upper and Lower Lip Measurements at 2 Years

	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Upper Lip						
chR-chL	0.21	**0.045**	0.31	**0.003**	0.38	**0.000**
cphL-chL	0.29	**0.006**	0.34	**0.001**	0.11	0.280
cphR-chR	0.33	**0.001**	0.41	**0.000**	0.09	0.376
cphR-cphL	0.18	0.080	0.21	**0.050**	0.29	**0.005**
ls-sn	0.00	0.991	-0.13	0.205	0.10	0.358
ls-stos	0.08	0.436	0.16	0.124	-0.00	0.974
sn-stos	0.12	0.261	0.01	0.930	0.12	0.248
sbalL-chL	0.32	**0.002**	0.29	**0.005**	0.22	**0.036**
sbalR-chR	0.30	**0.003**	0.30	**0.004**	0.16	0.134
Lower Lip						
chL-li	0.27	**0.010**	0.39	**0.000**	0.40	**0.000**
chR-li	0.28	**0.008**	0.38	**0.000**	0.33	**0.001**
li-stoi	0.19	0.067	0.17	0.103	0.06	0.548
sl-li	0.01	0.943	0.02	0.832	0.09	0.382
sl-stoi	0.17	0.100	0.16	0.141	0.13	0.213

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in **bold**.

Mouth width, philtrum width and upper and lower vermilion lengths were all significantly but weakly correlated with body measurements with r values ranging from 0.21 to 0.40. Upper vermilion lengths did not correlate with head circumference and philtrum width did not correlate with body weight. Mouth width, philtrum width and upper and lower vermilion lengths all significantly correlated with each other.

Upper lateral lip heights were significantly correlated with body measurements although right lateral lip height did not correlate with head circumference. None of remaining lip heights was significantly correlated with body measurements. The upper and lower lip heights, except vermilion heights (ls-stos, li-stoi), were significantly correlated with each other. Only the lateral lip heights were significantly correlated with the mouth width and vermilion lengths.

4.5.5.6 Correlations with Angular Measurements

Correlations of angular measurements with body measurements at 2 years are shown in Table 4.52.

Table 4.52 Correlations of Body Measurements with Angles of the Face at 2 Years

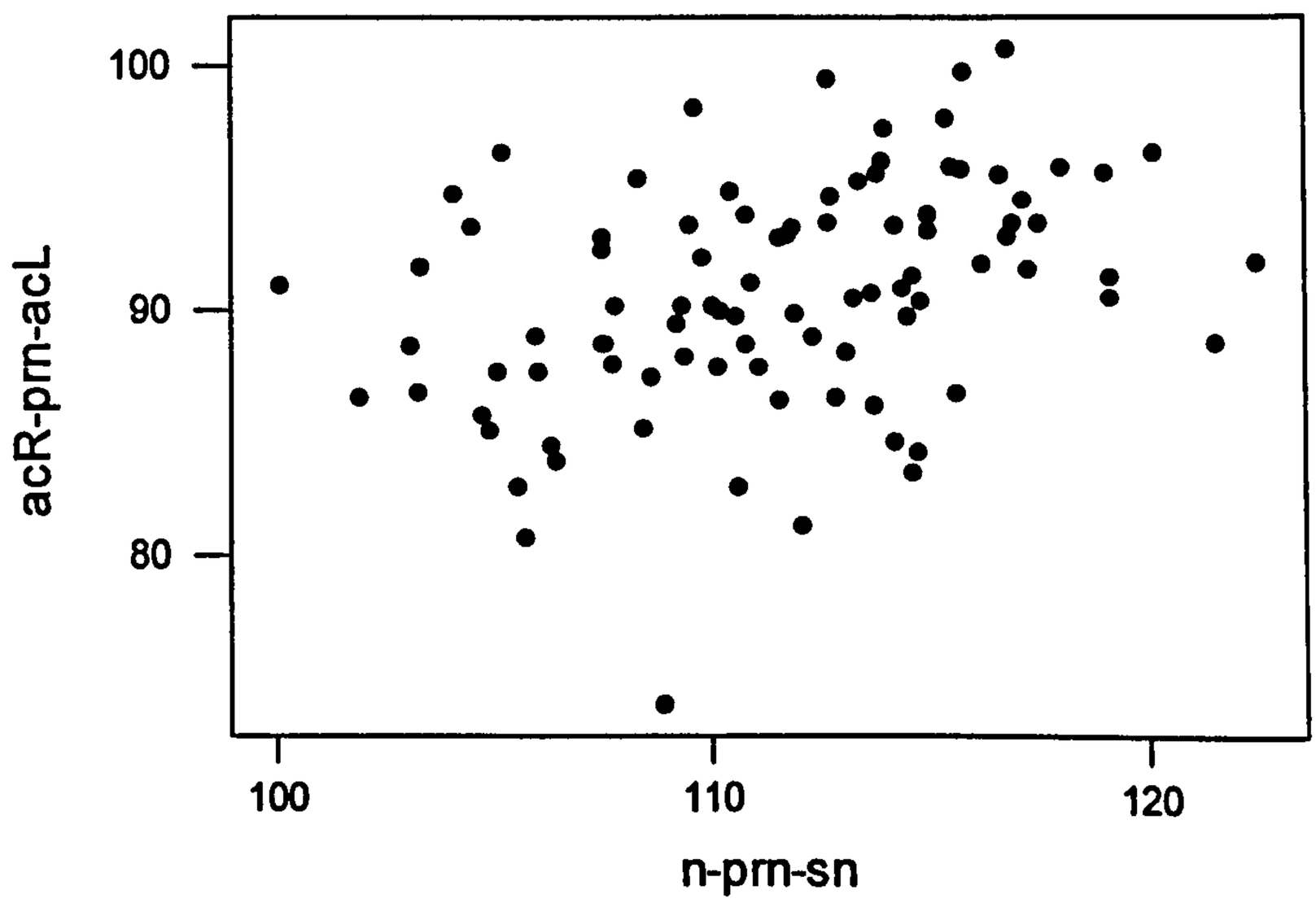
	Correlation with Weight*	P** Value	Correlation with Length*	P** Value	Correlation with Head Circumference*	P** Value
Angles						
acR-prn-acL	-0.01	0.908	-0.10	0.359	-0.10	0.323
n-prn-sn	-0.18	0.089	-0.10	0.366	-0.08	0.443
prn-sn-ls	-0.19	0.076	0.03	0.777	0.10	0.323
li-sl-pg	-0.11	0.298	-0.07	0.535	-0.02	0.889

*Pearson's correlation coefficients (r values). **Correlations significant at 5% level are shown in **bold**.

There were no significant correlations between the angles and body weight, length or head circumference at 2 years.

Once again nasal tip angle (n-prn-sn) was significantly correlated with nasal tip horizontal displacement angle (acR-prn-acL) and nasolabial angle (prn-sn-ls) (r=0.36, 0.47). None of the other angles were significantly correlated with each other. The correlation of nasal tip and nasal tip horizontal displacement angles is illustrated in Figure 4.68.

Figure 4.68 Plot of Nasal Tip Angle against Nasal Tip Horizontal Displacement Angle

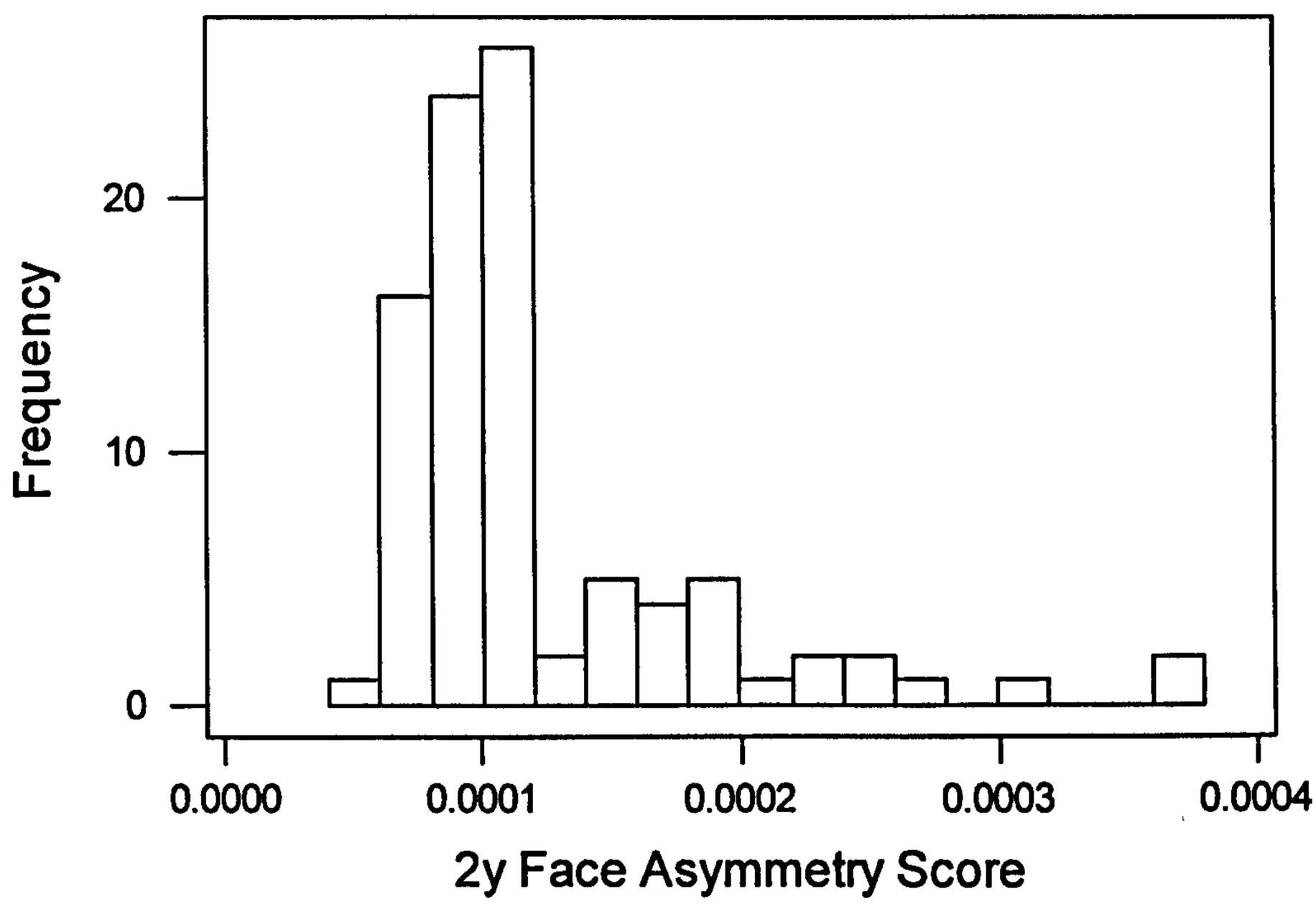


4.5.6 Asymmetry at 2 Years

4.5.6.1 Face

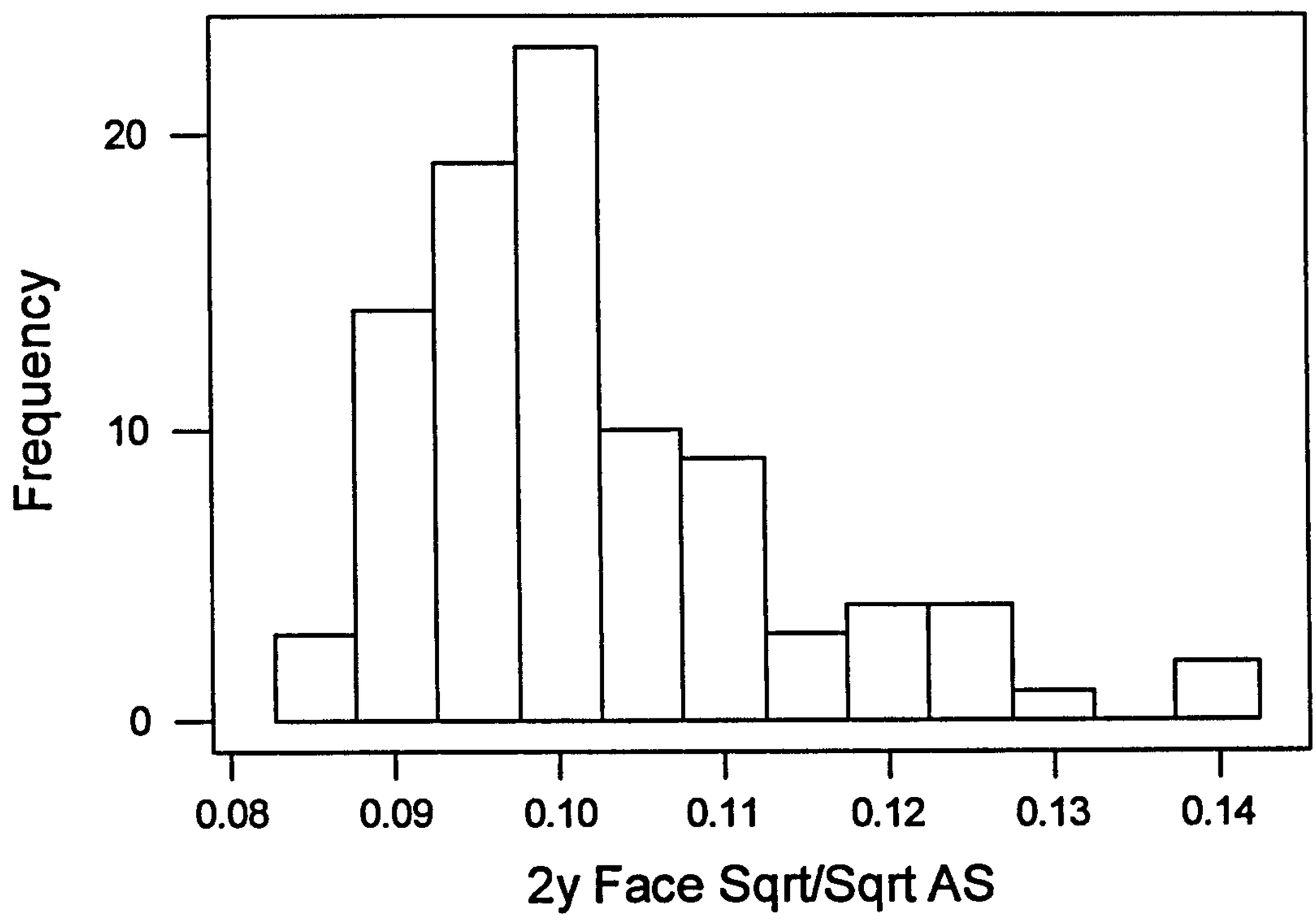
The distribution of the asymmetry scores for the face at 2 years is shown in Figure 4.69. All of the asymmetry scores were based on the landmarks in the midface, excluding the ear, lower lip and chin landmarks.

Figure 4.69 Distribution of Asymmetry Scores for the Face at 2 Years



As shown in Figure 4.69, the raw asymmetry scores were not normally distributed. However, the fourth roots of the asymmetry scores (sqrt/sqrt AS) were well approximated by a normal distribution, as shown in Figure 4.70. Standard parametric tests were therefore applied to this transformed data.

Figure 4.70 Distribution of the Sqrt/Sqrt AS for the Face at 2 Years



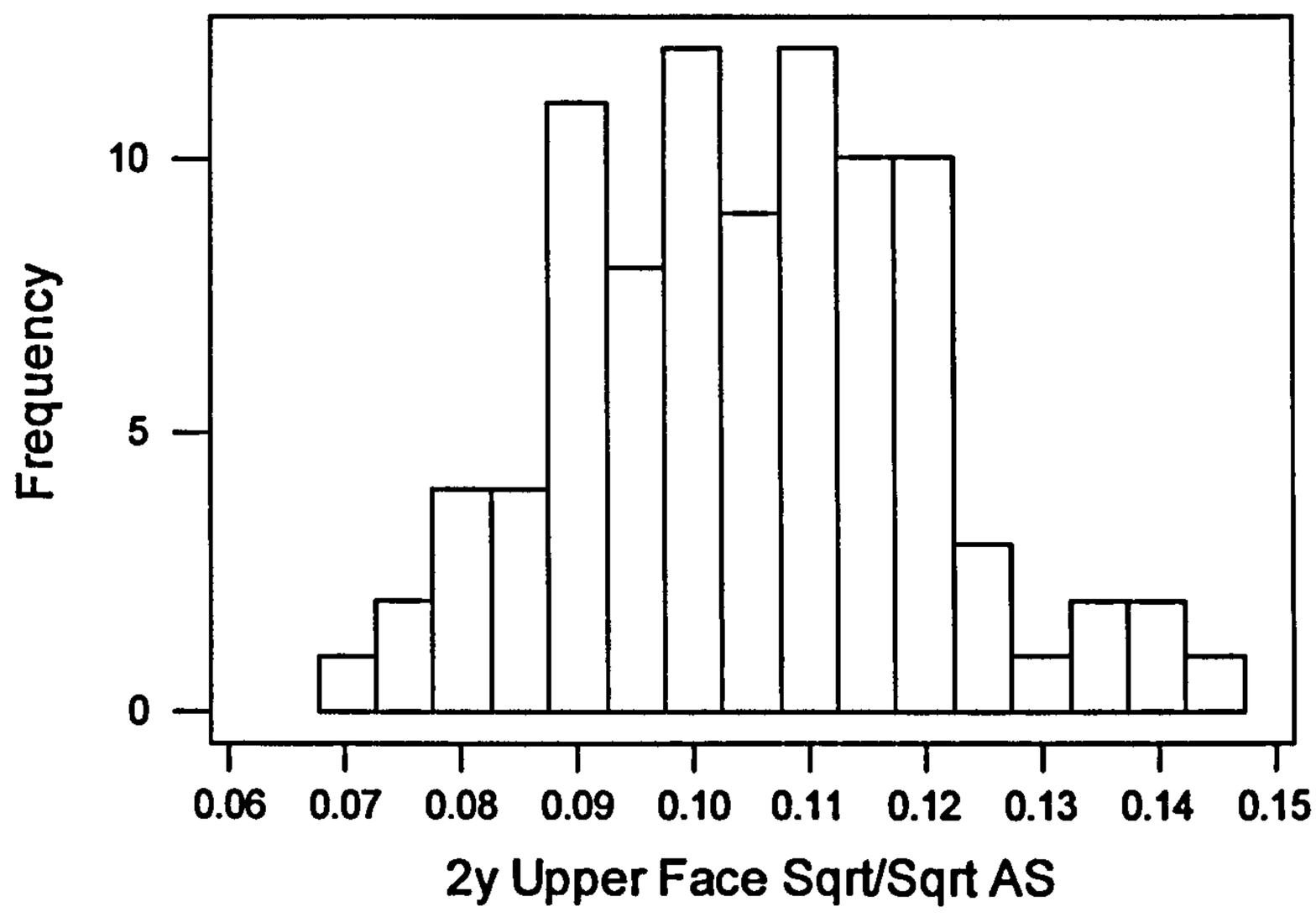
The mean sqrt/sqrt AS for the face was 0.102 ± 0.017. The mean sqrt/sqrt AS for the females was 0.100 ± 0.011 and for the males 0.104 ± 0.012. Two sample t test showed that this slight difference was bordering on being statistically significant (p=0.051). This is illustrated in Figure 4.71.

Figure 4.71 Sqrt/Sqrt AS for the Face of Males and Females at 2 Years

4.5.6.2 Upper Face

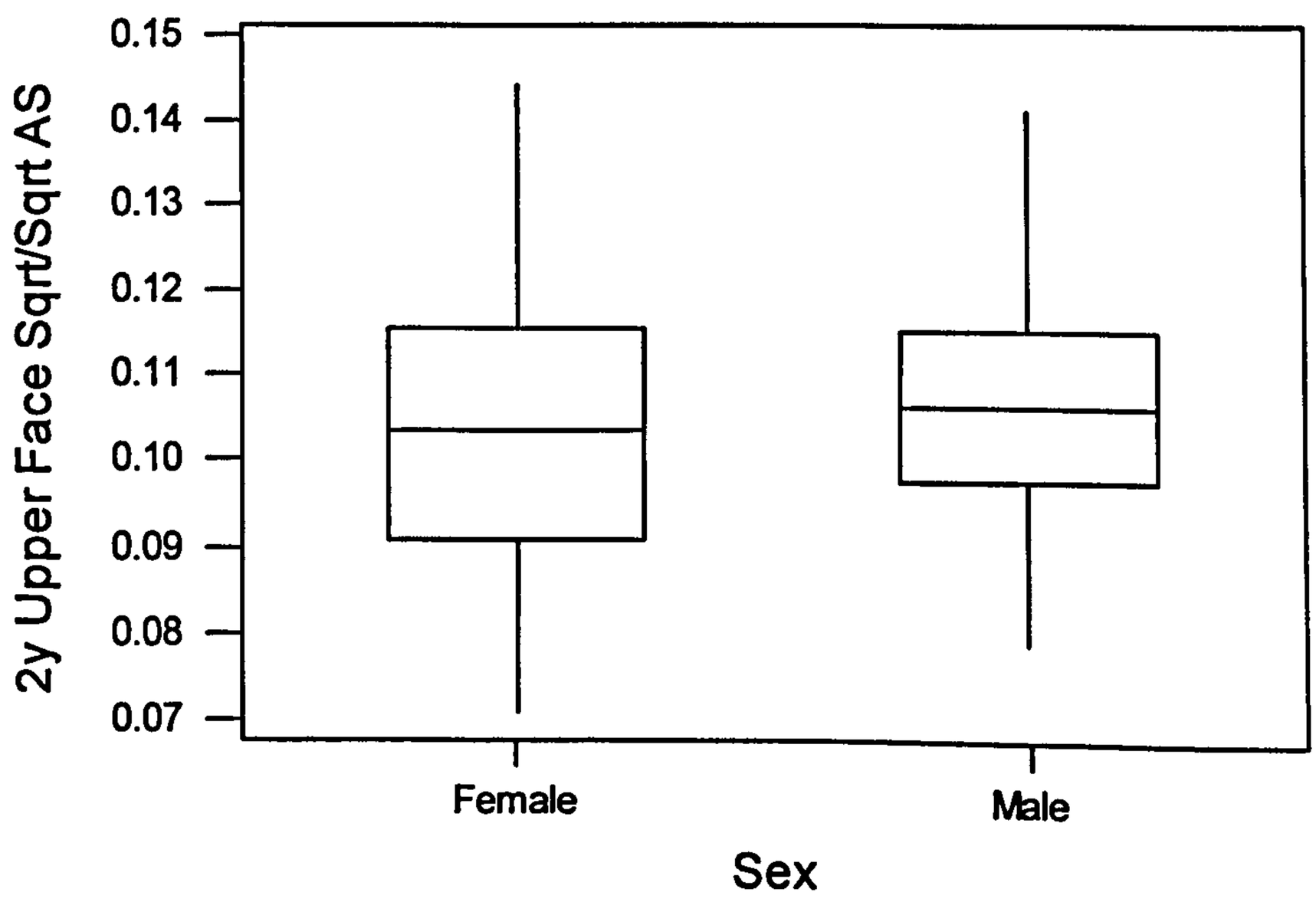
The distribution of the sqrt/sqrt AS for the upper face at 2 years is shown in Figure 4.72. The upper face asymmetry score included the endocanthion, exocanthion and nasion landmarks.

Figure 4.72 Distribution of the Sqrt/Sqrt AS for the Upper Face at 2 Years



The mean sqrt/sqrt AS for the upper face was 0.105 ± 0.015. There was no statistically significant difference between the males and females (p=0.28). This is shown in Figure 4.73.

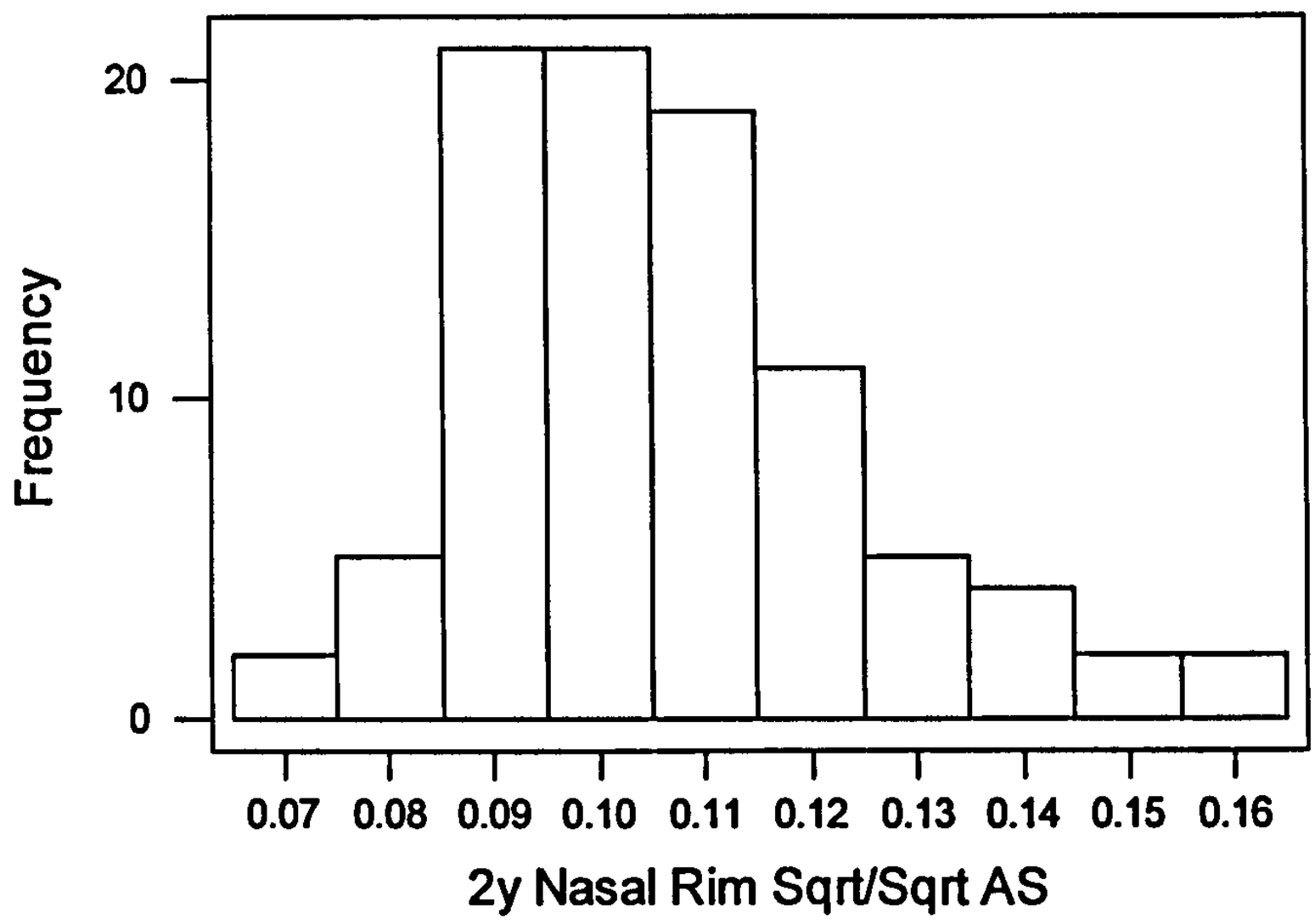
Figure 4.73 Sqrt/Sqrt AS for the Upper Face of Males and Females at 2 Years



4.5.6.3 Nasal Rim

The distribution of the sqrt/sqrt AS for the nasal rim at 2 years is shown in Figure 4.74. The asymmetry score for the nasal rim incorporated the alar crest, alare, alare' outer and pronasale landmarks.

Figure 4.74 Distribution of the Sqrt/Sqrt AS for the Nasal Rim at 2 Years



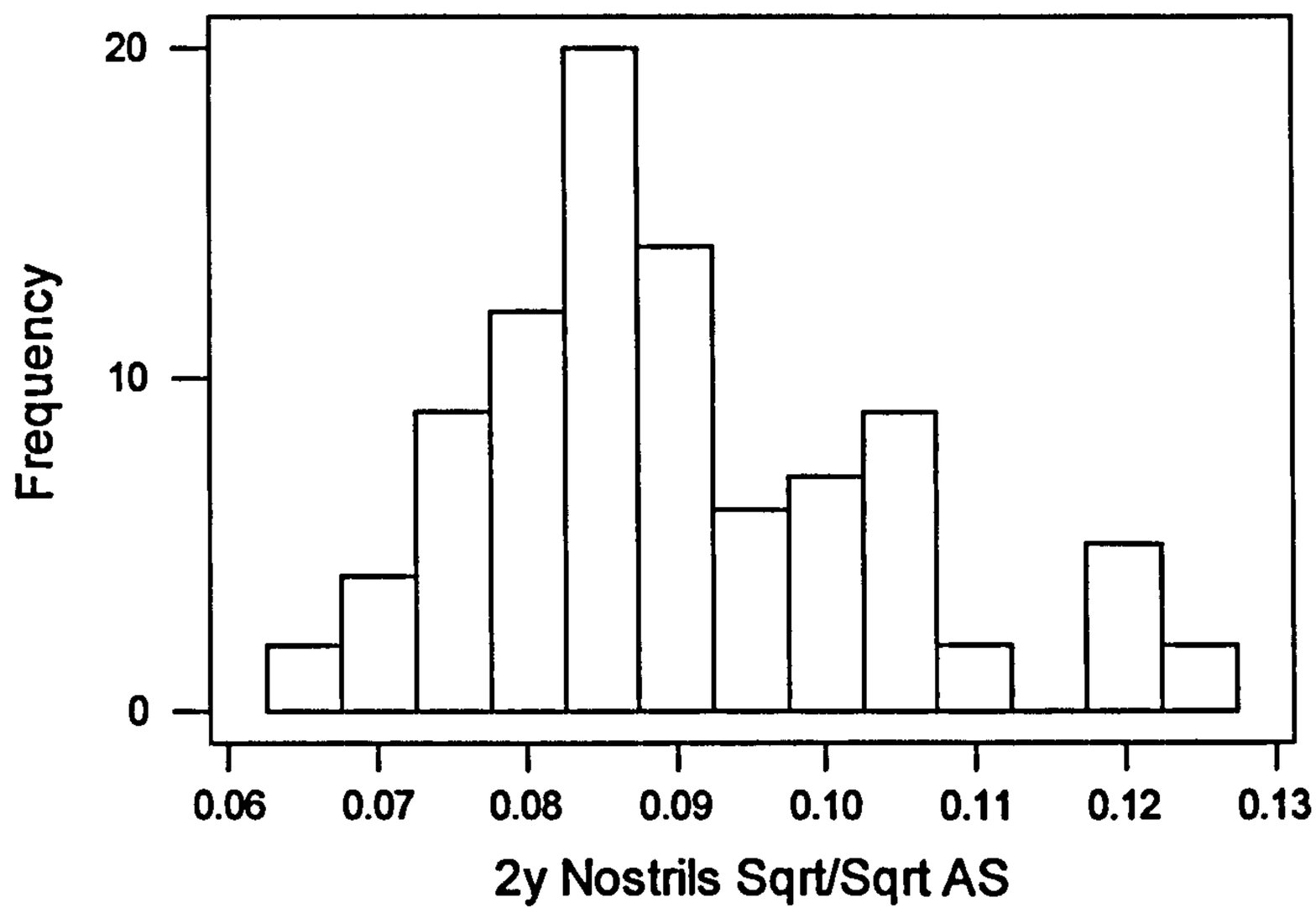
The mean sqrt/sqrt AS for the nasal rim was 0.105 + 0.018. The mean sqrt/sqrt AS for the females was 0.101 ± 0.017 and for the males 0.110 ± 0.018. Two sample t test showed that this slight difference was statistically significant (p=0.013). This is shown in Figure 4.75.

Figure 4.75 Gender Differences in Sqrt/Sqrt AS for the Nasal Rim at 2 Years

4.5.6.4 Nostrils

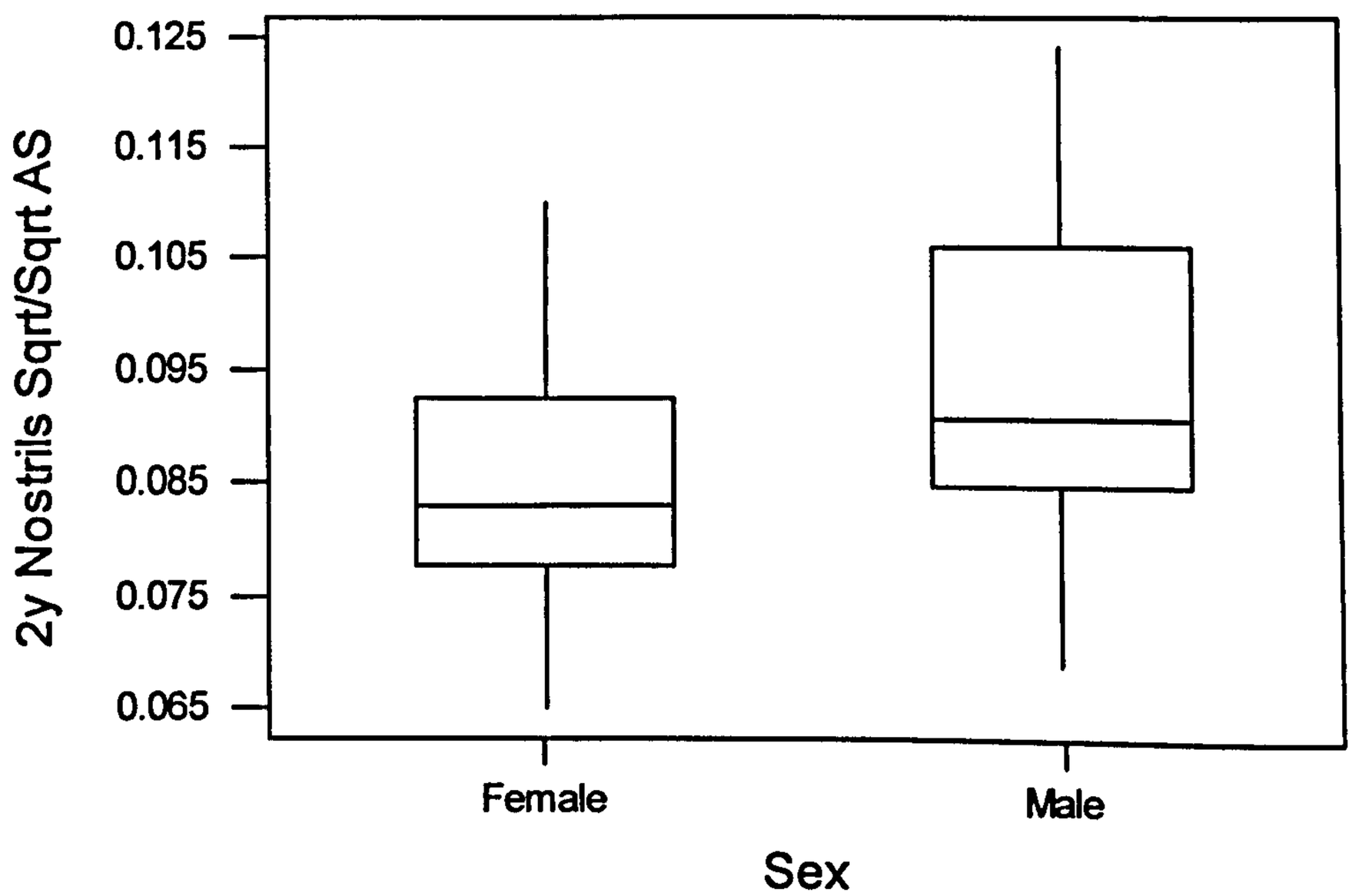
The distribution of the sqrt/sqrt AS for the nostrils at 2 years is shown in Figure 4.76. The landmarks used to calculate this asymmetry score were subalare, alare' inner, columella, subnasale' and subnasale.

Figure 4.76 Distribution of the Sqrt/Sqrt AS for the Nostrils at 2 Years



The mean sqrt/sqrt AS for the nostrils was 0.090 ± 0.014. The mean for the females was 0.086 ± 0.011 and for the males 0.094 ± 0.015. This slight difference was statistically significant (p=0.005) and is illustrated in Figure 4.77.

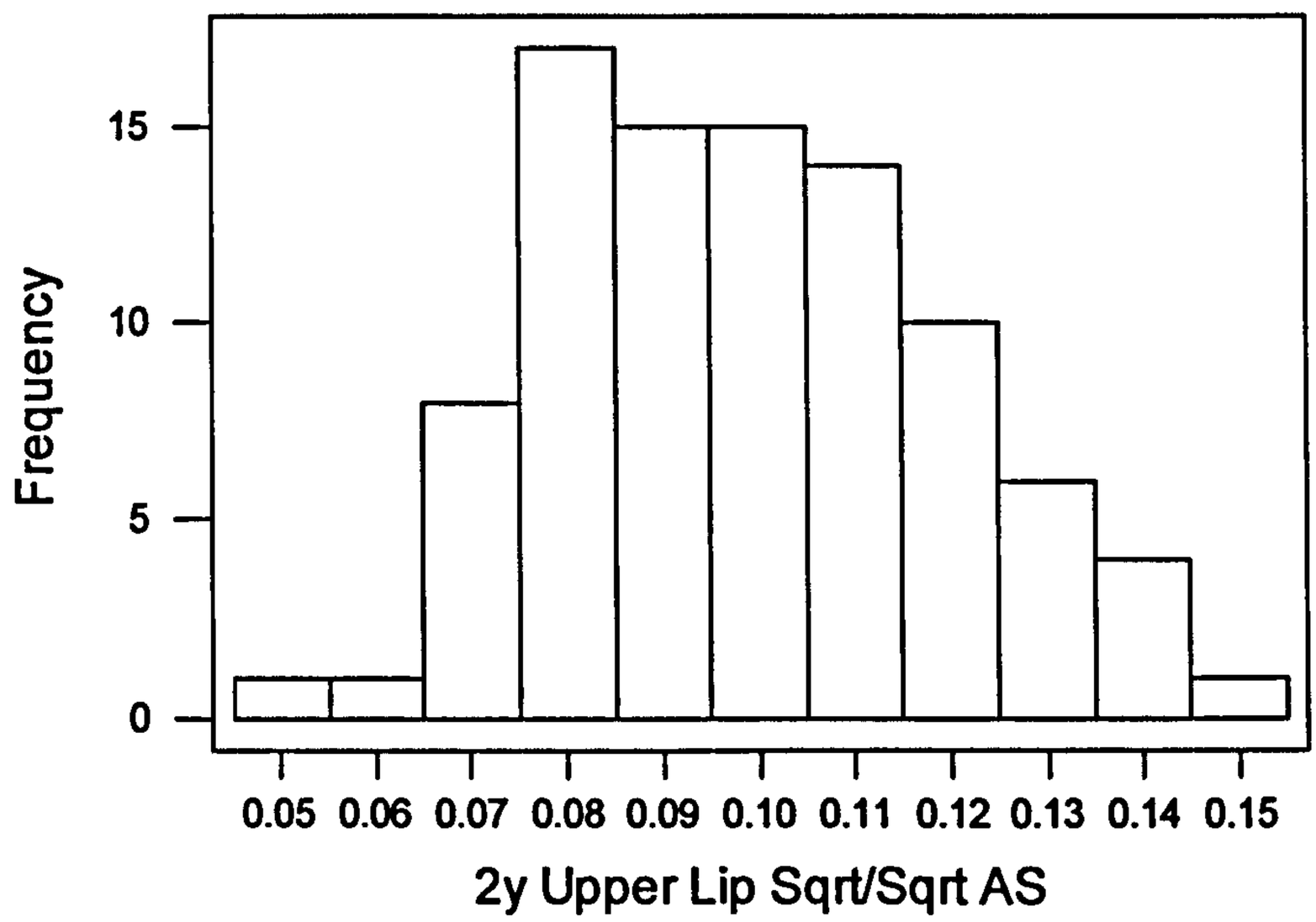
Figure 4.77 Gender Differences in Sqrt/Sqrt AS for the Nostrils at 2 Years



4.5.6.5 Upper Lip

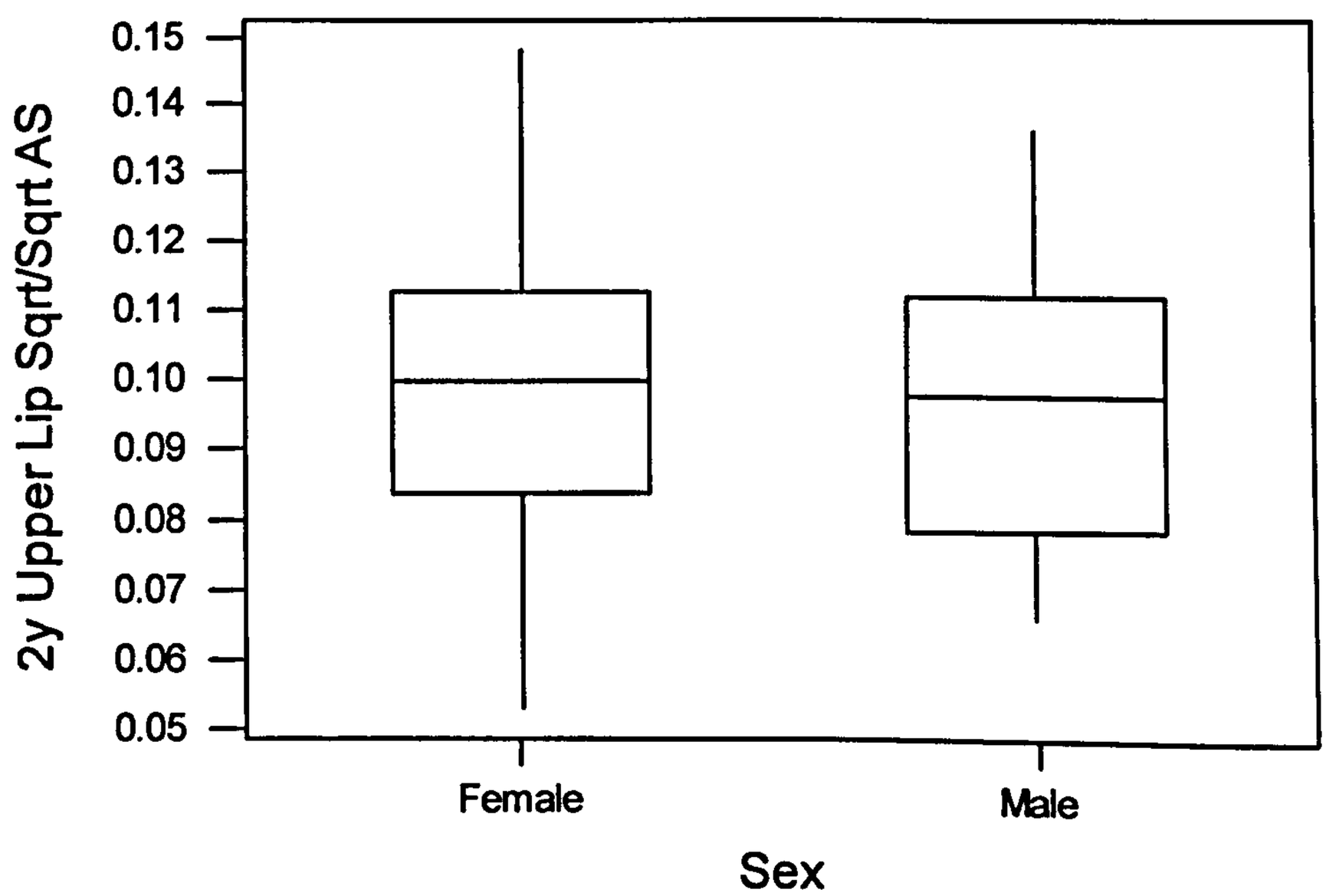
The distribution of the sqrt/sqrt AS for the upper lip at 2 years is shown in Figure 4.78. The landmarks included in this asymmetry score were cheilion, crista philtri and labrale superius.

Figure 4.78 Distribution of the Sqrt/Sqrt AS for the Upper Lip at 2 Years



The mean sqrt/sqrt AS for the upper lip was 0.098 ± 0.020. There was no statistically significant difference between the males and females (p=0.57). This is shown in Figure 4.79.

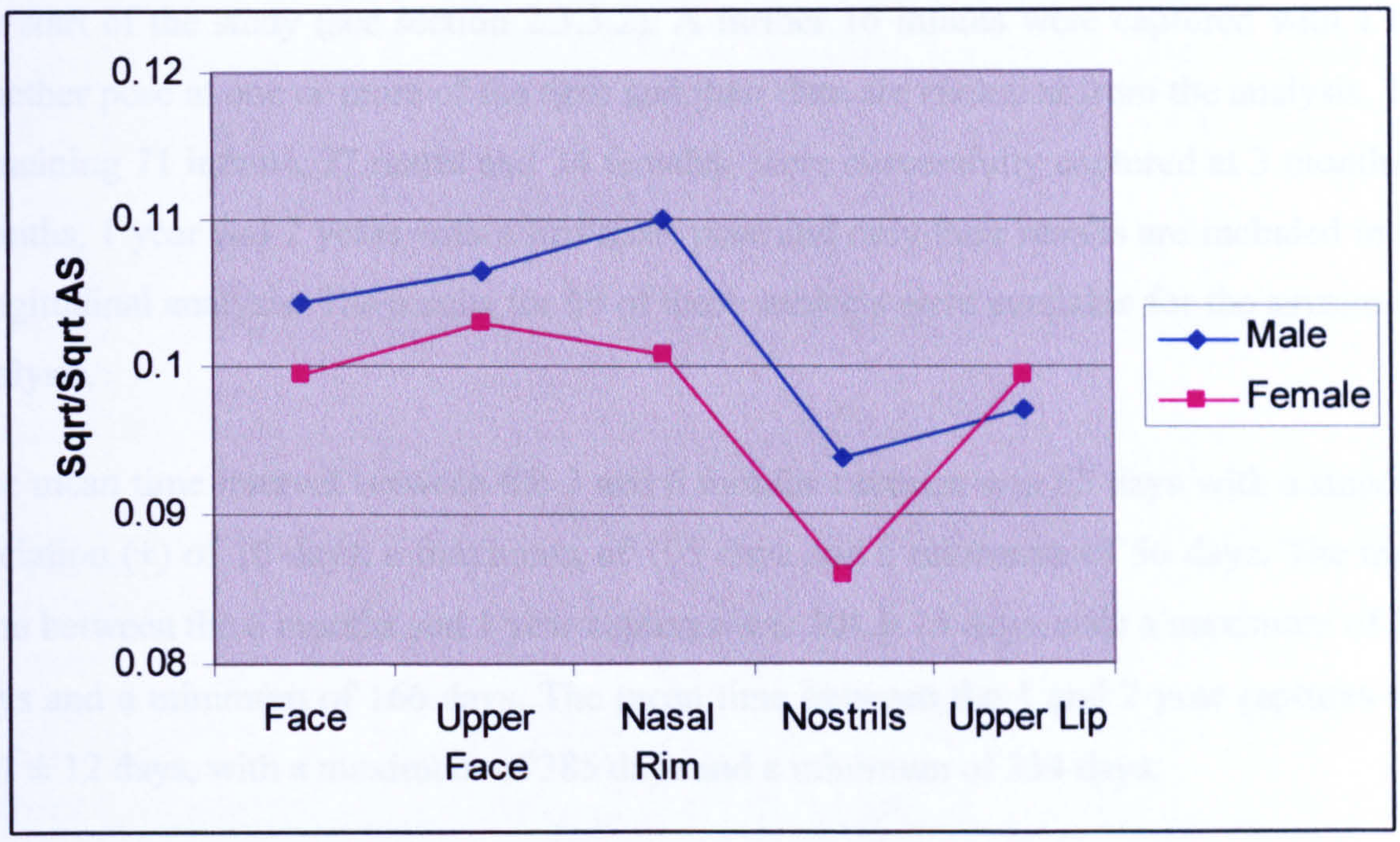
Figure 4.79 Sqrt/Sqrt AS for the Upper Lip of Males and Females at 2 Years



4.5.6.6 Comparisons of Asymmetry Scores at 2 Years

The results of comparing the asymmetry scores of the different regions of the face at 2 years are illustrated in Figure 4.80.

Figure 4.80 Comparison of the Asymmetry of the Regions of the Face at 2 Years



Similar to the results at 3 months and 1 year, there was a tendency for the asymmetry scores of the females to be lower than the males although these differences were only significant for the nasal rim (p=0.013) and nostrils (p=0.005). Paired t tests showed that there were significant differences between all of the asymmetry scores (p=0.000 to 0.029), except between the upper face and nasal rim. The least asymmetry was found in the nostrils, consistent with the results from 3 months to 1 year. Contrary to the earlier findings the greatest asymmetry was in the nasal rim rather than the upper face at 2 years.

4.5.6.7 Correlations of Asymmetry Scores at 2 Years

None of the asymmetry scores correlated significantly with the body measurements except a weak negative correlation between upper face asymmetry and body length (r=-0.31, p=0.003). The asymmetry score for the face correlated highly and significantly with the asymmetry scores for all of the individual regions of the face (r=0.63 to 0.74). All the individual asymmetry scores correlated weakly with each other (r=0.26 to 0.43), except the nasal rim with upper lip asymmetry (r=0.16, p=0.118).

5 Longitudinal Results

5.1 Subjects

Ninety three infants attended at all four time points. Six of the 3 months captures were unsuccessful due to the time delay between the texture image and colour image capture at the start of the study (see section 2.3.3.2). A further 16 infants were captured with a lips together pose at one or more of the ages and their data are excluded from the analysis. The remaining 71 infants, 37 males and 34 females, were successfully captured at 3 months, 6 months, 1 year and 2 years with a lips apart pose and only their results are included in the longitudinal analysis. The results for 69 of these subjects were available for the asymmetry analysis.

The mean time interval between the 3 and 6 months captures was 83 days with a standard deviation (±) of 10 days, a maximum of 105 days and a minimum of 56 days. The mean time between the 6 months and 1 year captures was 201 ± 13 days, with a maximum of 220 days and a minimum of 166 days. The mean time between the 1 and 2 year captures was 361 ± 12 days, with a maximum of 385 days and a minimum of 334 days.

5.2 Missing Landmarks

Several landmarks were missing in the models used for the longitudinal analysis (see section 4.1.3). The frequency of missing landmarks is shown in Table 5.1.

Table 5.1 Frequency of Missing Landmarks

	3 Months	6 Months	1 Year	2 Years
obsR	15	6	12	22
obsL	6	3	13	29
obiR	14	4	2	0
obiL	9	3	0	3
me	4	0	1	5
prn	0	1	0	0

Upper face width measurements were missing for 15 cases at 3 months, 8 cases at 6 months, 17 cases at 1 year and 32 cases at 2 years. Lower face width measurements were missing in 18 cases at 3 months, 6 cases at 6 months, 2 cases at 1 year and 3 cases at 2 years.

5.3 Growth in Body Measurements

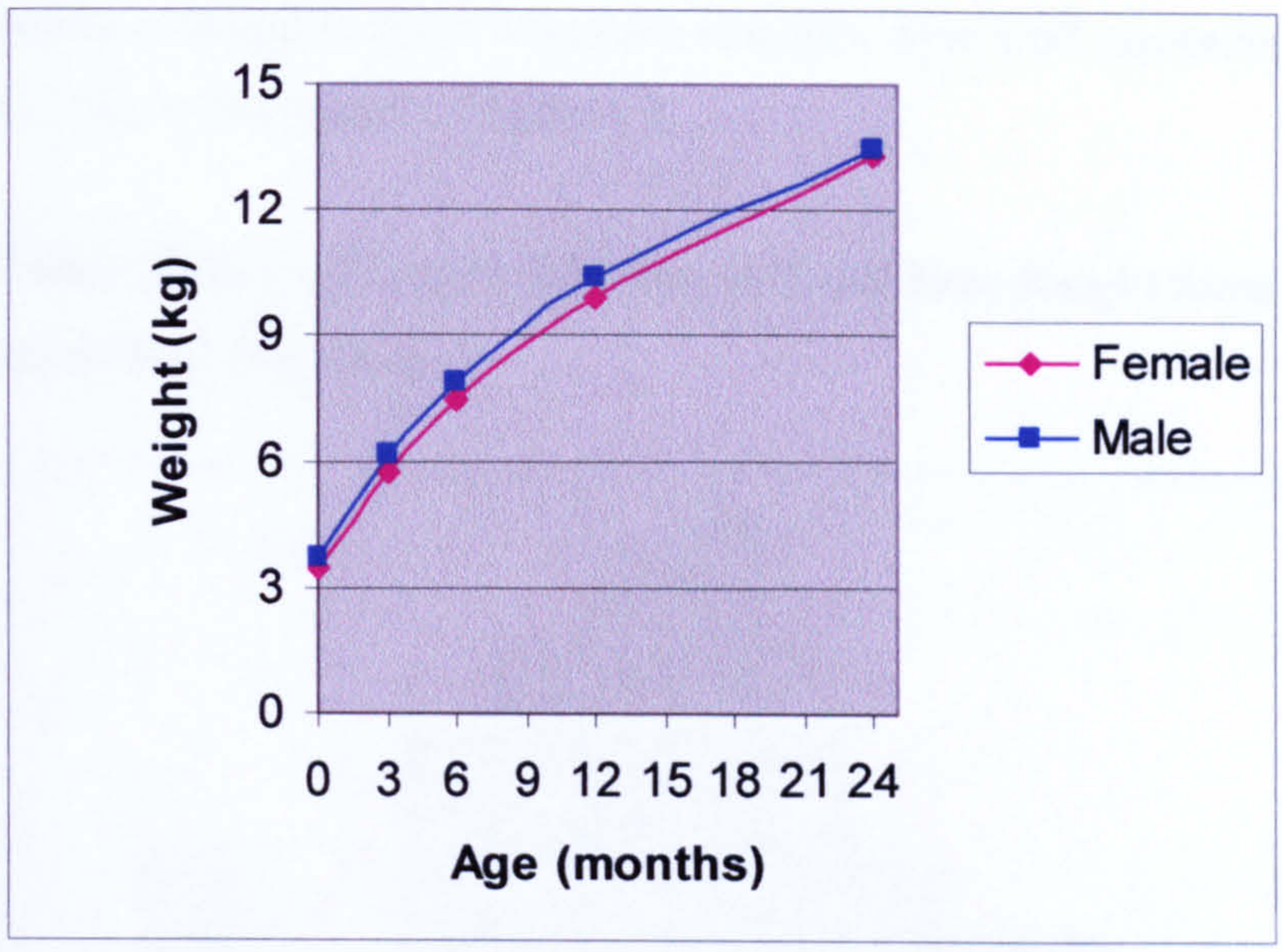
The means and standard deviations of growth in weight, length and head circumference from 3 to 6 months (3m-6m), 6 months to 1 year (6m-1y) and 1 to 2 years (1y-2y) are shown in Table 5.2 and illustrated in Figure 5.1.

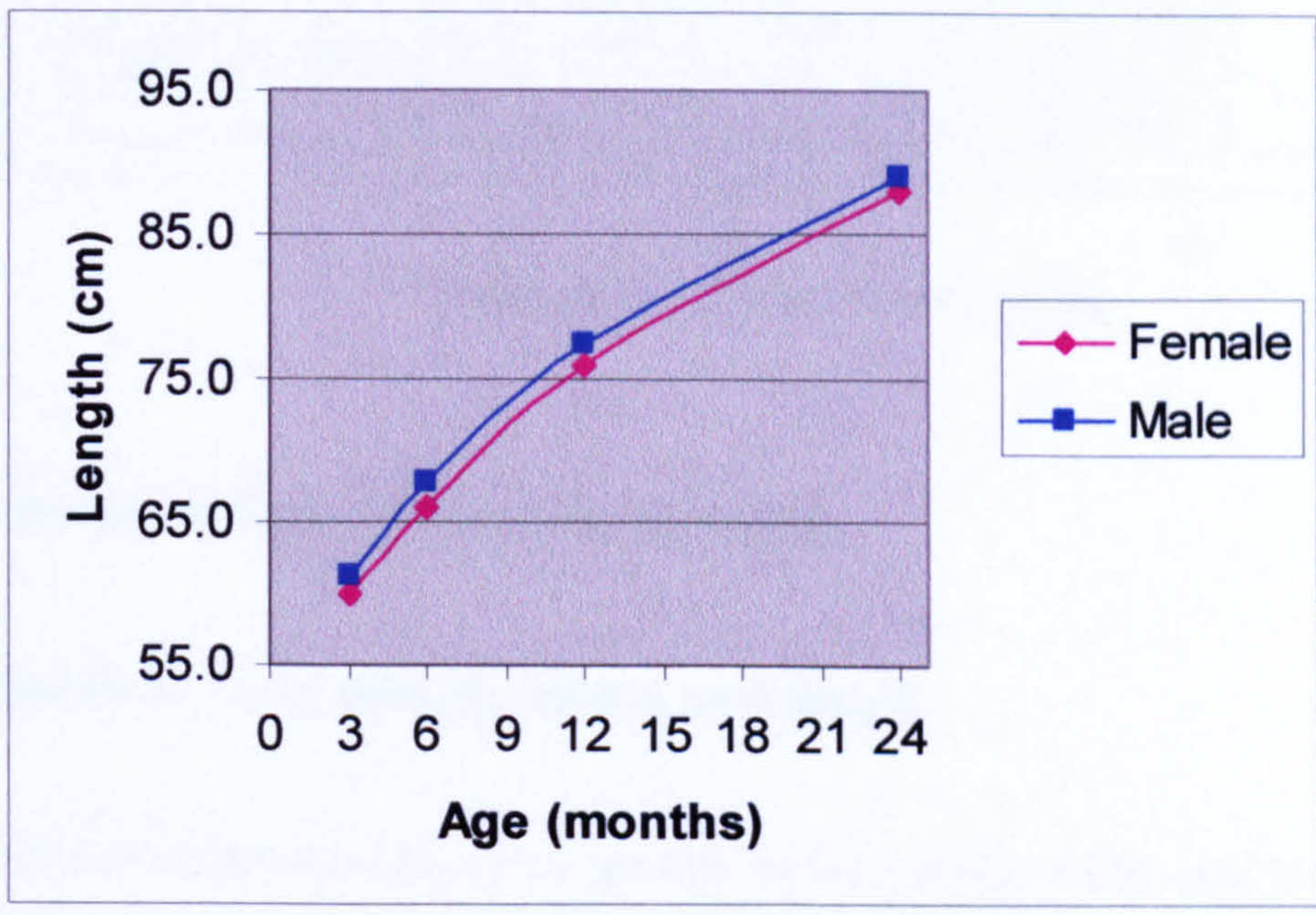
Table 5.2 Mean Growth in Body Measurements of Males (M) and Females (F)

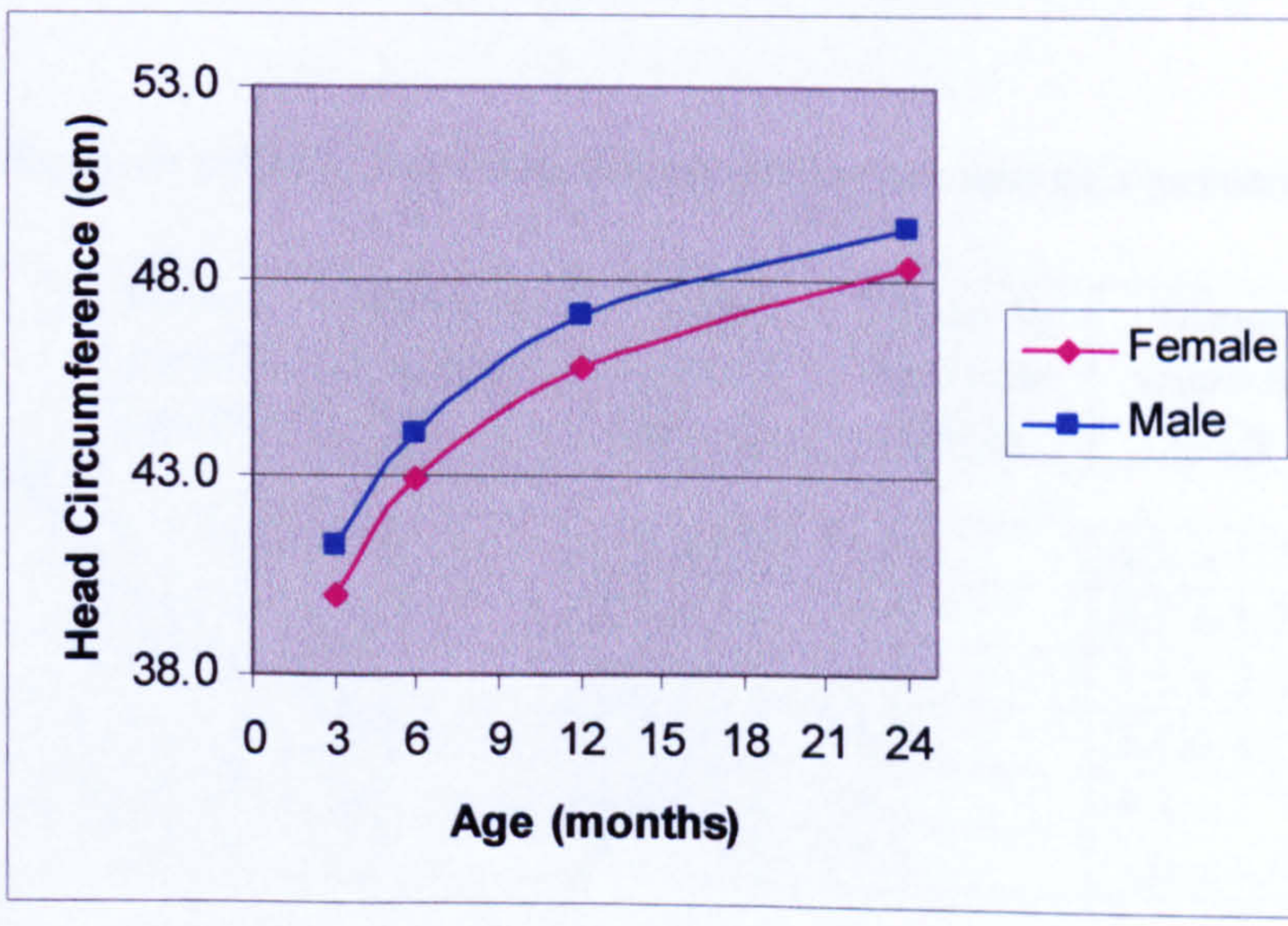
	3m - 6m F	3m - 6m M	6m - 1y F	6m - 1y M	1y - 2y F	1y - 2y M
Growth in Weight (kg)	1.65 ± 0.54	1.74 ± 0.42	2.50 ± 0.67	2.51 ± 0.64	3.33 ± 0.74	3.10 ± 0.60
Growth in Length (cm)	5.9 ± 1.7	6.5 ± 1.4	10.0 ± 1.4	9.8 ± 1.5	12.1 ± 1.8	11.5 ± 1.8
Growth in Head Circ (cm)	2.9 ± 1.1	2.8 ± 1.0	2.9 ± 1.0	3.0 ± 0.8	2.6 ± 0.8	2.2 ± 0.9

Paired t tests showed that all of the body measurements increased significantly (p=0.000) from 3 to 6 months (3-6m) , 6 months to 1 year (6m-1y) and 1 to 2 years (1-2y). Weight and length appeared to increase proportionally with age however growth in head circumference did not. This is illustrated in Figure 5.1. The fastest growth in head circumference was from 3 months to 6 months with a mean increase of 2.9 ± 1.0 cm in 3 months. The slowest growth of head circumference was from 1 to 2 years with a mean increase of only 2.4 ± 0.9 cm in the year. Two sample t tests showed no significant difference in growth of the body measurements between males and females although the difference of 0.4 cm in growth of head circumference from 1 to 2 years was close to being significant (p=0.059).

Figure 5.1 Growth in Body Measurements from 3 Months to 2 Years



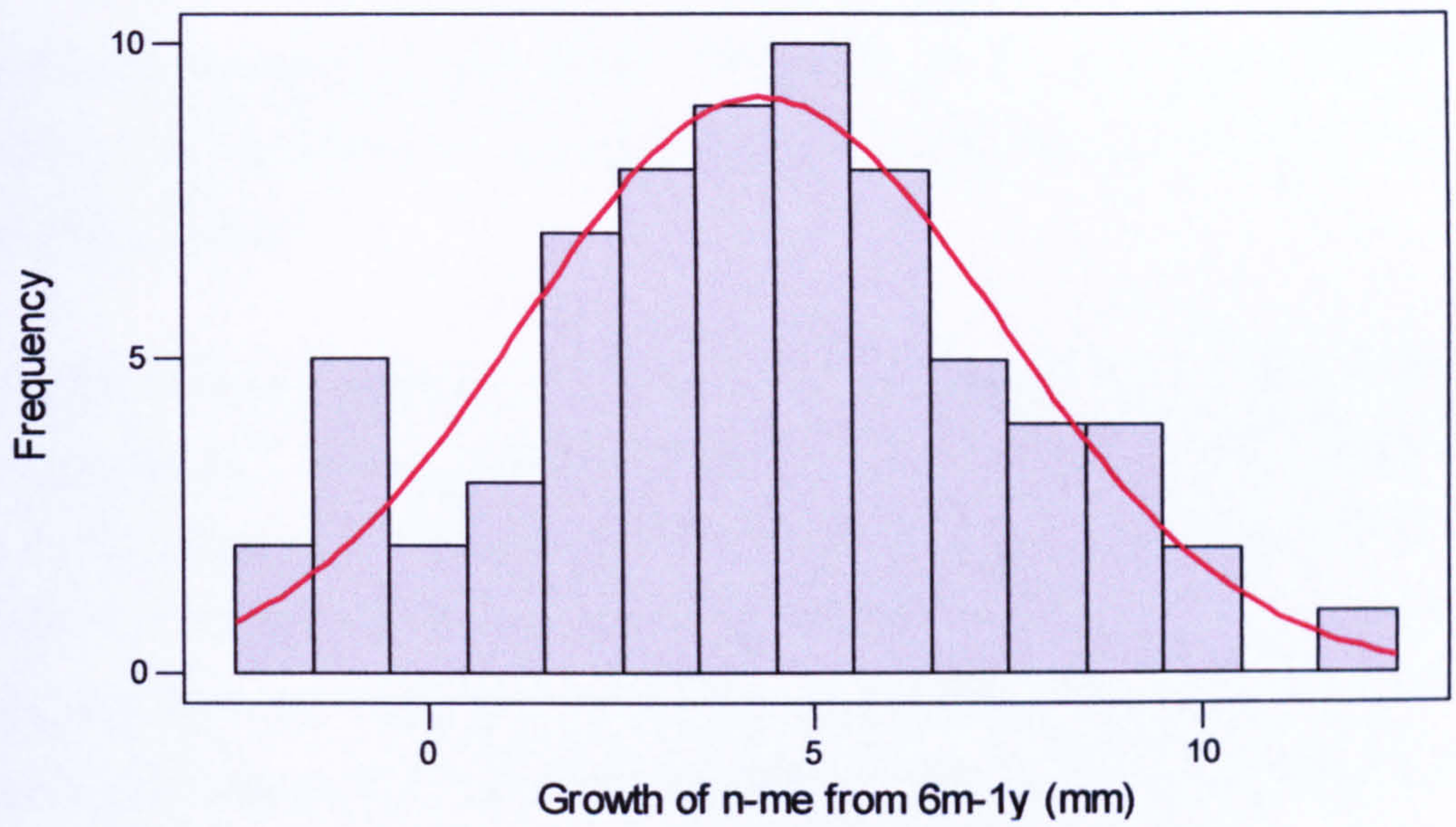




5.4 Linear and Angular Results

The longitudinal changes in facial measurements data were well approximated by a normal distribution. This is illustrated in Figure 5.2.

Figure 5.2 Distribution of Growth Changes in Total Face Height from 6m-1y, with Normal Curve Superimposed



5.4.1 Growth in Facial Measurements

5.4.1.1 Growth in Face Height, Width and Depth

The means and standard deviations of growth in face depth, width and height from 3 to 6 months (3m-6m), 6 months to 1 year (6m-1y) and 1 to 2 years (1y-2y) are shown in Table 5.3.

Table 5.3 Mean Growth in Face Measurements in mm and as a percentage (%)

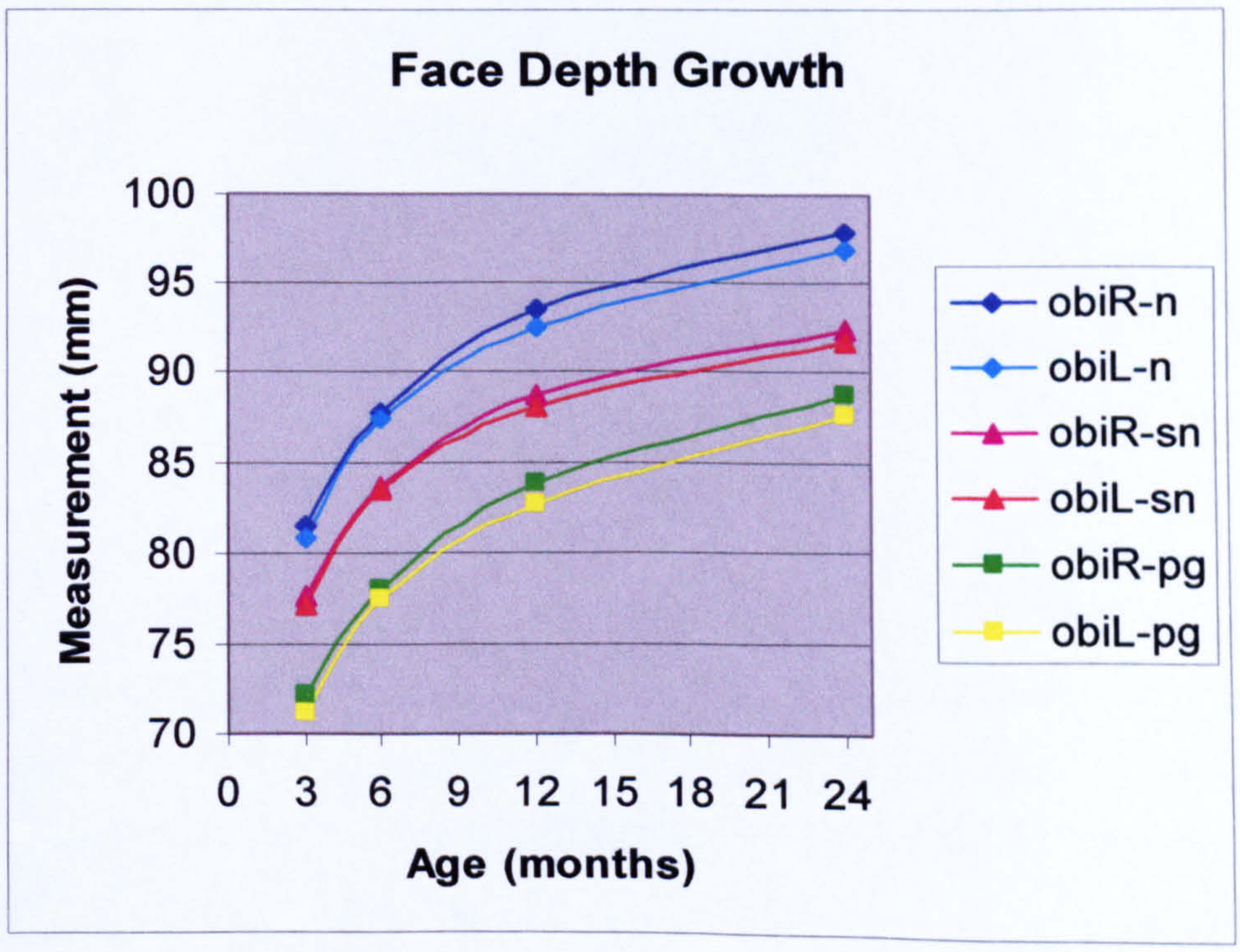
	Mean Growth 3m-6m	Mean % Increase 3m-6m	Mean Growth 6m-1y	Mean % Increase 6m-1y	Mean Growth 1y-2y	Mean % Increase 1y-2y
Face Depth						
obiL-n	6.8 ± 1.9	8.4	5.3 ± 2.0	6.0	4.2 ± 1.7	4.5
obiR-n	6.5 ± 3.7	8.0	5.8 ± 2.1	6.6	4.2 ± 1.7	4.5
obiL-sn	6.3 ± 1.9	8.1	4.8 ± 2.1	5.8	3.5 ± 3.0	4.0
obiR-sn	6.1 ± 3.1	7.8	5.4 ± 1.9	6.5	3.4 ± 4.2	3.9
obiL-pg	6.2 ± 2.0	8.7	5.2 ± 2.2	6.7	4.8 ± 1.9	5.9
obiR-pg	5.7 ± 2.0	7.9	6.0 ± 1.8	7.6	5.0 ± 1.9	6.0

Face Width						
obsR-obsL	7.2 ± 2.5	6.3	6.5 ± 2.7	5.4	5.1 ± 3.0	4.0
obiR-obiL	6.0 ± 2.9	6.4	4.7 ± 3.0	4.7	3.4 ± 2.5	3.2
Face Height						
n-me	5.0 ± 3.0	7.1	4.6 ± 3.1	5.8	5.1 ± 3.1	6.4
sn-me	3.4 ± 3.1	7.1	2.6 ± 3.2	5.0	2.9 ± 3.0	5.4
n-sn	1.6 ± 1.3	6.3	1.5 ± 1.1	5.6	2.1 ± 1.3	7.5

All of the measurements of face depth, width and heights increased significantly with age (p=0.000). The tendency for the right side measurements to be greater than the left continued at all ages.

Face depths increased a mean of 8.2% from 3 to 6 months but then increased by only 6.5% from 6 months to 1 year and 4.8% from 1 to 2 years. Upper face depths (obiL-n, obiR-n) grew significantly more than maxillary depths (obiL-sn, obiR-sn) from 3 to 6 months (p=0.000, 0.036) and from 6 months to 1 year (p=0.000) however the differences were not significant from 1 to 2 years (p=0.181, 0.194). Mandibular growth (obiL-pg, obiR-pg) was similar to maxillary growth from 3 to 6 months but then was greater than maxillary growth from 6 months to 1 year and from 1 to 2 years. These differences from 6 months to 2 years were all significant (p=0.000, 0.011, 0.007) except for the difference on the left side from 6 months to 1 year which was almost significant (p=0.059). The growth of face depths is illustrated in Figure 5.3.

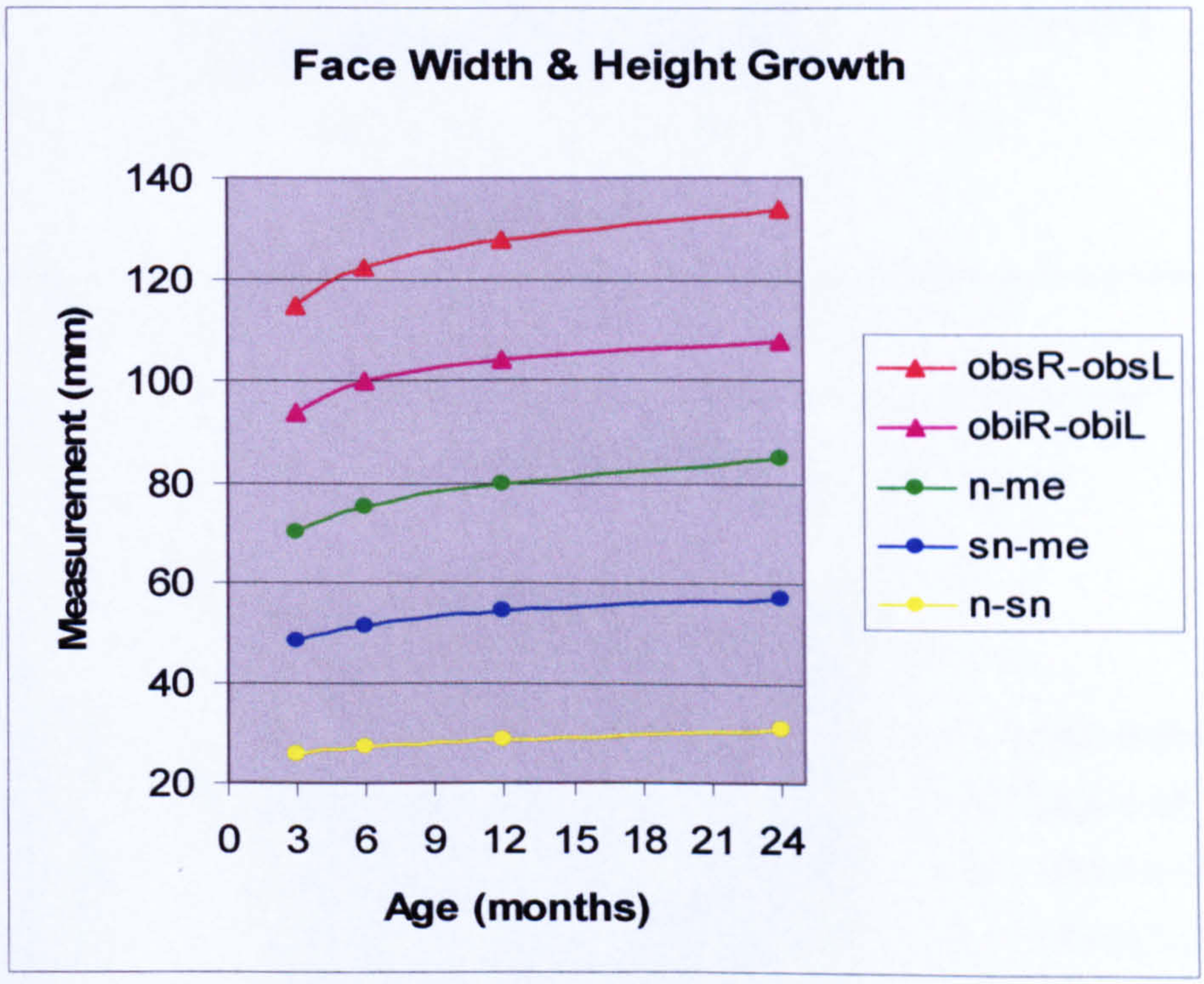
Figure 5.3 Growth in Face Depth from 3 Months to 2 Years



Paired t tests showed a significant difference in growth of the right and left sides of the face with more growth on the right in the upper face depth (p=0.011), maxillary depth (p=0.009) and mandibular depth (p=0.008) from 6 months to 1 year. These mean differences ranged from 0.5 to 0.7 mm.

Face widths also showed a reduction in growth rate from 3 months to 2 years. Upper face width (obsL-obsR) grew significantly more than lower face width (obiL-obiR) at all ages (p=0.000, 0.003, 0.010). Only 32 pairs of data, from 12 females and 20 males, were available for analysis of growth in upper face width from 1 to 2 years since otobasion superius was missing in so many cases at 2 years (see section 5.2). The reduction in growth rate from 3 months to 2 years was not so marked for face height. Lower face height (sn-me) growth was significantly greater than upper face height (n-sn) growth from 3 months to 1 year (p=0.000, 0.010) but then upper face height grew significantly more than lower face height from 1 to 2 years (p=0.045) by a mean of 0.8 ± 3.1 mm. The growth of face height and widths from 3 months to 2 years is illustrated in Figure 5.4.

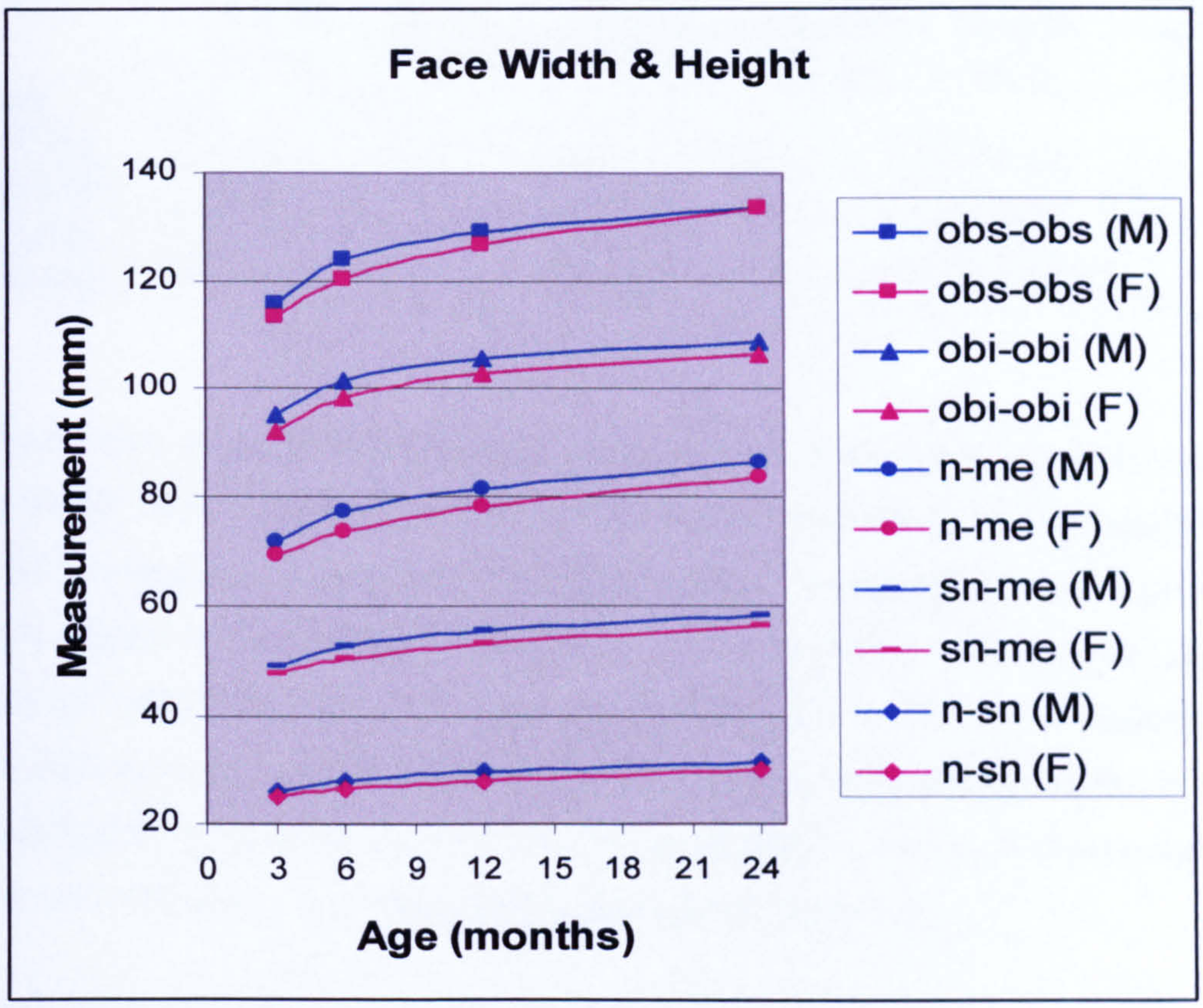
Figure 5.4 Growth in Face Width and Height from 3 Months to 2 Years

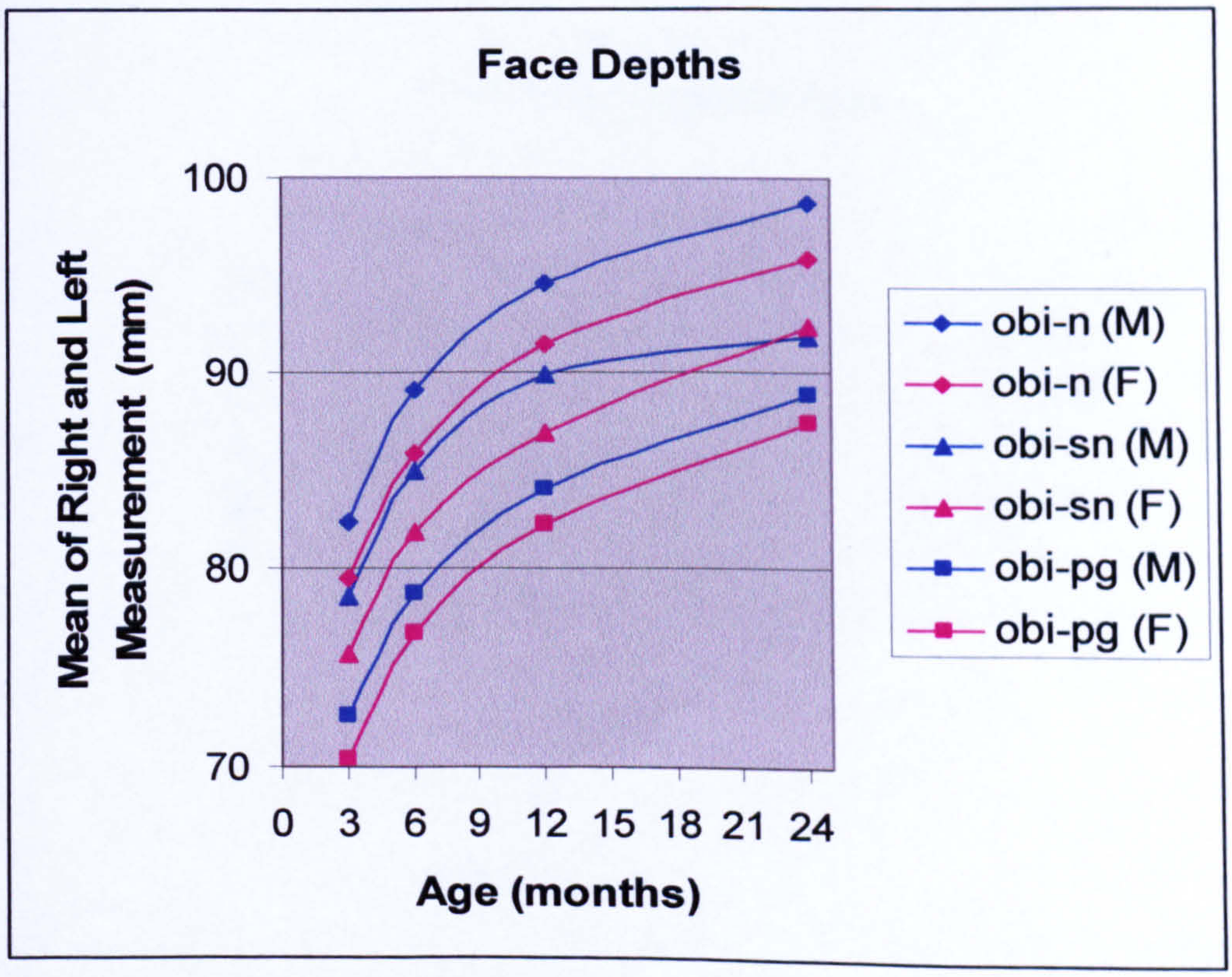


There were very few significant differences in the growth of the face measurements in males and females. This is illustrated in Figure 5.5. Maxillary depths (obiL-sn, obiR-sn) grew significantly more in females than males from 1 to 2 years by a mean difference of 3.7 ± 3.8 mm on the right and 3.4 ± 3.7 mm on the left (p=0.0005, 0.0002). Upper face width (obsR-obsL) grew more in females from 6 months to 1 year by a mean of 1.6 ± 2.5

mm (p=0.031), although this is only based on data from 20 females and 30 males without missing landmark data. Upper face height appeared to increase more in males than females by a mean of 0.6 mm from 3 to 6 months but this difference was only close to being significant (p=0.052).

Figure 5.5 Gender Differences in the Growth of Face Measurements





5.4.1.2 Growth Around the Eyes

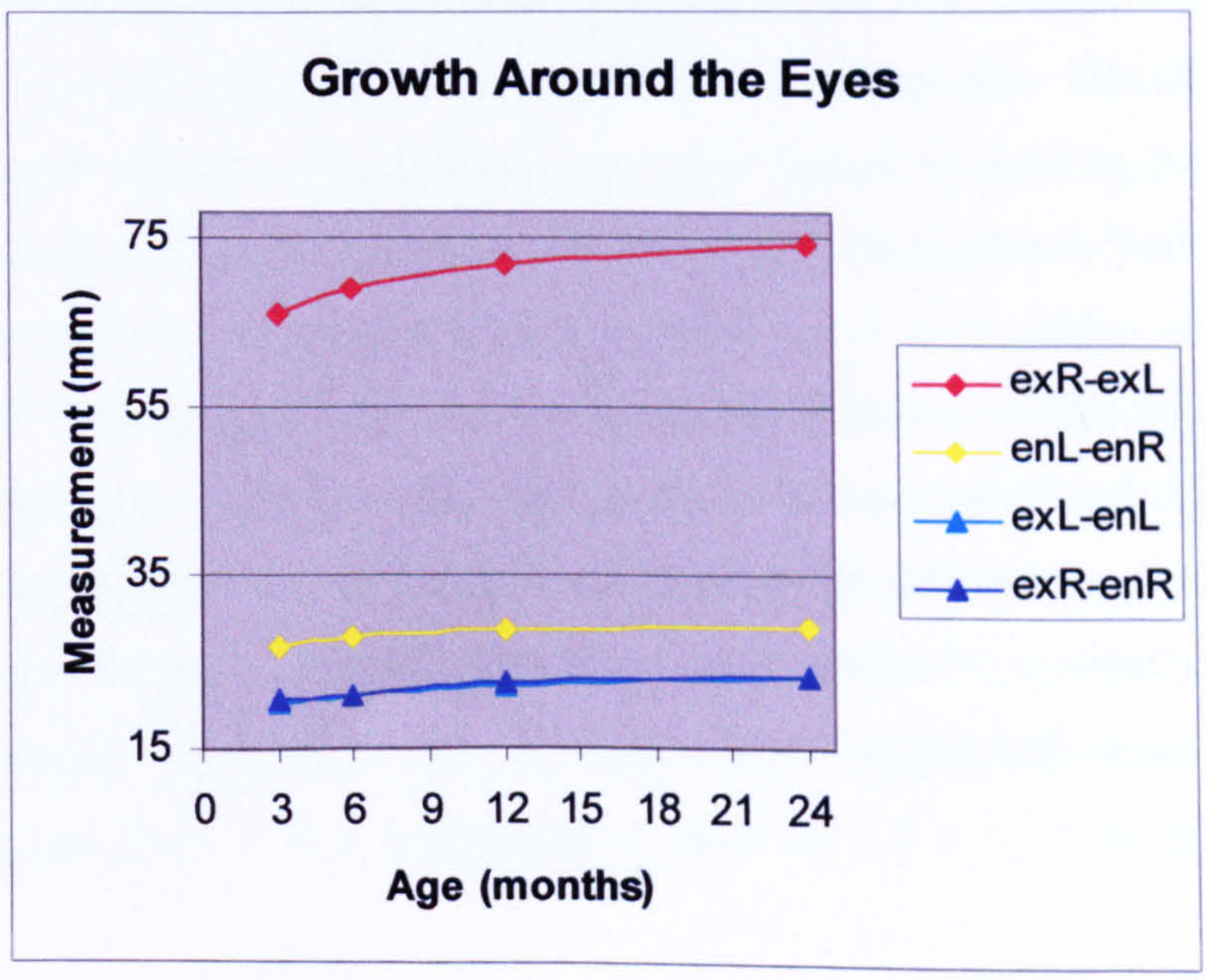
The means and standard deviations of growth around the eyes from 3 to 6 months (3m-6m), 6 months to 1 year (6m-1y) and 1 to 2 years (1y-2y) are shown in Table 5.4.

Table 5.4 Mean Growth Around the Eyes in mm and as a percentage (%)

	Mean Growth 3m-6m	Mean % Increase 3m-6m	Mean Growth 6m-1y	Mean % Increase 6m-1y	Mean Growth 1y-2y	Mean % Increase 1y-2y
Eyes						
exR-exL	2.8 ± 1.3	4.3	3.0 ± 1.3	4.3	2.4 ± 1.0	3.4
enL-enR	1.4 ± 1.0	5.3	0.6 ± 1.1	2.1	0.4 ± 0.9	1.6
exL-enL	0.9 ± 0.7	4.5	1.1 ± 0.7	5.1	1.0 ± 0.6	4.5
exR-enR	0.5 ± 1.0	2.3	1.4 ± 0.7	6.6	1.0 ± 0.8	4.4

Paired t tests showed there was significant growth of all the eye measurements at all ages (p=0.000). Paired t tests also showed significantly more growth of the left palpebral fissure from 3 months to 6 months (p=0.000) however there was significantly more growth of the right palpebral fissure from 6 months to 1 year (p=0.002). These mean differences, although statistically significant, were only 0.4 and 0.3 mm. The rate of growth of all the eye measurements reduced with time but this appeared most marked for the intercanthal width which increased by 5.3% from 3 to 6 months but by only 2.1% from 6 months to 1 year and 1.6% from 1 to 2 years. This is illustrated in Figure 5.6.

Figure 5.6 Growth Around the Eyes from 3 Months to 2 Years



Two sample t tests showed no significant differences between the males and females in the growth of the eye measurements except that biocular width grew more in the females from 6 months to 1 year by a mean of 0.7 mm (p=0.029).

5.4.1.3 Growth of the Nose and Nostrils

The means and standard deviations of growth of the nose and nostrils from 3 to 6 months (3m-6m), 6 months to 1 year (6m-1y) and 1 to 2 years (1y-2y) are shown in Table 5.5.

Table 5.5 Mean Growth of the Nose and Nostril Measurements in mm and as a percentage (%)

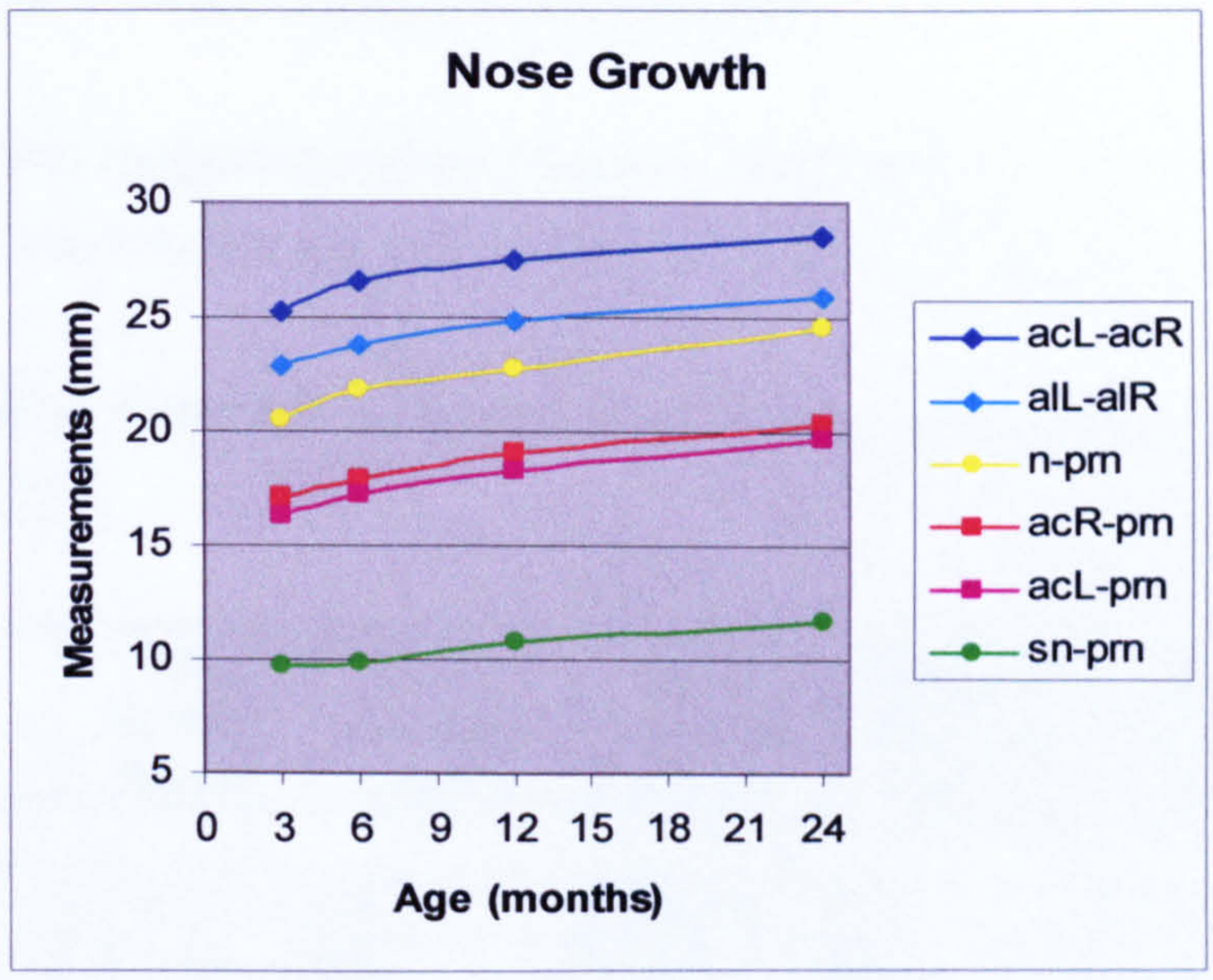
	Mean Growth 3m-6m	Mean % Increase 3m-6m	Mean Growth 6m-1y	Mean % Increase 6m-1y	Mean Growth 1y-2y	Mean % Increase 1y-2y
Nose						
acL-acR	1.4 ± 0.9	5.4	1.0 ± 1.0	3.6	1.0 ± 0.8	3.7
alL-alR	1.0 ± 0.9	4.2	1.0 ± 1.0	4.2	1.1 ± 1.0	4.4
acL-prn	0.9 ± 1.0	5.7	1.1 ± 0.9	6.5	1.4 ± 0.9	7.7
acR-prn	0.8 ± 0.8	4.8	1.2 ± 0.8	6.6	1.3 ± 0.7	6.8
n-prn	1.4 ± 1.3	6.7	0.9 ± 1.0	4.2	1.8 ± 1.4	8.0
sn-prn	0.2 ± 1.0ns	1.8	1.0 ± 1.0	10.0	0.9 ± 1.0	8.3
Nostrils						
sbalL-cL	0.5 ± 0.6	8.1	0.0 ± 0.5ns	-0.4	0.4 ± 0.7	5.4
sbalR-cR	0.6 ± 0.6	10.9	0.0 ± 0.7ns	-0.3	0.5 ± 0.8	7.2
sn'L-al'iL	0.1 ± 0.7ns	3.1	0.3 ± 0.7	5.9	0.5 ± 0.7	9.5
sn'R-al'iR	0.3 ± 0.7	5.4	0.2 ± 0.7	4.6	0.4 ± 0.7	7.1
sn'R-sn'L	0.4 ± 0.9	6.9	0.0 ± 0.9ns	0.3	0.2 ± 0.8	4.1

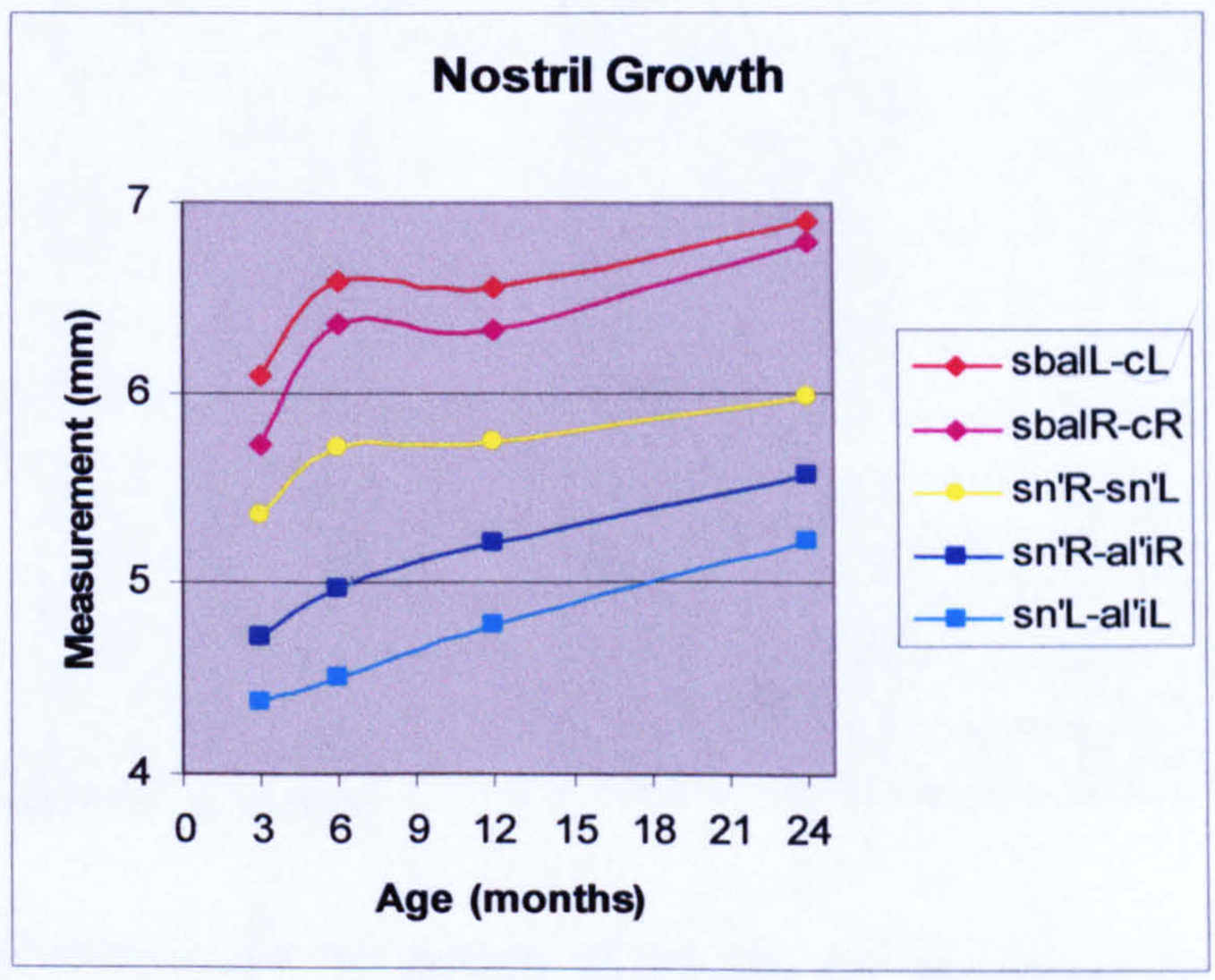
ns - no significant growth at 5% level

Paired t tests showed there was significant growth of all the nose measurements at all ages (p=0.000) except in nasal tip protrusion (sn-prn) from 3 to 6 months. The rate of growth of the nose decreased with time however this was least marked in nasal tip protrusion which had a mean growth of 0.2 mm from 3 to 6 months and 1.0 mm growth from 6 months to 1 year. Growth of this measurement slowed again from 1 to 2 years with a mean increase of 0.9 mm. Paired t tests showed there was no significant difference in the growth of the right or left alar lengths. Two sample t tests showed there were no significant differences in the growth of the males and females. Paired t tests showed that anatomic nose width (acL-acR) grew more than soft nose width (alL-alR) from 3 to 6 months by a mean of 0.4 ± 0.7 mm (p=0.000). Anatomic nose width (acL-acR) also grew significantly more than nasal tip protrusion (sn-prn) from 3 to 6 months by a mean of 1.2 ± 1.3 mm (p=0.000). These

findings were not repeated from 6 months to 1 year. Growth of the nose and nostrils from 3 months to 2 years is illustrated in Figure 5.7.

Figure 5.7 Growth of the Nose and Nostrils from 3 Months to 2 Years





Paired t tests showed there was significant growth of all of the nostril measurements at most ages (p=0.000-0.013). The mean growth of the right and left nostril long axis from 3 months to 2 years was 0.9 ± 0.7 mm. The mean growth of the right and left nostril widths from 3 months to 2 years was 1.0 ± 0.8 mm. Left nostril width (sn'L-al'iL) did not increase significantly from 3 months to 1 year (p=0.102). Nostril long axis (sbalL-cL, sbalR-cR) and columella width (sn'R-sn'L) did not increase significantly from 6 months to 1 year (p=0.680, 0.803, 0.862). Paired t tests showed no significant differences in the mean growth of the left and right nostrils at any age, although the left nostril was consistently longer and narrower than the right. Two sample t tests showed no difference in growth of

the males and females. Nostril long axis grew significantly more than nostril width on both sides from 3 to 6 months (p=0.000, 0.001) but then nostril width grew significantly more than the long axis from 6 months to 1 year (p=0.007, 0.028). These differences, although statistically significant, only ranged from 0.25 to 0.37 mm.

5.4.1.4 Growth of the Upper and Lower Lips

The means and standard deviations of growth of the lips from 3 to 6 months (3m-6m), 6 months to 1 year (6m-1y) and 1 to 2 years (1y-2y are shown in Table 5.6 .

Table 5.6 Mean Growth of the Upper and Lower Lip Measurements in mm and as a percentage (%)

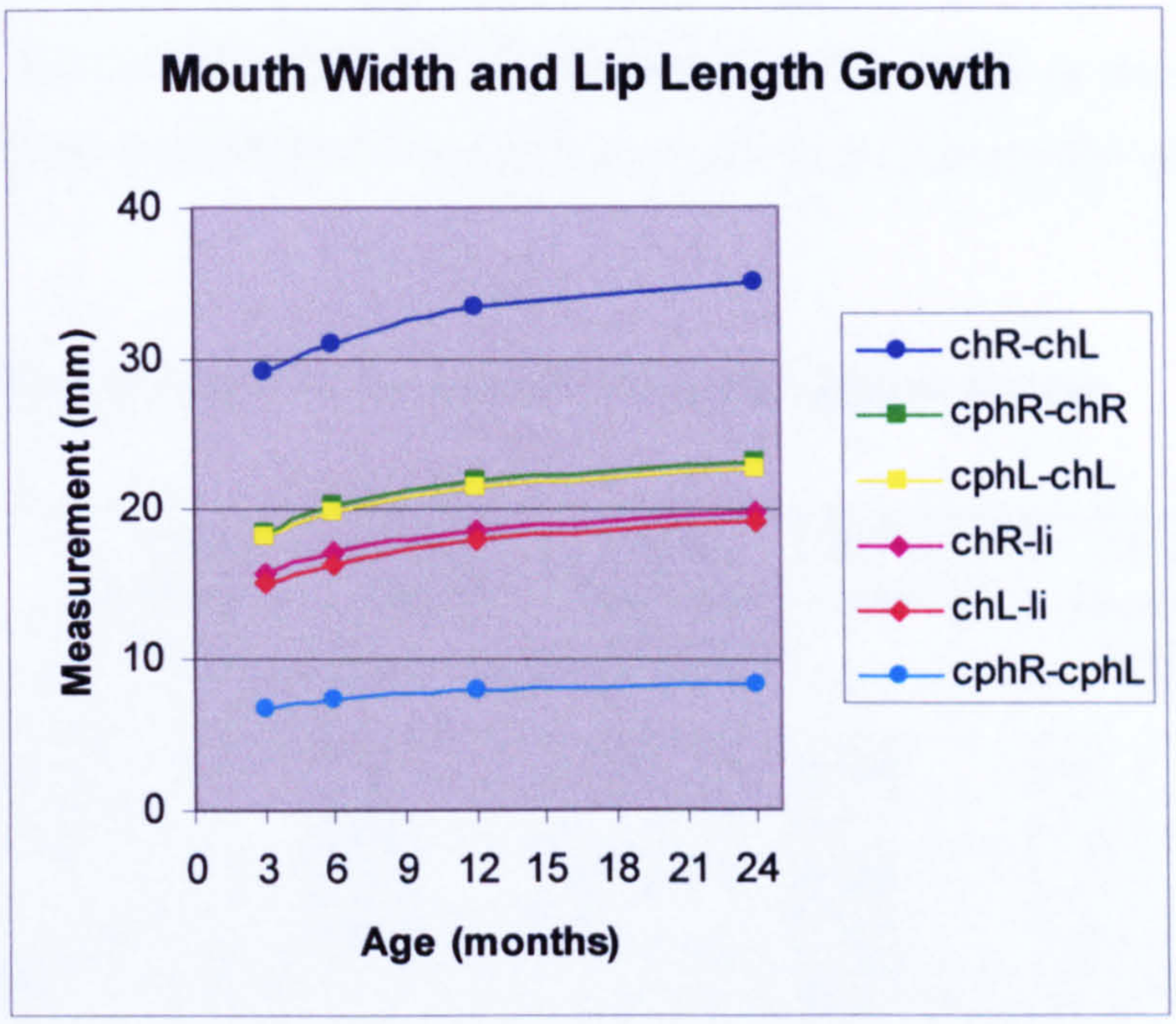
	Mean Growth 3m-6m	Mean % Increase 3m-6m	Mean Growth 6m-1y	Mean % Increase 6m-1y	Mean Growth 1y-2y	Mean % Increase 1y-2y
Upper Lip						
chR-chL	2.0 ± 1.9	6.8	2.4 ± 2.0	7.7	1.6 ± 1.9	4.7
cphL-chL	1.6 ± 1.6	9.0	1.7 ± 1.2	8.5	1.1 ± 1.2	5.2
cphR-chR	1.8 ± 1.5	10.1	1.6 ± 1.4	7.9	1.3 ± 1.4	5.9
cphR-cphL	0.6 ± 1.0	9.5	0.5 ± 0.7	7.3	0.4 ± 0.8	5.1
ls-sn	0.2 ± 1.1ns	1.9	0.1 ± 1.2ns	1.7	0.3 ± 1.1	3.2
ls-stos	0.0 ± 1.5ns	0.6	0.2 ± 1.4ns	4.5	0.7 ± 1.5	12.5
sn-stos	0.5 ± 1.1	3.3	0.4 ± 1.4	2.6	0.9 ± 1.1	5.8
sbalL-chL	1.6 ± 1.4	6.8	1.3 ± 1.5	5.1	1.3 ± 1.3	5.0
sbalR-chR	1.6 ± 1.7	6.9	1.4 ± 1.5	5.5	1.0 ± 1.4	3.8
Lower Lip						
chL-li	1.3 ± 1.2	8.6	1.5 ± 1.2	7.7	1.2 ± 1.1	6.5
chR-li	1.3 ± 1.2	8.8	1.5 ± 1.2	7.9	1.3 ± 1.1	6.9
li-stoi	0.1 ± 1.2ns	2.1	0.9 ± 1.2	10.8	1.1 ± 1.1	16.1
sl-li	0.5 ± 1.2	6.2	-0.1 ± 1.2ns	-2.3	0.1 ± 1.3ns	2.4
sl-stoi	0.7 ± 1.1	6.0	0.5 ± 1.1	5.3	0.6 ± 1.1	5.6

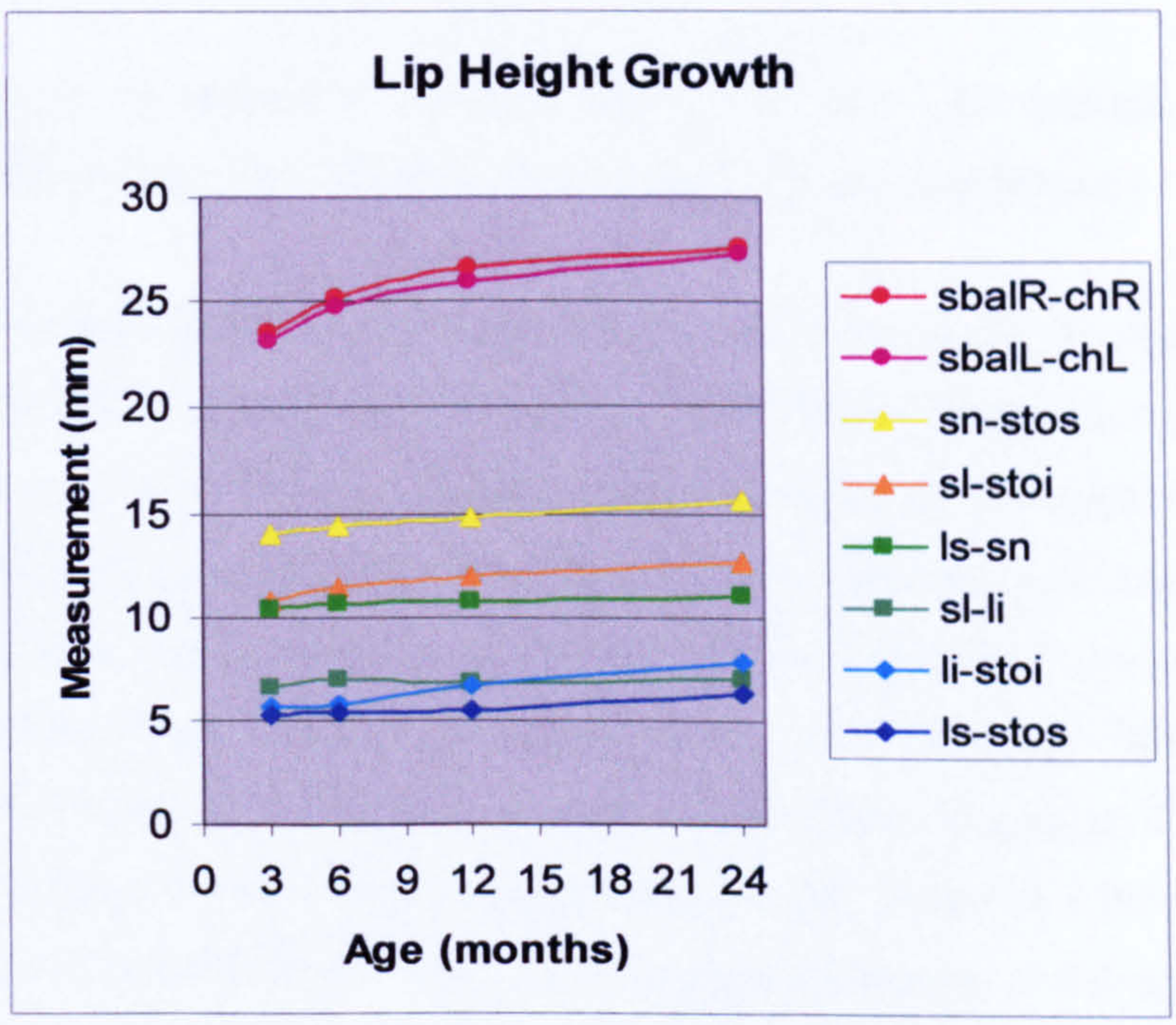
ns - no significant growth at 5% level

Paired t tests showed that the growth of the lips was significant for all the upper lip measurements at all ages (p=0.000) except upper cutaneous lip height (ls-sn) and upper vermilion height (ls-stos) from 3 to 6 months and 6 months to 1 year. The total difference from 3 months to 1 year was significant for upper cutaneous lip height (p=0.011), but was still not significant for upper vermilion height (p=0.155). There were no significant differences between the growth of the right and left sides of the lips for any of the measurements at any age although the difference in growth of the left and right lateral lip heights was close to being significant from 1 to 2 years (p=0.073). Two sample t tests showed there was no significant difference in growth between the males and females for

the lip measurements except for right lateral lip height which grew 0.7 ± 1.3 mm more in the females than males from 1 to 2 years (p=0.035). Growth of the lips is illustrated in Figure 5.8

Figure 5.8 Growth of the Lips from 3 Months to 2 Years





Paired t tests showed that the growth of the lower lip was significant for all measurements (p=0.000-0.006) except lower vermilion height (li-stoi) from 3 to 6 months (p=0.392) and lower cutaneous lip height (sl-li) from 6 months to 1 year (p=0.426) and from 1 to 2 years (p=0.305). Lower cutaneous lip height growth was not even significant from 6 months to 2 years (p=0.802). There was no significant difference in the growth of the right or left lower

vermilion lengths (p=0.618, 0.819, 0.993) at any age. Two sample t tests showed there was no significant difference in growth of the males or females for any of the measurements except lower right vermilion length which grew more in the females than males by 0.7 ± 1.3 mm from 6 months to 1 year (p=0.018).

5.4.1.5 Growth Changes in Angular Measurements

The means and standard deviation of the changes in the angles of the face from 3 to 6 months (3m-6m), 6 months to 1 year (6m-1y) and 1 to 2 years (1y-2y) are shown in Table 5.7.

Table 5.7 Mean Changes of the Angular Measurements in degrees

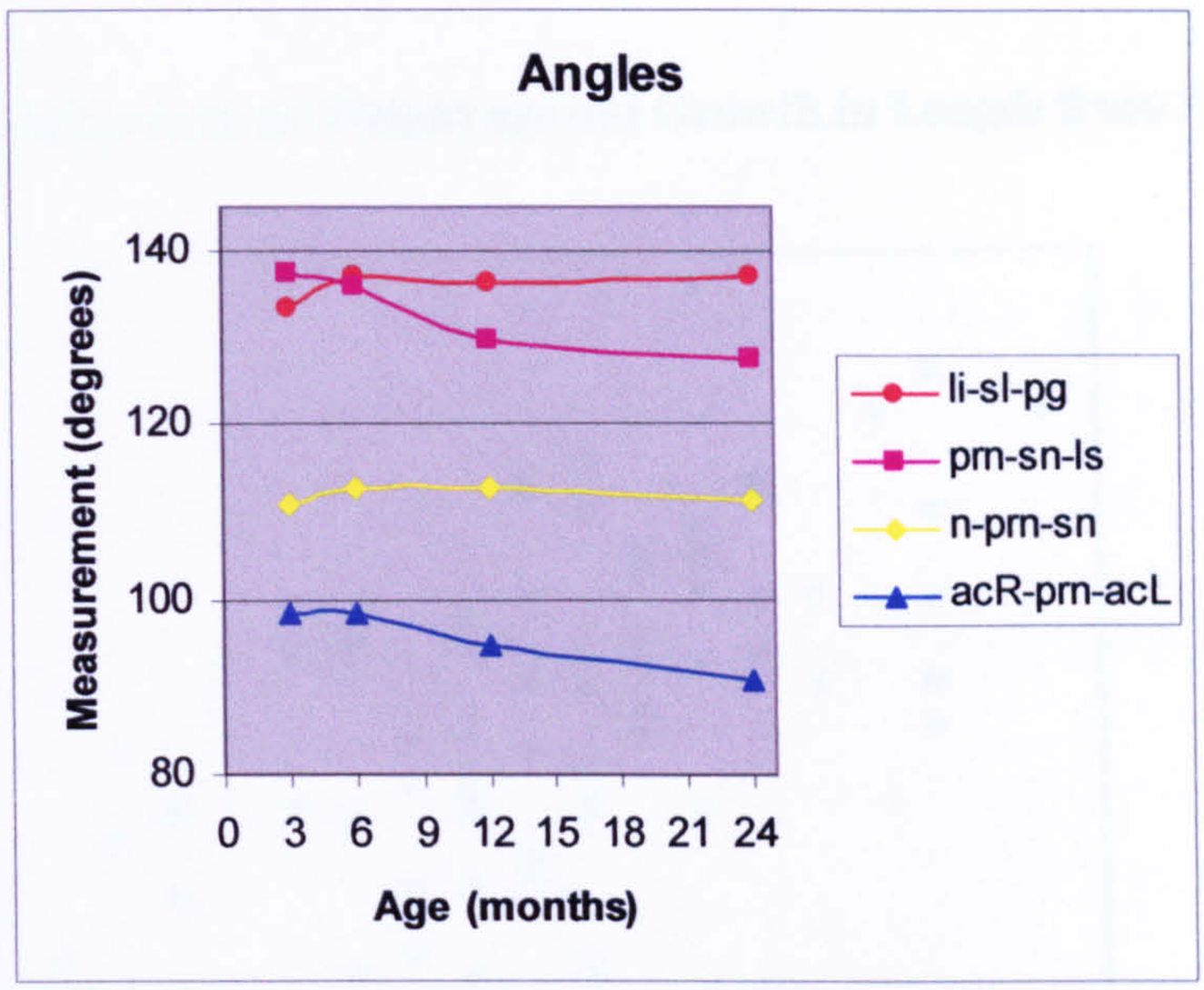
	Mean Increase 3m-6m	P Value* 3m-6m	Mean Increase 6m-1y	P Value* 6m-1y	Mean Increase 1y-2y	P Value* 1y-2y
Angles						
acR-prn-acL	0.2 ± 4.3	0.773	-3.6 ± 3.8	**0.000**	-4.0 ± 3.2	**0.000**
n-prn-sn	1.7 ± 5.5	**0.011**	-0.1 ± 4.4	0.920	-1.2 ± 3.4	**0.004**
prn-sn-ls	-1.6 ± 6.7	**0.045**	-6.2 ± 5.5	**0.000**	-2.0 ± 5.1	**0.002**
li-sl-pg	3.9 ± 13.1	**0.015**	-1.0 ± 11.3	0.447	1.0 ± 9.0	0.346

* Result of paired t test showing change in angles with growth. Significant changes at 5% level are shown in **bold.**

The changes in the angles of the face with growth were inconsistent. There were no significant differences in the changes of these angles in males or females.

Nasal tip horizontal displacement angle (acR-prn-acL) did not change significantly from 3 to 6 months but then reduced by a mean of 3.6 ± 3.8° from 6 months to 1 year and by 4.0 ± 3.2° from 1 to 2 years. This is consistent with the finding of increased relative growth in nasal tip protrusion (sn-prn) from 6 months to 2 years. Nasal tip angle (n-prn-sn) increased significantly from 3 to 6 months by a mean of 1.7 ± 5.5°. This angle did not change from 6 months to 1 year then decreased significantly from 1 to 2 years by a mean of 1.2 ± 3.4°. Overall there was no significant change in this angle from 3 months to 2 years (p=0.283). Nasolabial angle (prn-sn-ls) mean decreased significantly from 3 to 6 months, 6 months to 1 year and 1 to 2 years. Overall there was a significant reduction in this angle of 9.9 ± 7.2° from 3 months to 2 years. Labiomental angle (li-sl-pg) mean increased significantly from 3 to 6 months but then did not change from 6 months to 1 year or from 1 to 2 years. The changes in the angles of the face from 3 months to 2 years are illustrated in Figure 5.9.

Figure 5.9 Changes in Angles of the Face from 3 Months to 2 Years



5.4.2 Correlations of Measurements of Growth

5.4.2.1 Correlation of Growth of Body Measurements

Correlations of the growth of body weight, length and head circumference from 3 to 6 months (3m-6m), 6 months to 1 year (6m-1y) and 1 to 2 years (1y-2y) are shown in Table 5.8.

Table 5.8 Correlations of Growth in Weight, Length and Head Circumference

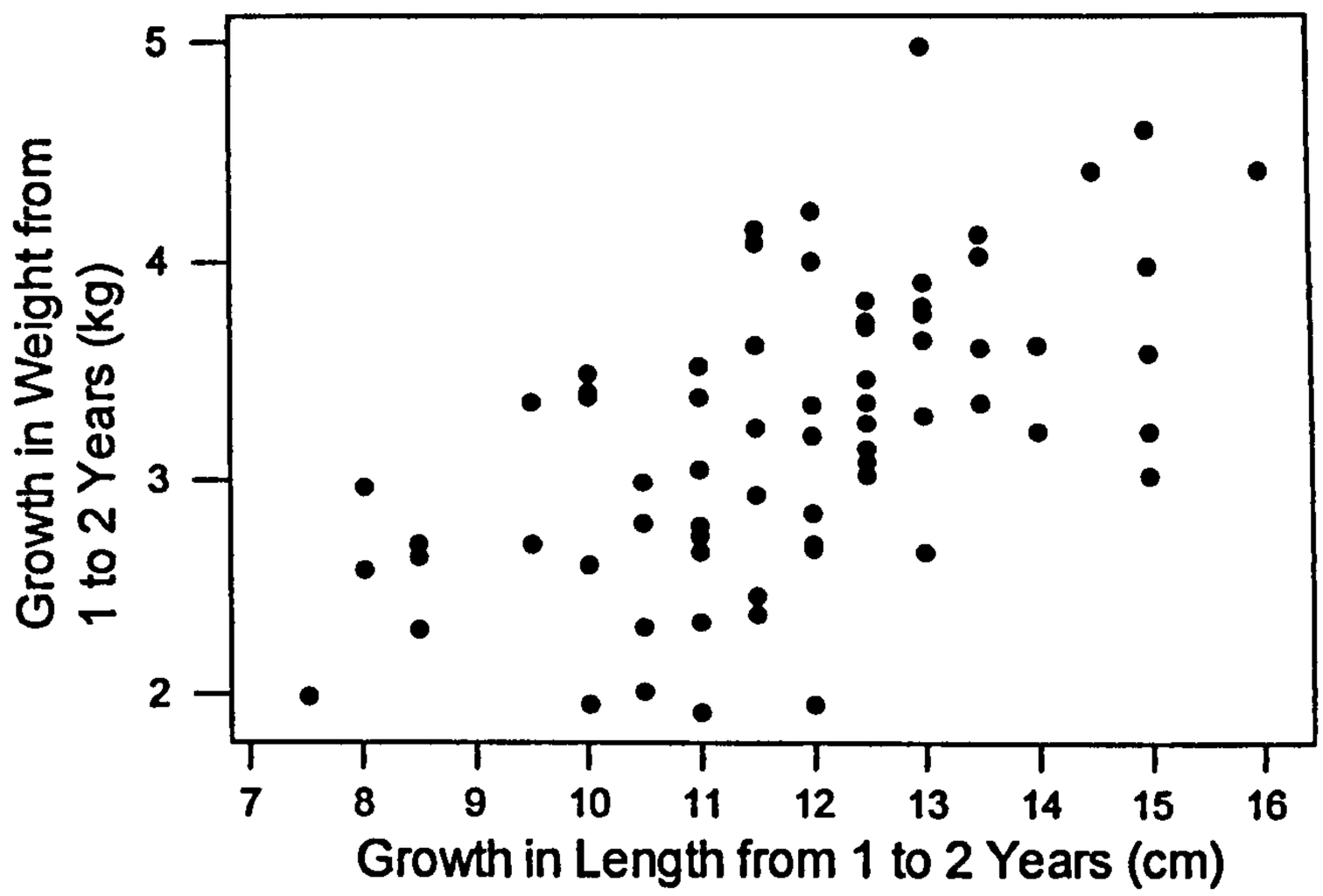
	Correlation with Length**	P Value*	Correlation with Head Circumference**	P Value*
Weight (3m-6m)	0.44	**0.000**	0.07	0.56
Length (3m-6m)			0.03	0.83
Weight (6m-1y)	0.41	**0.000**	0.21	0.07
Length (6m-1y)			0.10	0.43
Weight (1y-2y)	0.59	**0.000**	0.41	**0.000**
Length (1y-2y)			0.40	**0.000**

* Correlations significant at 5% level are shown in **bold.** ** Pearson's correlation coefficients

Table 5.8 shows significant correlations between growth in body weight and length at all ages. Significant correlations between the growth of head circumference and length or weight were only found from 1 to 2 years although a weak correlation which was close to being significant (p=0.07) was found between the growth of head circumference and

weight from 6 months to 2 years. The correlation between growth in weight and length is illustrated in Figure 5.10.

Figure 5.10 Plot of Growth in Weight against Growth in Length from 1 to 2 Years



5.4.2.2 Correlations of Growth of Face Depth, Width and Height

Correlations of the growth of face height, width and depth with the growth in body weight from 3 to 6 months (3m-6m), 6 months to 1 year (6m-1y) and 1 to 2 years (1y-2y) are shown in Table 5.9.

Table 5.9 Correlations of Growth in Face Depth, Width and Height with Growth in Body Weight

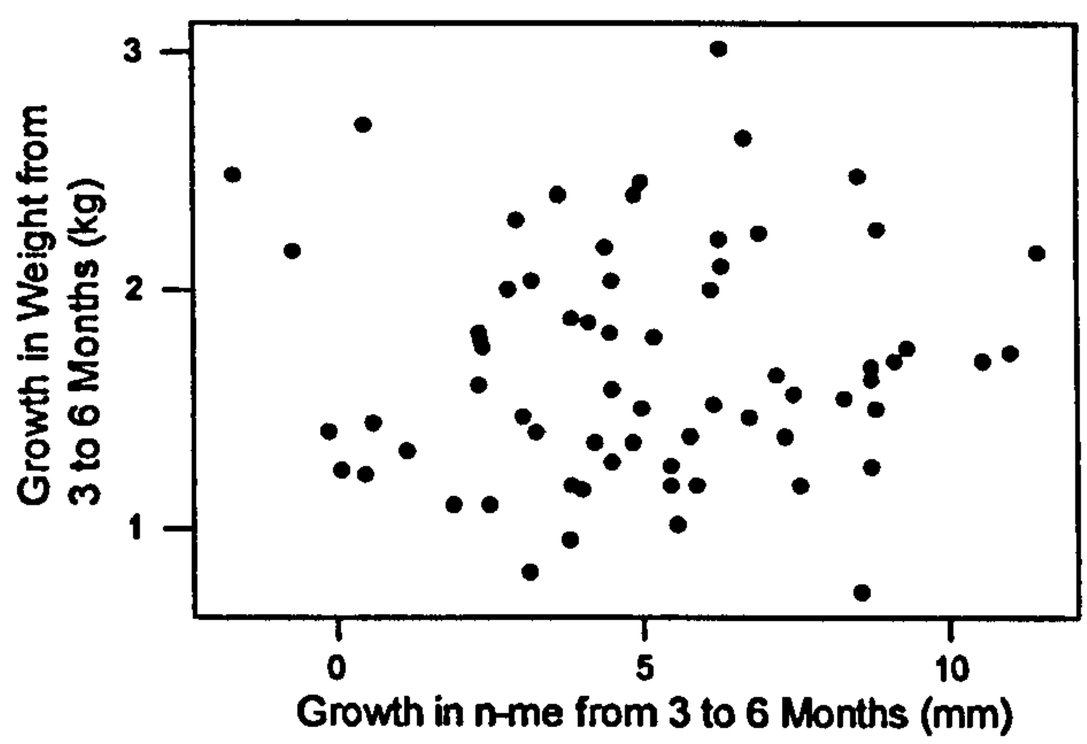
	Correlation Coefficient 3m-6m**	P Value*	Correlation Coefficient 6m-1y**	P Value*	Correlation Coefficient 1y-2y**	P Value*
Face Depth						
obiL-n	-0.13	0.34	0.04	0.72	-0.05	0.66
obiR-n	-0.08	0.56	-0.07	0.54	-0.04	0.73
obiL-sn	-0.11	0.39	0.07	0.54	-0.04	0.78
obiR-sn	0.06	0.67	-0.09	0.49	-0.13	0.29
obiL-pg	0.13	0.30	0.09	0.48	-0.02	0.89
obiR-pg	0.29	**0.034**	-0.05	0.69	0.04	0.76
Face Width						
obsR-obsL	0.01	0.95	-0.12	0.42	0.31	0.09
obiR-obiL	-0.02	0.89	-0.08	0.53	-0.16	0.19

Face Height						
n-me	0.03	0.82	0.02	0.84	0.01	0.96
sn-me	0.02	0.90	0.02	0.84	-0.04	0.76
n-sn	0.05	0.68	0.02	0.90	0.10	0.40

* Significant correlations at 5% level are shown in **bold**. ** Pearson's Correlation Coefficient

Table 5.9 shows no evidence of correlation of the growth of face measurements with the growth in body weight. This is illustrated in Figure 5.11. Similar results were obtained for correlations with the growth in body length and head circumference.

Figure 5.11 Plot of Growth in Weight against Growth in Total Face Height



No correlation was found between the growth of the upper (n-sn) and lower (sn-me) face height at any age (r=0.05, 0.15, 0.13). Growth of upper and lower face widths correlated significantly from 3 to 6 months (r=0.45, p=0.002) and from 6 months to 1 year (r=0.42, p=0.003) but the result was only borderline significant from 1 to 2 years (r=0.30, p=0.06).

No significant correlations in the growth of the right and left depths of the face were found from 3 to 6 months with r=0.03 for obiL-n and obiR-n, r=-0.02 for obiL-sn and obiR-sn, and r=-0.02 for obiL-pg and obiR-pg. However, significant correlations were found for the growth of all these measurements on the right and left of the face from 6 months to 1 year and 1 to 2 years.

Although the growth of the right and left sides of the face did not correlate, growth in upper face depth, maxillary depth and mandibular depth from 3 to 6 months correlated significantly, with the strongest correlations between upper face depth growth and maxillary growth on the left and right (r=0.99, 0.90) and the weakest between upper face depth growth and mandibular growth (r=0.37, 0.52). Growth in face depth from 6 months to 1 year again correlated significantly for all face depth measurements and showed the

strongest correlations between growth in upper face depth and maxillary depth (r=0.91, 0.92). However from 1 to 2 years there appeared to be no correlation between maxillary growth and upper face depth growth (r=0.12, 0.11), or mandibular growth (r=0.13, r=0.04). There were still significant correlations between upper face depth growth and mandibular growth at this stage (r=0.65, 0.68).

5.4.2.3 Correlations of Growth Around the Eyes

Correlations of growth around the eyes with growth in body weight from 3 to 6 months (3m-6m), 6 months to 1 year (6m-1y) and 1 to 2 years (1y-2y) are shown in Table 5.10.

Table 5.10 Correlations of Growth Around the Eyes with Growth in Body Weight

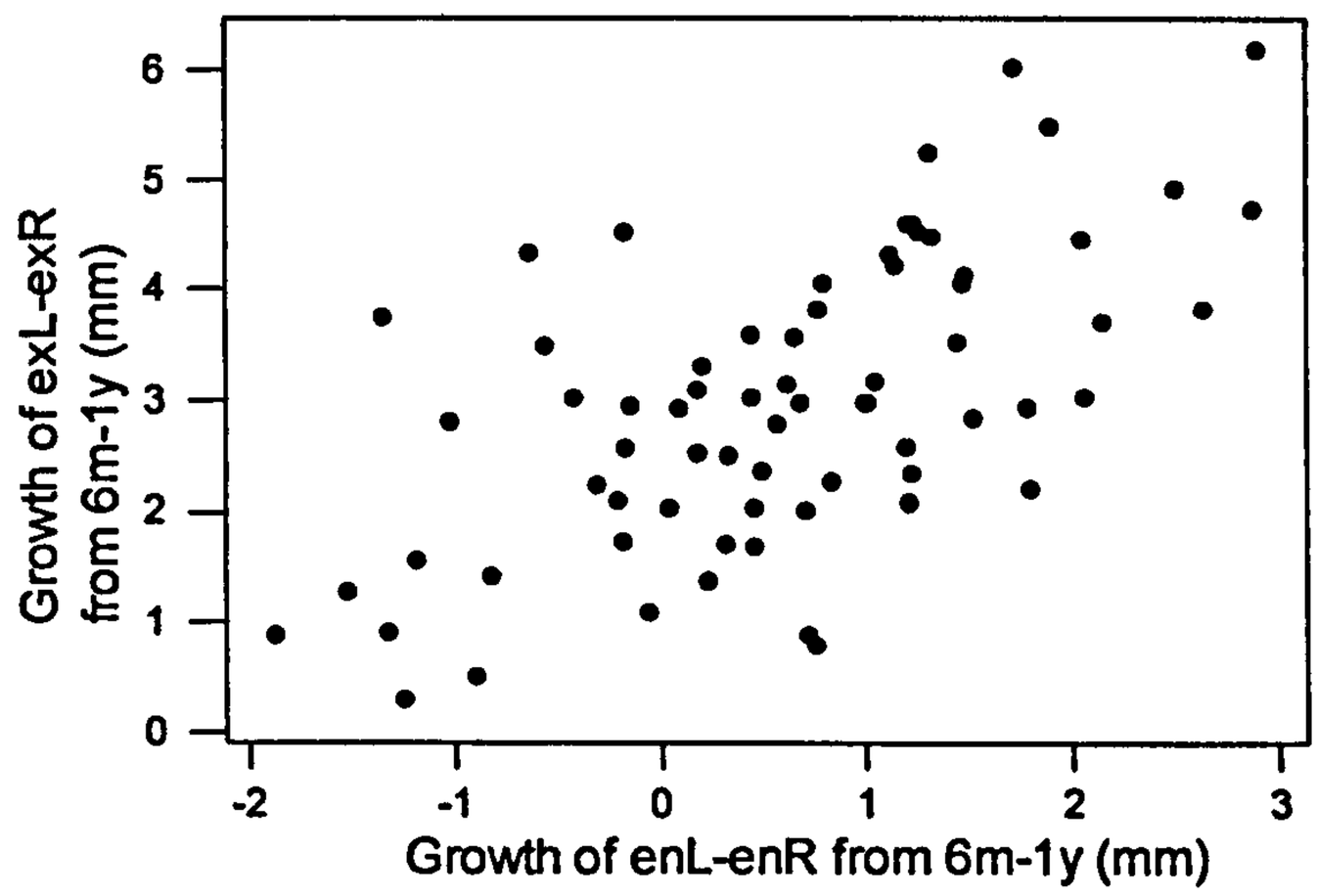
	Correlation Coefficient 3m-6m**	P Value*	Correlation Coefficient 6m-1y**	P Value*	Correlation Coefficient 1y-2y**	P Value*
Eyes						
exR-exL	0.08	0.52	0.04	0.74	-0.11	0.38
enL-enR	0.10	0.41	0.00	0.99	-0.14	0.23
exL-enL	-0.07	0.56	0.07	0.59	0.01	0.97
exR-enR	0.08	0.52	0.10	0.43	0.01	0.95

* Significant correlations at 5% level are shown in **bold**. ** Pearson's Correlation Coefficient

Table 5.10 shows there were no significant correlations between growth of the eyes and growth in body weight. Similar results were obtained for length and head circumference.

There were significant correlations between biocular width growth and intercanthal width growth from 3 months to 1 year (r=0.44, 0.62) but this correlation was much weaker from 1 to 2 years (r=0.23). The strongest correlation is illustrated in Figure 5.12. There were weak but significant correlations between growth of the right and left palpebral fissures at all ages (r=0.32-0.39). Stronger correlations were found between growth of the palpebral fissures and biocular width growth (r=0.47-0.59) at all ages.

Figure 5.12 Plot of Growth of Biocular Width against Growth of Intercanthal Width from 6 Months to 1 Year



5.4.2.4 Correlations of Growth of the Nose and Nostrils

Correlations of growth of the nose and nostrils with growth in body weight from 3 to 6 months (3m-6m), 6 months to 1 year (6m-1y) and 1 to 2 years (1y-2y) are shown in Table 5.11.

Table 5.11 Correlations of Growth of the Nose and Nostrils with Growth in Body Weight

	Correlation Coefficient 3m-6m**	P Value*	Correlation Coefficient 6m-1y**	P Value*	Correlation Coefficient 1y-2y**	P Value*
Nose						
acL-acR	0.06	0.61	0.04	0.73	0.04	0.75
alL-alR	0.14	0.23	0.10	0.43	-0.18	0.14
acL-prn	-0.02	0.89	0.07	0.58	0.13	0.27
acR-prn	-0.02	0.85	0.10	0.42	-0.03	0.80
n-prn	0.06	0.62	-0.10	0.41	0.14	0.24
sn-prn	-0.17	0.17	-0.00	0.99	-0.02	0.88
Nostrils						
sbalL-cL	-0.07	0.57	0.12	0.31	0.12	0.31
sbalR-cR	-0.08	0.50	-0.17	0.16	-0.17	0.16
sn'L-al'iL	0.17	0.16	0.08	0.52	0.08	0.52
sn'R-al'iR	0.10	0.40	0.17	0.15	0.17	0.15
sn'R-sn'L	0.02	0.85	-0.03	0.78	-0.03	0.78

* Significant correlations at 5% level are shown in **bold**. ** Pearson's Correlation Coefficient

Table 5.11 shows there were no significant correlations between growth of the nose or nostrils and growth in body weight. Similar results were obtained for length and head circumference.

Significant correlations were found between growth of the anatomic nose (acR-acL) and soft nose (alR-alL) widths at all ages (r=0.55 to 0.65). Significant correlations were found between the growth of the right and left alar lengths at all ages (r=0.41 to 0.47). Alar length growth also correlated with anatomic and soft nose width growth at all ages (0.26 to 0.65) although the correlations between soft nose width and alar length growth were weak from 1 to 2 years (r=0.12 to 0.26).

No significant correlations were found between nasal dorsum (n-prn) growth and any of the nose measurements except a negative correlation with nasal tip protrusion (r = -0.31 to -0.44). Nasal tip protrusion (sn-prn) growth also correlated positively but weakly with several of the other nose measurements at all ages.

Significant correlations were found between the growth of the right and left long axis of the nostrils (sbalL-c, sbalR-c) at all ages however the growth in width of the nostrils (sn'R-al'iR, sn'L-al'iL) on the right and left were only significantly correlated from 6 months to 1 year (r=0.25, p=0.03). There were minimal correlations between the growth of the nostril long axis and growth in width. Growth of the columella width (sn'R-sn'L) did not correlate with any of the other nostril measurements at any age.

Few correlations were found between the growth of the nostril long axis and the growth of nasal tip protrusion and alar length. More correlations were found between the growth of the nostril widths and growth of the nose widths (acR-acL, alR-alL) although these were weak (r=0.16 to 0.31).

5.4.2.5 Correlations of Growth of the Upper and Lower Lips

Correlation of the growth of the lips with growth in body weight from 3 to 6 months (3m-6m), 6 months to 1 year (6m-1y) and 1 to 2 years (1y-2y) is shown in Table 5.12.

Table 5.12 Correlations of Growth of the Upper and Lower Lips with Growth in Body Weight

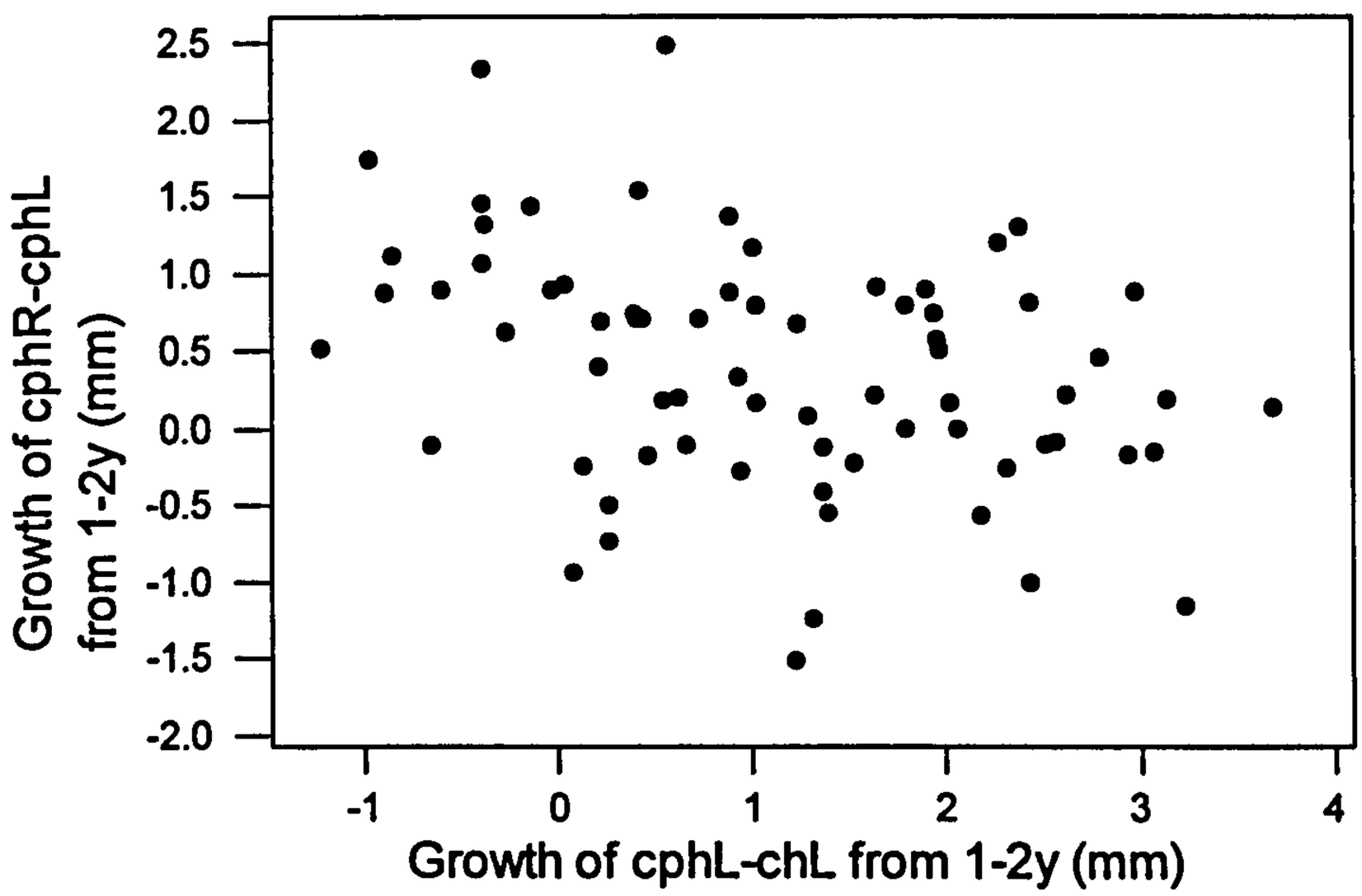
	Correlation Coefficient 3m-6m**	P Value*	Correlation Coefficient 6m-1y**	P Value*	Correlation Coefficient 1y-2y**	P Value*
Upper Lip						
chR-chL	0.02	0.84	0.09	0.45	0.08	0.50
cphL-chL	-0.03	0.84	-0.05	0.69	-0.13	0.26
cphR-chR	-0.10	0.43	0.08	0.52	-0.03	0.82
cphR-cphL	0.35	**0.003**	-0.01	0.95	0.05	0.66
ls-sn	0.22	0.07	0.01	0.95	-0.08	0.54
ls-stos	-0.10	0.42	-0.03	0.80	0.01	0.91
sn-stos	0.02	0.87	0.02	0.88	0.01	0.95
sbalL-chL	0.04	0.74	-0.17	0.16	-0.05	0.70
sbalR-chR	0.11	0.39	0.01	0.95	-0.02	0.87
Lower Lip						
chL-li	0.03	0.42	0.11	0.37	0.14	0.26
chR-li	0.09	0.47	0.01	0.97	0.21	0.09
li-stoi	-0.20	0.10	-0.04	0.76	0.20	0.01
sl-li	-0.01	0.93	0.04	0.77	-0.00	0.98
sl-stoi	-0.07	0.58	0.11	0.36	0.02	0.90

* Significant correlations at 5% level are shown in **bold**. ** Pearson's Correlation Coefficient

Table 5.12 shows there was no correlation between growth of the lip measurements and growth in body weight. Similar results were obtained for length and head circumference.

Mouth width growth did not correlate significantly with upper vermilion length or philtrum width growth at any age except a weak correlation with philtrum width growth from 3 to 6 months (r=0.24, p=0.04). Right and left upper vermilion length growth did correlate significantly at all ages (r=0.45 to 0.55). There were significant negative correlations between philtrum width growth and upper vermilion length growth from 1 to 2 years (r=-0.35,-0.24), although this was not found at the earlier stages. This correlation is illustrated in Figure 5.13.

Figure 5.13 Plot of Growth of Upper Left Vermilion Length against Growth of Philtrum Width from 1 to 2 Years



Significant and strong correlations were found between the growth of the upper vermilion lengths (cphR-chR, cphL-chL) and the growth of the upper lateral lip heights (sbalR-chR, sbalL-chL) at all ages (r=0.68 to 0.77).

Strong correlations were found between the growth of upper lip height (sn-stos) and both upper cutaneous lip height (ls-sn) and upper vermilion height (sn-stos) at all ages (r=0.50 to 0.74) however no correlation was found between the growth of upper cutaneous lip height and upper vermilion height (r=0.05 to 0.12). Few correlations were found between the growth of the upper lip heights (sn-stos, ls-sn) and the lateral lip heights (sbalR-chR, sbalL-chL).

Mouth width (chR-chL) growth correlated significantly with lower vermilion length growth (r=0.50 to 0.74) at all ages. Growth of the right and left lower vermilion lengths correlated significantly at all ages (r=0.50 to 0.71). Lower vermilion length growth did not correlate with lower vermilion height growth. Lower lip height (sl-stoi) growth correlated significantly with lower cutaneous lip height (sl-li) growth (r=0.68 to 0.76) at all ages however lower vermilion height (li-stoi) had minimal correlations with either lower lip height or cutaneous lip height. Upper and lower vermilion length growth correlated minimally but upper and lower lip height growth did not correlate at all.

5.4.2.6 Correlations of Changes in the Angles of the Face

Correlations of the changes in the angles of the face with growth in body weight from 3 to 6 months (3m-6m), 6 months to 1 year (6m-1y) and 1 to 2 years (1y-2y) are shown in Table 5.13.

Table 5.13 Correlations of Changes in the Angles of the Face with Growth in Body Weight

	Correlation Coefficient 3m-6m**	P Value*	Correlation Coefficient 6m-1y**	P Value*	Correlation Coefficient 1y-2y**	P Value*
Angles						
acR-prn-acL	0.08	0.50	0.04	0.75	-0.03	0.79
n-prn-sn	-0.06	0.61	-0.14	0.24	-0.06	0.63
prn-sn-ls	-0.05	0.67	-0.18	0.13	0.03	0.82
li-sl-pg	0.03	0.79	-0.04	0.77	-0.01	0.91

* Significant correlations at 5% level are shown in **bold**. ** Pearson's Correlation Coefficient

Table 5.13 shows no significant correlations between the changes of the angles of the face and growth in body weight. Similar results were obtained for length and head circumference.

Significant correlation was found between the change in the nasal tip angle (n-prn-sn) and nasal tip horizontal displacement angle (acR-prn-acL) from 3 to 6 months (r=0.40) and 6 months to 1 year (r=0.34) but not from 1 to 2 years (r=-0.00). Significant correlation was also found between the change in the nasal tip angle (n-prn-sn) and nasolabial angle (prn-sn-ls) at all ages (r=0.57-0.96).

5.5 Longitudinal Changes in Asymmetry

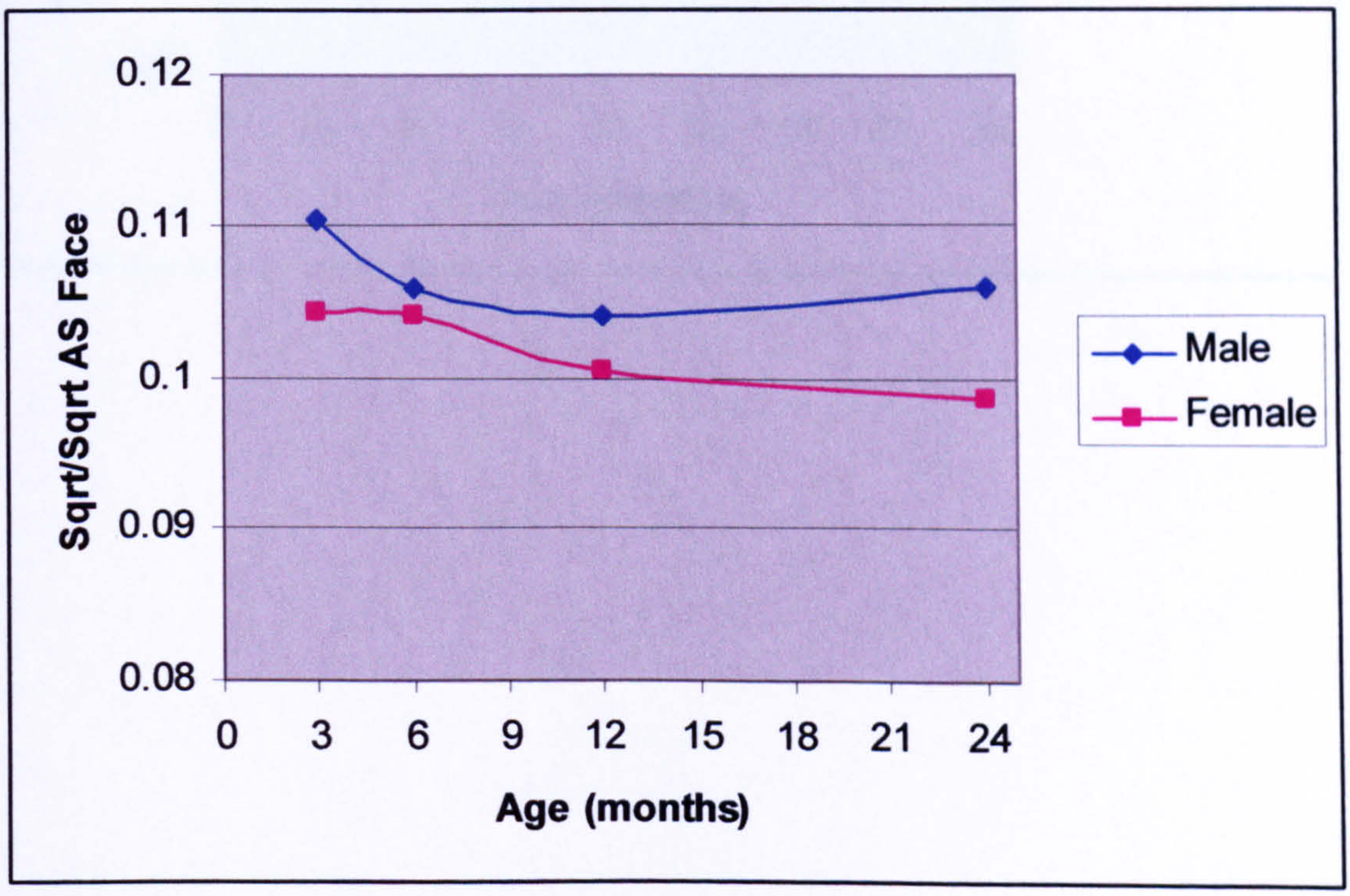
5.5.1 Longitudinal Change in Asymmetry for the Different Regions of the Face

The longitudinal changes in asymmetry scores were available for 69 subjects from 3 months to 2 years. The asymmetry scores were calculated for the midface landmarks only, excluding the ears, lower lip and chin.

5.5.1.1 Face

There was a tendency for the asymmetry score for the face to reduce with age. Paired t tests showed no significant change in the fourth roots of the asymmetry score (sqrt/sqrt AS) for the face from 3 to 6 months, 6 months to 1 year or 1 to 2 years. The difference was significant from 3 months to 1 year (p=0.007) and from 3 months to 2 years (p=0.023). Two sample t tests showed there was no significant difference in the change in asymmetry of the face between the males and females. This is illustrated in Figure 5.14.

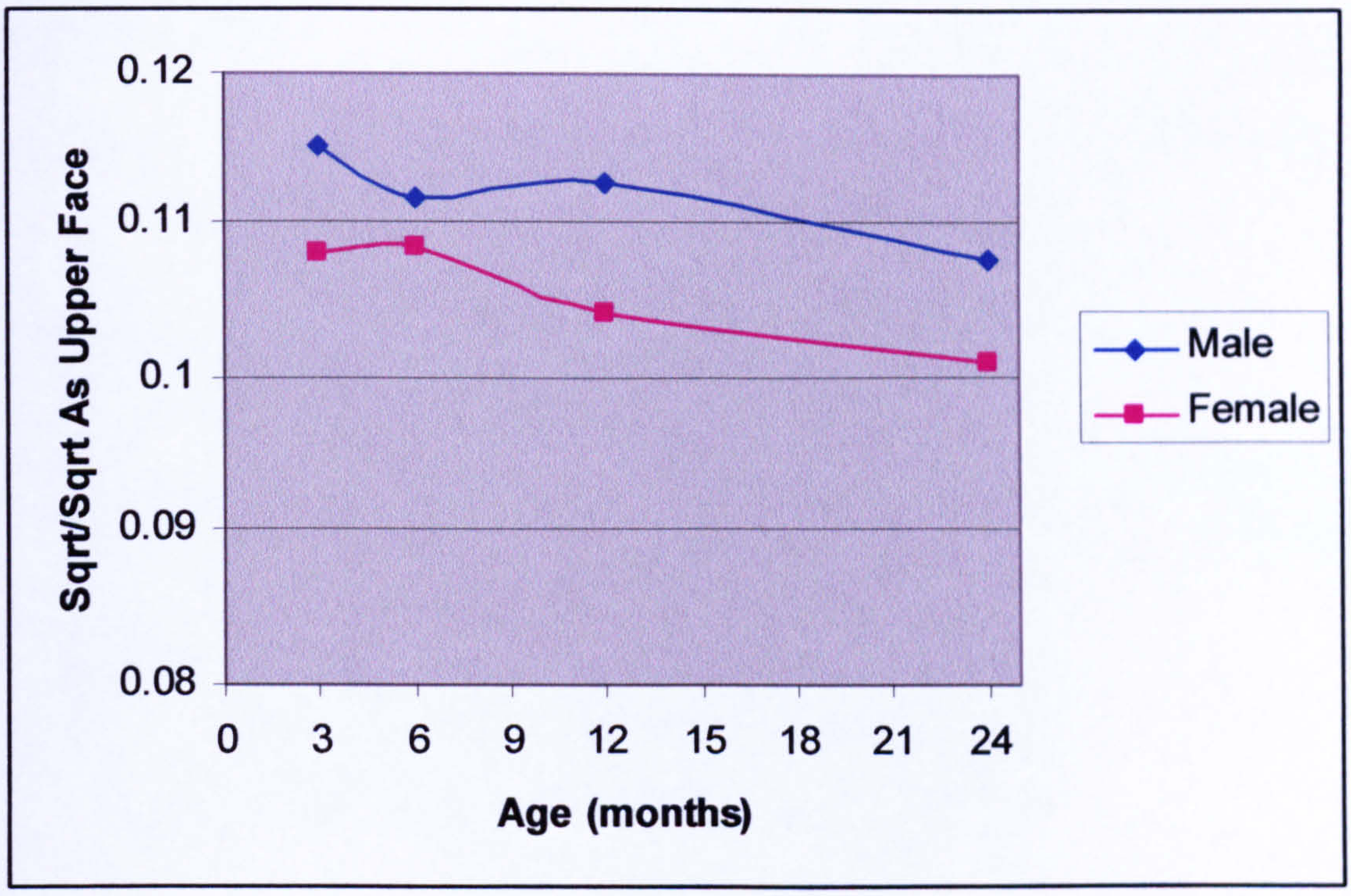
Figure 5.14 Change in Sqrt/Sqrt AS for the Face of Males and Females from 3 Months to 2 Years



5.5.1.2 Upper Face

There was a tendency for the asymmetry score for the upper face to decrease with age. Paired t tests showed no significant change in the sqrt/sqrt AS for the upper face from 3 to 6 months, 6 months to 1 year or 1 to 2 years. The differences were significant from 3 months to 2 years (p=0.009) and from 6 months to 2 years (p=0.023) Two sample t tests showed there was no significant difference in the change in asymmetry of the upper face between the males and females. This is illustrated in Figure 5.15.

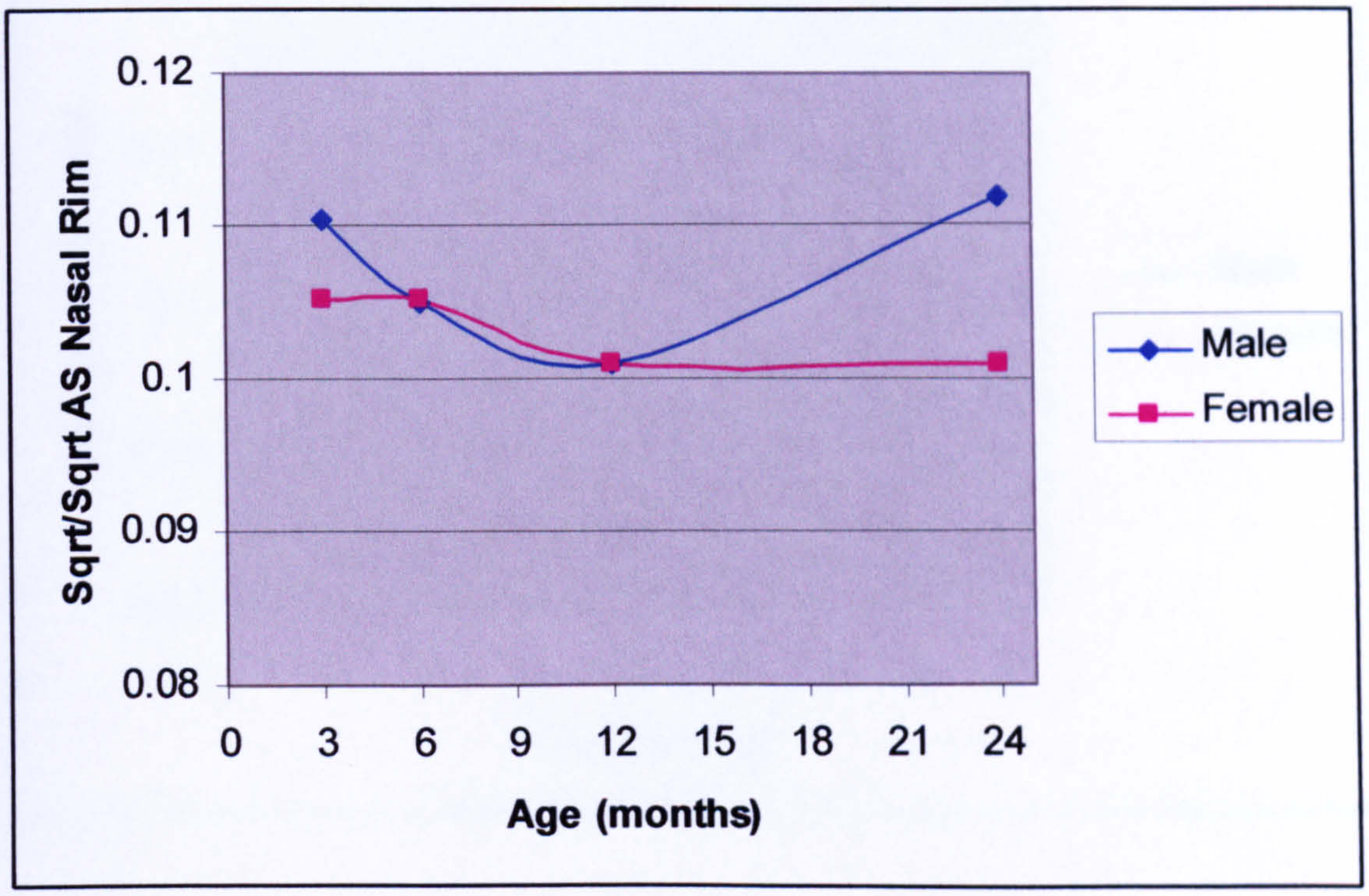
Figure 5.15 Change in Sqrt/Sqrt AS for the Upper Face of Males and Females from 3 Months to 2 Years



5.5.1.3 Nasal Rim

The asymmetry scores for the nasal rim did not change consistently with age. Paired t tests showed no significant change in the sqrt/sqrt AS for the nasal rim from 3 to 6 months or 6 months to 1 year. There was a significant decrease from 3 months to 1 year (p=0.009) and a significant increase from 1 to 2 years (p=0.033) but overall there was no significant difference from 3 months to 2 years (p=0.718). Two sample t tests showed there was a significant difference in the change in asymmetry of the nasal rim between the males and females from 1 to 2 year (p=0.039), with the male asymmetry increasing more than the female. This is illustrated in Figure 5.16.

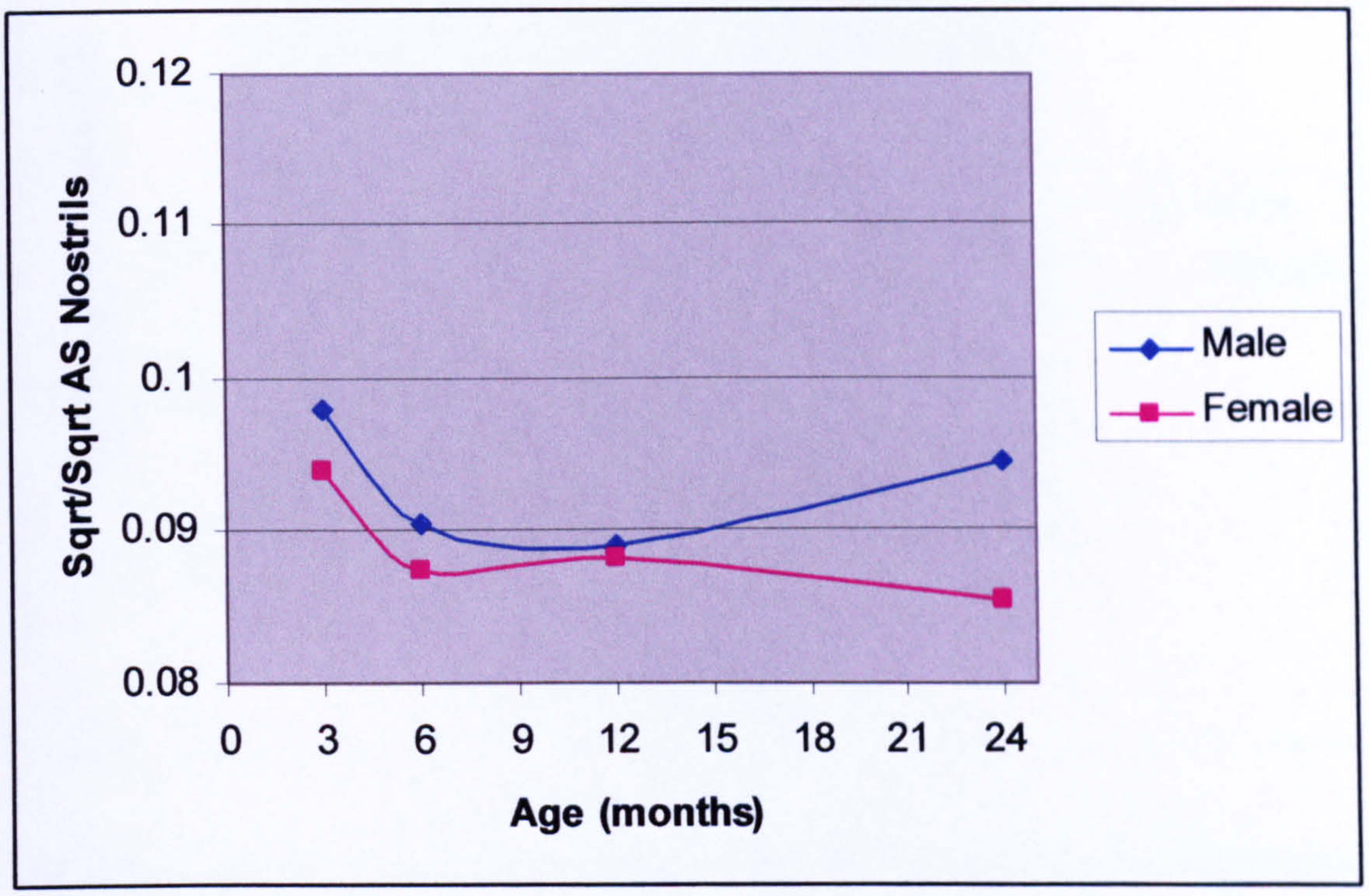
Figure 5.16 Change in Sqrt/Sqrt AS for the Nasal Rim of Males and Females from 3 Months to 2 Years



5.5.1.4 Nostrils

The asymmetry scores for the nostrils did not change consistently with age. Paired t tests showed a significant change in the sqrt/sqrt AS for the nostrils from 3 to 6 months (p=0.002) but not from 6 months to 1 year or 1 to 2 years. The difference was also significant from 3 months to 1 year (p=0.001) and to 2 years (p=0.015) with a slight reduction in asymmetry with age. Two sample t tests showed there was a significant difference in the change in asymmetry of the nostrils between the males and females from 1 to 2 years (p=0.035). This is illustrated in Figure 5.17.

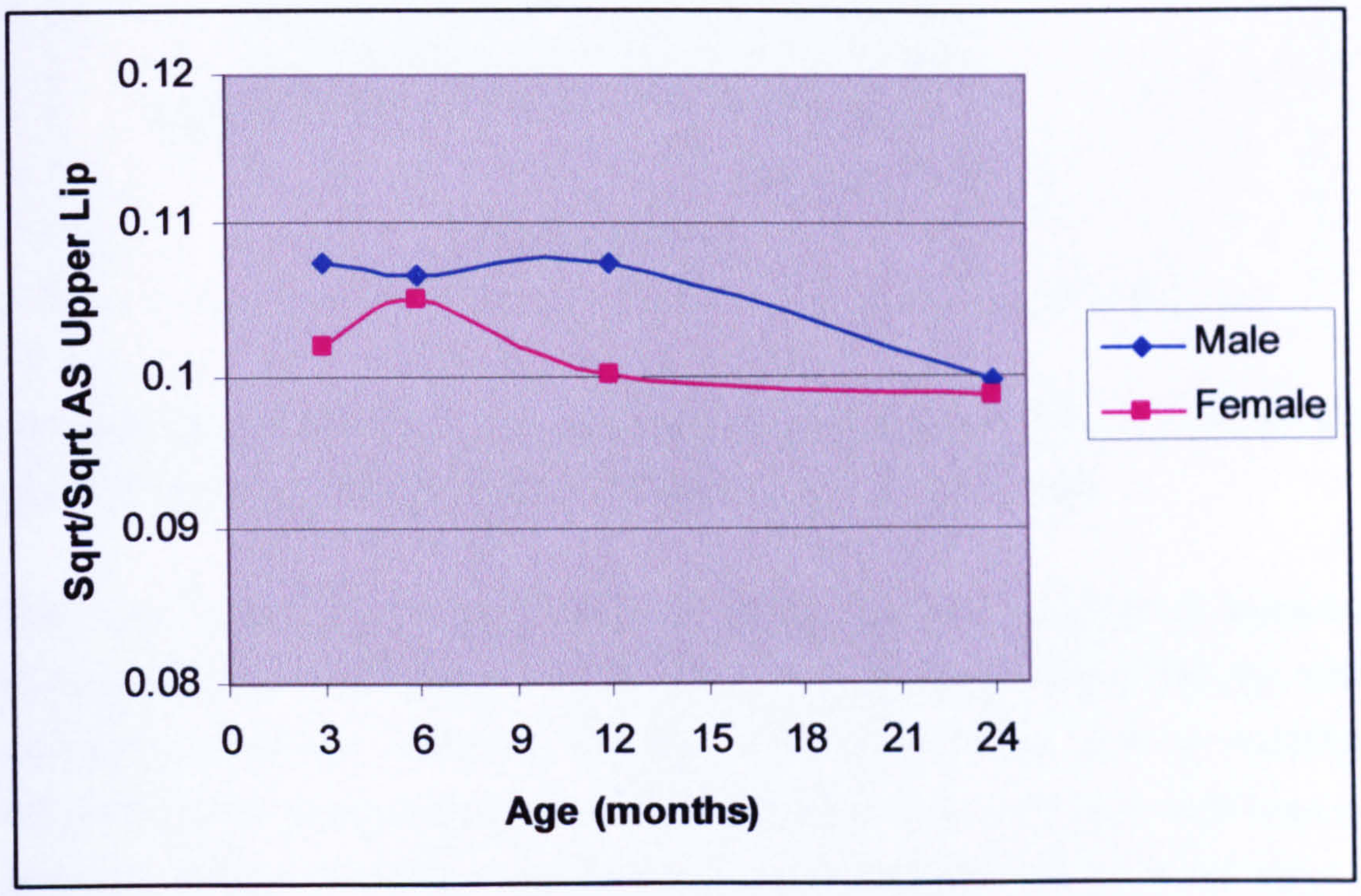
Figure 5.17 Change in Sqrt/Sqrt AS for the Nostrils of Males and Females from 3 Months to 2 Years



5.5.1.5 Upper Lip

Paired t tests showed no significant change in the sqrt/sqrt AS for the upper lip from 3 to 6 months, 6 months to 1 year or 1 to 2 years. The difference was significant from 6 months to 2 years (p=0.044) with a slight reduction in asymmetry with age. Two sample t tests showed there was no significant difference in the change in asymmetry of the upper lip between the males and females. This is illustrated in Figure 5.18.

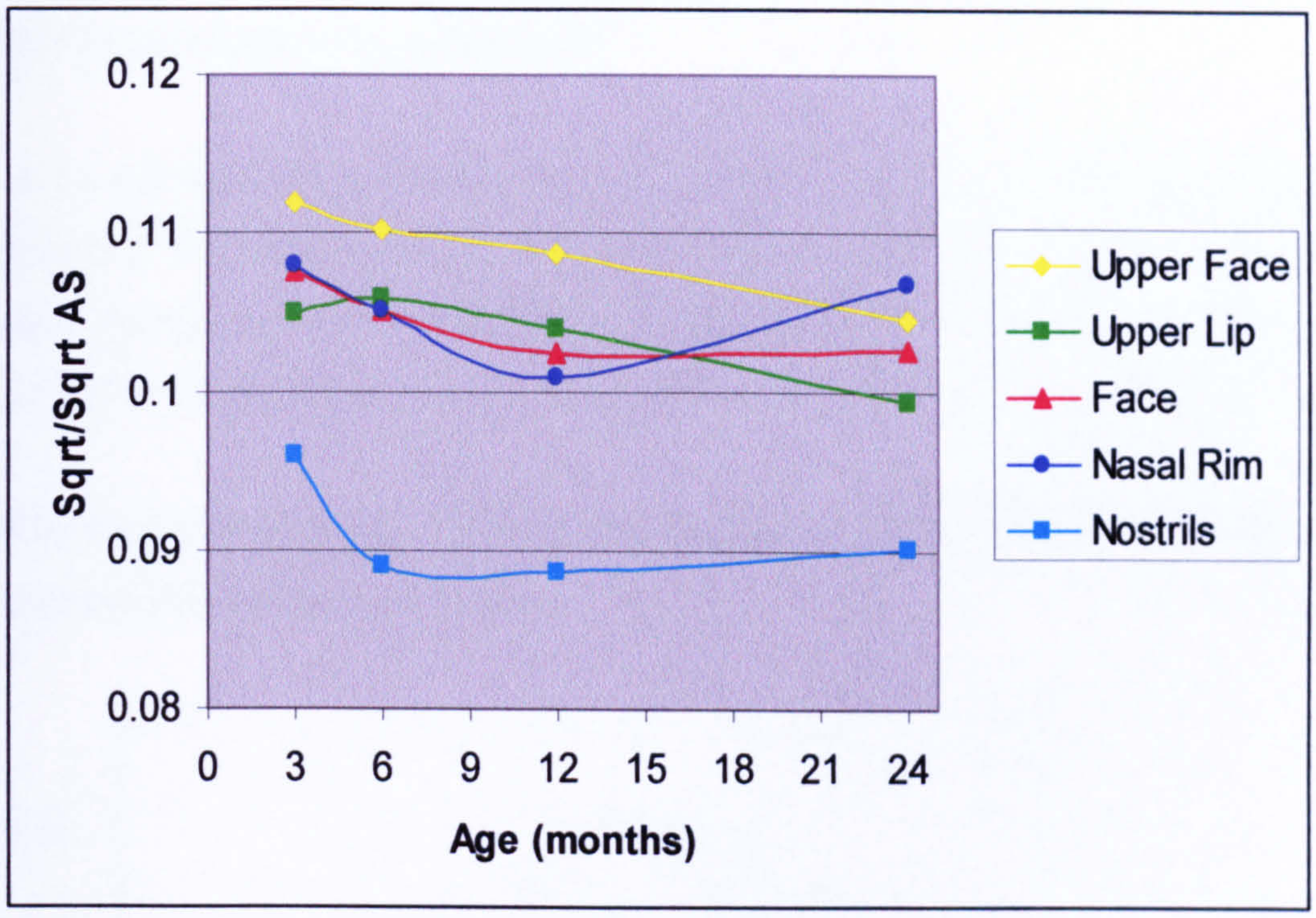
Figure 5.18 Change in Sqrt/Sqrt AS for the Upper Lip of Males and Females from 3 Months to 2 Years



5.5.2 Comparison of the Changes in Asymmetry in the Regions of the Face

The longitudinal changes in asymmetry scores for the different regions of the face from 3 months to 2 years of age are illustrated in Figure 5.19.

Figure 5.19 Change in Sqrt/Sqrt AS from 3 Months to 2 Years



The asymmetry of the nostrils was significantly less than the other regions of the face at all ages. The upper face was the most asymmetric at all ages except 2 years.

From 3 to 6 months there were significant differences in the changes in asymmetry between the nostrils and upper lip (p=0.037) and upper face (p=0.051) with the nostril asymmetry decreasing more than the other asymmetries. There were no significant differences in the changes from 6 months to 1 year but from 1 to 2 years there were two significant differences. These were between the changes in the nasal rim and upper lip (p=0.018) and upper face (p=0.003) with the nasal rim asymmetry tending to increase and the upper lip and upper face asymmetry decreasing from 1 to 2 years.

5.5.3 Correlations of the Changes in Asymmetry in the Regions of the Face

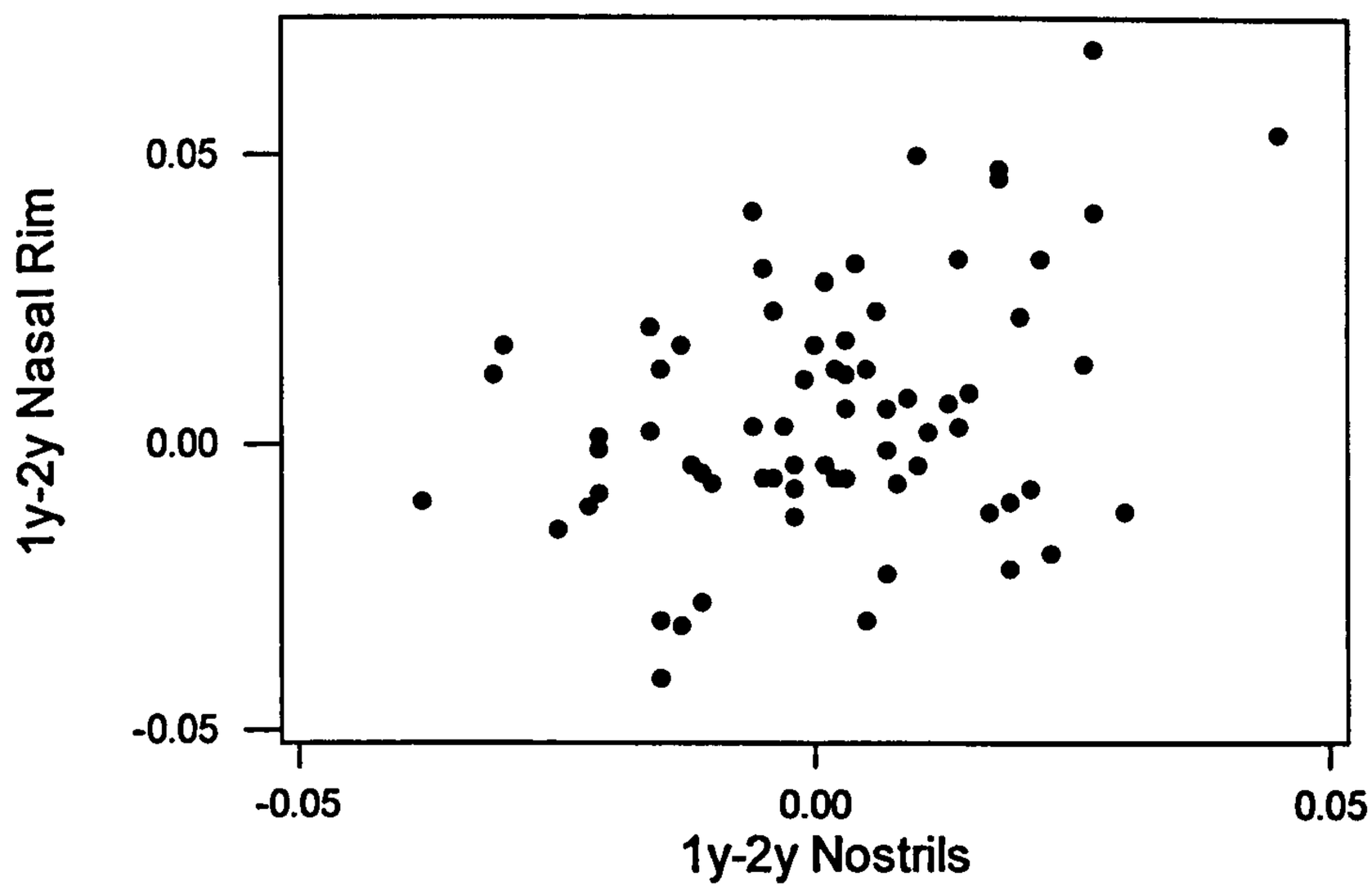
As expected there were strong and significant correlations between the change in face asymmetry and the change in asymmetry of each of the regions of the face since the face score was a weighted average of the individual scores.

From 3 to 6 months there were significant but weak (r=0.24-0.35) correlations between the change in asymmetry of the nasal rim, nostrils and upper face.

From 6 months to 1 year the change in upper lip asymmetry correlated weakly but significantly with the upper face, nasal rim and nostrils (r=0.27-0.33). The correlations found from 3 to 6 months were not repeated.

From 1 to 2 years significant correlations were found between the changes in the nasal rim and nostrils (r=0.36) and upper face (r=0.24) similar to the changes from 3 to 6 months. Significant correlation was also found between the upper face and upper lip changes at this age (r=0.32). The strongest correlation found at any age is illustrated in Figure 5.20.

Figure 5.20 Plot of the Change in Nasal Rim Asymmetry against the Change in Nostril Asymmetry from 1 to 2 Years



6 Discussion

6.1 Materials & Methods

6.1.1 Study Design

The study was designed as a longitudinal study due to the well recognised advantages in this type of design when studying growth (Proffit 2000). The infants in this study formed a control group for a larger study into facial growth in infants with cleft lip and /or palate. These patients had their first surgery to close the lip at around 3 to 4 months of age and the first visit in this investigation was aimed to capture the non cleft infants at a similar age. Images could have been collected earlier than 12 weeks however image capture was greatly facilitated by a degree of head control in the infants which improves at this age. The next capture, at 6 months, was timed to allow comparisons with infants with repaired cleft lip after any post operative swelling had subsided. The 1 and 2 year captures allowed data collection for comparison with cleft children before and after palatal surgery. Although the timing of data collection was dictated by the larger study, the 3 month, 6 month, 1 year and 2 year captures were logical time points to study facial growth since growth of the face is known to be most rapid in the first year and slower in the second year (Burke 1983;Strömland et al. 1999).

6.1.2 Subjects

The first 100 subjects who agreed to take part and who conformed to the exclusion criteria were recruited. It was aimed to recruit a group of subjects from a range of socio-economic circumstances. Socio-economic circumstances were judged by Carstairs deprivation index (depcat) which assigns the subject to a category from 1 to 7 according to their postcode (Carstairs & Morris 1990;McLoone 1993). The recruitment was successful in that a range of subjects from depcats 1 to 7 were recruited. The lack of subjects in depcat 5 can be explained by the fact that few of the postcodes in the Greater Glasgow area have this score.

An interesting finding was that 70% of the mothers reported to have been breast feeding at 3 months. In comparison, a study carried out in 1991 reported average breast feeding rates of 36% on day 7 in Scotland with a rate of 27% in Glasgow (Ferguson et al. 1994). Variables that are associated with breastfeeding are typically correlated with social status, such as maternal age, education and income (Piper & Parks 1996). Breast feeding has also

been correlated with positive parental attitudes and it has been shown that this is a stronger predictor of breast feeding rates than sociodemographic factors (Scott, Shaker, & Reid 2004). It could therefore be concluded that although the study sample came from a range of socio-economic circumstances it was not a truly representative sample of the West of Scotland. This selection bias is a common finding and is almost impossible to avoid in longitudinal studies (Farkas 1996). However, there is no reason to believe that the facial morphology of this group of infants would differ significantly from the general population.

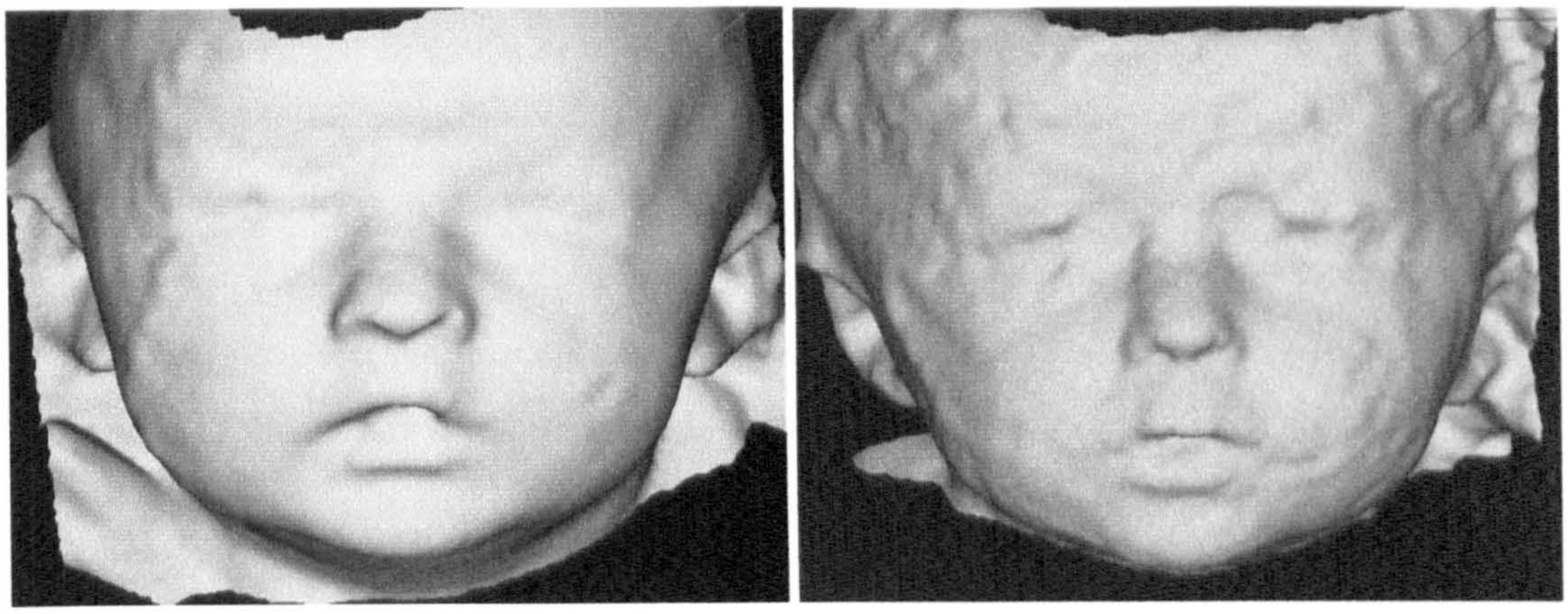
It was anticipated that there would be a significant drop out rate during the two year duration of the study. It was aimed to recruit 100 subjects in an attempt to ensure complete data for at least 30 males and 30 females. The return rate of 95% was unexpectedly high and was probably due to several factors. During the recruitment process the study was explained fully to the parents and only those subjects who were confident they would remain in the Glasgow area for the 2 year period of the study were recruited. Over 40% of the subjects moved house during the period of the study and the most important factor in keeping track of these subjects was collecting additional contact details such as email addresses, work details or grandparents addresses. At each visit the importance of completing the study was emphasised and the contact details updated. The short duration of each appointment and the ability of the subjects to attend at almost any time of their choosing were factors which encouraged good attendance. Finally, the persistence of the operator and the positive attitude of the parents probably contributed to the high completion rate.

6.1.3 C3D System

The C3D system used in this project was designed and set up to capture images of children from babies up to 5 or 6 years of age. The speed of capture, lack of ionising radiation, relative ease of positioning the child and accuracy of the system make it suitable to study facial growth and morphology in infants. However there were some disadvantages of the system. It was a prototype, made from components which were not as robust as commercial equipment. The cameras and flashes could be accidentally moved by the subjects and the operator which could affect the calibration and the image quality. Due to this potential problem the calibration was usually carried out within an hour of the subject's appointment. A second calibration was carried out as soon as the subject left and this was compared to the initial calibration to confirm that the cameras had not been moved. Ensuring good image quality was not so simple. The model surface was affected by the focus of the random texture pattern and this was affected by position of the infant as

well as the position of the flash. Examples of models collected with the texture in focus and slightly out of focus are shown in Figure 6.1.

Figure 6.1 Different Quality of 3D Models



a) In Focus – Smooth Surface **b) Out of Focus – Irregular Surface**

Unfortunately it was not reasonable to check and alter the focus while the child was still present since this could take a considerable time. It was therefore not possible to ensure that all 3D models of the children were as smooth as the one shown in Figure 6.1a. This meant that many of the images used in this study had a model surface similar to that shown in Figure 6.1b. On a number of occasions the parents and infants were asked to come back for another capture session if the models were not judged to be satisfactory. This judging was on a purely subjective basis, the smoothest models with a lip apart pose were chosen. Models were rejected if there were obvious defects in the models or if the surface was too uneven to clearly see the eyes, nose and lip landmarks on the range data. A faint line running down the right side of the face can also be seen on many models, including Figure 6.1a, and is due to a slight error in the process of merging the data from two pods (see section 2.3.1.2). The effect of the model surface quality and the merge line on the interlandmark distances and angles is assumed to be negligible however this remains to be verified.

Despite these problems, the C3D system used in this study compares well to other methods of 3D facial scanning described in the literature, such as laser scanning (Bush & Antonyshyn 1996) and the structured light techniques (Yamada et al. 1999). The system allows fast capture, essential to collect data in infants, and also produces a 3D model including the ears with a colour texture overlay. The only other system described in the literature to combine these first two advantages was a structured light technique employing

infra red light (Littlefield et al. 2004). This system was designed for use in infants and produced a 3D model of the head and face however the texture overlay was black & white.

6.1.4 Analysis

The landmarks used in this investigation were chosen by the research team and the author because they were able to be located with an acceptable repeatability. Most of the landmark definitions were the same as those of Farkas (1994) however several of the definitions had to be adapted for use on a 3D model rather than a live subject. For example, it was not possible to palpate the frontonasal suture therefore soft tissue nasion was redefined as the point of maximum concavity in the midline of the bridge of the nose. These alterations in definitions need to be appreciated when comparing the results of this study with other investigations.

Similar difficulties to those found in our pilot study in recording the landmarks trichion, glabella, and frontotemporale in laser scanned images of adults have been reported (Aung et al. 1995). The authors overcame these difficulties by premarking the landmarks on the face prior to image capture. This was not feasible in infants and these landmarks were not used in the current study.

One of the major advantages of 3D imaging techniques is the fact that measurements can be derived from archived data at any stage. It therefore did not seem necessary to generate all 150 measurements described by Farkas (1994) for this study. The measurements were chosen by the operator to cover the whole face and give the most clinically relevant information with the minimum of repetition. Unfortunately, tragion could not be reproducibly located on the model due to lighting difficulties around the ear. Upper face, maxillary and mandibular depths were therefore redefined as the distance from otobasion inferius to the points nasion, subnasale and pogonion respectively. The distance tragion to subnasale was shown to be consistently 10 mm greater than the measurement of otobasion inferius to subnasale in a study comparing direct anthropometric and laser scanning measurements in adults (Aung et al. 1995). The same study showed a consistent difference of 20 mm between the measurement tragion to gnathion and otobasion inferius to gnathion. It may therefore be valid to substitute the landmark otobasion inferius for tragion when measuring face depths although this remains to be verified in infants.

Simple statistical analysis such as calculating means and standard deviations, applying t tests and paired t tests and calculating correlation coefficients were used in this study.

This is only the first stage in the analysis of this data and allows comparison with previous studies. It is not intended as a comprehensive analysis of the data. The problem with carrying out multiple t tests is that the probability of obtaining a falsely significant result is greatly increased. The Bonferroni method calculates the increased significance level required to account for this effect. It assumes that the variables are independent and is therefore not suitable to apply to the interlandmark data in this study since it would lead to discounting some true significant results. Many of the individual significant results reported in this study may be false positive findings and therefore in the discussion most emphasis has been placed on the consistent findings which may be the most clinically relevant.

A further step in the analysis could be to apply analysis of covariance to determine whether the sex differences could be explained by differences in body measurements. This has already been carried out on the 3 month data and it has been shown that the apparent sex differences could be explained by differences in weight between the boys and girls (White et al. 2004). Further statistical analysis of the data will be discussed in section 6.5.

The asymmetry score has been devised as a method of measuring asymmetry of the whole face or of separate regions of the face. Its advantages include avoiding definition of a midplane, the full use of the three dimensional nature of the data and the fact that the result is independent of size. One potential disadvantage of the asymmetry score is the fact that it is expressed in units, rather than in mm or as a percentage. This may make it less easily interpreted by clinicians. The range of scores representing clinically obvious asymmetry needs to be determined before the clinical significance of the facial asymmetry scores can be fully understood. Another disadvantage is that asymmetry of peripheral landmarks, such as around the ears, can have a larger effect on the asymmetry score than a similar asymmetry in the midface. It is therefore advised that the asymmetry score should only be applied to a group of landmarks which are fairly evenly spaced over the face.

6.2 Validation

6.2.1 System Validation

Various means of validating 3D imaging systems have been reported in the literature. The most common way of validating a 3D imaging system has been to compare anthropometric distances measured directly with calipers with those measured indirectly on the 3D model. This has been performed on precision targets, facial models and on clinical subjects.

Generally the errors obtained by this method are least for the precision models and greatest in live subjects. In this method of validation the direct anthropometric measurements are regarded as the gold standard. However, there are significant errors in direct anthropometry which will affect the results. In one study the measurements recorded from 3D images were actually shown to be more repeatable than direct anthropometric measurements (Weinberg et al. 2004). This method of validation has been used to test laser scanning systems (Aung et al. 1995;Kusnoto & Evans 2002) and structured light scanners (Lee et al. 2004;Strömland et al. 1998) with mean differences in measurements ranging from 0 to 7 mm.

Coordinate measuring machines (CMM) provide highly accurate results, far superior to direct anthropometry and are a more suitable gold standard for validation studies. This method has been used to validate an infra red structured light system with a plaster model of the head (Littlefield et al. 2004). A root mean square mean deviation between the surfaces of 0.236 mm was reported. The images captured by the two systems were superimposed according to the best fit of the entire surface, no landmark location was involved and the error was low. A liquid crystal range finder was validated by a similar means comparing the location of 15 landmarks on a plaster model of the face captured by the range finder and a contact type 3D digitiser. The total error of the system was approximately 0.5 mm (Yamada et al. 1999).

It is difficult to compare all of these error studies due to inconsistencies in the use of terminology, differences in methods of data acquisition and analysis, and the choice of statistics for error reporting (Weinberg et al. 2004). Nevertheless the findings of all of the studies do confirm that indirect 3D anthropometry is capable of a high degree of precision and accuracy and is suitable for clinical studies.

Comparison with a coordinate measuring system was used in the current study for the system validation. The results are discussed in section 3.1.4. The mean difference between the C3D system compared to the coordinate measuring machine was found to be 0.83 mm. It is probable that this result has been adversely affected by the poor definition of the premarked landmarks on the plaster casts and that the system accuracy is actually greater than this. One disadvantage of the validation study was that the facial models used did not include chin or ear landmarks. This means that the validity of the peripheral landmarks has not been verified. It is possible that the 3D model quality is less accurate at the periphery of the image than in the centre. In other studies the measurements on 3D models incorporating peripheral landmarks, such as face depth and width, have been found to be

the least accurate compared to direct anthropometric measurements (Aung et al. 1995;Weinberg et al. 2004). It may have been possible to repeat this type of study on the infants but the inaccuracy in recording direct anthropometric measurements on infants would probably be greater than any inaccuracy in the periphery of the 3D image. The repeatability of measurements involving the peripheral landmarks has been shown to be good (see section 3.3.2.3), with error standard deviations ranging from 0.49 mm for left mandibular depth to 1.34 mm for lower face width. It is unlikely that these measurements would be so repeatable on different images of the same infant on the same day if the system was inaccurate in recording these areas. However, a further validation exercise including the peripheral landmarks on life size models of infant faces should be undertaken to confirm the accuracy of the C3D system in recording these areas.

6.2.2 Landmark Reproducibility

The reproducibility of landmark location has been investigated in several studies including direct assessment on the face (Ferrario et al. 1996c), indirect assessment on 3D models (Bush & Antonyshyn 1996;Kohn et al. 1995;McCance et al. 1992) and using semi automatic landmark extraction (Yamada et al. 1999). Often these studies include two stages in the investigation, the repeated digitisation of landmarks which have been premarked on the face and the repeated localisation of landmarks on the face which have not been premarked. In our study only the latter problem was investigated clinically since it was not feasible to mark landmarks on an infants face. The operator error in locating premarked landmarks on a plaster model had been investigated and repeated digitisations were found to have a mean displacement of 0.20 mm, with a range of 0.12 to 0.57 mm (see section 3.1).

Previous investigations into the repeatability of landmark location have reported mean differences ranging from 0.02 to 0.82 mm (McCance et al. 1992), standard deviations ranging from 0.01 to 3.9 mm (Bush & Antonyshyn 1996), and standard errors ranging from 0.03 to 0.83 mm (Yamada et al. 1998). In all of these studies the errors were reported in the x, y and z planes separately. Once again the different methods of statistical analysis chosen to report the errors make comparisons difficult.

In the current study a reproducibility score was defined as the square root of the mean squared distance, in mm, of each of the three repeatedly placed points around their mean. The score is therefore the standard deviation about a mean. The advantage of this method is that one score is calculated for each landmark which encompasses all of the errors in the

x, y and z planes. The range of reproducibility scores, from 0.24 mm for cheilion left to 0.99 mm for menton, compared favourably to other studies. The method of locating the landmarks twice and using the mean landmark position is well recognised in the cephalometric literature as a method of improving repeatability (Houston et al. 1986). This technique does not seem to have been applied in any other 3D anthropometric studies however in this study it has been used to reduce the score for the less repeatable landmarks. The reproducibility score for menton was therefore reduced from 0.99 to 0.70 mm, and for pogonion it was reduced from 0.81 to 0.57 mm. The resulting reproducibility scores for all other landmarks were below 0.5 mm.

One of the major factors in improving the reproducibility of the landmarks was controlling the position of the model during landmark location. Comparing the results of the pilot study to the definitive reproducibility study it can be seen that the set position has had the greatest effect on the landmarks alare, menton, pogonion and pronasale. Although the set position has improved the reproducibility of these landmarks it does mean that the definitions of these landmarks have been altered. For example Farkas definition of alare is 'the most lateral point on the alar contour' whereas in the current study our definition was the most lateral point on the alar contour with the head positioned at 60°. In many cases these points would be coincident but in some cases there could be a slight difference. This difference is of no importance when assessing longitudinal change or comparing the control group with the cleft group within our study, however it should be considered when comparing the results of our study with those of other researchers.

6.2.3 Facial Expression

Both the lips apart and lips together poses have been shown to be repeatable in this group of infants (see section 3.3). Anthropometric studies of children and adults are always carried out with the lips together and this is regarded as the at rest position for most subjects. In fact Farkas (1994) states that 'when examining the lips and mouth, closed lips are a sine qua non for correct measuring'. However, the results of the current study actually suggest that the lips apart pose is more repeatable in infants at 3 months of age. It is surprising that few anthropometric studies of infants and small children mention the fact that the rest position for infants is with the lips apart. In a longitudinal assessment of children from 3 months to 18 years using lateral cephalograms the lip position was not discussed (Subtelny & Rochester 1959). In a study of facial features in Scandinavian children around 40 infants were examined in each of 18 age groups, from 0 to 17. The lip position of the infants during data capture was not mentioned (Strömland et al. 1999). An

investigation of Japanese infants from 3 months to 4 years of age did not specify the lip position however one illustration showed a lip together pose and another showed a lip apart pose (Yamada et al. 2002). Only upper lip, nose and eye measurements were included and it may have been that lip position was not considered relevant. In the current study it has been shown that there is a significant difference in measurements of the face taken with the lips apart and lips together. The largest differences were in face height measurements however significant differences were also found in upper lip measurements such as upper lip height, upper vermilion length and nasolabial angle. It is therefore essential in any anthropometric study of infants that the lip position is specified.

Longitudinal changes in lip position in infants have been discussed in a case report (Burke 1980). The lip position at 3 weeks of age was described as a rosebud shape which gradually transformed during the first year of life changing from a sphincter for breast feeding to a slit for the access of food. This report suggests that by 1 year of age the lips are together at rest and that further growth in mouth width from 1 year to 2 years is small. This change in one of the subjects in the present study is illustrated in Figure 6.2.

Figure 6.2 Longitudinal Changes in Lip Position - Gradual Change

a) 3 Months

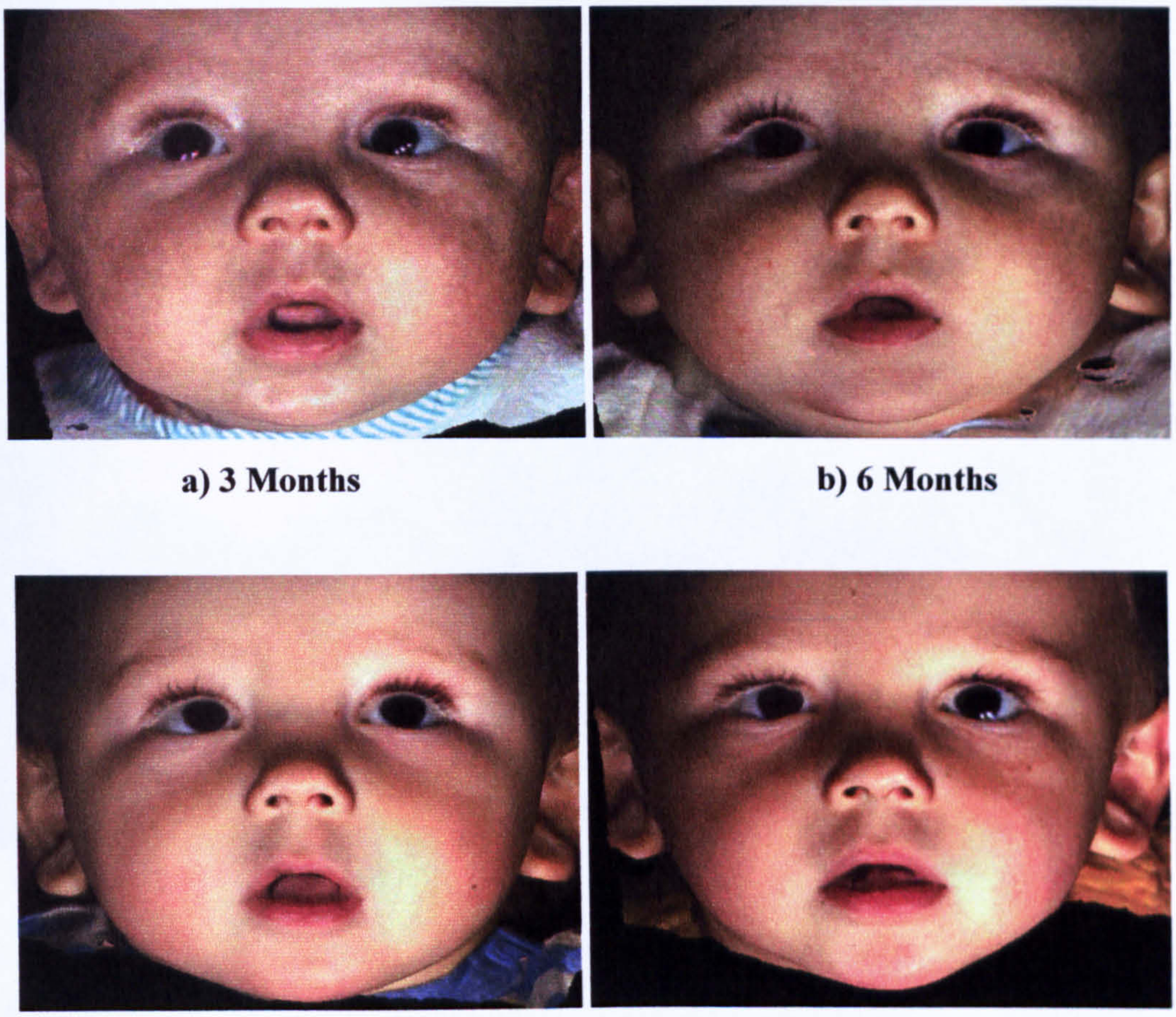
b) 6 Months

c) 1 Year

d) 2 Years

The gradual change in lip position described by Burke (1980) and shown in Figure 6.2 was only found in 3 of the subjects in the current study. However, a total of 16 subjects were captured with a lip together pose at one or more time points. The results of these captures were excluded from the analysis.

Figure 6.3 Longitudinal Changes in Lip Position - Consistent Lips Apart



a) 3 Months **b) 6 Months**

c) 1 Year **d) 2 Years**

All of the subjects included in the analysis of this study were captured with the lips apart. This is illustrated in Figure 6.3. This position has been shown to be fairly repeatable at all of the ages in this investigation (see section 3.3.2). However the lips apart pose was not always consistent for each individual child over time. This is illustrated in Figure 6.4.

Figure 6.4 Longitudinal Changes in Lip Position - Inconsistent Lips Apart

a) 3 Months **b) 6 Months**

c) 1 Year **d) 2 Years**

Figure 6.4 shows the subject at rest in each image but the lip position is slightly different at 3 months compared to the later captures. This was a problem in this study and will have affected the longitudinal analysis of the data, especially face height. The varying lip positions were as likely to occur at 6 months, 1 year or 2 years as at 3 months. This variation in lip position may be regarded as a random error since it was not related to age or gender. If this assumption is correct the standard deviations of measurements would be increased by this variation but the mean values would still be a valid representation of the population. The increased standard deviations would make it less likely to find significant differences however any significant results are still likely to be valid. It has been assumed in the analysis of the interlandmark distances and angles in this study that this variation in lip position over time is random. In the analysis of asymmetry it was decided to exclude the lower lip landmarks to minimise any effect of the inconsistent lip positions.

6.3 Cross Sectional Results

6.3.1 Body Measurements

The mean weight, length and head circumference of the males and females at all ages were slightly higher than the means published for the population with the greatest differences at the 3 and 6 month stages (Gairdner & Pearson 1988a;Gairdner & Pearson 1988b). The data for these commonly used growth charts was collected in the 1970s. Infant feeding practices have altered since the time of construction of these growth charts when most infants were bottle fed. This has altered the pattern of weight gain and made the development of new growth standards necessary. The growth of the infants in the current study is more similar to those in the UK90 study where the 3rd, 50th and 97th centiles for weight, length and head circumference were shown to be greater than the Gairdner-Pearson standards (Freeman et al. 1995). New growth charts based on the UK90 study will hopefully be produced for this age group and it is likely that the infants in the current study will more closely conform to these growth charts (Wright et al. 2002). However, it is also possible that the infants in this study were slightly larger than the general population due to some selection bias in favour of families with positive attitudes to health and stable social circumstances.

6.3.2 Missing Landmarks

The most frequently missing landmarks were otobasion superius right and left which were recorded as missing if hair obscured the top of the ear. These landmarks were commonly missing at the 2 year stage when the infants had most hair. Any future study intending to investigate this landmark should capture the images with the hair tied back, although this could be difficult in some infants.

At 3 months, in contrast to the other ages, the most frequently missing landmarks were otobasion inferius. The lack of head control at this age meant that some of the infants were captured with the head leaning back against the parent's chest and the chin tucked down distorting the landmarks at the base of the ear. It is probable that at this age better images could have been captured with the baby in a supine position. This was not possible in the current study since the C3D kit was not simple to alter, but this may be considered in any future studies of babies with limited head control.

The other landmark which was frequently missing was menton. This was missing when the infants were captured with the chin down. Every effort was made to capture each infant in

the ideal position but it was not possible with their limited cooperation. Using a 3 pod system would allow a larger capture field and would probably reduce the frequency of missing landmarks around the ears and chin.

6.3.3 Face Height, Width and Depth

All of the male face heights, widths and depths were significantly greater than the females at all ages except 2 years. At this age only the maxillary depth, left mandibular depth and upper face width were not significantly greater. These results are similar to the findings of direct anthropometry on a small group of infants in North America which show the male faces to be consistently larger than females at all ages (Farkas 1994a). Total face height was found to be 70.0 mm in a group of 8 males from 0 to 5 months and 68.0 mm in a group of 5 females of the same age. These measurements are similar to the 3 month findings in the current study of 71.2 mm for males and 68.8 mm for females. However, the results of an anthropometric study in Aberdeen are 6 to 9 mm less than the measurements in the current study at 1 and 2 years for face height (Low 1952). These differences may be due to differences in methodology including landmark definitions and lip posture. The males were consistently larger than the females in the Aberdeen study. Face breadth, defined as the bizygomatic distance, was lower than the upper face width and greater than the lower face width measurements in the current study. A cross sectional study of Scandinavian children with around 40 infants at both 1 and 2 years does report upper face height to be greater in males than females but does not report any other face height width or depth measurements (Strömland et al. 1999). Other indirect anthropometric studies of infants do not investigate face height, width or depths (Subtelny & Rochester 1959;Yamada et al. 2002).

Despite the many methodological differences all of the comparable total face height measurements for the infants in the current study are within 2 mm of the results of the direct anthropometric study in North America (Farkas 1994a). However, in the current study the mean lower face heights at 1 and 2 years are greater than those in the Farkas study whereas the upper face heights are less. This is probably due to the lip apart pose in the current study increasing the lower face height and the different definition of nasion decreasing the upper face height.

Only the face depth measurements for 38 infants at 1 year and 62 infants at 2 years recorded using direct anthropometry are available for comparison with our study (Farkas 1994a). In our study the measurements of upper face depth, from otobasion inferius to nasion, were found to be 2 to 3 mm greater than the measurements in the North American

group, who were measured from tragion to nasion. The measurements of maxillary depths in the current study were 3 to 4 mm less than those of the American study and mandibular depths were 15 to 17 mm less. These differences can be explained by the use of otobasion inferius instead of tragion to measure face depths in our study.

A consistent finding in the current study was that the right face depth measurements were larger than the left. These differences were all significant at 1 and 2 years of age. This finding has not been reported in any other study of infants. Right sided dominance has been reported in many studies of older children and adults using craniometry (Woo 1931), direct anthropometry (Farkas & Cheung 1981;Shaner et al. 2000;Skvarilova 1993) and posteroanterior radiographs (Shah & Joshi 1978). However, left sided dominance has also been reported (Chebib & Chamma 1981;Vig & Hewitt 1975). Some studies have found no differences (Peck et al. 1991) and other studies have reported varying asymmetry in the face (Ras et al. 1994). These variations in the findings of facial asymmetry may be due to the wide varieties of subjects, types of data, techniques of data capture and differences in treatment of the data. The clinical significance of this right sided dominance is still to be determined.

6.3.4 Eye Measurements

Biocular and intercanthal widths were found to be significantly larger in males than females at all ages except intercanthal width at 1 year. This is not consistent with the findings of Farkas in a direct anthropometric study of infants where no significant differences were found (Farkas et al. 1992b). In an indirect anthropometric study of Scandinavian children intercanthal width was found to be larger in females than males from birth to 1 year, thereafter that of boys was larger (Strömland et al. 1999). This was a cross sectional study with around 20 males and 20 females examined at both 1 and 2 years. A further 20 males and 20 females were examined under 1 year of age but their exact ages were not specified and the results for all infants under 1 year were grouped together casting doubt on the validity of these findings. In a study of Japanese infants no significant differences were found between the male and female intercanthal widths from 4 months to 3.5 years although there was a tendency for the males to be larger (Yamada et al. 2002). A study of orbital dimensions of 200 newborn infants in Bulgaria using direct anthropometry confirmed that the mean intercanthal and biocular widths were significantly smaller in females than males (Madjarova et al. 1999). Infants under 5 days showed a mean intercanthal width of 21.8 mm in males and 20.9 mm in females, and were much lower than the results of the current study at 3 months of 26.2 mm for females and 27.2 mm for

males suggesting considerable growth in this variable from birth to 3 months. The measurements of intercanthal widths found in the current study were similar to the measurements of Japanese infants (Yamada et al. 2002) but 1 to 2 mm larger than North American infants (Farkas et al. 1992b). The biocular widths in the current study were several mm smaller than the results of Farkas, with a mean of 76.0 mm for 1 year old males in the North American study compared to 72.4 mm in the current study and similar differences being found for female subjects (Farkas 1994a). Without direct anthropometric measurements of Scottish children for reference it is difficult to conclude whether these differences were due to ethnic or methodological differences.

Palpebral fissure widths were found to be significantly greater in males than females at most ages, with differences of only 0.5 mm. This was also found in a study of Bulgarian newborns (Madjarova et al. 1999). In the Bulgarian study the right palpebral fissure width was found to be greater than the left. This was also found in the current study at 3 months of age. However at 6 months the left palpebral fissure was greater and at 1 and 2 years there were no significant differences. The North American study found no right or left differences in palpebral fissure widths at 1 or 2 years of age, similar to our study (Farkas 1994a). It is likely that the difference in palpebral fissure widths in our study were simply false positive findings due to the large number of t tests performed.

6.3.5 Nose and Nostril Measurements

All of the nose and nostril measurements except nasal tip protrusion and columella width were larger in males than females at all ages. Similar differences were reported in a direct anthropometric study where no gender differences in nasal tip protrusion or columella width were found (Farkas 1994a). It may be that these nasal parameters are less related to gender and body size and more related to individual variation than the other nasal measurements. In contrast to our study, an investigation of Japanese infants found that only nose width and alar length were significantly greater in males than females at 4 months with no significant differences at 18 months (Yamada et al. 2002).

Most of the nose measurements in our study were within 1 mm of those of Farkas study however nasal dorsum length was up to 4 mm shorter (Farkas 1994a). Nasal dorsum length was also found to be greater in a analysis of lateral cephalograms from the Bolton study (Subtelny & Rochester 1959). These differences were probably due to the different definitions of the point nasion. Nasal tip protrusion and alar length measurements were remarkably similar in the studies. Soft nose width appeared slightly less and anatomic nose

width appeared greater in the Scottish sample compared to the American sample. These differences probably reflect the subtle differences in the definitions of the landmarks. Compared to the current study, a Japanese study found increased measurements for nasal tip protrusion and nose width and smaller measurements for nostril length (Yamada et al. 2002). Once again it is not possible to separate ethnic differences from methodological differences.

An interesting finding in our study was that the left nostril was longer and narrower than the right. This finding was significant at all ages except the difference in nostril long axis which was not significant at 2 years. Comparison of these results with other studies in infants is not possible due to the paucity of research in this area. In the Japanese study the results of the right and left measurements appear to have been combined and do not allow comparison of right and left sides (Yamada et al. 2002). In a comparison of nasal morphology in cleft and control subjects, 19 normal subjects with a mean age of 14 years were examined (Russell et al. 2000). This study found the right nostril was more elliptical and the left nostril rounder in the control subjects which contradicts the results of the current study. The differences in right and left nostril dimensions found in our study only range from 0.1 to 0.4 mm and may not be clinically significant.

6.3.6 Upper and Lower Lip Measurements

Mouth width measurements had large standard deviations and were only found to be significantly larger in males at 6 months. This is probably a reflection of the varying lip positions in the captured images rather than a lack of difference between males and females. The mouth widths in this study were narrower than those of Farkas presumably due to the lip apart pose used in this study. The mouth width measurements found at 1 and 2 years closely approximate those of Farkas with differences of only 0.1 to 1.3 mm (Farkas 1994a). The mean mouth widths of the 3 month infants, 28.5 mm for females and 29.7 mm for males, were very similar to those of the Japanese sample at 4 months of 27.6 mm for females and 28.2 mm for males (Yamada et al. 2002). It was not stated in this study whether the lips were apart or together when recording this measurement although the illustrations show the lips together. If this was the case these results are surprising since the lip together mouth width would be expected to be greater. In a cross sectional study of oral opening in 422 infants ranging from 6 weeks to 36 months, open and closed mouth breadths were measured (Nowak & Casamassimo 1994). The open mouth measurements were similar to those of the current study however they were consistently higher, with differences of 1.0 to 2.1 mm. These findings are surprising since the open mouth

measurements were reported to be for maximum opening. Maximum opening was measured by opening the mouth of the infant with pressure from the operator's fingers until resistance was felt. No repeatability study appeared to have been carried out and these results may not be reliable.

Philtrum width was significantly greater in males than females at all ages with differences ranging from 0.5 mm at 2 years to 1 mm at 3 months. These gender differences were not found in a direct anthropometric study of infants in North America (Farkas 1994a) and the mean values for philtrum width appear greater in the Scottish study with differences ranging from 1.0 to 1.8 mm at 1 and 2 years. No other results for philtrum width in infants have been found in the literature and it is difficult to determine the cause of the differences in the results of these two studies. It is possible that it is due to ethnic differences between the Scottish and North American population but it may be due to the different lip positions in the two studies.

Upper lip heights produced varying results when tested for gender differences. Generally the midline upper lip heights did not show gender differences however the lateral lip heights did. The results of Farkas study are unclear as to which gender differences were significant however it is clear that upper cutaneous lip height and vermilion heights were not significantly greater in males than females (Farkas 1994a). It is difficult to explain why lateral lip heights would show gender differences whereas midline lip heights would not. It may be that the larger values for the lateral heights allowed greater differences which were more likely to be found to be significant. However, it may be that midline lip heights are more independent of body size than lateral lip heights which are influenced by both nose and mouth width. The link between lip measurements, gender and body size is discussed more fully in section 6.3.8.

The mean lower cutaneous lip height was found to be very similar in this study to that of Farkas, however lower lip height was 0.5 to 1.3 mm less in the current study (Farkas 1994a). This is probably due to the use of stomion inferius in the lip apart models to measure lip height rather than stomion in the lip together subjects of Farkas. Similarly upper cutaneous lip heights were similar in the two studies but upper lip height, measured as subnasale to stomion superius, was 0.3 to 2.8 mm lower in the current study. These results confirm that lip apart and lip together measurements should not be combined.

There was a tendency at all ages for the right lip measurements to be greater than the left. These differences were significant for lateral lip height and lower vermilion length at all

ages and upper vermilion length at 6 months and 2 years. These results confirm the findings of right sided dominance found in the face depth measurements.

6.3.7 Angular Measurements

None of the angular measurements were consistently different in males or females. This confirmed the findings of Farkas on a group of 1 and 2 year olds, and the findings of Yamada in groups of 4 month and 18 month infants (Farkas 1994a;Yamada et al. 2002).

The mean nasal tip angle reported in the current study, of 111°, is much higher than both the mean angle reported by Farkas, of 82°, in groups of 1 and 2 years olds, and the mean angle reported by Yamada, of 63°, in groups of 4 month and 18 month infants (Farkas 1994a;Yamada et al. 2002). The difference with Farkas measurements can be explained since the direct anthropometric method of measuring this angle is different from measuring the angle nasion-pronasale-subnasale. In the direct anthropometric technique the angle is determined by intersection of the long axis of the nasal bridge and the tangent to the columella, leading to a much smaller angle than n-prn-sn. The nasolabial angle reported by Farkas was also much lower than the current study due to similar methodological differences. The nasolabial angles reported by Yamada, of 127° in 4 month infants and 120° in 18 month infants, were only slightly lower than those found in the current study of 138° at 3 months and 128° at 2 years. The marked differences in nasal tip angle and lesser differences in nasolabial angle with the Japanese sample are more difficult to explain since these investigators appear to have measured very similar angles with similar landmark definitions and techniques to our study. The only conclusion is that there is a considerable ethnic difference between the nasal angles in Japanese and Scottish infants, with the Scottish infants having more obtuse nasal tip and nasolabial angles. The nasal tip and nasolabial angles in our study are illustrated in Figure 6.6. The nasal tip horizontal displacement angle also appeared to be different in the two samples, being more obtuse in the Japanese group (Yamada et al. 2002).

The labiomental angles recorded in our study had large standard deviations of 9° to 14° reflecting the large variation in this angle in the study sample. These large standard deviations were also found by Farkas. The labiomental angles measured in Farkas North American sample of 1 and 2 year olds were around 10° less than those in the current study (Farkas 1994a). Once again the different method of recording these angles could explain these differences

6.3.8 Correlations

The significant correlations between weight, length and head circumference were not surprising and were also reported in a Japanese sample of infants (Yamada et al. 2002).

Significant but weak correlations were found between face height, width and depth and body measurements at all ages. This suggests that larger infants have larger faces and may explain the apparent gender differences, since the males were bigger than the females. The correlation of face measurements with each other gave different results at each age. A consistent finding appeared to be the minimal correlations of face heights and face widths suggesting that these parameters are less interdependent than the other facial measurements.

The eye measurements were all significantly correlated with body measurements, a fact which may appear surprising since growth of the orbits and cranium is reported to follow a more neural pattern than the rest of the face (Nanda 1955b). Intercanthal width was also found to correlate significantly with body weight in a group of 4 month infants in Japan, although this finding was not repeated at 18 months or 3.5 years (Yamada et al. 2002). Although growth around the eyes may not be expected to correlate with body measurements, the initial dimensions do appear to correlate with body size. The minimal correlations of intercanthal widths and palpebral fissure widths with each other found in this study have not been reported elsewhere and suggest these parameters are more independent of each other than anticipated.

Nose measurements all correlated significantly with body measurements except nasal tip protrusion. Nasal tip protrusion was no larger in males than females and so this finding confirms that this parameter is not linked to body size. This finding contradicts the finding in a group of Japanese infants where nasal tip protrusion was significantly correlated with height and weight in the 4 month infants but not in the 18 month group (Yamada et al. 2002). Conversely this latter study found no correlation between nose width and body size.

Few of the nostril measurements in the current study were significantly correlated with body measurements suggesting that nostril size is less related to body size than other facial parameters. Columella width did not correlate with nasal tip protrusion, a finding which may show that these parameters are fairly independent of each other and consistent with the finding that they were not significantly different in males and females.

The correlations of lip measurements with body measurements were variable but one consistent finding was the correlation of mouth width and vermilion lengths with body measurements. This is surprising since no significant gender differences were found in mouth width, except at 6 months. This finding confirms the belief that mouth width is linked to body size and gender and that the lack of significant gender differences can be attributed to the relatively large standard deviations and variable lip positions. The midline upper and lower lip length measurements were not consistently correlated with body measurements, consistent with the lack of gender differences in these measurements. This lack of correlation of lip height and body size was also found in the Japanese study (Yamada et al. 2002). Similar to nasal tip protrusion and nostril measurements, midline lip height measurements may be relatively independent of body size and gender.

Despite occasional significant correlations the angular measurements appeared to be fairly independent of body size. The significant correlation of nasal tip angle with both nasal tip horizontal displacement angle and nasolabial angle is not surprising since all of these angles incorporated the same pronasale landmark.

6.3.9 Asymmetry

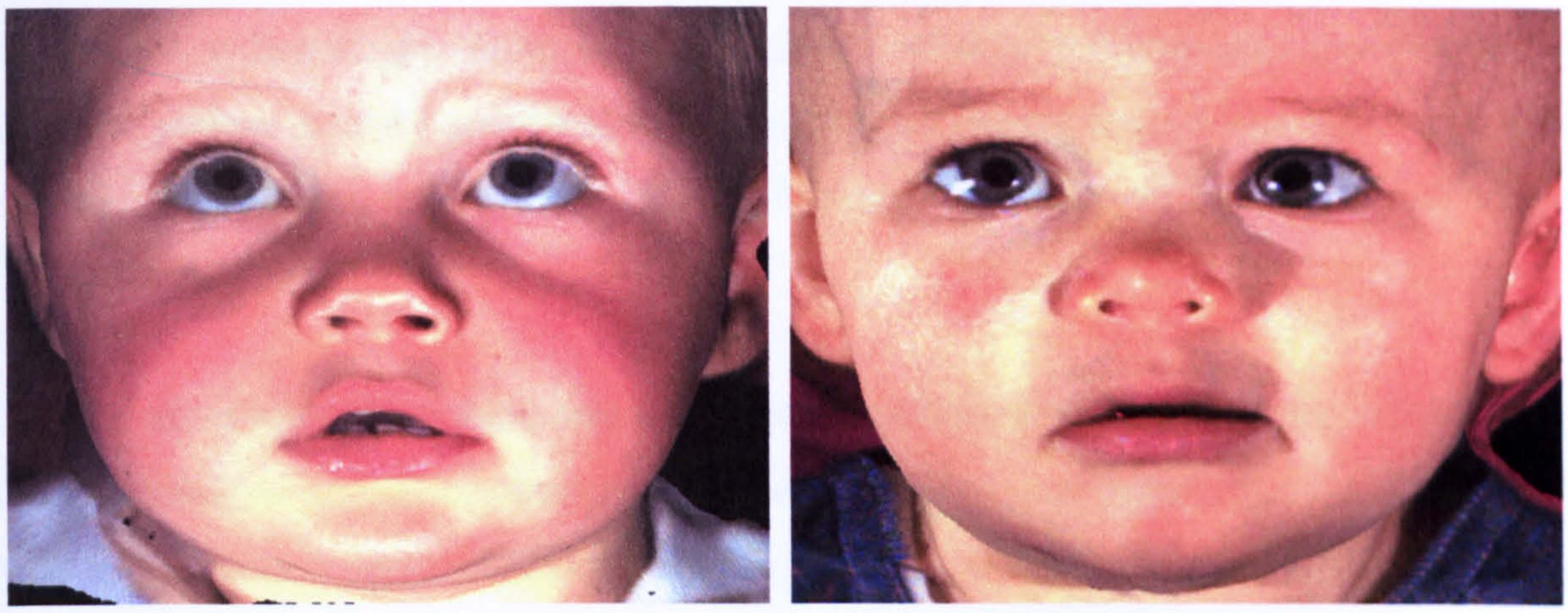
The asymmetry scores for the subjects at all ages were not normally distributed however the fourth roots of the asymmetry scores were well approximated by a normal distribution. This is not surprising since the asymmetry scores arise as sums of squared distances. Transformation of the data in this way is a well recognised method of providing normally distributed data which can be analysed with parametric tests (Bland 1990;Cressie 1995).

There was a tendency for the asymmetry scores to be lower in the females than the males, however the only significant gender differences were nostril asymmetry at 3 months, upper face asymmetry at 1 year and nasal rim and nostril asymmetry at 2 years, with p values of 0.005 to 0.034. It is possible that these were false positive findings since so many t tests were carried out.

Despite the many advantages of the asymmetry score already discussed, a possible problem with the asymmetry score is the lack of units and therefore difficulty in interpretation. It could be concluded that the infants in this study showed a degree of facial asymmetry, but an understanding of this degree can only be appreciated once the score has been in clinical use for some time and the range of normal values and pathological values have been determined. As an illustration, the range of normal values of the sqrt/sqrt

asymmetry score for the face ranged from 0.08 to 0.15 with means around 0.10 at all ages. In a parallel study of infants with cleft lip and palate the mean sqrt/sqrt asymmetry score was 0.25 prior to lip repair and 0.15 postoperatively (Bock & Bowman 2004). It can be clearly seen from this example that the cleft subjects were more asymmetric than the control subjects prior to lip repair and that postoperatively the asymmetry scores were closer but still significantly higher than in the control group. The highest and lowest scores for the non cleft subjects are illustrated in Figure 6.5.

Figure 6.5 Range of Asymmetry Scores



a) Sqrt/sqrt AS = 0.08 **b) Sqrt/sqrt AS = 0.15**

Figure 6.5 shows that the difference of asymmetry scores in the subjects was not clinically obvious. The range of scores representing clinically evident asymmetry needs to be determined before the clinical significance of the facial asymmetry scores can be fully understood.

6.4 Longitudinal Results

6.4.1 Growth in Body Measurements

The growth curves for weight, length and head circumference of the males and females in the study followed the curves of the Gairdner-Pearson charts fairly well. The mean values for weight and length at each age were slightly higher than the 50th centiles (Gairdner & Pearson 1988a;Gairdner & Pearson 1988b). The mean values for head circumference were above the 50th centile at 3 and 6 months but dipped below the 50th centile at 1 year. At 2 years the mean female head circumference increased to slightly higher than the 50th centiles but the male mean stayed below the 50th centile. As discussed in section 6.3.1, the

Gairdner-Pearson charts are considered to be out of date (Wright et al. 2002). It is likely that the growth of the infants in this study would conform more closely to a growth chart based on the UK90 data (Freeman et al. 1995). The results of the current study confirm those of numerous others that growth in body weight and length is most rapid in the first year and slows only slightly in the second year of life, with little difference in growth rates of males and females. In contrast the growth in head circumference follows a more neural pattern, growing rapidly in the first year and slowing dramatically in the second year.

6.4.2 Growth in Face Height, Width and Depth

The growth in face height, width and depths from 3 months to 2 years was shown to follow a similar pattern to body growth with the most rapid growth from 3 to 6 months and the slowest growth from 1 to 2 years. These findings are similar to those of other studies (Farkas et al. 1992a).

The growth of upper face depth was faster than maxillary depth up to 1 year, reflecting the neural pattern of growth in this area. Mandibular depth grew faster than maxillary depth from 6 months to 2 years which confirms the findings of Farkas in a cross sectional direct anthropometric study of 1 and 2 year olds (Farkas et al. 1992a). This differential growth of the mandible is a well recognised phenomenon (Enlow & Hans 1996).

Upper face width grew more than lower face width at all ages, once again showing a more neural growth pattern. However, the analysis of growth in upper face width from 1 to 2 years should be interpreted with caution since upper face width measurements were not available for 39 of the 71 cases from 1 to 2 years due to the missing ear landmarks.

The slowing of growth rate after 6 months was not so marked for face height as is was for face depth and width. This is consistent with the results of Farkas who showed that by 1 year total face height was 68% of adult size whereas mandibular width was 80% and maxillary depth was 77% (Farkas et al. 1992a). The pattern of growth of the face height from 3 months to 2 years therefore resembles the growth of the body skeleton rather than neural growth. This was also found in a longitudinal cephalometric study of subjects from 4 to 16 years (Baume et al. 1983).

The only marked difference in growth of the males and females was found in maxillary depths which grew significantly more in females than males from 1 to 2 years with mean differences of 3.4 and 3.7 mm ($p=0.002-0.005$). This was found at a later stage in the study

by Farkas where growth of the maxillary depth slowed from 2 to 3 years in males then the males grew more from 3 to 4 years (Farkas et al. 1992a). This latter study was based on cross sectional data with around 30 males and 30 females at each age therefore the apparent growth spurt may have been due to differences in the groups. Although the current study was truly longitudinal in nature it is possible that the difference in growth of the maxilla in males and females was simply a chance finding. Further study of this group of infants at later stages of development would confirm whether the greater maxillary growth of females was maintained.

Other significant differences in the growth of males and females were minimal and inconsistent. Significantly greater growth in upper face width was found in females from 6 months to 1 year ($p=0.03$) with a mean difference of 1.6 mm. Growth in upper face height in males from 3 to 6 months was also greater ($p=0.05$) with a mean difference of 0.6 mm. It is possible that these were false positive findings due to the large number of t tests performed.

6.4.3 Growth Around the Eyes

Growth around the eyes was greatest from 3 to 6 months and least from 1 to 2 years, as expected. This reduction in growth was most marked for intercanthal width, consistent with previous reports (Farkas et al. 1992b;Strömland et al. 1999). In the former study, intercanthal width was reported to be 84% of the adult width at one year and reached full maturation in males at 11 years and females at 8 years. A more continuous growth of biocular width was found in the current study and the North American and Scandinavian studies.

The only difference in growth of the males and females around the eyes was a greater growth of biocular width in females from 1 to 2 years ($p=0.03$) with a mean difference of 0.7 mm. It is possible that this was a false positive finding although it did correspond to a greater growth in upper face width in females at the same time period.

6.4.4 Growth of the Nose and Nostrils

Growth of the nose measurements was fairly continuous but slow from 3 months to 2 years. However nasal tip protrusion did not grow significantly from 3 to 6 months then increased 10.0% from 6 months to 1 year and 8.3% from 1 to 2 years. In a direct anthropometric study, nasal tip projection was shown to be at the least developmental level

of any of the nose or lip measurements at 1 year (Farkas et al. 1992c). Growth of the nose is known to occur late, with the major changes occurring from 7 to 12 years in both sexes. Nasal projection then changes little in females but can continue to grow up to 4 to 5 mm in males from 12 to 17 years (Genecov et al. 1990). The findings of the current study were consistent with these results.

The total growth of the nostril widths and lengths was similar from 3 months to 2 years. However, most of the growth in the long axis occurred from 3 to 6 months, whereas the growth in width was fairly continuous. These differences in growth although statistically significant, only ranged from 0.25 to 0.37 mm and were probably not clinically significant. The mean growth of the columella width was only 0.6 mm from 3 months to 2 years showing very slow growth in this area. Details of growth of the nostrils at this age do not appear to exist in the literature and this data could be useful in assessing reconstructive surgery in infants with cleft lip and palate.

6.4.5 Growth of the Upper and Lower Lips

Growth of the lips from 3 months to 2 years was varied with percentage increases ranging from 0 to 16%. The longitudinal assessment of the lips may have been adversely affected by varying lip posture and, as expected, the standard deviations of the lip measurements were high. Nevertheless the growth curves for the lips do follow a pattern similar to those of the nose and face with the most rapid growth from 3 to 6 months and the least growth from 1 to 2 years. The growth curves for the upper lip length and mouth width were similar to those found in a cross sectional study of Scandinavian children (Strömland et al. 1999). Comparing the lip measurements in the current study to the adult dimensions reported by Farkas, it could be concluded that by 3 months the upper cutaneous lip height had achieved 75% of its eventual adult size, and 83% by 2 years (Farkas et al. 1992c). This would therefore explain the relatively slow grow of the cutaneous lip heights found in our study from 3 months to 2 years. Considerably more growth was found in upper vermilion height than upper cutaneous lip height from 3 months to 2 years with a mean increase of 18%, compared to 7% for cutaneous lip height. These results confirm the findings of Farkas who reported that by 1 year upper cutaneous lip height had achieved 80% of the adult dimension but vermilion height had only achieved 64%. Knowledge of this differential growth of the cutaneous and vermilion parts of the upper lip would be helpful in planning reconstruction of congenital lip deformities.

Significantly greater growth in lower right vermilion length was found in females from 6 months to 1 year (p=0.02) and in the right lateral lip height in females from 1 to 2 years (p=0.04) although the mean differences were only 0.7 mm. Once again it is possible that these were false positive findings due to the large number of t tests performed

6.4.6 Growth Changes in Angular Measurements

Nasal tip angle (n-prn-sn) did not change significantly from 3 months to 2 years however the nasal tip horizontal displacement angle and nasolabial angle decreased by 7° and 10° respectively. This could be explained by a downward and forward displacement of the tip of the nose with growth in nasal protrusion being greater than growth in nose width. The change in nasolabial angle could also be explained by forward growth of the upper lip. These changes are illustrated in Figure 6.6.

Figure 6.6 Growth Changes in Nasolabial Angle from 3 months to 2 years

a) 3 Months **b) 2 Years**

These findings are similar to the results of a direct anthropometric study of the nose where nasal tip angle did not change but nasolabial angle decreased up to 1 year, although nasolabial angle was then found to increase from 1 to 2 years (Farkas 1994a). In a cross sectional study of Japanese infants nasal tip angle did not change markedly, nasolabial angle reduced from 4 months to 1.5 years but then increased again slightly at 3.5 years and nasal tip horizontal displacement angle decreased gradually from 4 months to 3.5 years. (Yamada et al. 2002). These results were consistent with the changes in the nasal angles found in our study.

The lack of change in labiomental angle and the large standard deviations are not surprising and are probably influence by the inconsistent lip positions of the infants over time. The labiomental angles reported by Farkas in 1 to 5 year olds also show large standard deviations and inconsistent changes with age (Farkas 1994a).

6.4.7 Growth Correlations

The lack of correlation of growth in facial dimensions with growth in body dimensions is surprising since there were significant correlations between the size of the face and the size of the body at each age. This finding may be due to the statistical effect of small increments of growth making a significant correlation difficult to find. However growth of the face is known to be a differential process with growth around the eyes occurring early and growth of the nose occurring late. It is likely that these timing effects have a greater influence on growth of the face than general skeletal growth and may account for the lack of correlation in body and face growth. A further illustration of the differential growth of the face is the lack of correlation between the growth of upper and lower face heights.

No significant correlations were found between the growth of the right and left depths of the face from 3 to 6 months, although these were correlated at the later stages. This is surprising since no significant change in right or left dominance or asymmetry was found from 3 to 6 months. It is likely that the small magnitude of change from 3 to 6 months, the large standard deviations and slight errors in landmark location could have contributed to this unusual result.

The correlation of maxillary growth with upper face growth was high until 1 year but dropped in the second year whereas the correlation of upper face and mandibular depth growth was low initially but later increased. This is probably a reflection of the fact that mandibular growth increased but maxillary growth remained the same in the second year of life.

The correlations between the growth of the eye measurements were significant but weak, once again showing the differential growth of the face with greater growth of the biocular width than the intercanthal width. Since the biocular width encompasses the palpebral fissures and the intercanthal width it is not surprising that the growth in biocular width had a strong correlation with growth of the palpebral fissures.

A negative correlation was found between nasal dorsum growth and nasal tip protrusion. Both of these measurements depend on the landmark pronasale which had a repeatability score of 0.4 mm. Placing the point pronasale further up would increase the nasal tip and decrease the nasal dorsum and vice versa. It is therefore probable that this negative correlation was due to variation in the placement of the point pronasale. Similarly the negative correlation between philtrum width growth and upper vermilion length growth could be explained by variation in placement of the landmark crista philtri.

The lack of correlation of mouth width growth with upper vermilion length growth is probably due to the variation in lip positions in the longitudinal data. However, mouth width growth did correlate with lower vermilion growth suggesting that lower vermilion length and mouth width are affected similarly by varying lip positions. There was also a lack of correlation between upper cutaneous lip height and upper vermilion lip height. The different growth of the cutaneous lip height and vermilion lip height was also noted by Farkas in a cross sectional study of lip growth (Farkas et al. 1992c). In that study it was reported that by 1 year the cutaneous portion of the upper lip height was 80% of its adult size but the vermilion portion was only 64%.

The significant correlation between the changes in nasal tip angle and nasolabial angle could also be explained by variation in location of the landmark pronasale. If this landmark was placed higher on the nose both angles would be reduced and if it was lower on the nose both angles would be decreased. This is a random error which may account for the high correlation of the changes in these angles but it does not influence the significance of the changes found in these angles with time.

6.4.8 Longitudinal Changes in Asymmetry

The asymmetry scores for the face results showed a slight reduction from 3 months to 2 years. The overall reduction from 3 months to 2 years was significant although the changes between each time point were not. Further study of the asymmetry scores is needed to determine whether this decrease was clinically significant.

When the asymmetry score was split into the different regions of the face, the upper face was found to be the most asymmetric and the nostrils were the least asymmetric. All of the asymmetry scores tended to decrease with age except the nasal rim which became more asymmetric with age.

There are no studies of asymmetry in infants for comparison of these results. The results of previous investigations of asymmetry on children and adults gave conflicting results. A study of posteroanterior cephalograms of children from 9 to 18 years found greater asymmetry in the cranial base and maxillary regions than in the mandibular and dentoalveolar regions (Vig & Hewitt 1975). A similar study in adults found the lateral maxillary region exhibited a greater degree of asymmetry than other components of the face (Shah & Joshi 1978). A further cephalometric study of adults with aesthetically pleasing faces found that asymmetry of the face increased from the orbits to the mandible (Peck et al. 1991). A study of twins from 9 to 15 years of age found the greatest asymmetry in the maxillary structures but serial evaluation showed no change in the individual's asymmetry over time (Mulick 1965). An anthropometric study of children from 6 to 18 years of age found the largest asymmetries in the upper third of the face but sex and age did not significantly influence the extent of the asymmetries (Farkas & Cheung 1981). A longitudinal study using stereophotogrammetry in children from 8 to 19 years could not relate asymmetry to age (Burke & Healy 1993). In a mixed longitudinal study of 63 controls aged 6 to 12 years, an increase in the asymmetry in the basal region of the nose with growth was found (Ras et al. 1995a). A more recent study investigating the effects of age and sex on soft tissue facial asymmetry was carried out on 314 subjects from 12 to 56 years of age using 3D facial morphometry (Ferrario et al. 2001). No gender or age related differences were found. Endocanthion was the least asymmetric landmark whereas tragion, gonion and zygion were the most asymmetric.

The slight reduction in asymmetry from 3 months to 2 years has not been reported elsewhere. The lack of significant gender differences in asymmetry were in general agreement with previous studies in children and adults. The finding of the greatest asymmetry in the upper face is in agreement with some studies (Farkas & Cheung 1981;Vig & Hewitt 1975). The current study only reported asymmetry from the upper lip to the eyes and did not investigate mandibular asymmetry or lateral facial asymmetry. This was due to the frequency of missing landmarks in the periphery of the face, and the possible influence of the lips apart posture on the symmetry of the lower face.

Further study of this group of infants at later ages would reveal whether the gradual decrease in asymmetry continued and whether the upper face remained the most asymmetric region of the face. Further investigation of the landmark coordinates would allow more detailed understanding of the asymmetry of the individual landmarks.

6.5 Future Research

There have been several recent advances in the C3D technology. The improved image quality means that stereomatching can be performed on the colour images without projecting a random texture pattern onto the face. This will allow faster capture of infants and eliminate the need to test for movement with the Check Align programme. This will also hopefully provide better quality models with smoother surface and without the merge line. A three pod system, with a central as well as right and left pods, would provide better coverage of the face including the ears and would allow more detailed analysis of the face depths as well as ear morphology. Further development of the C3D software will hopefully decrease the operator time required to build and edit the models. In the future semi automatic landmark extraction could significantly reduce operator time and reduce errors (Naftel & Trenouth 2004;Yamada et al. 1999).

The stereophotogrammetry system used in this study could also be applied to study facial growth in children and adolescents, to assess the effect of different treatment regimes such as twin block therapy on the soft tissues, to assess orthognathic surgery and facial animation.

Further analysis of the subjects in this study will involve curve analysis, principle component analysis of the landmark configurations, analysis of surface area and volumes and conformed meshes. These techniques will allow analysis of the shape of the face and provide more comprehensive understanding of the growth of the soft tissues of the face and the nature of any sexual dimorphism.

The data collected in this study has formed a control group for comparison with a group of infants with cleft lip and palate. The results of this larger study are still being analysed although some preliminary results have been published (Hood et al. 2004). This study will allow comprehensive assessment of pre and post operative cleft deformity with a long term goal of improving the care of patients with cleft lip and palate.

Development of the asymmetry score described in this study will allow the analysis of asymmetry of curves and meshes as well as landmarks. The asymmetry score can also be decomposed into three different types of asymmetry, positional, orientation and intrinsic asymmetry (Bock & Bowman 2005). This will be useful in determining the cause of asymmetry as well as the amount and will be helpful in surgical planning and assessment.

The range of scores representing clinically obvious asymmetry needs to be determined before the clinical significance of the facial asymmetry scores can be fully understood.

It is intended to continue this longitudinal study with the next data collection planned when the subjects are 5 years of age. Analysis of the children at this stage will allow further quantification of facial growth and assessment of longitudinal changes in asymmetry and shape.

7 Conclusions

7.1 Subjects

The subjects in this study formed a fairly representative sample of Caucasian infants in the West of Scotland to establish normal facial dimensions and growth.

7.2 Method & Validation

The C3D system and Facial Analysis Tool described in this thesis were appropriate methods to capture the faces of infants in 3D and study facial morphology and growth. The mean C3D system error, including operator, capture and registration error, was found to be 0.83 mm. The landmark reproducibility scores ranged from 0.24 to 0.70 mm which was judged to be clinically acceptable. The lip apart pose was a repeatable expression in this group of infants with a mean error standard deviation of 0.67 mm between measurements on repeated expressions. The most stable measurements were around the eyes and nostrils and the greatest variations were in face height.

7.3 Facial Morphology

Normal values for facial dimensions in males and females have been established for infants at 3 months, 6 months, 1 year and 2 years of age.

Correlation of facial measurements with body measurements found weak but significant correlations with the highest correlations between face depth and body weight, with correlation coefficients ranging from 0.27 to 0.69. Nasal tip protrusion, nostril dimensions and lip heights were not correlated with body dimensions showing these parameters were relatively independent of body size.

7.4 Facial Growth

The longitudinal changes in facial parameters from 3 months to 2 years have been established and mean growth curves have been produced. There was significant growth of all facial dimensions from 3 months to 2 years. The fastest growth was from 3 months to 6 months and the slowest from 1 year to 2 years for all of the measurements except nasal tip protrusion. This reduction in growth rate was most marked for intercanthal width.

The greatest growth was in face depth and height with a mean of 16.5 mm (23%) growth in mandibular depth and 14.5 mm (21%) growth in total face height from 3 months to 2 years. There was less growth in face widths with a mean of 13.9 mm (15%) growth in lower face width from 3 months to 2 years. Mandibular depth grew 3.1% more than maxillary depth from 6 months to 2 years showing early differential growth of the mandible.

The least growth was found in the cutaneous lip heights, with a mean of 0.7 mm (7%) growth in the upper and 0.4 mm (7%) growth in the lower from 3 months to 2 years. In contrast the upper and lower vermilion heights grew markedly in this time with mean increases of 18% and 37% respectively, although this only equated to 1.0 mm and 2.1 mm of growth. Mouth width also grew considerably more than lip height with a mean increase of 5.8 mm (20%) from 3 months to 2 years.

Nasolabial and nasal tip horizontal displacement angles decreased significantly from 3 months to 2 years however nasal tip angle did not change significantly in this time. This could be explained by a downward and forward growth of the nasal tip consistent with the findings of greater growth of nasal tip protrusion (21%) than nasal width (13%). Nasolabial angle could also have been decreased by forward growth of the upper lip.

There was no correlation between growth of the face and growth in body weight, length and head circumference. This was consistent with the finding that growth of the face was a differential process with growth around the eyes occurring early and growth of the nose occurring late.

7.5 Sexual Dimorphism

Statistically significant gender differences were found for most facial measurements at all ages with the males being larger than the females. These differences were greatest for face height, depths and widths from 3 months to 1 year with mean differences ranging from 1.7 to 4.0 mm. From 1 to 2 years maxillary depth grew significantly more in females and by 2 years there was no gender difference in this measurement. Other differences in growth of males and females were inconsistent and minimal and probably false positive findings.

Gender differences were not found in nasal tip protrusion or columella width at any age consistent with the finding that these were not correlated with body dimensions. Gender differences were inconsistently found around the lips. Although midline lip heights did not frequently correlate with body size, mouth width, lateral lip heights and vermilion lengths

did. It may be concluded that, like nasal tip protrusion and columella width, midline lip heights were relatively independent of body size whereas the variation in lip positions may have masked any gender differences in mouth width, lateral lip heights and vermilion lengths

There were no gender differences in the facial angles measured or in the change of these angular measurements with growth.

7.6 Facial Asymmetry

There was a strong tendency for the dimensions on the right side of the face to be larger than the left. This was most marked for face depths with mean differences of 0.8 mm. The clinical significance of this right sided dominance is still to be determined. The left nostril was consistently found to be longer and narrower than the right. These differences of 0.1 to 0.4 mm, although statistically significant, may not be clinically significant.

The facial asymmetry score described in this thesis is an objective and practical method of assessing facial asymmetry in 3D. The range of scores representing clinically obvious asymmetry needs to be determined before the clinical significance of the facial asymmetry scores can be fully understood.

Facial asymmetry was found in all of the infants with sqrt/sqrt asymmetry scores ranging from 0.08 to 0.15. No significant difference in asymmetry was found between the males and females although there was a tendency for the female scores to be lower. The upper face was found to be the most asymmetric region studied and the nostrils were the least asymmetric. Mandibular and lateral facial asymmetries were not investigated in this study due to the possible influence of the varying lip positions and the frequency of missing peripheral landmarks.

There was a slight tendency for asymmetry to decrease from 3 months to 2 years, with significant reductions in the overall facial asymmetry score as well as the individual asymmetry scores for all the regions of the face except nasal rim asymmetry. Further study of the asymmetry scores is needed to determine whether these decreases are clinically significant. Analysis of the subjects at later ages will reveal whether this gradual reduction in facial asymmetry continued with growth.

7.7 Future Research

The analysis of the data in this thesis is only the first stage in the investigation of the 3D facial models collected for this study. This simple analysis allows comparison with previous studies, is easily presented and readily understood by clinicians. Further analysis of the 3D landmark configurations using principal component analysis will allow determination facial shape change with growth and any sexual dimorphism in shape rather than size. Investigation of curves and conformed meshes will allow more comprehensive understanding of the 3D facial morphology and growth. A potential problem with these geometric morphometric techniques is presenting the results in a manner comprehensible to clinicians.

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Appendices

Appendix 1 Subject Information and Consent Form

3 Dimensional Assessment of Facial Growth

Jill White

Parents information sheet

Surprisingly very little work has been done to find out how normal babies faces grow although there have been many studies on adolescents and teenagers.
We are currently investigating the effects of surgery on babies with cleft lip and palate but because we don't know how a normal child's face develops we do not know how the surgery is affecting their growth.
We are therefore planning to assess facial growth in normal children and compare this to the growth of children with cleft lip and palate

We now have a new way of recording the shape of the face in three dimensions using two video cameras. This takes only one second to record a picture of the face.
We plan to take pictures of your child's face at 3 months, 6 months, 1 year and 2 years of age. You will be able to see the image on the computer screen within 5 minutes. You will be given a complementary copy of your child's picture. We will also measure your child's height, weight and head circumference at each visit in the same way as this is done at your baby clinic. The whole visit should last 20-30 minutes. We are also interested to know your child's height, weight and head circumference at birth so we will contact your GP or maternity hospital to find this out.

The cameras are located at Glasgow Dental Hospital and School, Sauchiehall Street and at the Royal Hospital for Sick Children, Yorkhill. You will be entitled to claim travel expenses for each visit.

The procedure does not expose your child to any radiation. The information collected in the course of this research will be used only for the purpose of the study. Your child's identity will remain confidential at all times. No child will be identified in the publications of the results.

Parents may not wish to take part in the study for a variety of reasons, this does not affect any future treatment for your child. Should you wish to participate in this investigation please sign the consent for overleaf.

Consent Form

	Please initial below
1. I confirm that I have read the information sheet above and have had the opportunity to ask questions.	_____
2. I understand that my child's participation is voluntary and that I am free to withdraw at any time, without giving a reason, without my child's future medical care or legal rights being affected.	_____
3. I understand that participation in this study will have no direct benefit to my child.	_____
4. I understand that sections of my child's medical notes may be looked at by responsible individuals from Glasgow Dental Hospital. I give permission for these individuals to have access to my child's records.	_____

I, _____(*name of person signing consent*) agree for

_____(*name of child*) to take part in the above study.

Signature_____Relationship to child_____Date_____

Name of researcher _____

Signature of researcher_____ Date _____

Appendix 2 Parent Questionnaire

SUBJECT NUMBER

NAME

DOB

PLACE OF BIRTH

BIRTH WEIGHT

BREAST FEEDING

ADDRESS

TEL

MUM'S NAME

MOTHER'S PLACE OF BIRTH

DAD'S NAME

FATHER'S PLACE OF BIRTH

ADDITIONAL CONTACT DETAILS

3 MONTH CAPTURE DATE

WEIGHT

LENGTH

HEAD CIRCUMFERENCE

6 MONTH CAPTURE DATE

WEIGHT

LENGTH

HEAD CIRCUMFERENCE

1 YEAR CAPTURE DATE

WEIGHT

LENGTH

HEAD CIRCUMFERENCE

2 YEAR CAPTURE DATE

WEIGHT

LENGTH

HEAD CIRCUMFERENCE

NOTES

Appendix 3 Publications