Archives of Orofacial Sciences (2010), **5**(1): 1-8

REVIEW ARTICLE

Facial three dimensional surface imaging: an overview

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(Received 18 February 2010, revised manuscript accepted 30 June 2010)

Keywords

laser scanning, facial morphology, stereophotogrammetry, three dimensional imaging.

Abstract The surface facial imagings have many applications in medical fields. The recent past has seen great advances in three dimensional imaging which include laser scanning or stereophotogrammetry. Here, we reviewed various systems with reference to image acquisition, advantages and disadvantages. Examples of important clinical application with reference to the human face are also discussed. Finally, a 3D imaging system at Universiti Sains Malaysia (USM) is described.

Introduction

The assessment of facial dimensions is of prime importance in the medical and dental fields in diagnosis and treatment planning. Since orthodontists, maxillofacial and plastic reconstructive surgeons often require quantitative information about the relations of hard and soft tissue. For many years, Farkas applied direct anthropometry technique for studying facial morphology (Farkas, 1994). This approach has been applied to study facial growth and to compare patients' phenotype to the norms of population (Farkas, 1994; Farkas, 1996). Anthropometry has the advantages of being inexpensive, simple to be applied and relatively non-invasive (Farkas, 1996, Allanson, 1997). Limitations of this approach include the need for subject's cooperation, longer time for data acquisition and capturing (Guyot *et al.*, 2003).

Cephalometric x-ray has been widely applied in the study of hard tissue morphology, prediction of changes related to the growth and quantitative assessment of references data (Thilander *et al.*; 2005; Inada *et al.*, 2008). It is also an important tool for diagnosis of craniofacial abnormalities and planning of treatment modalities (Uysal *et al.*, 2009). Errors in analysis due to magnification, superimposition of structures, limited experience and difficulty in landmark determination are common in this method (Kamoen *et al.*, 2001; Sayinsu *et al.*, 2007).

Photogrammetric digital imaging is a non-invasive, inexpensive and commonly used method to investigate pre and post-operative changes and provides a permanent record of patients (Ettorre *et al.*, 2006). The recent spread and development of digital 2D imaging has made it an essential and routine part of medical practice (Paredes *et al.*, 2006). Digital imaging has many advantages such as direct display of the image and simplicity in manipulation. Furthermore, data can be stored or managed in a digital format that makes measurements applicable (Ettorre *et al.*, 2006). This approach has been used to acquire facial norms of populations, detect inter ethnic variations and in the diagnosis of dysmorphic children (Choe *et al.*, 2004; Boehringer *et al.*, 2006).

Advance in technology, have now allowed three dimensional (3D) imaging such as the computed tomography (CT) (Hajeer *et al.*, 2002; Hajeer *et al.*, 2004). These technologies need expensive equipments, however its ability to determine the soft tissue features is limited (Honrado and Larrabee, 2004; Ayoub *et al.*, 2007). Moreover, ethical considerations preclude major use of radiation for facial studies (Bourne *et al.*, 2001). For these reasons, 3D surface imaging techniques such as laser scanning and stereophotogrammetry have been developed to capture the soft tissue

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facial structures (Ayoub *et al*., 2003; Holberg *et al*., 2006; De Menezes *et al*., 2009). Three dimensional surface imaging has become more common in computer animation and movies, but its application in medicine and dentistry is new especially in Malaysia. In addition most articles of 3D imaging in medicine highlighted the technical aspect of surface imaging such as mathematical algorithms and analysis (Halazonetis, 2001; Riphagen *et al*., 2008). This overview aims to provide the reader with overview of various 3D imaging techniques, its application in medicine and dentistry including advantages and disadvantages. This study also introduced and highlighted a 3D imaging system at Universiti Sains Malaysia (USM).

Background

In the 1960s and 1970s, creation of 3D views from two dimensional images was presented and algorithms for stereo reconstruction followed (Marr and Poggio, 1976). Among the earliest systems of measuring the spatial relationships, Ras *et al*. (1996) presented the three dimensional imaging as a new method for quantifying facial morphology and detecting changes in facial growth. The rapid development in computer technology opens new perspectives to improve 3D imaging. Large amounts of data were presented and further facial analyses were developed, especially when comparisons were made on models of the face to show the regional differences among the compared samples (Ayoub *et al*., 2003; Littlefield *et al*., 2004).

3D surface imaging

After data acquisition, several steps are needed to be conducted to create 3D surface images (Seeram, 1997; Riphagen *et al*., 2008). The first step includes the production of geometric mode of visualization or wireframe which is made up of a series of x, y and z landmarks coordinates. Mathematical algorithms are used to connect the points with each other and expressed 3D model in triangles or polygons. In the second step, colour information is added to the wireframe, which consists of a layer of pixels called texture mapping. The other step is to add shading and lighting, which brings more reality to the 3D object obtained. The final step is called rendering, in which the computer converts the anatomical data into a life-like 3D object viewed on the computer screen. Improvement of computer-vision tools makes it possible to conduct all measurements on 3D and subsequently statistical shape analysis can be applied (Moss, 2006; Weinberg *et al*., 2006).

Laser scanning

This technology depends on projecting a known pattern of laser light onto the object of interest which is based on geometric principles to create a 3D model of the object (Majid *et al*., 2007). Many studies test the accuracy and precision of laser scanner utilizing digital calipers (Kau *et al*., 2005; Gwilliam *et al*., 2006). The results showed that the accuracy of laser scanner was less than 2mm in the plaster model with a precision of 0.8 - 1mm on the human face. Laser scanning gives a noninvasive, accurate, and reproducible means for medical applications (Hajeer *et al*., 2002). However, this technology does have its shortcoming such as long scan time, making it difficult to apply for children (Bozic *et al*., 2009), and, the laser scanner is unable to capture soft tissue texture which results in difficulties in identification of landmarks. Moreover, the patient's eyes must also be closed for protection and the head must be kept in a fixed position (Honrado and Larrabee, 2004).

Stereophotogrammetry

The basic principle of the stereophotogrammetry is the use of 2 or more cameras configured as a stereo pair to capture simultaneous images of the subject (Kau *et al*., 2007). The cameras are placed apart from each other and the subject's face is enclosed by a calibration frame or placed in a space in which a calibration object was previously imaged (Majid *et al*., 2005). The cameras focal lengths, their exact position to each other and to the object are calculated during the calibration procedures (Halazonetis, 2001; Majid *et al*., 2005). After that, 3D facial image can be captured and displayed on the monitors so that landmarks can be selected either manually or by using image processing algorithms (Hajeer *et al*., 2004). The acquired 3D coordinates are used to calculate distances between points allowing subsequent 3D reconstruction of the entire face (Littlefield *et al*., 2004).

Many 3D stereophotogrammetric commercial systems are available in the markets. One developed at Glasgow

University Dental School (Siebert and Marshall, 2000), consists of 2 camera stations, each with a pair of monochrome cameras to capture the stereo image and a colour digital camera to capture the skin texture. The face illumination depends on random projected light or on natural lighting (Kau *et al*., 2007). Picture capture takes 50 milliseconds and a computer program constructs a 3D image from the data transferred form each camera station. The system has been validated and its accuracy was reported to be within 0.5mm (Ayoub *et al*., 2003). This system has been tested in the facial morphology of orthognathic patients to detect the magnitude of surgical change, along with the possible postsurgical relapse (Hajeer *et al*., 2004).

Another stereophotogrammetric system is called 3dMD FACE (3dMD; Atlanta, GA, USA), using multiple cameras to capture facial images (one colour and two infrared) with random light projected on the objects surface (Kau *et al*., 2007). The capture time is 1.5-2 milliseconds, which creates less distortion and is more useful for data capture for children with picture accuracy within 1mm (Weinberg *et al*., 2006; Wong *et al*., 2008). The 3dMD system can also capture images rapidly and can accommodate additional cameras with no reduction in capture speed (Weinberg *et al*., 2006). This system has been applied in several studies such as variation in facial morphology (Seager *et al*., 2009) and assessment of facial anomalies (Singh *et al*., 2007; Weinberg *et al*., 2008).

The Di3D, stereo imaging system (DI3D ™ Dimensional Imaging Ltd, Glasgow, UK) uses the commercially available high resolution cameras. The high resolution of the cameras resolves the local details of the face and removes problems associated with texture projection that affects the quality of images and also reduces the time needed for data acquisition. It consists of 2 stations each with 2 high resolution colour digital cameras (4000 pixels×3500 pixels). The capture time is 1ms and system error is in the range of 0.14–0.32mm (Khambay *et al*., 2008).

In comparison with laser scanner, stereophotogrammetry eliminated the need for direct contact and reduced the need for patients' cooperation due to the high speed of data acquisition (Ayoub *et al*., 2003). Moreover, subjects' image can be repeated without any harmful effects on the participant (Wong *et al*., 2008). Stereophotogrammetry has been reported to be accurate and reliable for landmark digitization (Lee *et al*., 2004; Khambay *et al*., 2008) and distance acquisition (Weinberg *et al*., 2006; Wong *et al*., 2008).

Applications of three dimensional surface imaging

Ethnic variation

Facial variations among ethnic groups and populations have been studied using direct anthropometry or by two dimensional imaging (Ngeow and Aljunid, 2009). With the development of the 3D technologies, additional methods in facial evaluation can be applied such as statistical shape analysis (Weinberg *et al*., 2008). In a review of comparisons between various ethnic groups, Lee and Park (2008) utilized laser scanners to evaluate craniofacial dimensions among Korean and Japanese in a sample of 550 individuals. They reported that Japanese showed longer vertical facial height, wider lower facial width and greater inter pupilary distance. The study demonstrated wide variation in facial morphology among Japanese and Koreans. In another study, the laser scanners were applied to compare facial differences among Slovenian and Welsh populations in a sample of 187 subjects aged between 18 and 30 years (Bozic *et al*., 2009). The authors found that male and female faces in Slovenia and in Wales differ in the nasal, zygomatic and mandibular areas. However, the Slovenian mandible is proved to be more protruded as compared to their Welsh counterpart. These studies further suggested that differences in ethnic groups could be useful guides for treatment planning. However, the patient's actual needs and desires need to be taken in account. Another study (Seager *et al*., 2009) applied stereophotogrammetry to compare the average faces for Egyptian and Texas populations with a sample of 186 subjects between 18 and 30 years of age. Significant variation between the populations was recorded whereby Egyptian faces were more prominent in the zygomatic and periocular regions. In contrast, the nasal bridge area is smaller but the lips are larger. Although, the information acquired from these studies refers to soft tissues, the differences could suggest underlying variations in skeletal structures.

Sexual differences

Another application for three dimensional imaging is the assessment of differences between genders. Baik *et al*. (2007) evaluated gender differences in 60 Korean subjects with normal occlusion utilizing laser scanner. Significant differences were recorded in most of the linear measurements, but differences in shape were small. Differences in facial morphology were also assessed in Slovenian and Welsh males and females (Bozic *et al*., 2009). The Wales's population showed differences in the area of the eyes and extended to the zygomatic area. However, Slovenian males exhibited greatest variation in the orbital, nasal, oral and mandibular areas. Gender difference between English males and females were further identified in 350 subjects using a laser scanner (Toma *et al*., 2008). Average facial templates with colour maps and histogram plots were created and superimposed to quantify differences and the results pointed to more prominent eyes and cheeks in females and noses and mouths in males.

Facial growth

Three dimensional surface imaging can evaluate growth changes by studying the variation in sequential captures of faces superimposed on one another (Kau *et al*., 2007). This method of facial assessments give an excellent opportunity since the calculated results may differ from 2D cephalometric studies, possibly because of the limitations of the two dimensional imaging (Paredes *et al*., 2006; Sayinsu *et al*., 2007).

Laser scanner was applied to detect longitudinally differences in facial features in 59 children with normal faces over a 2-year period (Kau *et al*., 2008) and the information was analyzed by superimposition method with changes shown by color mapping. Downward and forward movements were recorded with respect to the noses and lips with increased in the vertical dimension.

Craniofacial anomalies

The facial morphology plays important roles in the diagnosis and treatment planning for many dysmorphic syndromes (Grobbelaar and Douglas, 2007; Hammond, 2007). Classical anthropometry and 2D approaches have been applied in the study of craniofacial anomalies (Farkas, 1994; Boehringer *et al*., 2006) but technical approaches including 3D surface imaging are now available for further differentiation of facial distortions (Hammond *et al*., 2005). These systems quantify different types of anthropometric measurements and allow investigators to develop objective models for identifying syndromic patients (Hammond, 2007).

Stereophotogrammetry was utilized to compare craniofacial morphology of unaffected relatives of individuals with nonsyndromic clefts and matched controls (Weinberg *et al*., 2008). In one study, an attempt has been made to distinguish between those relatives with high susceptibility and those with minor risk under the assumption that relatives with most divergent craniofacial phenotype have the highest susceptibility to cleft lip and palate (Weinberg *et al*., 2008). Significant differences were recorded between the groups. Female relatives were further characterized by increased nasal, upper facial width and midface retrusion, with 30% of the relatives at potential high risk. In males, unaffected relatives demonstrated increase in lower facial height, upper face and cranial base width and decrease upper facial height compared to controls and 50% of the relatives with high risk.

In another study, Weinberg *et al*. (2009) compared 3D images of 80 unaffected parents with cleft children and 80 matched controls. The major features of unaffected parents included greater level of midface retrusion, mandibular protrusion and greater interorbital width. Also, decreased middle, upper facial height and altered breadth of nasolabial structures were recorded. Despite limitations of sample size, these studies suggested specific features for subjects of potential risk of cleft lip/ palate and allowed development of reliable method for assigning unaffected relatives regarding likelihood of suffering from the syndrome. Three dimensional imaging technologies were also used to compare post surgical nasal changes after orthognathic surgery (Singh *et al*., 2007).

Other studies were conducted to evaluate the treatment outcome of facial augmentation in upper lip reconstructive surgery (Downie *et al*., 2009), assess the 3D facial soft-tissue response to transverse palatal expansion (Ramieri *et al*., 2008) or to localize and quantify differences in facial soft tissue morphology in patients with obstructive sleep apnea (Banabilh *et al*., 2009). The importance of these studies is related to the possible changes that can affect the face postoperatively and the role of 3D imaging in demonstrating to patients the potential new facial features that can be achieved.

3D imaging in the School of Dental Sciences "USM"

A stereophotogrammetry system was developed in USM with the collaboration from Universiti Teknologi Malaysia (UTM). In this system, the stereo triangulation algorithms are applied to detect the three dimensional positions of digitized facial landmarks (Halazonetis, 2001). The landmark can then be fixed as the third point of a triangle with one known side and two known angles. The location of a landmark is detected by calculating angles from known points at either end of stereo cameras as shown in Figure 1.

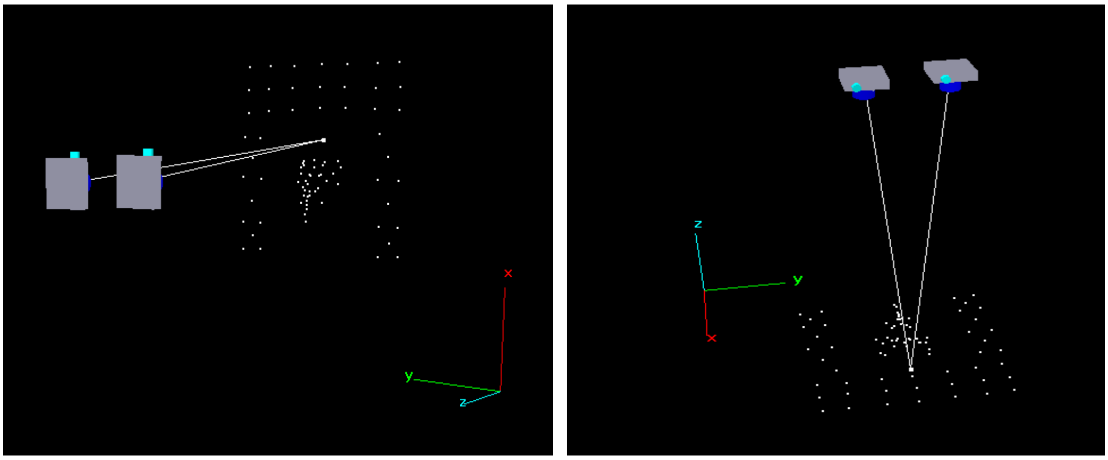

Figure 1 Image created by Australis software where the two imaginary lines intersected and the coordinates on the intersection point could be calculated.

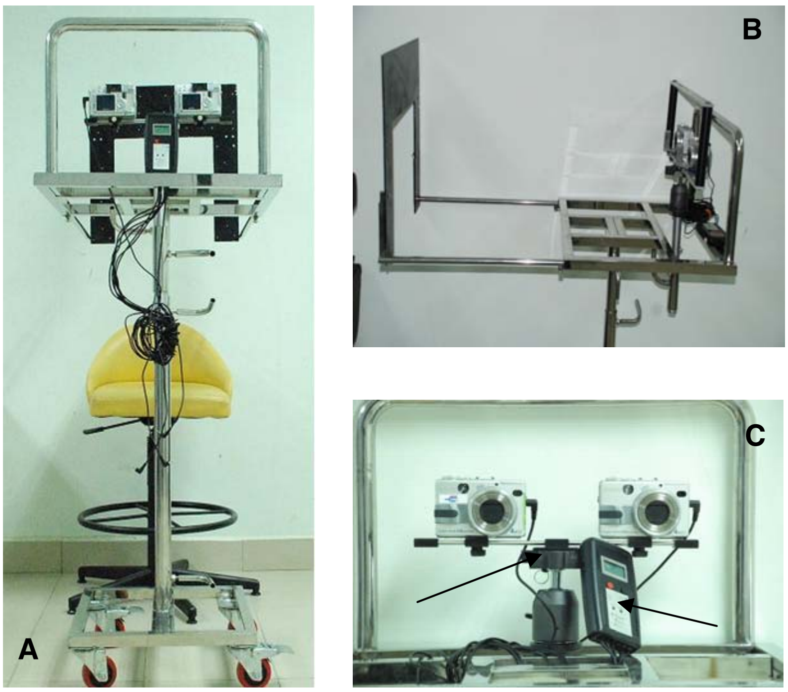

Figure 2 The complete imaging station from frontal view (A) and lateral view (B). Arrows are showing the camera base and remote control switch (C).

Figure 3 Photogrammetric control frame of the stereophotogrammetry system with the retro-reflective markers.

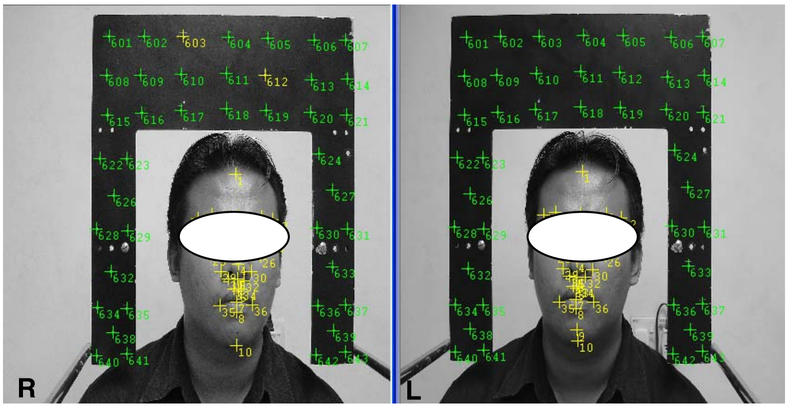

Figure 4 The digitized right and left images of the frontal view applying Australis software. The subject's head surrounded by the calibration frame.

This system consists of two digital cameras (Figure 2) separated from each others by 175 mm and mounted together on a specially prepared holder. The cameras are triggered simultaneously by a remote controlled synchronized switch. The control frame is adjusted to be in front of the cameras and held by two vertical arms (Figure 3). Forty four well distributed circular retro-reflective markers are placed around the control frame, so that they are clearly visible on both right and left images. The calibration frame and camera holder are placed on a solid base with a movable trolley for easy movement.

Individual cameras have been calibrated independently with the use of calibration frame to determine the camera parameters (Chong, 1999; Majid *et al.*, 2006). Different views of the camera are taken from different angles and the images are analyzed by Australis software version 6.06 (Photometrix Pty. Ltd., Victoria, Australia).

Data acquisition is conducted with the volunteer seated on a chair with a slightly elevated head. The distance from the participant to the stereo camera is fixed at 700mm and frontal views are taken (Majid, 2008). Subsequently, the participant is rotated to the right and left side by about 45 degrees to the wall to capture right and left oblique lateral views. All of the landmarks on the right and left images of each view are digitized simultaneously (Figure 4). After that, images are triangulated and measurements are displayed.

A preliminary study was conducted on the human face to evaluate the accuracy and precision of this system. The results showed an error in the range of 0.5-1mm for the studied variables. The system has been applied in the assessment of facial features of Malays residing in the southern and northern parts of Peninsular Malaysia (Rajion and Yusdirman, 2008). Thereby, it was found that the Java face differs from the Rawa face in the upper and lower facial regions which could be related to the genetic variations between and within same ethnics (Jorgenson *et al.*, 2005). Although the sample size was small, the study may suggest that there is some morphological dissimilarity in Malay groups in different regions of Peninsular Malaysia. A further study with a lager sample is being conducted to evaluate the facial soft tissue morphology in the Malay population.

Different types of stereo-photogrammetry systems were presented in the literature (Khambay *et al*., 2008; Wong *et al*., 2008). These systems express high degree of accuracy and precision (Weinberg *et al*., 2006). However, the challenges faced these systems are the expense of equipments and limitation in movement. Therefore, the applications of these systems are restricted in the specialized centers. The introduced system is originally design to overcome these restrictions and provided acceptable degree of the accuracy and precision. These could be improved in the future by providing additional and higher resolution cameras.

Conclusions

Various three dimensional techniques for measuring surface facial morphology were reported. They allow clinicians to manipulate quickly and accurately the 3D images of their patients. Each technique has potential advantages and limitations. The applicable 3D imaging system would be one that is accurate and reliable in data capturing, archiving and storing in a cost effective way. All of the technologies aim to increase understanding of the patient's facial morphology and thus enhance diagnostic approaches and treatment outcome.

References

Allanson JE (1997). Objective techniques for craniofacial assessment: what are the choices? *Am J Med Genet*, **70**(1): 1-5.

Ayoub A, Garrahy A, Hood C, White J, Bock M, Siebert JP, Spencer R and Ray A (2003). Validation of a vision-based, three-dimensional facial imaging system. *Cleft Palate Craniofac J*, **40**(5): 523-529.

Ayoub AF, Xiao Y, Khambay B, Siebert JP and Hadley D (2007). Towards building a photo-realistic virtual human face for craniomaxillofacial diagnosis and treatment planning. *Int J Oral Maxillofac Surg*, **36**(5): 423-428.

Baik HS, Jeon JM and Lee HJ (2007). Facial soft-tissue analysis of Korean adults with normal occlusion using a 3-dimensional laser scanner. *Am J Orthod Dentofacial Orthop*, **131**(6): 759-766.

Banabilh SM, Suzina AH, Dinsuhaimi S, Samsudin AR and Singh GD (2009). Craniofacial obesity in patients with obstructive sleep apnea. *Sleep Breath*, **13**(1): 19-24.

Bishara SE, Jorgensen GJ and Jakobsen JR (1995). Changes in facial dimensions assessed from lateral and frontal photographs. Part II--Results and conclusions. *Am J Orthod Dentofacial Orthop*, **108**(5): 489-499.

Bishara SE, Jakobsen JR, Hession TJ and Treder JE (1998). Soft tissue profile changes from 5 to 45 years of age. *Am J Orthod Dentofacial Orthop*, **114**(6): 698-706.

Boehringer S, Vollmar T, Tasse C, Wurtz RP, Gillessen-Kaesbach G, Horsthemke B and Wieczorek D (2006). Syndrome identification based on 2D analysis software. *Eur J Hum Genet*, **14**(10): 1082-1089.

Bourne CO, Kerr WJ and Ayoub AF (2001). Development of a three-dimensional imaging system for analysis of facial change. *Clin Orthod Res*, **4**(2): 105-111.

Bozic M, Kau CH, Richmond S, Hren NI, Zhurov A, Udovic M, Melink S and Ovsenik M (2009). Facial morphology of Slovenian and Welsh white populations using 3-dimensional imaging. *Angle Orthod*, **79**(4): 640-645.

Choe KS, Sclafani AP, Litner JA, Yu GP and Romo T 3rd (2004). The Korean American woman's face: anthropometric measurements and quantitative analysis of facial aesthetics. *Arch Facial Plast Surg*, **6**(4): 244-252.

Chong AK (1999). A multipurpose camera calibration range. *NZ Surveyor*, **289**: 19-22.

De Menezes M, Rosati R, Allievi C and Sforza C (2009). A photographic system for the three-dimensional study of facial morphology. *Angle Orthod*, **79**(6): 1070-1077.

Downie J, Mao Z, Rachel Lo TW, Barry S, Bock M, Siebert JP, Bowman A and Ayoub A (2009). A double-blind, clinical evaluation of facial augmentation treatments: a comparison of PRI 1, PRI 2, Zyplast and Perlane. *J Plast Reconstr Aesthet Surg*, **62**(12): 1636-1643.

Ettorre G, Weber M, Schaaf H, Lowry JC, Mommaerts MY and Howaldt HP (2006). Standards for digital photography in cranio-maxillo-facial surgery - Part I: Basic views and guidelines. *J Craniomaxillofac Surg*, **34**(2): 65-73.

Farkas LG (1994). Examination, Photogrametry of the face, Craniofacial anthropometry in clinical genetics. In: Farkas LG (ed.), *Anthropometry of the Head and Face*. New York: Raven Press Ltd, pp 22, 80, 104, 192.

Farkas LG (1996). Accuracy of anthropometric measurements: past, present, and future. *Cleft Palate Craniofac J*, **33**(1): 10-18; discussion 19-22.

Grobbelaar R and Douglas TS (2007). Stereo image matching for facial feature measurement to aid in fetal alcohol syndrome screening. *Med Eng Phys*, **29**(4): 459-464.

Guyot L, Dubuc M, Richard O, Philip N and Dutour O (2003). Comparison between direct clinical and digital photogrammetric measurements in patients with 22q11 microdeletion. *Int J Oral Maxillofac Surg*, **32**(3): 246-252.

Gwilliam JR, Cunningham SJ and Hutton T (2006). Reproducibility of soft tissue landmarks on three-dimensional facial scans. *Eur J Orthod*, **28**(5): 408-415.

Hajeer MY, Ayoub AF, Millett DT, Bock M and Siebert JP (2002). Three-dimensional imaging in orthognathic surgery: the clinical application of a new method. *Int J Adult Orthodon Orthognath Surg*, **17**(4): 318-330.

Hajeer MY, Millett DT, Ayoub AF and Siebert JP (2004). Applications of 3D imaging in orthodontics: part I. *J Orthod*, **31**(1): 62-70.

Halazonetis DJ (2001). Acquisition of 3-dimensional shapes from images. *Am J Orthod Dentofacial Orthop*, **119**(5): 556-560.

Hammond P, Hutton TJ, Allanson JE, Buxton B, Campbell LE, *et al.* (2005). Discriminating power of localized three-dimensional facial morphology. *Am J Hum Genet*, **77**(6): 999-1010.

Hammond P (2007). The use of 3D face shape modelling in dysmorphology. *Arch Dis Child*, **92**(12): 1120-1126.

Holberg C, Schwenzer K, Mahaini L and Rudzki-Janson I (2006). Accuracy of facial plaster casts. *Angle Orthod*, **76**(4): 605-611.

Honrado CP and Larrabee WF Jr. (2004). Update in three-dimensional imaging in facial plastic surgery. *Curr Opin Otolaryngol Head Neck Surg*, **12**(4): 327-331.

Inada E, Saitoh I, Hayasaki H, Yamada C, Iwase Y, Takemoto Y, Matsumoto Y and Yamasaki Y (2008). Cross-sectional growth changes in skeletal and soft tissue cephalometric landmarks of children. *Cranio*, **26**(3): 170-181.

Kamoen A, Dermaut L and Verbeeck R (2001). The clinical significance of error measurement in the interpretation of treatment results. *Eur J Orthod,* **23**(5): 569-578.

Kau CH, Richmond S, Zhurov AI, Knox J, Chestnutt I, Hartles F and Playle R (2005). Reliability of measuring facial morphology with a 3-dimensional laser scanning system. *Am J Orthod Dentofacial Orthop,* **128** (4)**,** 424-430.

Kau CH, Richmond S, Incrapera A, English J and Xia JJ (2007). Three-dimensional surface acquisition systems for the study of facial morphology and their application to maxillofacial surgery. *Int J Med Robot*, **3**(2): 97-110.

Kau CH and Richmond S (2008). Three-dimensional analysis of facial morphology surface changes in untreated children from 12 to 14 years of age. *Am J Orthod Dentofacial Orthop*, **134**(6): 751-760.

Khambay B, Nairn N, Bell A, Miller J, Bowman A and Ayoub AF (2008). Validation and reproducibility of a high-resolution three-dimensional facial imaging system. *Br J Oral Maxillofac Surg,* **46**(1): 27-32.

Lee HJ and Park SJ (2008). Comparison of Korean and Japanese head and face anthropometric characteristics. *Hum Biol*, **80**(3): 313-330.

Lee JY, Han Q and Trotman CA (2004). Three-dimensional facial imaging: accuracy and considerations for clinical applications in orthodontics. *Angle Orthod*, **74**(5): 587-593.

Littlefield TR, Kelly KM, Cherney JC, Beals SP and Pomatto JK (2004). Development of a new three-dimensional cranial imaging system. *J Craniofac Surg,* **15**(1): 175-181.

Majid Z, Chong AK, Ahmad A, Setan H and Samsudin AS (2005). Photogrammetry and 3D laser scanning as spatial data capture techniques for a national craniofacial database. *Photogramm Rec*, **20**(109): 48-68.

Majid Z, Chong AK, Setan H, Ahmad A and Rajion ZA (2006). Natural features technique for non-contact three dimensional craniofacial anthropometry using stereophotogrammetry. *Arch Orofac Sci,* **1**: 42-50.

Majid Z, Chong AK, and Setan H (2007). Importamt considerations for craniofacial mapping using laser scanners. *Photogramm Rec*, **22**(120): 290-308.

Majid Z (2008). Design and calibration of multi-model imaging system for craniofacial soft tissue mapping. In: *Geomatic Engineering*, PhD thesis. Universiti Teknologi Malaysia, Johor.

Marr D and Poggio T (1976). Cooperative computation of stereo disparity. *Science,* **194**(4262): 283-287.

Moss JP (2006). The use of three-dimensional imaging in orthodontics. *Eur J Orthod*, **28**(5): 416-425.

Ngeow WC and Aljunid ST (2009). Craniofacial anthropometric norms of Malays. *Singapore Med J,* **50**(5): 525-528.

Paredes V, Gandia JL and Cibrián R (2006). Digital diagnosis records in orthodontics. An overview. *Med Oral Patol Oral Cir Bucal,* **11**(1): E88-E93.

Rajion ZA and Yusdirman AY (2008). Computer aided photogrammetry for facial analysis. In: Abu Osman NA, Ibrahim F, Wan Abas WAB, Abd Rahman HS, Ting HN (eds.), *Biomed 2008, Proceedings 21*. Berlin: Springer Berlin Heidelberg, pp. 548–551.

Ramieri GA, Nasi A, Dell'acqua A and Verzé L (2008). Facial soft tissue changes after transverse palatal distraction in adult patients. *Int J Oral Maxillofac Surg,* **37**(9): 810-818.

Ras F, Habets LL, van Ginkel FC and Prahl-Andersen B (1996). Quantification of facial morphology using stereophotogrammetry--demonstration of a new concept. *J Dent*, **24**(5): 369-374.

Riphagen JM, van Neck JW and van Adrichem LN (2008). 3D surface imaging in medicine: a review of working principles and implications for imaging the unsedated child. *J Craniofac Surg*, **19**(2): 517-524.

Sayinsu K, Isik F, Trakyali G and Arun T (2007). An evaluation of the errors in cephalometric measurements on scanned cephalometric images and conventional tracings. *Eur J Orthod*, **29**(1): 105-108.

Seager DC, Kau CH, English JD, Tawfik W, Bussa HI and Ahmed Ael Y (2009). Facial morphologies of an adult Egyptian population and an adult Houstonian white population compared using 3d imaging. *Angle Orthod*, **79**(5): 991-999.

Seeram E (1997). 3-D imaging: basic concepts for radiologic technologists. *Radiol Technol,* **69**(2): 127-44; quiz 145-148.

Siebert JP and Marshall SJ (2000). Human body 3D imaging by speckle texture projection photogrammetry. *Sensor Rev*, **20**(3): 218-226.

Singh GD, Levy-Bercowski D, Yanez MA and Santiago PE (2007). Three-dimensional facial morphology following surgical repair of unilateral cleft lip and palate in patients after nasoalveolar molding. *Orthod Craniofac Res,* **10**(3): 161-166.

Toma AM, Zhurov A, Playle R and Richmond S (2008). A three-dimensional look for facial differences between males and females in a British-Caucasian sample aged 151/2 years old. *Orthod Craniofac Res*, **11**(3): 180-185.

Thilander B, Persson M and Adolfsson U (2005). Roentgen-cephalometric standards for a Swedish population. A longitudinal study between the ages of 5 and 31 years. *Eur J Orthod,* **27**(4): 370-389.

Uysal T, Yagci A, Basciftci FA and Sisman Y (2009). Standards of soft tissue Arnett analysis for surgical planning in Turkish adults. *Eur J Orthod,* **31**(4): 449-456.

Weinberg SM, Naidoo S, Govier DP, Martin RA, Kane AA and Marazita ML (2006). Anthropometric precision and accuracy of digital three-dimensional photogrammetry: comparing the Genex and 3dMD imaging systems with one another and with direct anthropometry. *J Craniofac Surg*, **17**(3): 477-483.

Weinberg SM, Neiswanger K, Richtsmeier JT, Maher BS, Mooney MP, Siegel MI and Marazita ML (2008). Three-dimensional morphometric analysis of craniofacial shape in the unaffected relatives of individuals with nonsyndromic orofacial clefts: a possible marker for genetic susceptibility. *Am J Med Genet A*, **146A**(4): 409-420.

Weinberg SM, Naidoo SD, Bardi KM, Brandon CA, Neiswanger K, Resick JM, Martin RA and Marazita ML (2009). Face shape of unaffected parents with cleft affected offspring: combining three-dimensional surface imaging and geometric morphometrics. *Orthod Craniofac Res,* **12**(4): 271-281.

Wong JY, Oh AK, Ohta E, Hunt AT, Rogers GF, Mulliken JB and Deutsch CK (2008). Validity and reliability of craniofacial anthropometric measurement of 3D digital photogrammetric images. *Cleft Palate Craniofac J*, **45**(3): 232-239.