ISSN: 2581-5989
PubMed - National Library of Medicine - ID: 101738774

International Journal of Dental Science and Innovative Research (IJDSIR)

IJDSIR : Dental Publication Service

Available Online at: www.ijdsir.com

Volume – 3, Issue – 5, September - 2020, Page No. : 261 - 274

Image processing in orthodontics and dentofacial orthopedics – A review

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Citation of this Article: Dr. Amulya Sundara Raj, Dr. G. Sreejith Kumar, "Image processing in orthodontics and dentofacial orthopedics – A review", IJDSIR- September - 2020, Vol. – 3, Issue - 5, P. No. 261 – 274.

Type of Publication: Review Article

Conflicts of Interest: Nil

Abstract

Medical image processing has been established as a rapidly developing area of modern health care system due to huge progress in technological innovations in the areas of medical informatics and bioinformatics. The core of medical imaging lies in the various advancements in image processing. This emerging technology has many applications in dentistry also including identification of pathologies, hard and soft tissue defects, management of trauma etc. This paper aims to review the advanced applications in the field of orthodontics and dentofacial orthopedics with the revolutionary development of digital imaging and image processing techniques. The important techniques in image processing like image enhancement, image segmentation, image registration and image pattern recognition are highlighted.

Keywords: Image processing, diagnostic imaging, face recognition, facial imaging, virtual models.

Introduction

Image processing is a technique to convert an input image in to an enhanced image or to extract informations from it.[1] The sole purpose of medical image processing is to improve the interpretability of the depicted contents. This may involve an enhancement of the image itself to increase the perception of certain features as well as the automated or manual extraction of information[2]. The field of orthodontics and dentofacial orthopedics is the branch of dentistry that deals with the alignment of teeth and the associated skeletal system, maxilla and mandible. The specialty has the responsibility to establish a balance between dentoalveolar system, skeletal system and soft tissue for harmonious functioning and pleasing facial contours, also in supervision of growth and development of orofacial structures. The fundamental objective for the specialty is in improving the facial esthetics, today with the advent of excellent imaging and image processing techniques orthodontist can easily assess the facial features and proportions for better analysis to lead a harmonious and esthetic treatment results. Image processing has several applications in orthodontics even from the beginning of patient database creation to the most significant stage of orthodontic treatment, diagnosis and treatment planning which determines course of orthodontic treatment. Furthermore, its applications include assessment of growth in younger individuals and other associated tissue changes during treatment period. Now image processing applications are outstretched to even in the prediction of treatment prognosis to a much better communication tool, and also extended even to fabrication of orthodontic appliances.[3]

Evolution Of Digital Image Processing

The history of meaningful digital image processing is associated with works on images from a space probe began at the Jet Propulsion Laboratory (Pasadena, California) in 1964 when pictures of the moon transmitted by Ranger 7 were processed by a computer to correct various types of image distortion inherent in the on-board television camera[4]. From its development to till now, the image processing technology have grown in to a different level of applications in almost all fields of science and technology including medical imaging and other biological sciences like craniofacial imaging. With the invention in the early 1970s of computerized axial tomography (CAT), by Sir Godfrey N. Hounsfield and Prof. Allan M. Cormack, the field of image processing entered in to another dimension of application in medical diagnosis. The history of imaging in orthodontics begins from the invention of the cephalometer by B. Holly Broadbent in 1930.Sheldon Baumrind, greatest visionary in the area of imaging in orthodontics , created the Craniofacial Imaging Laboratory at the University of San Francisco in 1979 and has published over 75 articles in the imaging literature[5].He detailed on landmark identification as well as the use of digital images for sharing image information[6].Initial attempts of image processing in orthodontics was by A M Cohen in 1984 by using a cellular logic image processor (CLIP4) and demonstrated feasibility of automated cephalometric landmark identification using this system.[7] M L Cocklin et al in 1984 described the application of digital image processing techniques to chest radiographs. On the basis of studies conducted along with Cocklin, P H Jackson used general purpose digital image processing system at the IBM Winchester Scientific Centre. Thus a prototype system, based on that used for image processing of chest X-rays, was developed to examine its application to cephalometry[8].

Fundamental Steps In Medical Image Processing

The critical steps in medical image processing are image enhancement, image segmentation, image registration, and pattern recognition as illustrated in Fig.1

A. Image enhancement

Image enhancement is the process of removal of image distortions, such as noise and the enhancement of image contours and other relevant properties[2] .Image filtering is often the first step of image enhancement. Image filtering converts an input image to another image with a different property. Smoothing, edge detection, image sharpening are different image filtering methods to remove noise and enhance the image.[1] The smoothing filters minimize the gray-level differences among neighbouring pixels, which is often caused by the noise. Blurring filter, median filter, and bilateral filter are different smoothing filters. Edge detection is basically a method of segmenting an image into regions based on discontinuity, i.e. it allows the user to observe those features of an image where there is a more or less abrupt change in grey level or texture, indicating the end of one region in the image and the beginning of another.By edge detection filter, edge pixels are highlighted. Laplacian filter, Canny filter, and Sobel filter are three different edge detection filters.A sharpening filter is an extension of the edge detection filter and can emphasize the edge region.

Contrast enhancement: The purpose for transforming the contrast in a medical image is to remove undesirable characteristics of the image detecting system, and hence normalize the image to a 'standard' exposure[9].Morphological processingdeals with tools for extracting image components that are useful in the representation and description of shape[4]

B. Image segmentation

Image segmentation is one of the most important image processing techniques for biological images. Biological images have ambiguous boundaries, thus they are difficult to separate from background and other objects. Also, anatomical and particularly pathological regions often show a high variability due to structure, deformation, or movement, which is difficult to predict and is thus a great challenge for image processing[10].In medical imaging, image segmentation is the process of identification of the contours of an anatomical structure, such as an organ, a vessel, or a tumor lesion[2]. Its purpose is to partition an input image into regions[1].

Different methods used for image segmentation are image binarization, background subtraction, watershed method, region growing, clustering, active contour model, template matching recognition based method and Markov random field. Background subtraction method is used to detect target objects by removing the background part. Watershed method functions by detecting the ridge lines of an image and represent it as a three dimensional surface.Clustering is the segmentation method for grouping pixels with similar properties. Template matching recognition based method is used forfinding pixels or blocks whoseappearance or other characteristics are similar toreference patterns of the target object. Markov random field is an integrated method to optimize the segmentation resultconsidering the similarity ofneighboring pixels.[1]

C. Image registration

Image registration is a method to fit a reference image to its deformed version or vice versa. The purpose of image registration is to overlay two images while fitting them to each other (Fig. 2). A dental model is registered on to a CBCT image to obtain a CBCT based dentofacial image. To this image another set of images obtained from 3D facial imaging is superimposed, thus image registration of two sets of dentofacial images is made possible.[11]Another purpose of image registration is to understand relative deformation of an image to the other image. The optimized fitting function between two images directly represents the deformation. The spatial transformation of one image such that it directly matches a given reference image. This is necessary in the combined visualization of images from different modalities (e.g., PET/CT).[2]

D. Image pattern recognition

Image pattern recognition is a task to assign a predefined class label to an image (or a part of an image). Image pattern recognition is comprised of two modules: feature extraction and classification. Feature extraction is the module to convert an input image as a set of values, that is, a vector. Feature extraction is an important module for pattern recognition. This is because it affects recognition performance drastically.Classification is the module to classify the input feature vector into a class according to some rule, called a classifier. A classifier is trained automatically using patterns whose class is known. This training mechanism of the classifier is called machine learning and feature vectors for training are called training patterns[1]. There are no clear-cut boundaries in the continuum from image processing at one end to computer vision at the other[4].

Applications In Medical And Medicolegal Procedures

The evolutionary progress in the field of medical imaging and procedures has a core impact of developments in digital image processing. With development of different image segmentation engines segregation of informations from different multimodal diagnostic imaging like magnetic resonance imaging (MRI), computed tomography (CT), ultrasonography, retinoscopy, electroencephalophy, mammograms, positron emission tomography (PET), and single photon emission computed tomography (SPECT) and integration of informations from these imaging modalities for better understanding of these condition is made possible. Image processing thus increases sensitivity of diagnostic imaging and which has allowed deeper insights into the pathogenesis of different medical conditions like cerebrovascular accidents, traumatic brain injuries, heart diseases, retinopathies, speculated lesions and malignant conditions for early detection and assessment of prognosis (Fig.3). Furthermore, this technique also enhanced the endoscopic imaging technique and leads to the development of a system to automatically identify and track surgical instruments, e.g. supporting robotic surgery approaches.[10,12,13]

Another important application of image processing is in medicolegal and forensic studies. From enhancement, analysis and recognition of patterns like bite-mark injuries, fingerprints, footprints to forensic identification and virtual autopsies that utilizes additional imaging of the interior of corpses is using Multislice computed tomography (MSCT) and magnetic resonance imaging (MRI) demands the needof image processing technology.[14–18] Nowadays,thermal imaging using infrared rays has several number of applications both in medical and medicolegal aspects from temperature measurements to determination of time of death and type of injuries.[19]

Applications In Orthodontics

A. Face recognition

The facial recognition technology relies on the comparison of new images to ones already stored in a searchable database and the subsequent identification of matches and potential matches.[20]Not only growth and age related changes but also orthodontic treatment procedures influence the facial contours, especially the orthognathic surgical procedures and traction procedures drastically influence facial soft tissuesand directly affects biometrics. In addition a study among patients who had orthognathic surgery found that orthognathic surgeries invariably have an impact on biometrics of patient and which affects their identification at border controls[21]. Another recent study assessed the similarity between pre and post orthognathic photographs using a face recognition application with the help of image processing technology and found that there is a significant reduction in recognition score after orthognathic surgery especially after combined surgeries on both jaws[20].

The 3D surface acquiring systems are becoming more readily available and are accurate and reliable.[22]There are different image acquisition systems for face recognition including 3D cephalometry, 3D CT scanning,3D laser scanning, and more noninvasive, non-contactvision based imaging techniques like Moire topography, structural light technique and stereophotogrammetry[23]. 3D face images are useful for different facial analysis. 3D raw face scan image are fitted with Base face model, which has principal components for analysis of shape parameters, to form a deformable model fitted facewhich can be used for facial analysis[24](Fig.4). The identification of intrinsic features like these shape parameters, is a critical step in face recognition.

In face recognition, the set of images that shows all individuals whoare known to the system is often referred to as gallery. Recognition is then performed on novel acquired probe images.Face recognition is done based on comparing the fitting coefficient, that is intrinsic features like shape and texture of the images independent of imaging condition. For identification, the system reports after comparing the coefficients, which person from the gallery is shown on the probe image[25] (Fig.5).

B. Facial esthetics

Long before scientists first attempted to appraise beauty, artists in the fourth century B.C. attempted to formulate rules for the ideally-proportioned face[26]. The normal face and the occlusion of the teeth with the quality of golden sectioningattracts the attention and which is recorded in the limbic system as beauty, harmony, and balance[27]. Enhanced esthetic appearance is consistently an objective of orthodontic treatment.Vitruvius concept of threefold partition of the face, adhered to even today in orthodontics and oral- and maxillofacial surgery to evaluate golden proportion and facial thirds for proportional assessment[28] (Fig.6).

The experiments on facial assessment using proportional assessment require improved feature extraction.After morphological operations images were enhanced and feature extraction were made possible. Accurate feature extraction is of fundamental importance for reliable measurement of facial esthetics. Then based on the results an automated classifier capable of reproducing the average human judgment of facial beauty by using a feature set was created. This has many potential applications including decision of orthognathic or plastic surgery or associated orthodontic treatment.[28] With the evolution of the concept of problem- and goal oriented diagnosis and treatment planning the identification of both the normal and the positive elements of a patient's appearance or smile should be maintained or enhanced. Thus, with the new soft tissue paradigm, characteristics of soft tissue and harmony among them became the most important criteria in treatment planning.[29] With this shift in concern, there are numerous studies on evaluation of soft tissueand influence on facial esthetics with the help of recent advances in imaging and image processing techniques.

Nowadays with the help of image processing software, social smile is evaluated using three-dimensional (3D) stereo photogrammetric images. The rest position was considered as the reference image and the social smile image was aligned on this image using the best-fit alignment method (Fig.7). Morphological land mark identification and analysis was done using the possibilities of image processing software for pattern analysis and found that social smile was observed to show asymmetry in varying amounts in the different directions[30]. Through the image processing possibility, in a study acquisition of multiple images at frequent intervals through 3-D stereophotogrammetry made to assess the reproducibility of the social smile by evaluating all points in the designated area in 3-D with considerably high reliability with the alignment of images, segmentation of smile area for 3-D deviation analysis. A single image was taken as the reference, and 15 images were compared with the reference image to evaluate positive and negative deviations[31].

Another study aimed to evaluate the intermediate precision of three types of facial expression tasks: rest posture, posed or social smile, and maximum effort smile using 3D facial topography with surface-based analysis utilized image processing applications to superimpose the facial expressions images for evaluation. Study found that maximum effort smile would be more reliable in estimating the capability of lip movement and effects of interventions such as orthodontic treatment[32].The influence of varied cheek volume on facial esthetics was investigated in another study to explore the potential value of including cheek volume in orthodontic diagnostic analysis. With images taken by 3D stereophotogrammetry and image processing, the dimensional transformation of cheek volume were assessed digitally[33].

C. Diagnosis and Treatment Planning

In orthodontic treatment the most important requirement is an accurate diagnosis. The ability to rapidly and accurately assess the tooth and bone position and condition in all three dimensions is invaluable for accurate diagnosis and treatment planning[34]

D. Diagnostic imaging

In order to make an orthodontic diagnosis, diagnostic imaging is a critical component. Landmark identification, asymmetry assessment, andidentification of skeletal and dental malformations play a key role in orthodontic diagnosis.[35,36] Fig. : 8 is a 3D facial image with established soft tissue landmarks. This can be used as a template for 3D facial analysis with individual calibrations.[36]

Stereophotogrammetry, which has proved to be the ‘‘gold standard’’ in the field of facial anthropometry.[37] This technique uses one or more converging pairs of views to build up a 3D model that can be viewed from any perspective and measured from any direction. In numerous studies possibilities of digital image processing were used for integrating images from stereophotogrammetry, and three dimensional information acquired were used for orthodontic purposes, especially for orthognathic surgeries.[11,31,38,39] The landmark-based 3D analysis for facial asymmetry using image processing software is an invaluable diagnostic tool for the assessment of soft-tissue asymmetry in patients with dentofacial deformities[40].

In a recent study efficiently used a 3D photographs made by a system of multicamera array for assessing facial symmetry and midline analysis using a custom made image processing software program, function in MATLAB. A point cloud is formed from 3D Facial scan image. Paired points with equal pixel length separation on each side can be considered for asymmetry analysis (Fig.9). The points could then be separated into various color categories, which represented certaindistance ranges. The chosen color ranges were green for values mild asymmetry (less than 2 mm), blue for moderate asymmetry (2-5 mm), and red severe asymmetrical. The point cloud was then converted into a mesh of triangular facets (Fig.10). The triangle was assigned its color corresponding to the largest asymmetrical value of its corner vertexes. Area of each triangular facets are compared for facial analysis. This provided an automated, rapid, and accurate 3D quantitative and qualitative assessment of facial symmetry using the symmetry and midline analysis[24].

E. Cephalometric landmark identification

The application of image processing for automated landmark identification and cephalometric analysis for assessment of craniofacial dimensions were very well utilized for diagnosis and treatment planning in patients with abnormalities in dental, skeletal, and softtissueparameters.[8,41–43] The photographic subtraction studies in direct superimposition of radiographs over reference areas provides maximum utilization of structural details and elimination of tracing errors for orthodontic diagnostic purpose[44]. There are studies on a procedure to make color-coded images by means of image addition from original black-and-white radiographs exposed on film and also to test the applicability of this procedure on sequential intraoral radiographs. This possibility of image processing technique opened its different orthodontic applications including the possibility to identify any radiographic changes that take place over time like growth, apposition or resorption of bone, and progression or regression of pathological processes and development changes and movements of teeth during normal eruption or orthodontic treatment.[45]

F. Treatment simulation using virtual models

Medical image processing has been progressed from the simple 2D radiograph via 3D imaging modalities to multi-modal processing and analyzing[10].Technique of combining images from different imaging modalities are now becoming integral part of clinical orthodontics also. There are literatures on the improved diagnosis and treatment planning based on digital three dimensional craniofacial imaging developed through the possibilities of multimodal image processing techniques and different segmentation engines.[46] There are several detailed studies on image acquisition methods for creation of an integrated three - dimensional model.[47–51] Any surface or group of surfaces of interest can be made visible and invisible, and the transparency of each surface can be changed separately as desired in this three dimensional patient model[52] . Image processing techniques can be used to create virtual setup. It was also mentioned that the virtual setups can be used to gradually move the dentition into the planned position (Fig.11)[51].

Image fusion using different image processing methods involves combining images from different imaging modalities. This can be used to create a virtual record of anindividual called a patient-specific anatomical reconstruction (PSAR). Thiscan then be used to perform virtual surgery and establish a definitive andobjective treatment plan for correction of the facial deformity (Fig.12).[53–55] This ability to build a craniofacial virtual model with the help of different image processing techniques from different imaging modalities like cone beam computed tomography, serves as a great treatment planning tool for clinicians, an effective communication tool, and a method for patients to visualize the predicted outcome, instill motivation and encourage compliance in order to achieve the desired treatment outcome.[35,56–60] By this the scope of image processing also opened the door to the possibility of teleorthodontics, that is simultaneous viewing at distance by two or more clinicians for relevant information on individual patients.[61]

The concept of digital orthodontic office practice management, through the application of image processing provides a new vision of orthodontic practice. The particular study utilized a software for 3D digital study models, with this software, digital study models were made available chair side anytime anywhere.[62]

G. Applications in treatment execution

Customized appliance manufacturing

Furthermore, this virtual models can be used in manufacturing surgical splints using CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) technology in orthognathic surgery[63]. Fixed appliance manufacturing is another area in orthodontic field were the image processing techniques were used. The technique utilizes virtual set-ups along with customized bracket printing and robotic wire bending to create a fully customized appliance[64]. The aligner systems were another treatment method, uses virtual treatments to create a series of clear,removable, esthetic appliances that can treat a wide range of malocclusions, is yet another application of image processing.[65]

H. Orthodontic Research

With the help of image processing techniques field of orthodontics become more and more innovative from the step of collection and manipulation of images and database formation to more sophisticated applications in advanced diagnosis and appliance fabrication.Enhanced detectability of informations even from low contrast images, additionally with the application of image subtraction technique or with colour mapping have great impact not only in clinical orthodontics but also in research applications.

Micro-computed tomography (MCT), Tuned-aperture computer tomography (TACT) are recent imaging techniques, future of these techniques in orthodontic applications with the help of image processing software will be of higher value in different researches in evaluation of dento-alveolar bone volume, detection of root resorption, and evaluation of the TMJ disorders. MCT, a non-invasive and a non-destructive technique, is used for the analysis of mineralized tissues. The future of MCT lies in its capacity to sample input over a much minor volume than full body, considerably reducing the radiation exposure.[66]

Recent Advances In Image Processing

Emergence of Deep Neural Network (DNN) has made a tremendous progress in image segmentation and classification. Semantic image segmentation, also called pixel-level classification, is the task of clustering parts of image, which has multiple applications like detecting tumors and tracking medical instruments in operations.[67] The object detection techniques using deep learning, were actively studied in recent years, has high success in image classification and face recognition.[68] Image Super-Resolution (SR) is an important class of image processing techniques to enhance the resolution of images and videos. Recently, deep learning based image super resolution have been actively explored for recovering low resolution images, which has wide range of applications including in medical imaging.[69] Recent advances in convolutional neural networks leads to the development of a novel high-resolution multi-scale encoder-decoder network (HMEDN)to finely exploit comprehensive semantic information, which promises extensive experiments on CT, MR, and microscopic images.[70]

Experiments to integrate recent advances in image processing and 3D rendering extended the scope of the field. Augmented reality (AR) is an innovative technology allowing merger of data from the real environment with virtual information.[55] Researches on visualization of radiological images using Augmented and Virtual Reality provide a better interpretation of the radiological results and which is a breakthrough for treatment planning especially for surgical procedures[71]. Emerging fields of technology like virtual reality, robotics, artificial intelligence creates a new dimension to the orthodontic clinical practice. These technologies relay on image processing techniques for transforming clinical imaging data.

Figures And Tables

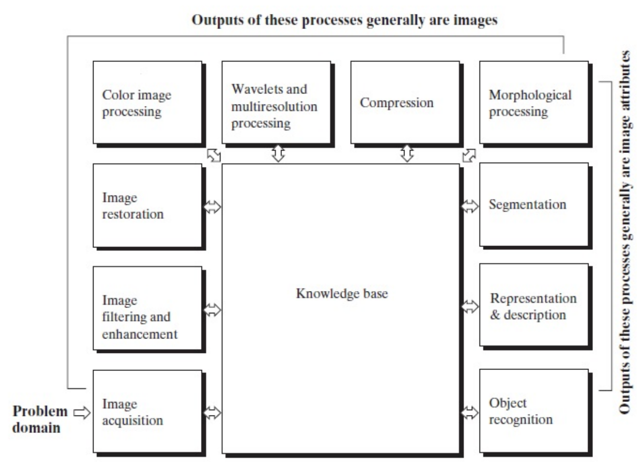

Fig. 1: Flowchart depicting fundamental steps of image processing

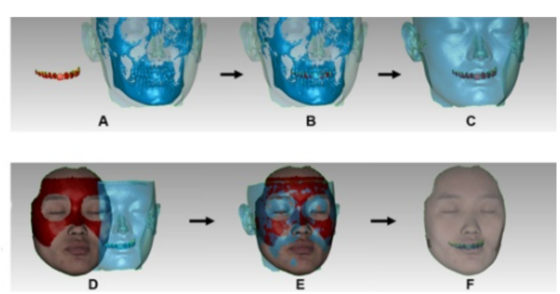

Fig.2: CBCT-based dentofacial image superimposition. Image registration of dental model into CBCT image. Registration of two sets of dentofacial models obtained from CBCT and 3D facial imaging

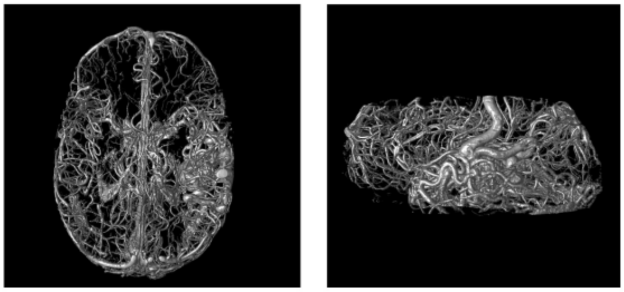

Fig.3: Image obtained after segmentation of cerebral vessel on a magnetic resonance angiography (MRA) image.

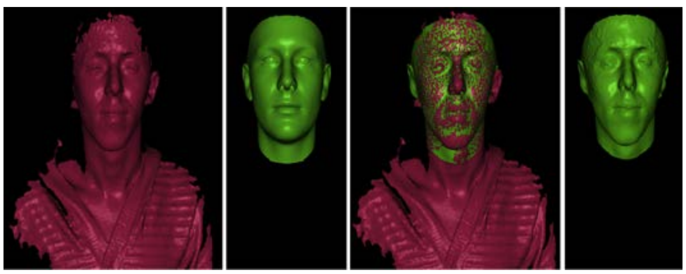

Fig. 4: Face recognition using shape parameters in 3D image acquisition system .

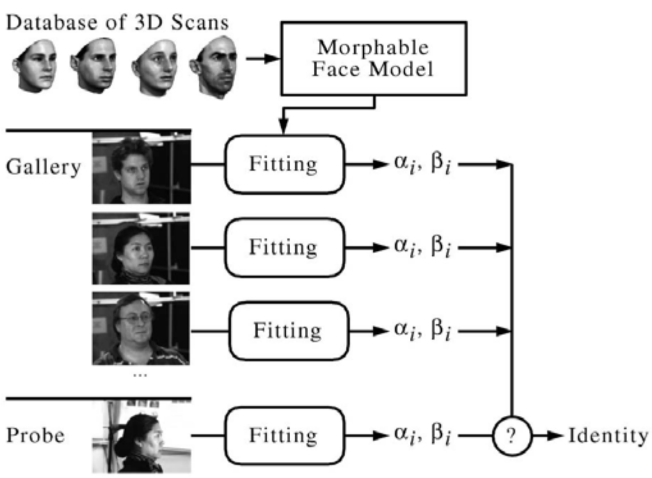

Fig. 5: The process of face recognition depicted

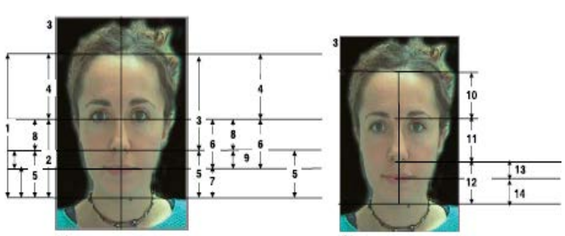

Fig. 6: Template image showing golden proportion and facial thirds.

Fig. 7: Smile image analysis using colour mapping on a stereophotogrammetric image.

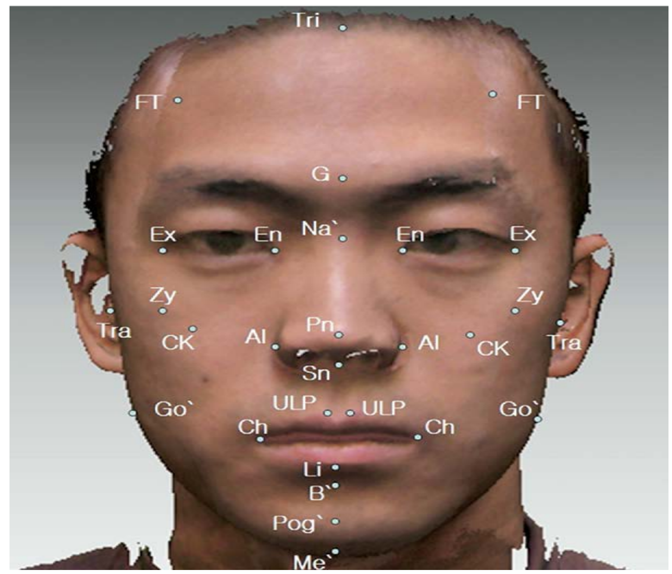

Fig. 8: Facial soft tissue landmarks, considered as standard reference points, identified on a three dimensional face image after merging 3D laser scanned images.

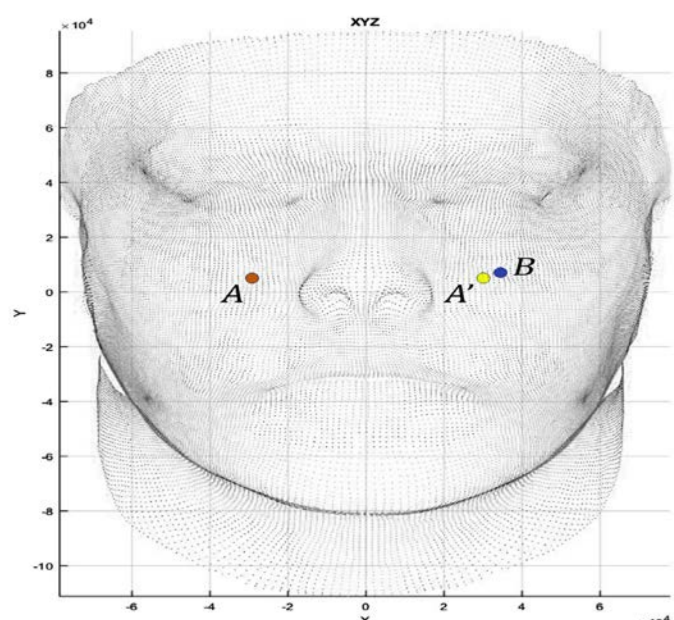

Fig. 9: Example for asymmetry analysis on point cloud.

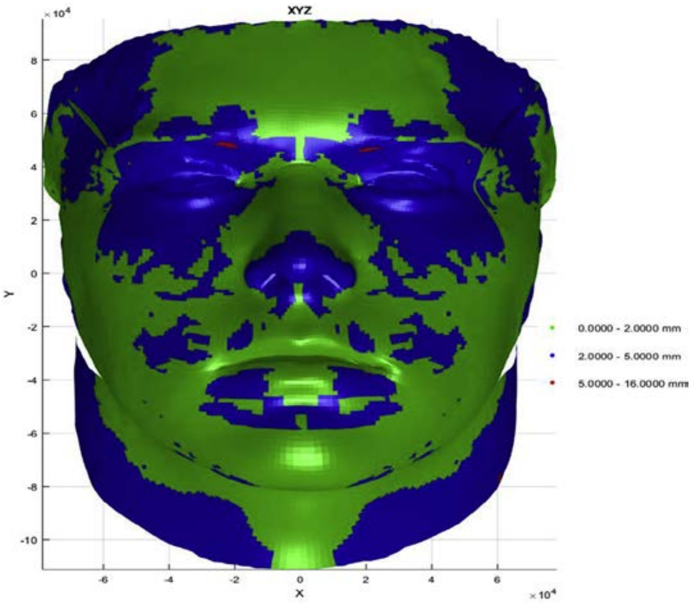

Fig.10: Colour map mesh of shaded triangular facets made to assess the asymmetry values image.

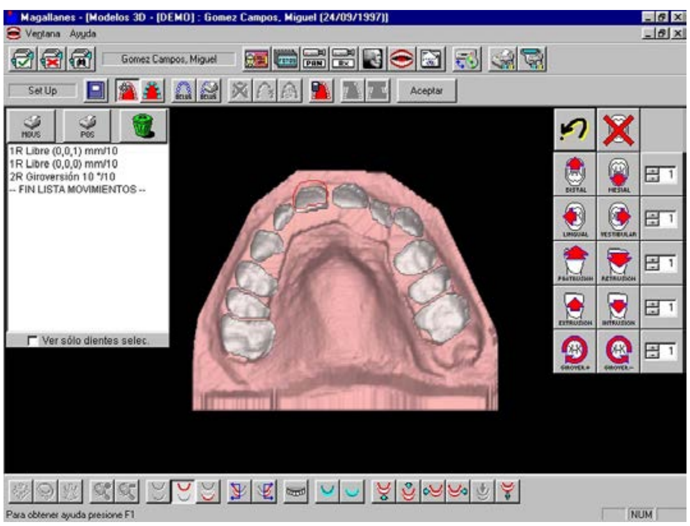

Fig. 11: An example of teeth movement simulation tools for assessing virtual treatment

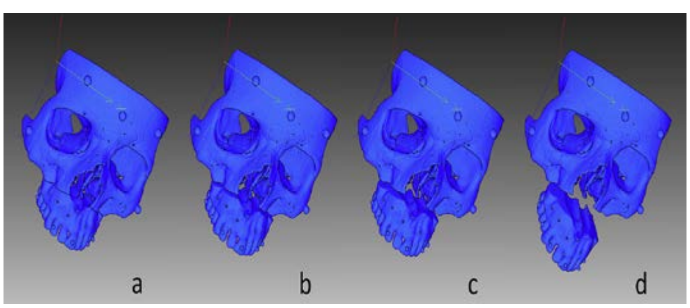

Fig.12: Image of virtual surgical planning, the virtual maxilla was moved in space for planning LeFort1 osteotomy

Conclusion

Image processing is a systematic method of operations done on an image, for obtaining an enhanced image or to extract informations from it. Manipulation of an image to get improved information or its integration with other images enhances the visualization of condition which improves the orthodontic diagnosis and treatmentplanning.With the development of different segmentation engines and multimodal image processing techniques the application of image processing techniques in the field of orthodontics was also evolved.

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