Digital diagnostics: Three-dimensional modelling

Article *in* British Journal of Oral and Maxillofacial Surgery · February 2008

DOI: 10.1016/j.bjoms.2006.10.008 · Source: PubMed

Prof. G. Dave Singh
Vivos BioTechnologies, Inc.

Available online at www.sciencedirect.com

ScienceDirect

British Journal of Oral and Maxillofacial Surgery 46 (2008) 22–26

BRITISH
Journal of
Oral and
Maxillofacial
Surgery

www.bjoms.com

Review

Digital diagnostics: Three-dimensional modelling

G.D. Singh *

BioModeling Solutions, 20699 NE Glisan Street # 233, Fairview, OR 97024, USA

Accepted 13 October 2006
Available online 28 November 2006

Abstract

Three-dimensional imaging techniques, such as computed tomograms (CT), structured light, and stereophotogrammetry, can be used to capture three-dimensional coordinate data, but comprehensive analysis is required to transform these techniques into powerful diagnostic tools. The object of this review is to highlight analytical functionality using software developed to study three-dimensional digital imaging and communications in medicine (DICOM) based digital data for diagnosis, planning of treatment, and evaluation of craniofacial changes. My specific aim was to apply three-dimensional software routines using geometric morphometrics or conventional measurements. These routines rely on robust algorithms to construct mean objects by manipulating the three-dimensional x, y, and z coordinates of all the objects' vertices. Conventional measurements and statistical tests can then be applied to the changes in the vertices, say, before and after treatment. Using graphical and geometric morphometric techniques such as finite-element analysis and principal components analysis, clinical craniofacial modelling can be used for the localisation and quantification of soft and hard tissue changes; diagnostic modelling can be undertaken for planning of treatment, and data-driven predictive modelling can be undertaken for the planning of many procedures based on the surgeon's own experience, patients, and resources. Three-dimensional modelling of digital data may therefore have added value for clinical diagnosis, and planning and assessment of treatment, including audit.

Keywords: Digital imaging; Diagnosis; Geometric morphometrics; Predictive modelling

Introduction

Digital imaging technology continues to advance. Recently, with the introduction of cone-beam tomography,[1] volumetric rendering of hard and soft tissue craniofacial structures with increased resolution and decreased exposure to ionising radiation will result in more clinicians using these new techniques. However, the huge files generated by these techniques require fast processing, as well as a large virtual memory and storage media. Decimation is one possible compromise as it reduces the resolution, and segmentation of digital data permits selection of dental, skeletal, and soft tissue domains. In addition, newer techniques, such as pseudo-colour triangulation, permit a considerable reduction in the size of a file before any compression. Despite these options, analysis of these digital imaging and communications in medicine (DICOM)-based data requires robust analytical techniques after processing. The overall aim of this paper is to review the analytical functions of software that is available to study three-dimensional DICOM-based digital data using geometric morphometrics or traditional measurements with statistical tests. The specific aim is to apply three-dimensional software routines for diagnosis, planning of treatment, and assessment of outcomes.

Imaging protocols

Three-dimensional imaging techniques can be classified as either invasive or non-invasive. Invasive techniques require "immersion" of the subject to capture three-dimensional coordinate data adequately and include: computed tomograms (CT), including cone-beam tomography, magnetic resonance imaging (MRI), digital radiography, and digital ultrasound. These techniques provide both surface and deeper

---

* Tel.: +1 503 432 1945; fax: +1 503 674 9552.
E-mail address: info@biomodelings.com.

0266-4356/$ – see front matter © 2006 The British Association of Oral and Maxillofacial Surgeons. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.bjoms.2006.10.008

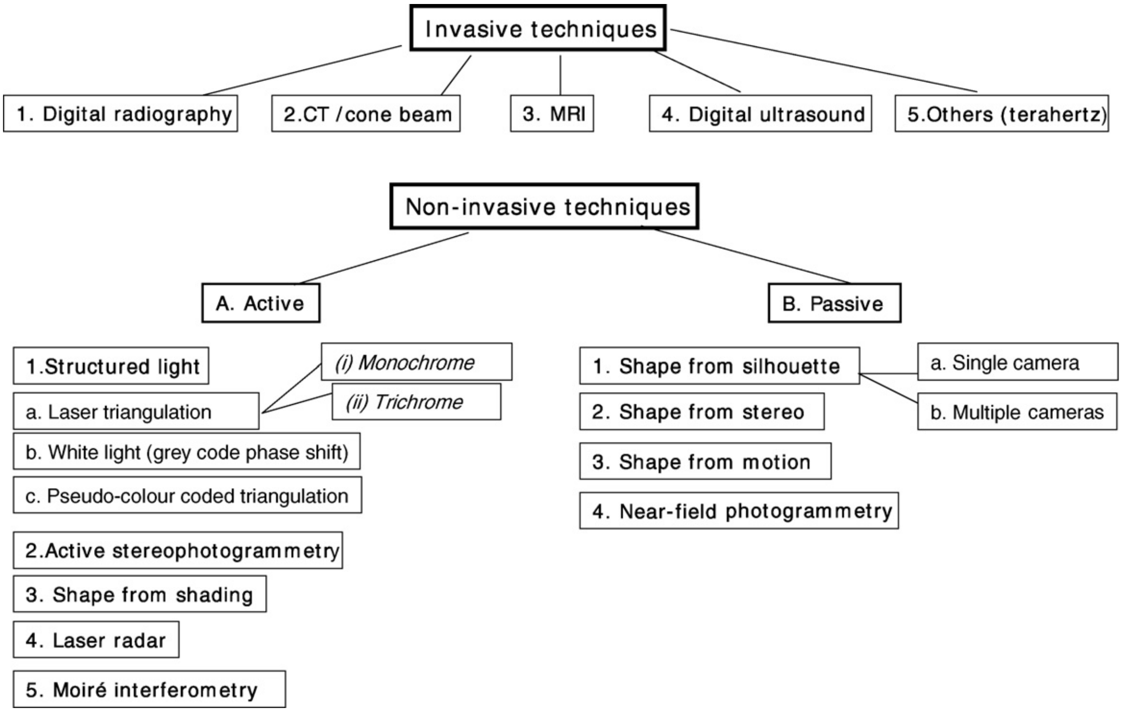


Fig. 1. Summary of the 3D imaging market segments by technology. Note that 3D airway imaging using pharyngometry/rhinometry is not included.

data, depending on the degree of segmentation. In contrast, non-invasive or "non-immersive"' techniques do not expose subjects to radiation but may use laser or intense beams of light. They provide only surface data, on to which texture can be mapped to produce photorealistic models. These non-invasive techniques can be further sub-divided into those that include active imaging, such as stereophotogrammetry, or passive imaging using one or more cameras. Fig. 1 briefly summarises the three-dimensional imaging segments by type of technology.

Three-dimensional modelling

To construct robust mean objects, mathematical algorithms are used, which manipulate the three-dimensional x, y, z coordinates of the objects' vertices. This protocol involves the manual digitisation of a handful of (9–10) homologous landmarks when using data from the surface of the face. Next, Procrustes superimposition is used to create a mean set of landmarks from the sample being studied (Table 1). Using a spline function, each object in the sample is warped to the Procrustes mean, ensuring that all objects are highly aligned in the shape space. After Procrustes and spline transformations, a base file is selected. Each landmark in the basic form is matched to the closest point in the triangular mesh of the warped form. The triangle that contains the closest point is identified, and the rotational matrix and translational vector required to unwarp it are calculated. The closest point is then unwarped. This routine is repeated for all of the warped forms, and so the dense correspondence is achieved. After successful completion of the dense correspondence routine, all vertices of all objects are transformed into homologous landmarks at the end of the computation. Finally, Procrustes superimposition can be repeated on all of the vertices to create a mean object, using any combination of (densely corresponding) objects.[3,4] These mean three-dimensional models are now ready for analysis.

Table 1
Glossary of terms[2]

Term	Definition
Procrustes superimposition	A version of least squares analysis using artificial landmarks for superimposition
Spline function	The kind of estimate produced by a spline regression in which the slope varies for different ranges of the regressors. It is continuous but not normally differentiable
Procrustes mean	The mean shape
Base file	The first file to which other files are mapped
Rotational matrix	Three-dimensional matrix formation
Translational vector	A method for obtaining the pure 3D translational motion parameter (without rotation)
Dense correspondence	The process of converting landmarks to behave as a series of homologous landmarks
Eigenvalue	Any of the possible values for a parameter of an equation for which the solutions will be compatible with the boundary conditions

Analytical techniques

Finite-element analysis

Finite-element scaling analysis (FESA) can be used to depict clinical changes in terms of allometry (size-related shape-change), and the change in form between a reference configuration and target configuration can be viewed as a continuous deformation, which can be quantified based on major and minor strains (principal strains). If the two strains are equal, the change in form is characterised by a simple increase or decrease in size. However, if one of the principal strains changes in a greater proportion, both size and shape are transformed. The product of the strains indicates a change in size if the result is not equal to 1. For example, a product >1 indicates an increase in size equal to the remainder; 1.30 indicates a 30% increase. Similarly, a product of 0.65 indicates a 35% decrease. The products and ratios can be resolved for individual landmarks within the configuration and these can be made linear using a log-linear scale. For ease of interpretation, a pseudocolour-coded scale can be used to provide a graphic display of change in size (using MorphoStudio^{TM} software). Fig. 2 shows a comparison using finite-element analysis of the mean three-dimensional models before and after treatment of 11 adult patients treated with a functional orthodontic appliance.[5]

Principal components analysis

Principal components analysis is an eigenvalue analysis of a sample's covariance matrix. The principal components can be defined as a set of vectors, and they can also be defined sequentially. For diagnostic purposes, this analysis can be used to compare different groups of objects (patients), with specific characteristics.[6] Normally a few modes (the principal components) are sufficient to describe all of the shapes approximately. Importantly, the points indicating the shapes in the mode space are grouped according to their main characteristics, so principal components analysis is determining axes that account for the maximal variance of the sample. If it is applied, the two most significant modes can be used for classification or diagnostic purposes. Fig. 3 shows an analysis of two samples of patients (before and after treatment) with unilateral cleft lip and palate.[7] Note that the new patient has been successfully classified correctly in the group before treatment.

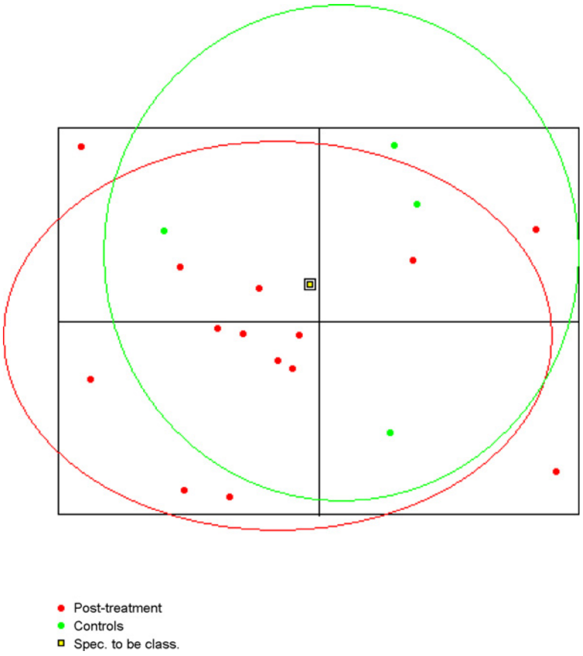
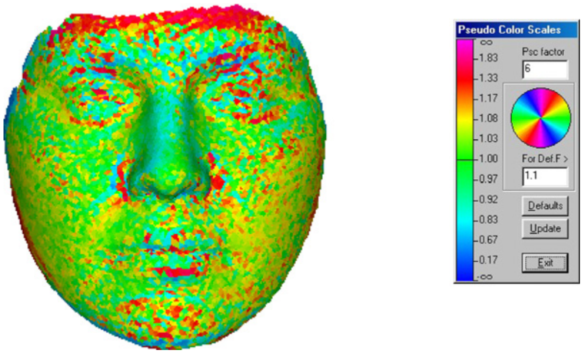


Fig. 3. Principal components analysis of two samples (pre- and post-treatment) of patients with unilateral cleft lip and palate. The green circles denote the pre-treatment sample and the red circles denote the post-treatment sample. Note that a new patient (yellow square) has been successfully classified correctly in the pre-treatment group.



Psc factor 6

For Def.F > 1.1

Fig. 2. Finite-element analysis comparison of the mean 3D pre- and post-treatment models of 11 adult patients treated with a functional orthodontic appliance. The pseudo-colour scale indicates the relative size changes after treatment.

J-Links

J-Links are line segments between two landmarks and are used to describe changes in distance between two landmarks during a specific transformation (such as a surgical treatment). These inter-landmark distances are pseudo-coloured according to the change and, if the calculated change is significant, this will be indicated by *t* tests. According to finite element analysis, a two-dimensional form can be partitioned into triangular elements to describe the transformation of a specimen between two stages. Three measures are used to describe each element's transformation: area factor, deformation factor, and direction of principal axis. However, it is also possible to use another three variables—the sides of the triangle. In this way, a triangular element can be described using J-Links of the three lengths corresponding to the sides of the triangle, and the transformation can be described by the three length factors of the J-Links. J-Links can be pseudo-coloured, using a scale to visualise changes in length. This approach can easily be extended to three-dimensions; a pyramid is simply defined by the six J-Links associated with its

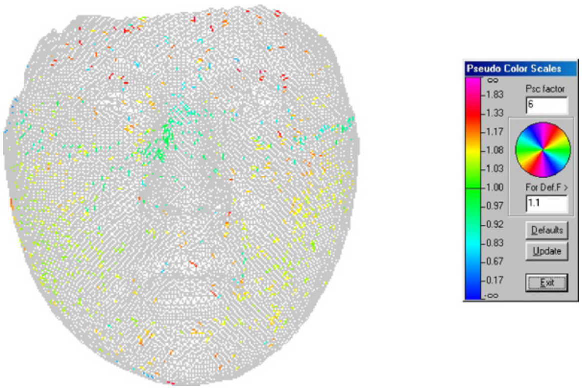


Fig. 4. J-Link analysis of the mean 3D pre- and post-treatment models of 11 adult patients treated with a functional orthodontic appliance. Only the links shown in colour are statistically different ($p < 0.05$). The amount of size change is indicated by the pseudo-colour scale.

borders. Additionally, J-Link lengths can be used to describe not the transformation, but the structure of the geometry itself, in a way that does not change with respect to the coordinate system. Put simply, J-Links represent an optimised description of the form system. Fig. 4 shows a comparison using J-Link analysis of the mean three-dimensional models of 11 adult patients before and after treatment who had been treated with a functional orthodontic appliance.[4] Only the J-Links (automatically) shown in colour were significantly different ($p < 0.05$).

Predictive modelling

In this protocol, a patient's likely morphology and appearance can be forecast after a specific procedure, such as a mandibular advancement osteotomy, or functional orthodontic correction. Note that this protocol does not rely on 'morphing' of the patient's features but rather depends on data-driven predictive modelling. For example, if a sample of patients matched for age, sex, and ethnicity had a specific procedure by a particular surgeon, the mean transformation of that dataset can be captured and recorded. Using a new patient as the 'base file', the transformation can be applied to that object to provide a predictive model, and if information about texture is available (such as a *.gif, *.jpg or *.bmp file) then the likely appearance of the patient after treatment can be virtually visualised. The main assumption in this routine is that the new patient will behave on average in the same way as the previous patients did.

Using the above routine, if all the landmarks are translated according to vectors associated with the homologous landmarks, a forecasted form is obtained by applying "absolute coordinate changes". This option is useful if a surgical implant is inserted into a patient, for example during genioplasty. If the vectors are proportionately re-sized, however, taking into account the mean size of the group given the treatment, and the size of the form that is about to be forecast, then "proportional coordinate changes" may be applied instead. This option is preferable for orthodontic treatments where the transformation is closely related to the size of the patients' structures. Fig. 5 shows a predictive model based on the mean transformation illustrated in Fig. 2 using absolute coordinate changes.

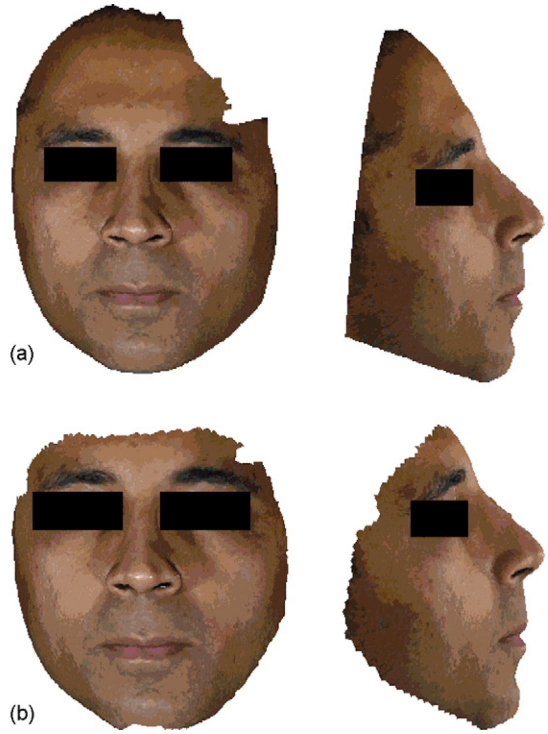


Fig. 5. (a) 3D stereophotogram of a patient prior to treatment. (b) 3D predictive model using absolute coordinate changes of patient shown in (a) based on the mean transformation of the sample illustrated in Fig. 2. The modelling makes the assumption that this new patient will behave the same way as the previous patients did on average. Permission to publish obtained.

Discussion

This early part of the 21st century has been characterised by rapid advances in digital imaging technology, each of which has its own advantages and disadvantages. For example, cone-beam tomography uses voxel imaging instead of the classic 'slices' but might not image the entire craniofacial region; for example, the cranial base might not be captured. Other methods, such as structured light and stereophotogrammetry, provide only surface data, but their rapid capture time (say 4 ms) means that they may be used preferentially when the patient's movement cannot be minimised (for example in young children). Other imaging techniques, such as laser scans, may also be useful, but three-dimensional airway imaging may be best captured using digital acoustics, which are still in their infancy. Despite the drawbacks noted above, digital data have other advantages over analogue techniques. Perhaps an underrated added value is their digital diagnostic potential. While clinicians may form professional opinions simply by viewing data with the trained eye, digital modelling provides an objective technique of analysing information about shapes, which can augment subjective criteria. Geometric morphometrics also provides techniques that are robust with respect to traditional cephalometry,[8] which might be supplanted in the near future.[9]

These digital archives can also form online databases and libraries so that a new patient can be compared in shape space with other similar previously treated cases, providing a virtual insight of anticipated outcome. Physical models can be constructed using stereolithography or rapid prototyping, and "missing data" can be recovered by on-screen modelling followed by computer aided design–computer aided management (CAD–CAM) techniques to fabricate resected tissues. Indeed, the bioengineering of smart devices is underway so that "guestimation" can be reduced in complex procedures such as distraction osteogenesis, and non-surgical procedures such as functional orthodontics. In summary, the future of surgical dentistry is digital. The advent of user-friendly turnkey imaging and analysis solutions and digital diagnostic centres is on the horizon.

Acknowledgements

I thank J. Lourido Ph.D. and M. Bradley for their assistance. The software is commercially available from Professor Dr. Singh, who is Medical Director of BioModeling Solutions, LLC.

References

1. Winter AA, Pollack AS, Frommer HH, Koenig L. Cone beam volumetric tomography vs. medical CT scanners. *NY State Dent J* 2005;**71**:28–33.
2. Slice DE, Bookstein FL, Marcus LF, Rohlf FJ. A glossary for geometric morphometrics. In: Marcus LF, Corti M, Loy A, Naylor GJP, Slice DE, editors. *Advances in morphometrics. NATO ASI series*, vol. A 284. London: Plenum Press; 1996. p. 531–51.
3. Hutton TJ, Cunningham S, Hammond P. An evaluation of active shape models for the automatic identification of cephalometric landmarks. *Eur J Orthod* 2000;**22**:499–508.
4. Hammond P, Hutton TJ, Allanson JE, et al. 3D analysis of facial morphology. *Am J Med Genet (A)* 2004;**126**:339–48.
5. Singh GD, Diaz J, Busquets-Vaello C, Belfor TR. Facial changes following treatment with a removable orthodontic appliance in adults. Funct Orthod 2004;**21**:18–20, 22–3.
6. O'Higgins P. Ontogeny and phylogeny: some morphometric approaches to skeletal growth and evolution. In: Chaplain MAJ, Singh GD, McLachlan JC, editors. *On growth and form: spatio-temporal patterning in biology*. Chichester: John Wiley; 1999. p. 373–93.
7. Singh GD, Levy-Bercowski D, Santiago PE. Three-dimensional nasal changes following nasoalveolar molding in patients with unilateral cleft lip and palate: geometric morphometrics. *Cleft Palate Craniofac J* 2005;**42**:403–9.
8. Halazonetis DJ. Morphometrics for cephalometric diagnosis. *Am J Orthod Dentofacial Orthop* 2004;**125**:571–81.
9. Halazonetis DJ. From 2-dimensional cephalograms to 3-dimensional computed tomography scans. *Am J Orthod Dentofacial Orthop* 2005;**127**:627–37.