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Invited Review Paper
Orthognathic Surgery

Digital three-dimensional image fusion processes for planning and evaluating orthodontics and orthognathic surgery. A systematic review

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Abstract. The three important tissue groups in orthognathic surgery (facial soft tissues, facial skeleton and dentition) can be referred to as a triad. This triad plays a decisive role in planning orthognathic surgery. Technological developments have led to the development of different three-dimensional (3D) technologies such as multiplanar CT and MRI scanning, 3D photography modalities and surface scanning. An objective method to predict surgical and orthodontic outcome should be established based on the integration of structural (soft tissue envelope, facial skeleton and dentition) and photographic 3D images. None of the craniofacial imaging techniques can capture the complete triad with optimal quality. This can only be achieved by 'image fusion' of different imaging techniques to create a 3D virtual head that can display all triad elements. A systematic search of current literature on image fusion in the craniofacial area was performed. 15 articles were found describing 3D digital image fusion models of two or more different imaging techniques for orthodontics and orthognathic surgery. From these articles it is concluded, that image fusion and especially the 3D virtual head are accurate and realistic tools for documentation, analysis, treatment planning and long term follow up. This may provide an accurate and realistic prediction model.

Keywords: computer-assisted three-dimensional imaging; image fusion; orthodontics; maxillofacial surgery; surface-soft-tissue; facial skeleton; dentition; review.

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Facial soft tissue (skin, connective tissues, fat and muscles), facial skeleton (bone and cartilage) and dentition are the three important tissue groups in orthodontics and orthognathic surgery, which can be referred to as a triad[9]. Together with other structures such as the superficial musculoaponeurotic system, the skeleton and dentition support the facial soft tissue surfaces. The triad plays a decisive role in planning orthodontic therapy and orthognathic surgery. Patients with a dysgnathic deformity need careful assessment of the facial soft tissues surface, the underlying maxillofacial skeleton and the dento-alveolar position and their interdependency.

Imaging and fusion techniques to analyse the facial profile, the facial skeleton and dentition for planning orthodontic therapy and orthognathic surgery have been available for over a century and can be described as analogue and digital techniques and image fusion models.

Analogue techniques. 10 years after the first orthognathic surgery for a congenital deformity was carried out[2,12], Babcock[7] (1897) introduced the use of plaster casts for model surgery. This method of preoperatively performing the planned osteotomy on a dental plaster cast is still known as the 'gold standard' for planning postoperative occlusion. One decade later orthodontists start using anthropometry, clinical photographs, dental and facial plaster casts and early fusion models (1915–1926)[1,67,105,107,108] for treatment planning. The development of these early fusion models was almost entirely abandoned in 1931 when Broadbent claims that cephalograms are more accurate for treatment planning, because they display the dentition in relation to the facial skeleton[17]. Cephalograms were soon accepted as 'the gold standard' for planning orthodontic treatment and orthognathic surgery. In this way, clinicians started to concentrate on two of the three structures of the triad (facial skeleton and dentition), despite the fact, that the overlying soft tissues define the facial outline[99].

The disproportional focus on facial skeleton and dentition is evident in the treatment outcome of the patient, as this approach sometimes results in a good functional but poor aesthetic result. The use of cephalograms shows clinicians that some profile-related problems cannot be solved by creating a perfect dental arch with normal occlusion[3] and that sometimes surgical displacement of the mandible and/or maxilla is required[45].

In the 1970s and 1980s, there was growing awareness that the aesthetic outcome is of equal importance to the patient as the rearrangement of the occlusion. Methods of studying the facial profile[48,86,90] or for planning surgical treatment, with for instance Obwegeser's 'Wunschprofiel'[84] and methods of analysing the facial soft tissue surfaces were (re)introduced, including facial plaster casts[94,95], anthropometry[27,28] and analogue photography[4,66,86].

Digital techniques. Digital photography was introduced to evaluate facial harmony[4]. It allows clinicians to establish a more proportional focus on all three structures of the triad, to assess the patient's deformity[4]. An accurate and objective assessment of a facial deformity or a preoperative prediction of the surgical outcome in two dimensions, especially regarding asymmetry, will always be deficient since it does not address the volumetric changes of all the facial portions that determine neuromuscular balance and facial harmony. As a consequence, with a computer graphic two-dimensional (2D) representation of facial appearance[46], it is not possible to achieve a realistic and acceptable result. From the 1980s, the shortcomings of these techniques induced an increase in the use of three-dimensional (3D) imaging techniques[114], such as facial surface laser scanning[54,73], 3D stereophotogrammetry (3D photography)[97] and (3D) video-imaging[80,100] to render the facial soft tissue surface. Reconstructions of digital imaging and communications in medicine (DICOM) files from multislice CT (MSCT), cone-beam CT (CBCT) imaging[36,77,78,117] or MRI slices[34] to display the skeletal structures and digital dental models to display the dentition[61,87,92] were also investigated (Table 1).

With CT data, it becomes feasible to produce a life-sized 3D milled model[15,16,64], a two stage resin model[19,24,37] or a stereolithographic model[11,32,33,74] of a patient. Various methods have been developed to integrate plaster casts into such models[30,51,82,98,118]. The facial skeleton models allow the surgeon to analyse the patient's deformity and plan orthognathic surgery in three dimensions. In such a 3D (augmented) model, model surgery can be performed only once and the soft tissue changes cannot be simulated. So although the third dimension is introduced, one of the structures of the triad (the facial soft tissues surface) is underestimated.

3D virtual planning software programs with a virtual operating room (VOR) were introduced at the end of the 1980s[18]. The IT revolution (2000s) has enabled significant improvements of these software modules.[25,104,125]. The reconstruction of DICOM files in a VOR enables the clinician to document, analyse and plan orthognathic surgery on a facial skeleton model as often and in as many different ways as required[104]. Programs to analyse the facial soft tissue surface[41,50] and dental models[23] were also introduced. For the first time, these programs gave the clinician a true insight into all three structures of the triad, albeit separately and routinely on a 2D computer screen.

Since most of the 3D imaging techniques only display one of the three structures with optimal quality[6,68,82], it is evident that these imaging techniques are more powerful when they are used together. This emphasises the importance of image fusion of 3D image modalities to document and analyse the triad of a patient's face accurately[9]. This has enhanced a search for an 'all in one' assessment of the face. Such an assessment should be performed using one holistic digital data set as the result of an image fusion process, including the facial soft tissue surface, the facial skeleton and dentition: the 3D virtual head. This results in a realistic and accurate 3D fusion model, with the true rational relationships between the facial soft tissue surface, the facial skeleton and the dentition.

Image fusion models. An image fusion model is defined as a composition of at least two different imaging techniques. The principle of image fusion is based on the creation of a single data set that contains all three structures of the triad. With segmentation by thresholding it is possible to reconstruct a volumetric facial skeleton with dentition and an untextured 3D facial soft tissue surface[106]. For example, a reconstruction of a (CB)CT contains the facial soft tissue surface representing the soft tissue, the bone volume representing the facial skeleton and the dentition, but the (CB)CT skin is untextured and the dental structures may contain streak artifacts caused by (in)direct restorations and/or orthodontic fixed appliances. To improve the quality of the virtual face and dentition, it is necessary to superimpose a textured facial soft tissue surface (e.g. acquired with a stereophotogrammetrical camera setup)[6,36,59,68] and to upgrade or replace the dental images (e.g. with digital dental casts)[29,82,102,109–113].

3D data can be fused using three different methods[115]: point based matching with or without the use of a reference frame; surface based matching[36,59,68]; and voxel based matching[110,111,115]. The matching process of the first method is based on corresponding points, while the other two use congruent surface points or voxels (volumetric picture elements) of a manually selected region. Based on the triad, four possible 3D fusion models can be distinguished: image fusion of the facial skeleton and the dentition; image fusion of the facial soft tissue surface and the facial skeleton; image fusion of the facial soft tissue surface and the dentition; and image fusion of the facial soft tissue surface, the facial skeleton and the dentition.

Three methods are used to display the facial skeleton and the dentition: the life-sized stereolithographic (STL)[71] or