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Bio-Modelling Reconstruction Based on MRI Image Acquisition and there Application in Orthognathic Surgery

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1. Abstract

Orthodontic and surgical technical advances in recent years have resulted in treatment opportunities for a whole range of craniofacial skeletal disorders either in the adolescent or adult patient. In the growing child these can include myofunctional orthodontic appliance therapy or distraction osteogenesis procedures, whilst in the adult the mainstay approach revolves around orthognathic surgery.

The literature agrees that for a change in craniofacial morphology to remain stable, the muscles acting upon the facial skeleton must be capable of adaptation in their structure and, therefore, their function. Failure of the muscles to adapt to the change in their length or orientation will place undesirable forces on the muscle attachments leading to potential instability of the skeleton. Adaptation can occur through various processes including those within the neuromuscular feedback mechanism, through changes within muscle structure or through altered muscle physiology, and through changes at the muscle/bone interface.

The innovation in this study resides in the combination of the protocol presented to obtain the area and volume of the masseter muscle using Magnetic Resonance together with the bio-modelling reconstruction with the AnatomicsTM software.

2. Introduction

The size of the masticatory muscle varies with craniofacial morphology and is an important indicator of the functional capacity of the masticatory system [1-5]. The masseter muscle is considered to generate force biting or chewing and is one of the structures that is most altered by orthognathic surgery. Its postoperative status may influence the patient’s physical appearance as well as masticatory function [1-3].

Orthognathic surgery in combination with orthodontic treatment, corrects the dentofacial deformity and improves occlusal contacts, masticatory efficiency, bite force, and electromyographic (EMG) activity. A number of studies reported the increased bite force and occlusal contact area after orthognathic surgery [2].

The functional and morphological characteristics of the masticatory muscle have been investigated in patients with dentofacial deformities. Patients with mandibular prognathism exhibit lower bite force, decreased occlusal contact, and lower electromyographic (EMG) activity than the normal subjects [2,3].

The masseter muscle displays a penniform structure typically characterized by the presence of alternating muscular/aponeurotic layers. The anatomical sections and the magnetic resonance imaging (MRI) section in the same plane allowed the appearance of the intra-muscular aponeurotic layers on the MRI to be defined [4].

The architecture of the masseter muscle has been studied for a long time but the lack of clinical applications led to descriptions which were often global or contradictory, giving the muscle sometimes two bundles sometimes three [4]. The successive studies of Gaspard [5-7], Yoshikawa [8,9] and Gaudy [10] allowed the definition of the arrangement of the muscular aponeurotic layers making up the human masseter muscle. Unger affirmed the value of magnetic resonance imaging in the oro-facial field for the study of the musculature of the tongue and the walls of the oral cavity, but gave only very general information on the masticatory muscle [11].

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Traditional methods in orthognathic surgery rely on the surgeon's skill and experience for precision, which can lead to variability in outcomes [12]. Moreover, translating two-dimensional pre-surgical plans into three-dimensional surgical procedures can be challenging and may affect the accuracy of the operation [13]. While experience and skill can help predict outcomes to some extent, the inherent unpredictability of human tissue responses post-surgery often leads to unexpected results [14]. This lack of predictability can result in dissatisfaction from patients who had different expectations of surgical results [15]. Every patient presents a unique anatomical framework and individual needs and expectations. Traditional methods, while customizable to an extent, do not provide the level of personalization and adaptability necessary to meet these varied needs [16].

As medicine moves towards patient-centric care, the demand for personalized surgical methods increases. Surgeons need to tailor surgical plans to the individual patient's anatomy and desired outcomes. The need for greater surgical precision and predictable outcomes is paramount in improving patient satisfaction rates and reducing complications [17]. Utilizing advanced technology can help achieve this by improving surgical planning, execution, and follow-up care. Incorporating 3D technology in surgical procedures can aid in better visualization of the surgical area, enhancing precision during surgery [18]. Furthermore, the ability to simulate different surgical scenarios can lead to better preparedness and more predictable outcomes. By enabling patients to visualize their surgical outcomes beforehand through virtual surgical planning, we can manage their expectations better and potentially enhance satisfaction rates. Moreover, less invasive surgery due to precise planning can lead to quicker recovery times and less post-operative discomfort, further improving the patient experience.

3. MRI Protocol Acquisition

MRI provides functional information in an anatomic presentation allowing to distinguish soft tissues with high sensitivity [19,20]. In a study of Dheyriat, to investigate the normal anatomy of masseter muscle, both at rest or during contraction by using three dimensional (3D) MRI the results are very interesting. The normal anatomical position of the masseter was reported to the skin plan as the mean internal distance (7.9 +/- 0.42 mm) and external distance (15.2 +/- 0.41 mm). While there was no difference between internal distance, for sex or side, the external distance was significantly ($p = 0.02$) shorter in male (7.7 +/- 0.5 mm) than in female (8.8 +/- 0.4 mm) for both sides. The mean volume for all subjects and both sides (20.3 +/- 1.1 cm3) did not change significantly between rest and exercise. The masseter volume was significantly ($p < 0.00001$) greater in male (24.2 +/- 2.0 cm3) than in female (16.4 +/- 3.6 cm3) groups [19]. These physiological references may be useful for further MRI investigations of masticatory system pathologies, like orthognathic surgery.

During this study the MRI machine used was a Sigma MR/I Twinspeed from GE Medical Systems, after several attempts the software was further developed to produce slices through the muscle at 1mm intervals rather than 2mm; the scanning time was about seven minutes. As a consequence, the resolution of the muscles was greatly enhanced. Further developments (reconstruction of muscles and bone from the same scan) have allowed visualisation of the muscle fibre orientation in relation to the muscle's bony attachments. Enabled the measurement of potential changes in orientation in relation to a static landmark unaffected by surgery (e.g., Frankfort plane) or in relation to functional identifiers (e.g., Occlusal plane) (Figure 1).

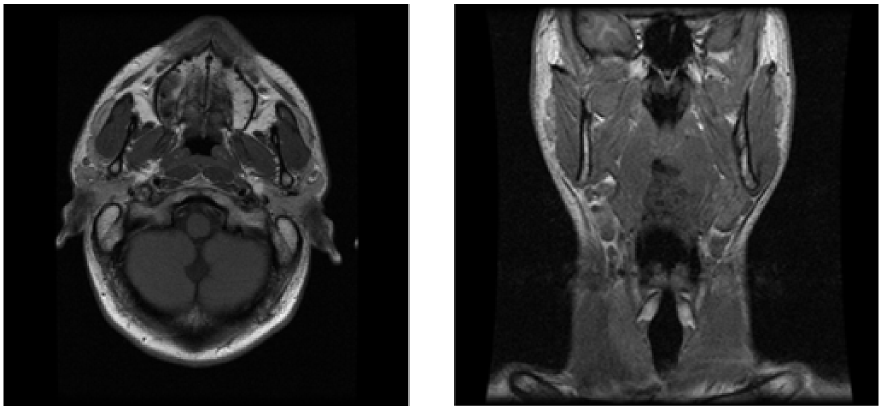

Figure 1: Images from the MRI scanner allowing the identification of the masseter muscle limits and fibres orientation.

4. Anatomics® Rx Software

The Anatomics® Rx software is a 3D DICOM viewer and allows to view CT and MRI scan data in both slice format and fully interactive 3D. Anatomics® can convert 3D images to the STL format for rapid prototyping, or as a bridge from medical imaging to Computer Aided Design (CAD). A good quality 3D scan is required to create an accurate biomodel or implant [21].

To standardise the scanning process, a scanning protocol was developed and applied that describe the preferred imaging parameters and provide the imaging technician with an area to note specifics. The patient must remain completely still during the scan, if the patient moves during the scan, it will need to be repeated. Only the original fine slice data must be used in the software, reformats will not be accepted. Fine overlapping slices must be used, the thickness of 1 mm (or nearest to) and a spacing of 0.8 mm.

The objective was to extract the muscle from the image (margins identification, extract the muscle considering the 3 planes of space, calculation of area and volume). The software allows the correction of limits at any time what gives the observer the capacity of double-check all the process (Figure 2).

The first masseter muscle 3D images reconstruction were acceptable in terms of definition, area and volume but with a lack of detail in terms of muscle fibres visualisation and orientation. Increasing the scanning time from five to seven minutes and changing the muscle slices to 1mm intervals was possible the acquisition of more muscle details. As a consequence, the resolution of the muscles was greatly enhanced and the final masseter muscle 3D images reconstruction permits a good visualisation of muscle fibres and their orientation. This type of reconstruction has also allowed visualisation of the muscle's bony attachments and enabled the measurement of potential changes in orientation in relation to a static landmark unaffected by surgery (eg. Frankfort plane) or in relation to functional identifiers (e.g., Occlusal plane) (Figure 3).

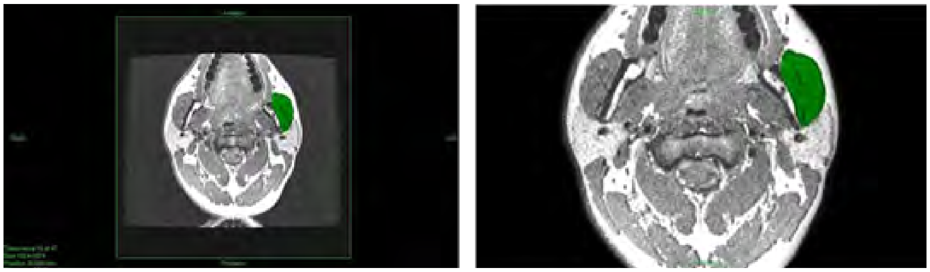

Figure 2: Identification of masseter muscle limits in a sagittal plane.

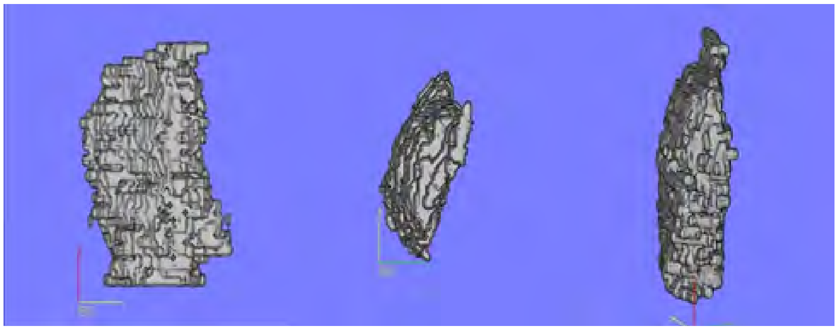

Figure 3: Final images from the left masseter muscle reconstruction using AnatomicsTM Software.

5. Bio-Modelling Reconstruction

Bio-Modelling is the generic term describing the ability to replicate the morphology of a biological structure in a solid substance. Specifically, bio-modelling has been defined as “the process of using radiant energy to capture morphological data on a biological structure and the processing of such data by a computer to generate the code required to manufacture the structure by rapid prototyping apparatus”. A biomodel is the product of this process, and virtual reality is the generic term coined for the visualization medium [22].

The ability to extract accurate 3D images from MRI, has proven to be a very useful diagnostic tool, using the scanning process with fine overlapping slices of 1 mm thickness and a spacing of 0.8 mm during 7 minutes, was possible to extract the muscles and the facial bones from same scan. To judge the quality of the imaging protocol described and the bio-modelling reconstruction process in terms of detail, definition and fibre orientation two bilateral masseter muscles were printed using stereolithography.

The objective was to extract the muscle from the scan with secure margins identification and also to extract the facial bones with considerable detail. The software used was the AnatomicsTM that allows the correction of muscle and bone limits at any time. The reconstruction of muscles and bone from the same scan have allowed visualisation of the muscle fibre orientation in relation to the muscle’s bony attachments. This could enable the measurement of potential changes in orientation in relation to a static landmark unaffected by surgery (eg. Frankfort plane) or in relation to functional identifiers (eg. Occlusal plane) (Figure 4).

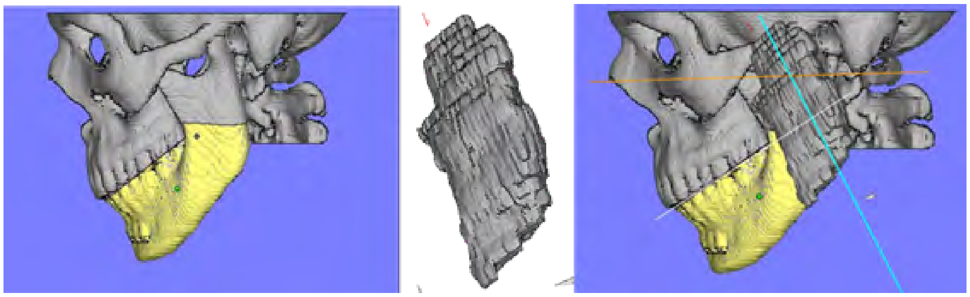

Figure 4: Bio-Modelling reconstruction of facial bones and masseter muscle.

6. Muscles Role

Many forms of interceptive treatment, whether they be purely orthodontic in nature or in combination with surgery, bring about changes in the muscles of mastication with regard to one or more of the following changes: a) in muscle fibre orientation, b) changes in the functioning length of fibres, c) changes in muscle structure and d) changes in muscle phenotype. Successful treatment requires both reorganisation in the connective tissue and regeneration of muscle fibres. Reorganisation of connective tissue is an extremely complex process involving muscle derived stem cells (satellite cells), extra-cellular matrix molecules and receptors for the extra-cellular matrix (for example integrins).

Remodelling of the extra-cellular matrix is mediated by a family of enzymes known as matrix metalloproteinases (MMPs) [9,10]. MMP2 is expressed during the regeneration of new myofibres and is a known mechano-responsive gene. A knowledge of how muscles respond to clinical interventions is pivotal to treatment success and can influence the way in which a particular treatment modality is applied. Functional appliances, for example, can be either fixed or removable, can be constructed to varying degrees of vertical opening and there are protagonists and antagonists for both gradual versus one-step activation of the appliances. Similarly, distraction osteogenesis is considered by many to be preferable to orthognathic surgery in specific cases because it induces a gradual as opposed to a one-step activation believed to be more physiologically appropriate for bone and possibly, muscle adaptation [9,10, 23, 24].

With regard to orthognathic surgery the golden rule is that surgery must not stretch the pterygo-masseteric sling, otherwise relapse is likely to occur. This is predominantly through the speed of insult to the muscle in relation to the timing of the muscle adaptive process. The consequence is either an immediate reversion back to the original functioning length of the muscle and return of the bony fragments back to their original pre-surgical position, and/or migration of the muscle attachment along the surface of the bone, thereby leading to an area of bone denuded of muscle force, which ultimately leads to resorption of the bony muscular processes [23,24].

One way in which this can be studied more closely is through refinements in protocols for 3-D magnetic resonance imaging of the face and jaws. Increasing the resolution of the tomographic cuts to 1.0mm has led to a resolution which facilitates the identification of not only the origins and insertions of the muscles of mastication but even the orientation of individual muscle fibre bundles (Figure 5A and B). It is therefore possible to study the changes in muscle fibre orientation in relation to landmarks such as the functional occlusal plane and also those landmarks unaffected by surgery, for example the cranial base (Figure 5C and D). Ideally, as mentioned, surgery to correct an increased vertical facial deformity should involve posterior maxillary impaction together with a mandibular procedure where the final outcome does not increase the posterior facial height and hence, does not stretch the pterygo-masseteric sling. As such the orientation of the muscle fibres in relation to their functioning occlusal plane remains unaltered (Figure 5E). However, if there is failure to adequately impact the posterior part of the maxilla in such cases then there is a rotation of the mandibular segments around the premolar/first molar region resulting in a reduction of the anterior face height but an unwelcome increase in the posterior vertical dimension (Figure 5F) and thereby leading to an increase in the length of the ptergo-masseteric sling (Figure 5G). Furthermore, this leads to a much less efficient musculo-occlusal relationship and as such more extensive adaptation has to take place within the muscles in order to be able to accommodate the unwanted surgical change. In clinical cases where this unwanted change has occurred, there is not only a return towards the original pre-surgical bony relationships (Figure 5H) but also migration of the muscle attachment leaving an area of bone at the gonial angle which subsequently resorbs and leads to the unwanted and unsightly hour glass deformity of the mandibular border (Figure 5I).

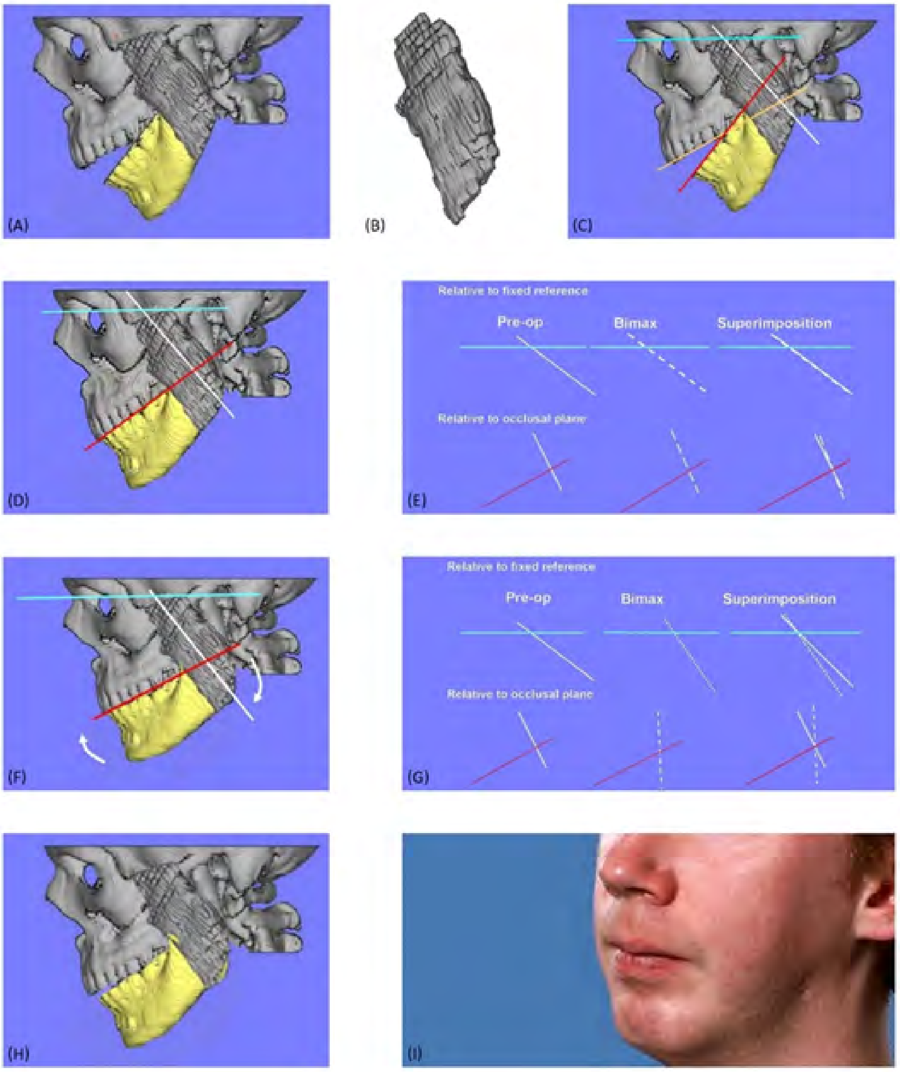

Figure 5: 3-D MRI showing detail of masseter muscle fibre bundle orientation (A and B). Favourable change in muscle length and fibre orientation following maxillary impaction and mandibular advancement surgery for closure of anterior open bite (C, D and E). Unfavourable change following insufficient posterior maxillary impaction with resultant stretch of pterygo-mandibular sling (F and G) and subsequent relapse (H and I).

7. Conclusions

A number of studies have reported increased bite force, occlusal contact area, and EMG activity and improved masticatory efficiency after surgery [25]; however, the reason for this improvement is unclear. It is a subject still under debate that surgery itself improves masticatory function. Previous studies reported that the postoperative improvements in muscular activity were due to better occlusal stability and not to surgically induced biomechanical advantages [25]. The importance of occlusion for the neuromuscular equilibrium and dental supports was investigated in patients undergoing orthognathic surgery. Changes in of muscle size; increased occlusal contact area providing greater dental support; sensitivity of teeth, muscles, and the temporomandibular joints; and even the patients' willingness to exert maximum effort have been suggested as factors in determining the occlusal force after surgery [26].

MRI therefore seems to be a valid tool for measuring differences in the masseter muscle area (mm2) and masseter muscle volume (mm3) associated with high-severity occlusal deformities, although showing not to be as efficient in detecting the same differences in cases of low-severity occlusal deformities.

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