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Research Article

Correlation between MRI and Biomodelling Analysis in Masseter Muscle Following Orthognathic Surgery

Fernando Duarte[*1], João Neves Silva[2], Carina Ramos[3], Colin Hopper[4]

[1]Oral Surgeon Specialist by OMD (Portuguese Dental Association), Master of Science in Oral and Maxillofacial Surgery at Eastman Dental Institute University College of London, PhD student at UCL – University College of London
[2]Professor at ISAVE – Instituto Superior de Saúde – Portugal, Member of the Interdisciplinary Center for Health Sciences (ICHS) – ISAVE –Instituto Superior de Saúde
[3]MSc student in Oral Oncology at Instituto de Ciências Biomédicas Abel Salazar – Oporto University – Portugal
[4] Oral and Maxillofacial Surgery Department at Eastman Dental Institute – University College of London

Corresponding author: Fernando Duarte
Clitrofa - Centro Médico, Dentário e Cirúrgico, Avenida de Paradela 622, 4785-248 Trofa - Portugal
Tel: +351252428960 E-mail: fduarte@clitrofa.com

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Abstract

Purpose: This pilot investigation was designed to apply several and innovative methods of measuring muscle area, volume, structure, function and fibre orientation to a situation where adaptation of muscle is pivotal to the success of a therapeutic approach.
Materials and Methods: Patients attending the combined orthodontic/orthognathic surgery clinic at Clitrofa – Centro Médico, Dentário e Cirúrgico, in Trofa - Portugal were screened using a standardized Magnetic Resonance Imaging protocol, with fine overlapping slices of 1 mm thickness and a spacing of 0.8 mm during 7 minutes. The software used was the AnatomicsTM that allows the correction of muscle and bone limits.
The landmarks considered for this study were: a) the anterior angle from the long axis of masseter muscle versus angle between lower border of the zygomatic bone and the mastoid process; and b) the anterior angle from the long axis of the masseter muscle versus the mandibular plane. The angles were measured by two different observers. The values were registered (T0) and the procedure was repeated after 1 hour (T1), and 6 to 12 months after surgery (T2).
Conclusions: Significant statistical differences ($p < 0,05$) have been identified between Time 2 (1-6 months after surgery) and Times 0 and 1 (prior to surgery) in the mean P2 angle measured, both for Examiner F and C. These differences reveal the masseter muscle adaptation following bimaxillary osteotomy involving a combination of maxillary Le Fort I impaction procedure coupled with a sagittal split advancement of the mandible in this study-case. The measurement of "P1 Masseter Muscle/Zygomatic Bone/Process Mastoid Anterior Angle" and "P2 Masseter Muscle/Mandibular Angle" can therefore be a valuable tool for controlling the reworking of masseter muscle upon orthognathic surgery.

Keywords
Orthognathic Surgery, Masseter Muscle, MRI Analysis, Biomodelling Analysis

Declaration of Conflicting Interest
The authors declare that they have no conflict of interest.

Introduction:

Advances in medical imaging have created ever increasing volumes of complex data obtained from the patient. The interpretation of such information has become a specialty in itself and the surgeon at times may be left bewildered as to how best to apply the available information to the practicalities of physical intervention. The surgeon seeks to understand the exact morphology of the abnormality, its relationships to surrounding anatomy and the best way to access and correct the pathology operatively. Such specific information is not readily available in the radiologist's report and however experienced the surgeon may be at interpreting images such questions, often cannot be easily answered[1].

Three-dimensional (3-D) imaging has been developed to narrow the communication gap between radiologist and surgeon. By using 3-D, imaging a vast number of complex slice images can be quickly appreciated. The term "three-dimensional" however, is not a truly accurate description of these images as they are still displayed on a radiological film or flat screen in only two dimensions[1].

For harmonious vertical facial growth and development to exist, the growth on the front of the face must be the same as on the back. If this does not occur, there may be a relative growth rotation of the mandible. For example, if the growth in the posterior part of the face exceeds what occurred previously, the net effect will be an anterior rotation of the mandible, producing the typical deformity of the short face and the deep overbite associated with the short face syndrome[2]. At the opposite end, where growth at the back of the face can be severely reduced compared to what occurred earlier, a clockwise opening or rotation of the jaw is evident, with the net effect of being an excessive anterior facial height and often a bitten anterior opening, associated with a deformity of the long face[3].

For generations, both clinicians and scientists have argued as to the respective contribution of genetics and, so called, environmental factors in influencing ultimate facial form and associated malocclusion. Of all the possible environmental influences, it is not surprising that bearing in mind the origins and insertions of the muscles of mastication, and in particular the masseter and medial pterygoid muscle, that the question has arisen as to whether, or not, abnormalities in the structure and function of the muscular pterygo-masseteric sling could, in any way, influence vertical development in the posterior part of the face. Furthermore, if treatment interventions necessitate a change in function of the muscles that support the mandible, do the adaptive capability of these muscles in any way influence the stability of the treatment outcome[4].

MRI and Bio-Modelling:

Computers are used increasingly as a supportive tool for the diagnosis, operation planning, and treatment in medicine and dentistry. They are used in connection with the modern digital imaging techniques such as computer tomography and magnetic resonance imaging, as well as ultrasound to improve the visualization of anatomical and physiological conditions in keeping with the human imagination[5].

The ability to extract accurate three-dimensional (3D) images from magnetic resonance imaging (MRI), has proven to be a very useful diagnostic tool to extract the muscle from the scan with secure margins identification and also to extract the facial bones with considerable detail[6].

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 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 (eg. Occlusal plane).

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). Remodeling of the extra-cellular matrix is mediated by a family of enzymes known as matrix metalloproteinases (MMPs)[7,8]. 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[7,8].

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.

One way in which this can be studied more closely is through refinements in protocols for 3-D MRI of the face and jaws. Increasing the resolution of the tomographic cuts 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. 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.

Materials and Methods:

Ten patients attending the combined orthodontic/orthognathic surgery clinic at the Clitrofa – Centro Médico, Dentário e Cirúrgico, in Trofa - Portugal were tested according to the following protocol:

Accurate extraction of muscles and facial bones using the same scan from MRI three-dimensional (3D), using a standardize scanning process, with fine overlapping slices of 1 mm thickness and a spacing of 0.8 mm during 7 minutes[6]. The software used was the AnatomicsTM that allows the correction of muscle and bone limits at any time[6].

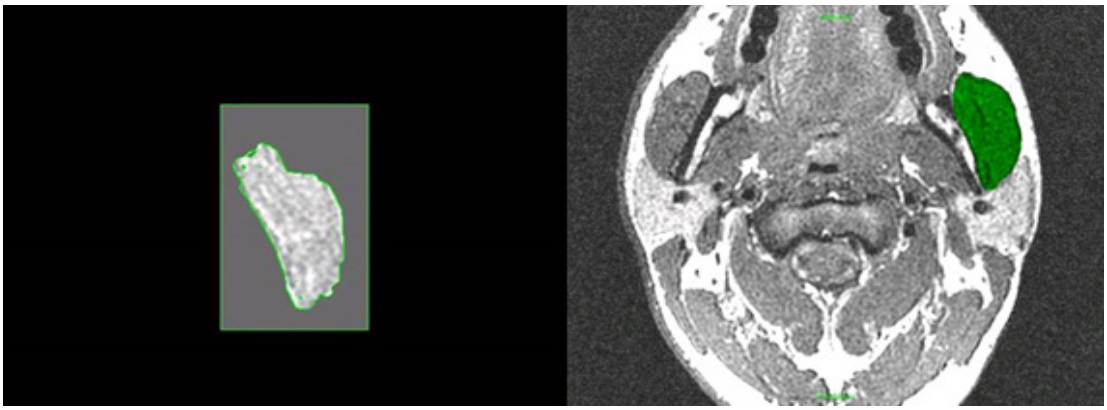

Figure 1: Identification of masseter muscle limits in a sagital plane.

The landmarks considered for this study were: (a) the anterior angle from the long axis of masseter muscle versus angle between lower border of the zygomatic bone and the mastoid process, (b) the anterior angle from the long axis of the masseter muscle versus the mandibular plane[9].

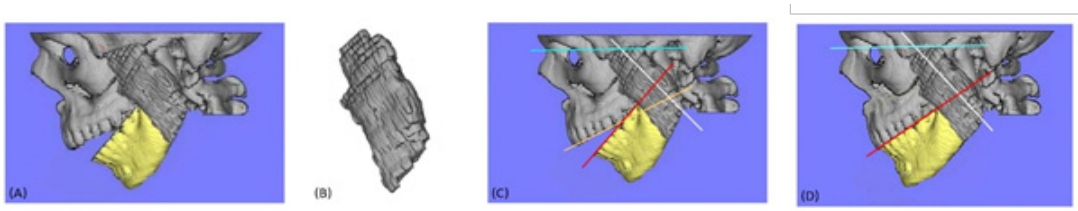

Figure 2: 3-D MRI showing detail of masseter muscle fibre bundle orientation (A and B). Favourable change in muscle length and fibre orientation following maxillary impaction and mandibular advancement surgery for closure of anterior open bite (C, D).

In this pilot study, the angles were measured by two different observers. The values were registered (T0) and the procedure was repeated after 1 hour (T1), and 6 to 12 months after surgery (T2). The results have been measured by two different observers. These 10 patients were scheduled for a bimaxillary osteotomy involving a combination of maxillary Le Fort I impaction procedure coupled with a sagittal split advancement of the mandible. A combination of different parametric tests has been used to compare the different experimental variables.

T he experimental design devised for this study is depicted in Figure 3, comprising a combination of different examiners, surgical angles and times of measurement (pre- and post-operation).

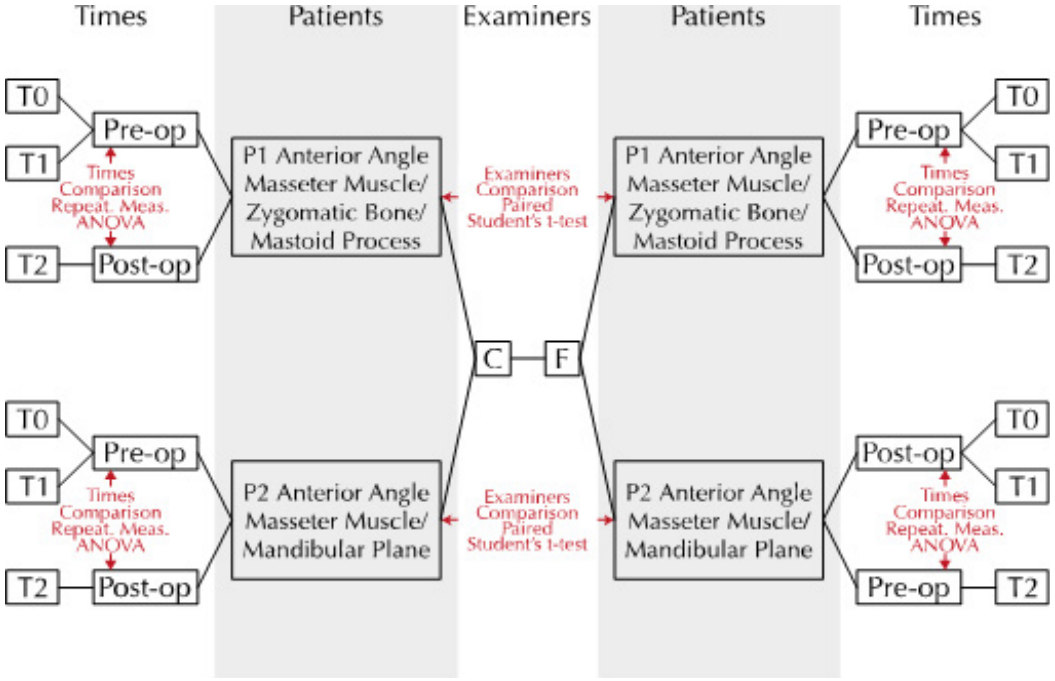

Figure 3: Experimental design used for assessing the biomodelling analysis. The study involved the contribution of two independent examiners (F and C), that measured the "P1 Masseter Muscle/Zygomatic Bone/Process Mastoid Anterior Angle" and the "P2 Masseter Muscle/Mandibular Angle" at two different times (pre- and post-operation).

IBM® SPSS® version 25 was used to analyze the data obtained. The data were first tested to ensure they conformed to a normal distribution by using the Kolmogorov-Smirnov test, the Shapiro-Wilks test or by determining the values of skewness (acceptable values for normality between -2 and +2) and kurtosis (acceptable values for normality between -2 and +2). Descriptive statistics included the arithmetic mean ($\bar{x}$), standard deviation (SD), and standard error of the mean (SE), as well as the 95% confidence interval (95% CI). Where the data were not normally distributed, the median and the inter-quartile range (IQR) were noted.

In those situations where the data were normally distributed and the variances were constant, comparative analysis involved either the unpaired or paired two-tailed Student's t test. Multiple comparisons were made using the One-Way Analysis of Variance (ANOVA) or Repeated Measure Analysis of Variance (ANOVA) depending if the data were, respectively, unpaired or paired.

Post-Hoc Gabriel test and post-hoc Bonferroni test were used, respectively for One-Way ANOVA and Repeated Measures ANOVA, to identify the pairs where the significant statistical differences were located.

Where the requirements for parametric statistical analysis were not met, the data were analyzed using either the Wilcoxon Signed Rank *(U)* test for paired data or the Mann-Whitney *(U)* test for unpaired data as appropriate. Comparison between three or more groups were made using the Kruskal-Wallis *(H)* or the Friedman *(H)* test depending if the data were, respectively, unpaired or paired.

The minimum level of significance (α level) accepted throughout the development studies was 0.05 (*), considered to be "moderately significant". Levels of 0.01 (**) were considered as "significant" and 0.001 (***) designated as "highly significant". A lack of statistical significance was designated as (ns).

Comparison A – Testing the Differences between Examiners (F *versus* C)

Research question: Are there any significant statistical differences in the mean values of P1 and P2 angles measured by Examiner F and Examiner C in the same experimental conditions?

H0: There are no significant statistical differences in the mean values of P1 and P2 angles measured by Examiner F and Examiner C in the same experimental conditions.

H1: There are significant statistical differences in the mean values of P1 and P2 angles measured by Examiner F and Examiner C in the same experimental conditions.

Comparison B – Testing the Differences between Times (Time 0 versus Time 1 versus Time 2)

Research question: Are there any significant statistical differences in the mean values of P1 and P2 angles measured between moments Time 0, Time 1 and Time 2 in the same experimental conditions?

H0: There are no significant statistical differences in the mean values of P1 and P2 angles measured between moments Time 0, Time 1 and Time 2 in the same experimental conditions.

H1: There are significant statistical differences in the mean values of P1 and P2 angles measured between moments Time 0, Time 1 and Time 2 in the same experimental conditions.

Results:

Variable	Mean (°)	SD (°)	Variance (°^2)
P1_F_T0	81,000	14,787	218,667
P1_F_T1	81,000	14,787	218,667
P1_F_T2	80,800	15,208	231,289
P1_C_T0	80,900	14,881	221,433
P1_C_T1	81,000	14,787	218,667
P1_C_T2	80,800	15,208	231,289
P2_F_T0	77,100	6,887	47,433
P2_F_T1	77,100	6,887	47,433
P2_F_T2	75,300	6,734	45,344
P2_C_T0	77,300	7,134	50,900
P2_C_T1	77,100	6,887	47,433
P2_C_T2	75,400	6,620	43,822

Table I: Values of "P1 Masseter Muscle/Zygomatic Bone/Process Mastoid Anterior Angle" and "P2 Masseter Muscle/Mandibular Angle" of ten different patients observed prior to surgical operation ("pre-op"), at the different experimental conditions shown in Figure 4.

Comparison A – Testing the Differences between Examiners (F *versus* C)

The statistical comparison between the examiners F and C regarding the measurement of "P1 Masseter Muscle/Zygomatic Bone/Process Mastoid Anterior Angle" and "P2 Masseter Muscle/Mandibular Angle" of ten different patients was performed using a Paired Student's t-test for three different time moments of measurement (Time 0, Time 1 and Time 2) (Figure 4 and Table II).

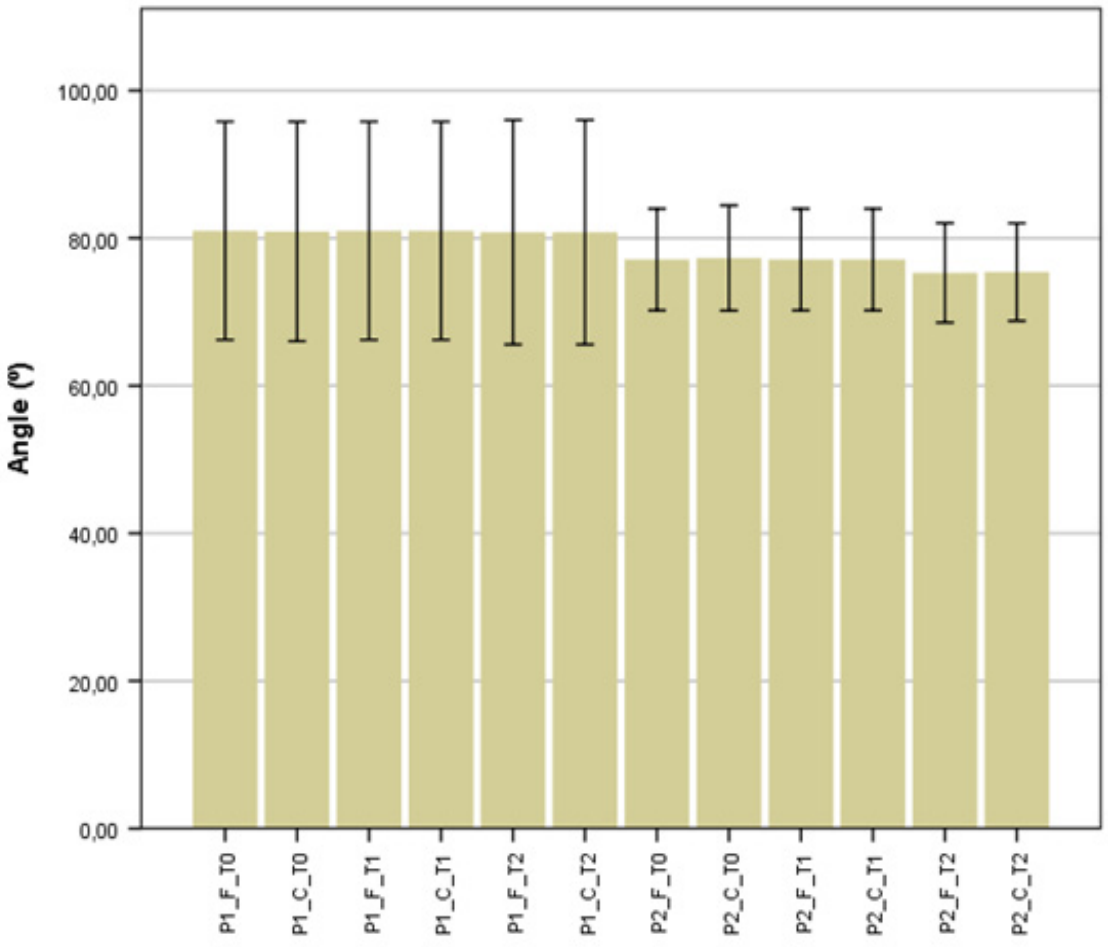

Figure 4: Mean values of "P1 Masseter Muscle/Zygomatic Bone/Process Mastoid Anterior Angle" and "P2 Masseter Muscle/Mandibular Angle" of ten different patients observed Examiner F and Examiner C at three different time moments (Time 0, Time 1 and Time 2).

Examiners Comparison	Mean Difference	Standard Deviation of Differences	Degrees of Freedom *(df)*	Test statistic from Paired *t*-test	*P-value* from Paired *t*-test
Examiner F versus Examiner C, Time 0, P1 Angle	0,100	0,316	9	1,000	0,343
Examiner F versus Examiner C, Time 1, P1 Angle	0,000	0,000	9	-	-
Examiner F versus Examiner C, Time 2, P1 Angle	0,000	0,000	9	-	-
Examiner F versus Examiner C, Time 0, P2 Angle	-0,200	0,422	9	-1,500	0,168
Examiner F versus Examiner C, Time 1, P2 Angle	0,000	0,000	9	-	-
Examiner F versus Examiner C, Time 2, P2 Angle	-0,100	0,316	9	-1,000	0,343

Table II : Statistical parameters obtained in the Paired Student's t-test for comparison of examiners F and C regarding the measurement of "P1 Masseter Muscle/Zygomatic Bone/Process Mastoid Anterior Angle" and "P2 Masseter Muscle/Mandibular Angle" of ten different patients observed at three different time moments (Time 0, Time 1 and Time 2).
* moderately significant to 0.05 level; ** significant to 0.01 level; *** highly significant to 0.001 level.

Comparison B – Testing the Differences between Times (Time 0 *versus* Time 1 *versus* Time 2)

The statistical comparison between the three-time moments (Time 0, Time 1 and Time 2) regarding the measurement of "P1 Masseter Muscle/Zygomatic Bone/Process Mastoid Anterior Angle" and "P2 Masseter Muscle/Mandibular Angle" of ten different patients was performed using a Repeated Measure ANOVA for Examiner F and Examiner C (Figure 5 and Table III).

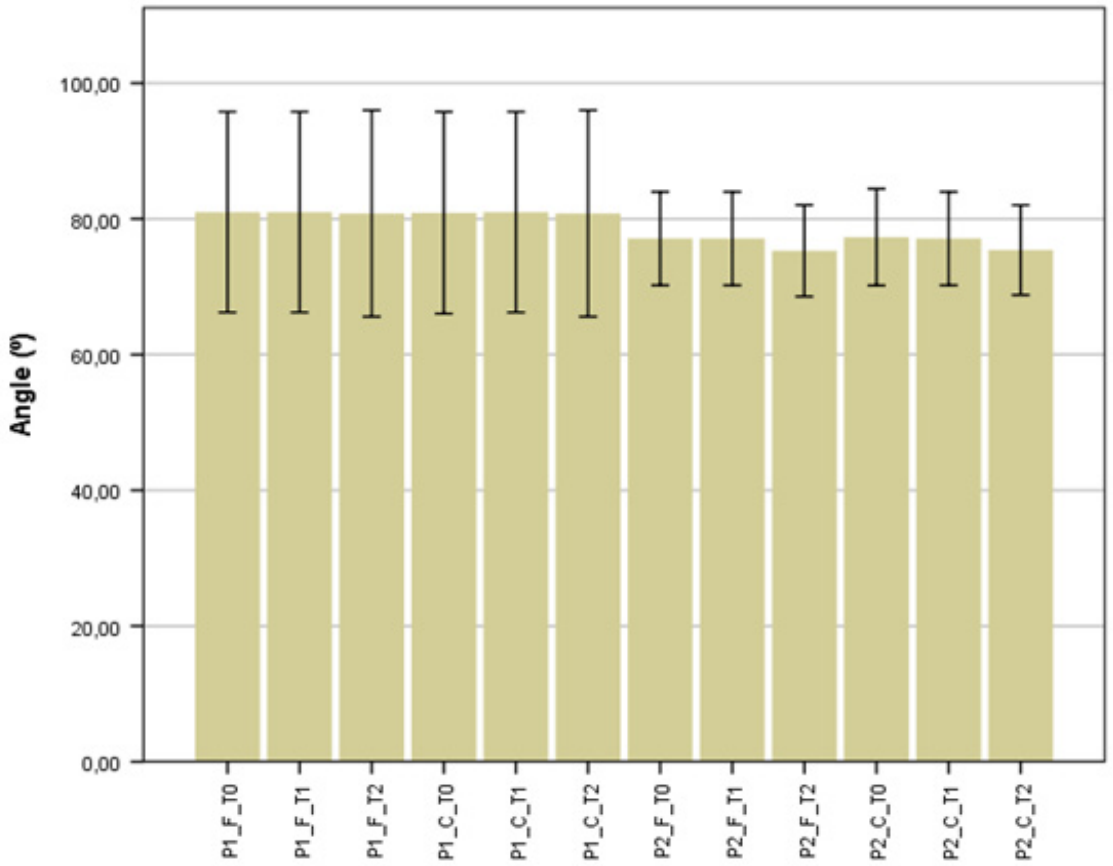

Figure 5: Mean values of "P1 Masseter Muscle/Zygomatic Bone/Process Mastoid Anterior Angle" and "P2 Masseter Muscle/Mandibular Angle" of ten different patients observed at three different time moments (Time 0, Time 1 and Time 2) by Examiner F and Examiner C.

Times Comparison	Degrees of Freedom *(df)*	Test statistic *(F)*	*P-value (Sig)*
Time 0 vs Time 1 vs Time 2, Examiner F, P1 Angle	2, 18	1,000	0,387
Time 0 vs Time 1 vs Time 2, Examiner C, P1 Angle	2, 18	0,730	0,496
Time 0 vs Time 1 vs Time 2, Examiner F, P2 Angle	2, 18	14,878	0,000***
Time 0 vs Time 1 vs Time 2, Examiner C, P2 Angle	2, 18	15,249	0,000***

Table III: Statistical parameters obtained in the Repeated Measures ANOVA for the comparison of time moments (Time 0, Time 1 and Time 2) when measuring the "P1 Masseter Muscle/Zygomatic Bone/Process Mastoid Anterior Angle" and "P2 Masseter Muscle/Mandibular Angle" of ten different patients observed by Examiner F and Examiner C.

Because Repeated Measures ANOVA only gives information about the presence of differences, not specifying where these differences are located, a Post-Hoc Bonferroni test was used to perform pairwise comparisons between the times in the mean P2 angle, and these results are represented in Table IV.

Independent Variable			Mean Difference (I-J)	Std. Error	Sig.
F_Q2/P2	T0	T1	0,000	0,000	-
		T2	1,800	0,467	0,012*
	T1	T0	0,000	0,000	-
		T2	1,800	0,467	0,012*
	T2	T0	-1,800	0,467	0,012*
		T1	-1,800	0,467	0,012*
C_Q2/P2	T0	T1	0,200	0,133	0,504
		T2	1,900	0,433	0,005**
	T1	T0	-0,200	0,133	0,504
		T2	1,700	0,473	0,017*
	T2	T0	-1,900	0,433	0,005**
		T1	-1,700	0,473	0,017*

Table IV: Statistical parameters obtained in the Post-Hoc Bonferroni test for the comparison of Times (Time 0, Time 1 and Time 2) when measuring the mean P2 angle in different experimental conditions.
* moderately significant to 0.05 level; ** significant to 0.01 level; *** highly significant to 0.001 level.

Discussion:

No significant statistical differences have been identified between Examiner F and Examiner C regarding the measurement of "P1 Masseter Muscle/Zygomatic Bone/Process Mastoid Anterior Angle" and "P2 Masseter Muscle/Mandibular Angle" of the ten patients analysed ($p > 0,05$).

No significant statistical differences have been detected in the mean P1 angle measured at Time 0, Time 1 or Time 2, irrespective of the Examiner (F or C), which means that H0 proposition is valid ($p > 0,05$).

With respect to the mean P2 angle, significant statistical differences have been identified throughout time (Time 0, Time 1 or Time 2), as can be observed in Table 3 ($p < 0,05$) The differences are mainly located in Time 2 (post-op), when compared with Times 0 and 1 (pre-op) as can be observed in Table 4, revealing that this technique can be successfully used to evaluate the reworking of masseter muscle upon orthognathic surgery.

Conclusions:

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

Significant statistical differences ($p < 0,05$) have been identified between Time 2 (1-6 months after surgery) and Times 0 and 1 (prior to surgery) in the mean P2 angle measured, both for Examiner F and C. These differences reveal the masseter muscle adaptation following bimaxillary osteotomy involving a combination of maxillary Le Fort I impaction procedure coupled with a sagittal split advancement of the mandible in this study-case. The measurement of "P1 Masseter Muscle/Zygomatic Bone/Process Mastoid Anterior Angle" and "P2 Masseter Muscle/Mandibular Angle" can therefore be a valuable tool for controlling the reworking of masseter muscle upon orthognathic surgery.

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