

Three-dimensional analysis of mandible functional units in adult patients with unilateral posterior crossbite. A cone beam study with the use of mirroring and surface-to-surface matching techniques.

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Abstract

Background: Posterior unilateral crossbite (PUXB) is one of the most prevalent malocclusions. Due to the lateral shift of the mandible and to an asymmetric activity of masticatory muscles, previous studies aimed to identify potential effects on mandibular growth.

According to the functional matrix theory, mandibular development, is the sum of independent growth of each mandibular functional unit, thus their evaluation can lead to a better understanding of any relationship between PUXB and mandibular pattern of growth.

Aim: the aim of this study was to carry out a 3D analysis of mandibular functional units on CBCT scans from adult patients with PUXB, who had not received any corrective treatment for the malocclusion, by, using 3D mirroring and surface-to-surface techniques.

Subjects and methods: CBCT records from twenty-four white Caucasian adult consecutive patients (mean age, 27.5 years; range 22.6–39.7 years; 14 females and 10 males) seeking treatment for maxillary transverse deficiency were assessed in this study. CBCT scans from age-and gender-matched patients comprised the control group. Segmentation masks were generated in order to obtain 3D surface mesh models of the mandibles and analyze the six skeletal functional units, which were further analyzed with a reverse engineering software.

Results: statistically significant differences in the mean surface distance when comparing the study sample and the control sample were found at the condylar process, mandibular ramus, angular process ($p \leq 0.0001$) and alveolar process ($p \leq 0.01$) and no statistically significant differences were found for the coronoid process, the chin and the mandibular body ($p \geq 0.5$).

Conclusion: Asymmetry was found when comparing some functional units from controls and study sample.

Introduction.

Unilateral posterior crossbite (PUXB) is one of the most prevalent malocclusions in the primary and early mixed dentition and is reported to occur in 8% to 22% of the cases (1-3). The most common form, in children and adolescent, is a unilateral presentation with a functional shift of the mandible toward the crossbite side, which occurs in 80% to 97% of cases (4).

Because spontaneous correction of posterior unilateral crossbite (PUXB) is rare, it is believed to be transferred from primary to permanent dentition, with long-term effects on the growth, development and function of the stomatognathic system.

In fact, due to the mandibular functional lateral shift towards the cross-bite side, there are an asymmetric activity of the masticatory muscles, and an asymmetrically positioned condyles (5, 6). It is believed, that these effects can influence normal mandibular growth, leading gradually to permanent mandibular asymmetry (6-8).

However, the extent to which untreated PUXB affects the craniofacial structures has not been fully defined and opposite results have been reported (9-11). In this respect, the belief that untreated PUXB leads to skeletal asymmetry of the mandible is not supported by some studies (9, 10), but sustained by another one which reported not only mandibular asymmetry but also remodelling of the condylar head and glenoid fossa (11).

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3 However, these conflicting opinions, are from previous investigation which involved two-
4 dimensional (2D) image analysis with their limited accuracy and reliability as they are not a good
5 representation of the patient's 3D anatomic truth.
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8 Only recently, some investigations assessed the mandibular asymmetry in children and adolescents
9 with crossbite by using linear measurements on Cone Beam Computed Tomography (CBCT)
10 derived 3D images (12-14). However, a drawback of these studies is that measurements on 3D
11 mandibles were carried out on a 2D fashion, with their inherent limitations. In fact, conventional
12 linear and angular measurements, provide only some quantitative information about size and
13 position, but fail to define features such as shape and volume of any bony structure.
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16 Recently a study (15) analyzed mandibular shape through mirroring and surface-to-surface
17 matching technique in mandibles from CBCT scans of adult patients with PUXB. Findings from
18 this study, pointed out that mandibles from patients with PUXB were more asymmetric than control
19 sample. As the percentage of asymmetry was greater in some areas of the mandible respect others,
20 Authors hypothesized a regional mandibular asymmetry (16, 17). However, this study did not
21 provide any data, at this regard, as percentage of surface-to-surface matching was calculated for the
22 whole hemi-mandibles, i.e. the one from crossbite side and the normal side.
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25 According to the functional matrix theory (18) mandibular development and growth, are the sum of
26 independent growth of each mandibular functional unit (condylar process, coronoid process,
27 angular process, alveolar process, body, and chin). As mandibular functional units are known to be
28 growing independently, their evaluation could lead to a better understanding of any relationship
29 between PUXB and mandibular pattern of growth.
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32 Thus, we carried out a 3D evaluation analysis of mandibular functional units on CBCT scans from
33 adult patients with PUXB, who had not received any corrective treatment for the malocclusion, by,
34 using 3D mirroring and surface-to-surface matching techniques. This technology allowed to
35 evaluate any difference in shape and morphology of mandibular bone.
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38 The following null hypothesis was tested: there are significant differences in the functional units'
39 shape and morphology, of the two halves of the mandible between the crossbite side and non-
40 crossbite side of the same patient, respect to a control sample.
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43 **Materials and Methods.**

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52 CBCT records from twenty-four white Caucasian adult consecutive patients (mean age, 27.5 years;
53 range 22.6–39.7 years; 14 females and 10 males) seeking treatment for maxillary transverse
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3 deficiency were assessed in this study. Patients' CBCT scans were recruited from the Department of
4 Oral and Maxillofacial Surgery of a University Hospital between January 2015 and February 2018.
5 This study was approved by the Ethics Committee of the Catania School of Dentistry (reference
6 number #2759) and was in accordance with the Declaration of Helsinki guidelines for human
7 research. Participant consent was not needed for this study.
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10 The sample size, was determined by a power analysis was carried out (DSS Research, Washington,
11 USA,) which indicated that data from 24 participants would yield a confidence level of 95% and a
12 Beta error level of 25%, making it sufficient to determine statistically significant differences.
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14 The inclusion criteria, for the study group (SG), were: 1) maxillary transverse deficiency and PUXB
15 (involving at least the molar and the premolars); The exclusion criteria were: 1) cleft lip and palate
16 or congenital craniofacial syndromes; 2) signs or symptoms of temporo-mandibular joint disorder;
17 3) medical history of systemic disease or neuromuscular deformities; 4) trauma or previous
18 orthodontic or prosthodontic treatment, or maxillofacial or plastic surgery. 5) movement artifacts of
19 CBCT records.
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22 These patients were age-and-gender matched with 20 subjects (8 males and 14 females, mean age
23 25,8) who served as the control group (CG). The inclusion and exclusion criteria were the same as
24 the SG plus the absence of PUXB.
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27 All CBCT images were taken with the NewTom 3G (QR SRL, Verona, Italy) device (110 kV, 6.19
28 mAs, 0.25 mm voxel size, and 8-mm aluminum filtration) with the patient in maximum
29 intercuspation and Frankfort horizontal plane parallel to the floor following common CBCT
30 imaging protocols (17).
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33 The scans were de-identified to protect patient confidentiality. All the data sets were exported and
34 converted using the Digital Imaging and Communications in Medicine (DICOM). The scanning,
35 segmentation, and model fabrication, protocols, used in this study, were previously validated and
36 described (19-22).
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39 Briefly, in order to obtain the 3D surface mesh models of the mandibles and analyze the skeletal
40 functional units, a segmentation mask was generated (Figure 1) using the "Threshold function" of
41 the software (Mimics Research, version 19.0.0.347, Materialise NV, Liege, Belgium) by selectin
42 the bone density and then by manually erasing the segmentation mask that exceeding the
43 mandibular boundaries. Following segmentation, a 3D graphical rendering of each mandible was
44 obtained.
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47 A plane passing through the mandibular symphysis (MSP) was drawn, as previously described (15),
48 in order mirror the mandibular model and to separate it in two halves.
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51 In order to obtain a preliminary superimposition, the original and the mirrored models were
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3 registered on four points: the apical tip of the lingual, around the mandibular foramen, and the
4 geometric center of mental foramina, both respectively for the right and left sides, as previously
5 described (15).
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8 Thereafter, landmarks (Table 1 and Figure 2A), that enabled to delimitate each mandibular
9 functional unit (condylar process, coronoid process, angular process, alveolar process, body, and
10 chin, plus mandibular ramus), were identified on the axial, coronal, and sagittal views and then on
11 the reconstructed 3D images (Figure 2B-D) and each functional was separated by surrounding
12 mandibular bone. Afterwards, the 3D models of the functional units from crossbite and non-
13 crossbite side for SS and from the right and left side of CS, were finely superimposed using a “best
14 fit” algorithm and underwent to the surface-to-surface deviation analysis (Figure 3). Functional
15 units from crossbite versus non-crossbite side for the study group and right to the left for the control
16 sample were compared by averaging the surface distances obtained from these mirrors (Figure 4),
17 with the aid of a reverse engineering software (Geomagic Control X, version 2017.0.0, 3D Systems,
18 USA).
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21 Computation of surface distances was based on iterative closest point algorithm. This method
22 utilizes maximization of mutual information to avoid observer-dependent techniques. The measures
23 of surface distances were complemented by visualization of the 3D color-coded maps, which was
24 set with a range of tolerance of 0.50 mm (Figure 4).
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27 After the deviation analysis, the percentages (%) of all the distances values within the tolerance
28 range were calculated. These values indicated the matching percentage between the pairs of
29 specular mandibular models at each different functional mandibular units.
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32 To minimize random error and systematic errors, landmark detection was performed by a single
33 examiner, with a 25 years of experience (R.L.), who was calibrated previously. The examiner
34 landmarked and matched only 8 models each day to avoid fatigue. The sequence in which the
35 models were measured was blinded.
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38 Furthermore to assess intra-rater repeatability, digital casts from the SG and models from the CS
39 were measured again, by the same operator after a washout period of 4 weeks (T2).
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43 44 45 46 47 48 49 **Statistical analysis.**

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51 All measurements were noted on Microsoft Excell® spreadsheet (Microsoft, Redmond, WA, USA)
52 and analyzed using SPSS® version 24 Statistics software (IBM Corporation, 1 New Orchard Road,
53 Armonk, New York, USA). Intra-examiner repeatability, of landmark location was assessed using
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3 an Intraclass Correlation Coefficient (ICC). The Kolmogorov–Smirnov test was used to test the
4 normality of the data. As all the data was normally distributed with homogeneous variance,
5 parametric tests were used.
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9 Thus, mesh value percentages, obtained by deviation analysis from the SG and CG were compared
10 by independent *t*-test. P values ≤ 0.05 were considered statistically significant.
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14 15 16 17 **Results.**

18 The ICC values, obtained for landmarking and matching by the examiner showed that the sets of
19 recordings were highly correlated (ICC values ranged from 93,4 to 97,2 per cent).
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22 The variability in matching percentages obtained plane for each functional unit ranged from
23 45,01% to 90,96% for the study group and from 59,89% to 91,05% for the control sample (Table
24 2).
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28 The lowest percentage of matching recorded between the crossbite side and non-crossbite side, in
29 the study group and between the right and the left side in the control group, was at the alveolar
30 process.
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34 Of the 7 anatomical areas measured, the condylar process, mandibular ramus, angular process at
35 the gonion ($p \leq 0.0001$) and alveolar process ($p \leq 0.01$), showed statistically significant differences in
36 the mean surface distance when comparing the study sample and the control sample.
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40 The greatest differences between the two samples were obtained for condylar process with a mean
41 difference of 14,09 percentage points.
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45 There was no statistically significant difference in the mean of surface distance measurements
46 between the SS and CS for the coronoid process, the chin and the mandibular body ($p \geq 0.5$) (Table
47 2).
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52 53 54 55 56 57 **Discussion.**

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4 In this study, a very recent 3D technique was used to evaluate mandibular functional units shape
5 and morphology, in adults with PUXB who had not received corrective treatment for this
6 malocclusion. Results, were compared with those from a control group of adult subjects without
7 PUXB.
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10 Variety of clinical and supplementary data, including the facial photos, plaster dental models, and
11 radiographic images, have been used for diagnosis of mandibular asymmetry (12). Especially, the
12 two-dimensional (2D) cephalometric radiography, has been the main diagnostic tool. However, 2D
13 cephalometric has inevitable limitations, such as the image expansion and distortion and the
14 blurring of superimposed anatomical structures. Thus, the conflicting results (23-25) reported in
15 previous studies can be in part related to the type of 2D radiographic analysis performed to
16 determine the presence of asymmetry.
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19 On the other hand, 3D image analysis, is able to clarify detailed morphological and functional
20 aspects, with a greater accuracy and reliability, as it allows 3D reconstructions of craniofacial
21 structures from acquired volumetric data.
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24 In our study, we used an image-analysis procedure, which included the construction of 3D models
25 from CBCT scans, in order to obtain a 3D virtual hard-tissue model of mandible and their mirroring
26 on an arbitrary plane. Then, the surface-to-surface matching method was used for the calculation of
27 the distances between the 3D superimposed surfaces. This latter tool, calculates thousands of color-
28 coded point-to-point by a comparison (surface distances in millimeters) between 3D models, so that
29 the differences between two surfaces, at any location, can be obtained. This in turn allows to
30 quantify differences in shape and morphology (26).
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33 In our investigation, for the first time, these new digital technologies were used to compare and
34 evaluate each architectural and functional mandibular units, i.e. condylar process, coronoid process,
35 angular process, alveolar process, body, and chin.
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38 The functional units and their analysis are a way of understanding from a geometrical point of view
39 the biology of a structure because they are known to be growing independently (17, 18), as it
40 happens in the mandible. According to the functional matrix theory, each unit is affected by the
41 surrounding functional matrix (18, 27), and the overall mandibular growth is a sum of the
42 independent growth of each unit (28).
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45 In our study, we presumed that shape and morphology of functional units from mandible of patients
46 with PUXB, were different when comparing the CB side to the non-CB side. Findings obtained
47 from our investigation pointed out statistically significant differences when comparing the two sides
48 of the mandible of the same patient with PUXB, contrary to the control sample, thus the null
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3 hypothesis was accepted. The highest differences were observed at condylar process, at angular
4 process and at alveolar process units, less at coronoid process, nearly and none at the body of the
5 mandible and chin.
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8 These results may be explained by some previous studies, which indicated in PUXB patients, an
9 asymmetrical muscle activity of masticatory muscles and differences in condyle position within the
10 fossa between the CB side and non-CB side.
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13 So far, it has been claimed that an optimal masticatory muscle force during growth is necessary for
14 normal mandibular growth (29), and masticatory muscle function is a determinant of bone quality in
15 the growing mandible (30). In this respect, mandibular asymmetry has been related either to
16 experimental unilateral removal of masseter muscle or to its resection (31, 32). Furthermore, in
17 patients with PUXB an asymmetric postural and functional activity of the masticatory muscles has
18 been recorded by surface electromyography (sEMG) measurements, being the posterior temporalis
19 of non-crossbite side more active than the cross-bite side, whilst the masseter was less active on the
20 cross-bite side (33). This asymmetric activity results also, in a thinner masseter muscle on the cross-
21 bite side (5, 34).
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28 Also, bone formation and chondrogenesis of condylar cartilage, has been related to unilateral
29 masseter muscle resection (35), this in turn seems to determine a mandibular asymmetry. Static and
30 dynamic loadings are continuously applied to bone tissues, tending to deform both extracellular
31 matrix and bone cells. When an appropriate stimulus parameter exceeds threshold values, the
32 loaded tissue responds by the triad of bone cell adaptation processes (17, 27).
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36 Thus, it maybe speculated that the asymmetrical muscles activity is transferred to the mandibular
37 bone determining a regional mandibular asymmetry, located especially in the area of muscle
38 insertions, as demonstrated in our study. Following the subsequent adaptation of the
39 neuromusculature to the acquired new mandibular position an asymmetric mandibular growth, can
40 occur.
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44 As far as, the condylar process is concerned, previous investigations found that the mandible was
45 "rotated" posteriorly on the crossbite side when related to the cranial floor (10,36) the condyles on
46 the crossbite side were positioned relatively more superiorly and posteriorly in the glenoid fossa
47 than those on the non-crossbite side. Since the some studies were not able to demonstrate
48 differences in the position of the condyle in the fossa between crossbite and non-crossbite sides, the
49 hypothesis of temporomandibular joint (TMJ) remodeling as a consequence of unilateral posterior
50 crossbite (10), has been supported.
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55 Thus, displacement of the mandible seems to be compensated trough an increased growth of the
56 contralateral condyle, reduced growth of the ipsilateral condyle, a corresponding surface
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3 remodeling in the articular fossae, or a combination of these factors (36).

4 Following TMJ bone remodeling, the condyles become more symmetrically positioned in their
5 fossa, and facial asymmetry and mandibular midline deviation toward the crossbite side might
6 persist, due to long-term adaptive changes (9).

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9 Taken together our findings suggest that positional asymmetry can produce a mild mandibular
10 regional asymmetry, especially affecting the condyle, the mandibular angle, the alveolar processes
11 and the mandibular ramus (6). This belief that untreated unilateral crossbite lead to skeletal
12 asymmetry of the mandible is supported by this study. Interestingly, not every mandibular
13 functional unit is involved to the same extent, being the condyle, angular and alveolar processes the
14 anatomical area showing the greatest variation in shape and morphology.

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17 A drawback of this study, is small size sample. However, the calculation of the sample size which
18 was obtained by a power analysis, assured adequate power to detect statistical significance.
19 Furthermore, despite the small sample size difference in shape and morphology were so
20 unambiguous that were statistically significant. Nevertheless, studies of larger sample of subjects
21 are warranted to cover the full range of biological variability in PUXB.
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30 **Conclusions.**

31 The null hypothesis that there are no differences in the mandibular functional unit shape and
32 morphology between adult subjects with and without PUXB was discarded.
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36 Findings from this study suggest that, condylar, angular and alveolar processes plus mandibular
37 ramus are the functional units showing the lowest percentage of matching.
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41 When these results are combined, the condylar, angular and alveolar processes plus mandibular
42 ramus appear to play a more dominant role in the asymmetry of the crossbite mandible than did the
43 body the coronoid and chin units.
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49 **Legend to figures.**

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53 **Figure 1:** The segmentation mask is manually selected on the axial view of the CBCT patients'
54 scans by using the "Threshold function" of the Materialise Mimics software.
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Figure 2: To delineate the condylar process (Co) and the coronoid process (Cr) a perpendicular line to Sg-Li passing through Sg is drawn. This line represents the inferior border of the Co and Cr functional units. The mandibular ramus (Ra) is bounded by the perpendicular to Sg-Li at the top and by two lines at the bottom respectively the Go1.0-Gor2.0 and the Go1.0-Gob2.0 lines.

The angular process (Ap-Ga) is delimited at the top respectively the Go1.0-Gor2.0 and the Go1.0-Gob2.0 lines. The mandibular body (Mb) is bounded, posteriorly by Go1.0-Rm and Go1.0-Gob2, anteriorly Mb is delimited by a line drawn through point B and Me1.5. The chin process (Cp) is delineated posteriorly by the line drawn through point B and Me1.5. The alveolar process (Ap) is delimited posterior by a line Go1.0-Rm and inferiorly by the line Go1.0-B (A). The functional mandibular units are then separated (B-D)

Figure 3: The mandibular functional units from crossbite side and non crossbite side of SS and from right and left side of CS are superimposed using the “best fit” algorithm (A-G).

Figure 4: 3D Deviation analysis is carried out using surface-to-surface technique. A scale bar is shown on the right side. Green color shows the range of tolerance (0,5 mm), red and blue show respectively the minimum and maximum deviation values (A-G).

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Landmark	Definition
Sg	The deepest point on the sigmoid notch.
Li	The most superior point of mandibular lingual.
B point (Supramentale)	Most concave point on mandibular symphysis.
Me (Menton)	The lowest point on mandibular symphysis.
Me 1.5	A point on the mandibular plane, located 1,5 cm posteriorly Menton point.
Go (Gonion)	A point, on the bony contour, constructed by bisecting the angle formed by intersection of mandibular plane and ramus of mandible.
Go 1.0	A point on the line which bisects the mandibular angle into two angles of the same degree, and located 1 cm above the Go point.
Go-r 2.0	A point on the posterior bony contour of the mandibular ramus drawn 2.0 cm from the gonion point.
Go-b 2.0	A point on the inferior bony contour of the mandibular body drawn 2 cm mesially to the gonion point.
Rm	A point located on the retromolar trigone, located where the line that bisects the gonial angle meets the outer bony portion of the trigone.

Table 1. Landmark on the 3D rendered mandible from CBCT scans.

	Total	% Co	P	% Ra	P	% Ap	P	% Cr	P	% Ap-Ga	P	% Chin	P	% Mb	P
Study Group	40	65.86	*	75.81	*	45.01	*	90.96	NS	75.91	**	83.55	NS	82.96	NS
Control Group	30	79.95		83.47		59.89		91.05		81.22		83.78		81.86	

Table II. Mean matching percentage, obtained through surface-to-surface analysis, of each functional mandibular units for study and control groups. P values based on independent Student T test, obtained by comparing the mean matching percentage of each functional unit from CS and SS.

*p ≤0.0001; **p ≤0.01; NS= Not significant

Co= condylar process

Ra= mandibular ramus

Ap= alveolar process

Cr= coronoid process

Ap-Go= angular process at gonion

Ch= chin process

Mb= mandibular body

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Figure 1

537x321mm (72 x 72 DPI)

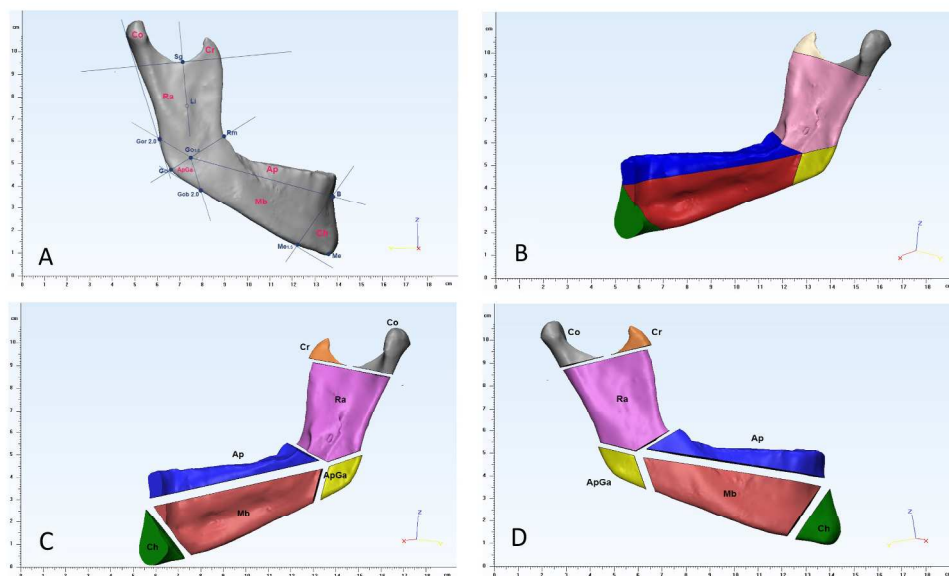


Figure 2

430x270mm (177 x 177 DPI)

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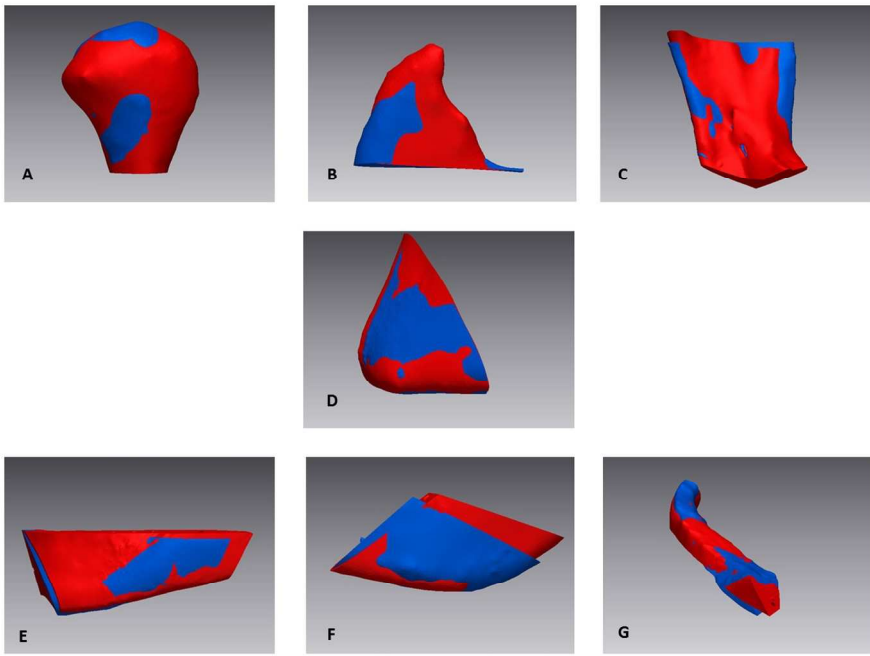


Figure 3

389x275mm (96 x 96 DPI)

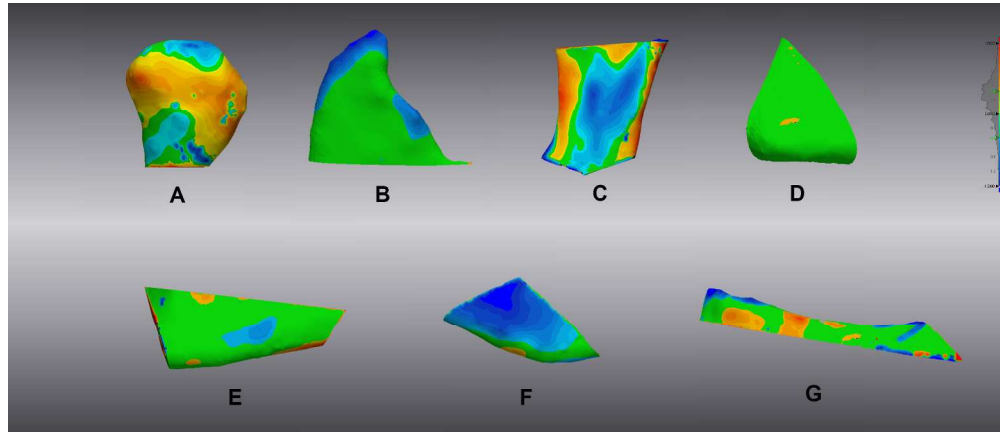


Figure 4

1171x502mm (72 x 72 DPI)