Biomechanical and Finite Element Analysis of Mandibular Vertical Ramus Marginal Resection Designs

S. Shyam Sundar · B. Nandlal · D. Saikrishna ·
G. Mallesh

Received: 28 November 2011 / Accepted: 15 July 2012 / Published online: 14 September 2012
© Association of Oral and Maxillofacial Surgeons of India 2012

Abstract This study aims to know the post-surgical Von Mises stress of the mandible after two different vertical ramus marginal resection designs, analyze the results, compare with stress pattern of normal adult mandible without simulation and infer regarding the better of the two. Three groups of 3D finite element models of human adult mandibles were created. Group I (control)—normal mandible. Group II: Mandible with a quadrilateral vertical ramus marginal resection simulated. Group III: Mandible with an arc shaped vertical ramus marginal resection simulated. Finite element analysis (FEA) models were subjected to a point load of 475 N over right and left first molars, along with masticatory loads of masseter, medial pterygoid, anterior belly of digastric and temporalis loads in varying combinations (with and without bilateral temporalis and without right temporalis). The models were analyzed to infer the overall Von Mises stress in (a) the mandible (b) the sigmoid notch (c) postero-inferior resection corners. Results of our present study provides scientific evidence for the common practice of using arc form for marginal resection of vertical ramus of mandible whenever executed. Scientific evidence behind the concept

of marginal resection of horizontal ramus is available but only scanty biomechanical evidence using finite element method (FEM) is available behind the same when performed in the vertical ramus, as magnitude and direction of loads in this region vary when compared to the horizontal ramus. The results ratify that incorporating arc shaped design pattern and removal of ipsilateral temporalis load by removal of coronoid, an area prone to stress concentration on loading, significantly decreases the post surgical Von Mises stress and hence would reduce the progressive micro-damage of the mandible after marginal resections of the vertical ramus of mandible.

Keywords Finite element analyses · Temporalis load · Von Mises stress · Marginal resection of vertical ramus

Introduction

Mandibular defects could arise because of either resection with continuity defects or resection without continuity defects. Resection with continuity defects (segmental mandibular resection) may be classified based on Soutar's ideas, where 'C' (central segment) includes the mandible from mental foramen to mental foramen and then is divided into right (Cr) and left (Cl). The 'L' (lateral segment) extends from mental foramen to lingula preserving the condyle and posterior vertical ramus. The 'A' denotes mandibular ascending ramus [1].

The standardized surgical terminology for resection without continuity defect of a bony lesion is 'excision of a lesion, including a measureable perimeter of investing bone, without interruption of bone continuity' [2]. The marginal resection falls into this category of conservative mandibular preservation surgery, where a rim of mandible

S. Shyam Sundar (✉) · D. Saikrishna
Department of Oral & Maxillofacial Surgery,
JSS Dental College and Hospital, JSS University, Bannimantap,
Mysore 570015, India
e-mail: shyam.surgeon@gmail.com

B. Nandlal
Department of Pedodontics and Preventive Dentistry,
JSS Dental College and Hospital, JSS University, Bannimantap,
Mysore 570015, India

G. Mallesh
Department of Mechanical Engineering, Sri Jayachamarajendra
College of Engineering, Manasa Gangotri, Mysore, India

is preserved after satisfactory removal of the pathology and after which mandible is functional post-operatively and also precludes the need for bony reconstruction.

Whenever such marginal resection is done in the mandible there is always some amount of uncertainty regarding the strength of the residual mandible. One possible complication following marginal mandibulectomy is stress fracture of the residual bone. Accumulation of micro damage in the bone due to accumulation of concentrated stress over a period of time can cause spontaneous non traumatic or fatigue fractures [3, 4]. The basic shape of vertical ramus, unlike the horizontal ramus which is a parabola, consists of two additional processes (condylar and coronoid processes) with a sigmoid notch in between them. Hence, the marginal resection of this vertical ramus component does carry the uncertainty of post-surgical stress fracture because of change in vectors of masticatory and occlusal forces. The anatomical 3D design of mandible and hence, the effect of these variations, induce Von Mises stress (stress generated in a ductile material due to load) with changing masticatory force vectors would also vary. Though the procedure executed (marginal mandibulectomy of vertical ramus) is one and the same and it does not have any types, based on basic concepts on which horizontal ramus marginal resections are performed, this study was designed to provide scientific validation regarding the effect of post-surgical 3D structural change of vertical ramus on Von Mises stress in the residual mandible by using in vitro finite element method as in vivo studies are practically impossible in such patients.

Aim

The purpose of the study was to use finite element method (FEM) to

1. Know the post-surgical Von Mises stress of the mandible after two different marginal resection designs.
2. Analyze the results, compare with stress pattern of normal healthy unsimulated mandible and infer regarding the better of the two (which resection design produces comparatively minimal Von Mises stress)

Material and Method

Three 3D finite element models of human adult mandible, with the condyles constrained in the glenoid fossa are constructed using Solid Edge (Version 19) software and consists of eight node hexahedral solid elements. The materials are assumed to be linearly elastic and anisotropic

with different cortical and cancellous bone material properties (Table 1).

The models are constructed manually, using point to point measurements using the anthropometric measurements given by Swasty et al. [5] as a guide. The masticatory muscle forces are also simulated according to data available from previous studies as a guide [6, 7].

FE models constructed are grouped into three groups

Group I (control): FEA Model of normal adult mandible without simulated resection.

Group II: FEA model of adult mandible simulated with marginal ramal resection in quadrilateral design with round edge borders.

Group III: FEA model of adult mandible simulated with marginal ramal resection in an arc shape.

Description of the Design Pattern

Group II

On the right vertical ramus, quadrilateral resection with all joints and the margins of the quadrilateral rounded off with a 5 mm radius (Fig. 1) is designed leaving behind 0.9 cm of bone from the inferior border of mandible, 0.5 cm of

Table 1 Material properties of mandible

Sl. no.	Material	Young's modulus (GPa)	Poisson ratio
1	Cortical bone	14	0.3
2	Cancellous bone	1.5	0.3

Fig. 1 Quadrilateral right ramus resection design

posterior ramus, 0.5 cm of vertical ramal cortex till deepest concavity of the sigmoid notch above and anteriorly extending 0.5 cm into the retro molar area.

Group III

On the right vertical ramus, an arc shaped resection (Fig. 2) is designed with its centre at the intersection of a vertical line drawn from tip of coronoid and the horizontal line from along the posterior alveolar surface of the mandible, leaving behind 0.9 cm of bone from the inferior border of mandible, 0.5 cm of posterior ramus, 0.5 cm of ramal cortex till deepest concavity of the sigmoid notch above and anteriorly extending 0.5 cm into the retro molar area. The edges of the resection are also rounded off with a 5 mm radius.

Boundary and Loading Conditions

The constructed model is then imported to *Ansys* Finite element analysis software for FEA after applying the boundary and loading conditions. Each group is subjected to masticatory muscle forces (masseter, temporalis, medial pterygoid and anterior belly of digastric) in the 'Z' axis and a point load of 475 Newton applied in the 'Z' axis on a selected point on the occlusal surface of either right or left first molar tooth (Fig. 3). Both condyles are constrained in all three axes and subjected to following variables:

- A. Left molar load with bilateral temporalis
- B. Right molar load with bilateral temporalis
- C. Left molar load without right (ipsilateral) temporalis

- D. Right molar load without right (ipsilateral) temporalis
- E. Left molar load without bilateral temporalis
- F. Right molar load without bilateral temporalis

The FEA models were analyzed under the above loading conditions for:

1. The general range of Von Mises stress distribution patterns throughout the FE models of all groups.
2. Von Mises stress at the right sigmoid notch of FE models of all groups.
3. Von Mises stress at the postero-inferior resection corner in groups II and III FE models.

The values of all the variables of the normal mandible were kept as a control and values of the samples (groups I and II) were compared with each other and to that of control. Paired test was applied to statistically analyze the value between the control and the samples. Pooled 't' test was applied to statistically analyze the value between the two samples.

Results (Tables 2–5) and Statistical Analysis (Tables 6–10)

The study analyzed the amount of Von Mises stress generated over the ipsilateral sigmoid notch, the postero-inferior resection corner and also in residual mandible to a point load of 475 Newton after marginal resection of right vertical ramus of mandible. The maximum overall stress range between all groups is 180–350 MPa (mean 265 MPa) in group II with left molar load without bilateral temporalis

Fig. 2 Arc shaped right ramus resection design

Fig. 3 Finite element model of mandible with loading and boundary conditions

Table 2 Comparison of Von Mises stress range throughout the mandible (in MPa) between groups

Sl. no.	Loading conditions	Group I	Group II	Group III
1	Left molar load with bilateral temporalis	60–180	150–300	145–290
2	Right molar load with bilateral temporalis	60–180	150–300	150–300
3	Left molar load without right temporalis	70–180	150–270	100–150
4	Right molar load without right temporalis	70–180	125–230	100–160
5	Left molar load without bilateral temporalis	90–210	180–350	100–130
6	Right molar load without bilateral temporalis	90–210	150–300	100–130

Table 3 Comparison of Von Mises stress range at right sigmoid notch (in MPa) between groups II and III

Sl. no.	Loading conditions	Group II	Group III
1	Left molar load with bilateral temporalis	150–155	40–120
2	Right molar load with bilateral temporalis	150–180	40–120
3	Left molar load without right temporalis	30–50	10–40
4	Right molar load without right temporalis	30–50	10–15
5	Left molar load without bilateral temporalis	50–75	10–15
6	Right molar load without bilateral temporalis	50–70	10–15

Table 4 Comparison of Von Mises stress range at right sigmoid notch (in MPa) between groups I and III

Sl. no.	Loading conditions	Group I	Group III
1	Left molar load with bilateral temporalis	60–110	40–120
2	Right molar load with bilateral temporalis	60–120	40–120
3	Left molar load without right temporalis	30–50	10–40
4	Right molar load without right temporalis	30–50	10–40
5	Left molar load without bilateral temporalis	50–70	05–010
6	Right molar load without bilateral temporalis	50–70	10–015

Table 5 Comparison of Von Mises stress range at postero-inferior resection angle (in MPa) between groups II and III

Sl. no.	Loading conditions	Group II	Group III
1	Left molar load with bilateral temporalis	150–155	80–120
2	Right molar load with bilateral temporalis	150–200	140–170
3	Left molar load without right temporalis	150–155	100–120
4	Right molar load without right temporalis	130–150	120–150
5	Left molar load without bilateral temporalis	150–170	100–120
6	Right molar load without bilateral temporalis	175–190	100–130

(Fig. 4). The minimum overall stress range between all groups is 60–180 MPa (mean 120 MPa) in group I with left and right molar load with bilateral temporalis (Fig. 5). The results infer that the group I FEA model with intact temporalis is more stable and the generalized Von Mises stress is lesser in a normal mandible which has more surface area for stress distribution than a resected mandible (group II and III) and higher in quadrilateral resection pattern simulated mandible with more points of stress concentration,

when compared to mandible with arc shaped resection pattern. The maximum stress range at sigmoid notch is 60–120 MPa (mean 90 MPa) (group I—right molar load with bilateral temporalis) (Fig. 6) and the minimum stress range at sigmoid notch is 10–15 MPa (mean 12.5 MPa) in group III—right/left molar load without bilateral temporalis and right molar load without right temporalis (Fig. 7). The stress at the sigmoid notch decreased once temporalis load was removed regardless of the group, implying that

Fig. 4 Maximum generalized stress range in group II with left molar load without bilateral temporalis

Fig. 6 Maximum stress at right sigmoid notch in group I with right molar load with bilateral temporalis

Fig. 5 Minimum overall stress in group I with left molar load with bilateral temporalis

Fig. 7 Minimum stress at right sigmoid notch in group III with right molar load without right temporalis

temporalis load has a significant effect on stress over the sigmoid notch. The maximum stress at postero-inferior resection corner is 175–190 MPa (mean 182.5 MPa) in group II—right molar load without right temporalis (Fig. 8). The minimum stress at postero-inferior resection corner is 80–120 MPa (mean 100 MPa) in group III—left molar load with bilateral temporalis (Fig. 9). The stress in postero-inferior resection corner is lesser when the bilateral temporalis forces are preserved in group III mandible with left molar load and the same is more when the right temporalis force alone is removed, as once right temporalis force is removed the FEA model bends towards the bottom

leading to a clockwise couple. When the temporalis force is intact, it leads to an anticlockwise couple making the stress at the postero-inferior resection corner less and the FEA model is stable.

For overall Von Mises stress comparisons between group I and group II statistical analyses were significant at $p < 0.05$. For overall Von Mises stress comparisons between group I and group III, statistical analyses were insignificant at $p < 0.05$. Von Mises stress comparison at ipsilateral (right) sigmoid notch between group II and group III are statistically insignificant at $p < 0.05$.

Fig. 8 Maximum stress at postero-inferior resection corner in group II with right molar load without right temporalis

Von Mises stress comparison at right sigmoid notch between groups I and III were statistically significant at $p < 0.05$. Von Mises stress comparison at postero-inferior resection corners between groups II and III were statistically significant at $p < 0.05$.

Discussion

The Need for FEA

The anatomy and the mechanical properties of the micro and the macro structure of the bones and associated structures differ from individual to individual and hence concepts of osseous surgery cannot be generalized to all the members of the human population. Finite element analyses is a mathematical way of solving biomedical engineering problems by simulating the real scenario of each patient virtually on a computer and then planning the treatment according to the structure and loads generated in that individual, so that treatment given to each patient can be customized [8]. Without such virtual treatment planning, though the pathology is clinically removed to surgeon's and pathologist's satisfaction, concern regarding the consequences of the surgical treatment (amount of residual bone, stress generated and factors which could possibly reduce or which would increase the stress generated) definitely needs to be addressed just like a car is simulated to multiple impact analysis and accordingly designs are modified accordingly, to avoid failure before mass production. Finite element analyses not only calculate post-surgical (simulations) stresses but also guides the surgeon

Fig. 9 Minimum stress at postero-inferior resection corner in group III with left molar load with bilateral temporalis

regarding the influence of the design of surgery (osteotomy) on increase or decrease of amount of stress in the post-surgical mandible.

Our present study used 3D FEA, as there are less assumptions and higher order elements than 2D FEA (Fig. 10). The study used 3D eight noded solid element from the hexahedral family of elements. This is because, for complex structures like the craniofacial skeleton, simple triangular or rectangular elements are insufficient. Also, the elements used for three dimensional analyses are of higher order compared to those used in the two dimensional analysis. 3D stress analysis problems are solved using solid elements. The solid elements are broadly grouped under tetrahedral, triangular and hexahedral family elements. In the present work, the 3D eight noded solid element (SOLID-185) is chosen from hexahedral family for the element representation that uses for 3D analysis based on isoparametric formulation. SOLID-185 structural solid or 3D 8-node structural solid or layered solid element is suitable for modeling general 3D solid structures. It is defined by eight nodes having three degrees of freedom at each node: translation in the nodal X, Y, and Z directions. The element has plasticity, hyper elasticity, stress stiffening, creep, large deflection and large strain capabilities. Theory of summation of torque states that all the muscle fibers of a muscle group sum together to create a joint torque in a particular direction [9]. The muscle forces were hence assumed to be summation of torque of individual muscle group of masticatory system. The lateral pterygoid load was ignored as Koolstra and van Eijden have suggested that its load had negligible influence on mandibular movements [10].

Table 6 Statistical analysis of Von Mises stress range (in MPa) between groups I and II by paired *t* test

Variables	Group I	Group II	d = B – A	d ²
Left molar load with bilateral temporalis	120	225	105	11,025
Right molar load with bilateral temporalis	120	225	105	11,025
Left molar load without right temporalis	125	210	85	7,225
Right molar load without right temporalis	125	177.5	52.5	2756.25
Left molar load without bilateral temporalis	150	265	115	13,225
Right molar load without bilateral temporalis	150	225	75	5,625
	<i>n</i> = 6	<i>n</i> = 6	537.5	50881.25

Mean = 89.58, SD = 23.38286381, *t* = 9.384021262, DOF = 5, *p* < 0.05

Table 7 Statistical analysis of Von Mises stress range (in MPa) between groups I and III by paired *t* test

Variables	Group I	Group III	d = B – A	d ²
Left molar load with bilateral temporalis	120	217.5	97.5	9506.25
Right molar load with bilateral temporalis	120	225	105	11,025
Left molar load without right temporalis	125	120	–5	25
Right molar load without right temporalis	125	125	0	0
Left molar load without bilateral temporalis	150	115	–35	1,225
Right molar load without bilateral temporalis	150	115	–35	1,225
	<i>n</i> = 6	<i>n</i> = 6	127.5	23006.25

Mean = 21.25, SD = 63.71322469, *t* = 0.816967863, DOF = 5, *p* < 0.05

Table 8 Statistical analysis of Von Mises stress at right sigmoid notch (in MPa) between groups I and III by paired *t* test

Variable	Group I	Group III	d = B – A	d ²
Left molar load with bilateral temporalis	85	80	–5	25
Right molar load with bilateral temporalis	90	80	–10	100
Left molar load without right temporalis	40	25	–15	225
Right molar load without right temporalis	40	25	–15	225
Left molar load without bilateral temporalis	60	7.5	–52.5	2756.25
Right molar load without bilateral temporalis	60	12.5	–47.5	2256.25
	<i>n</i> = 6	<i>n</i> = 6	–145	5587.5

Mean = –24.17, SD = 20.40767797, *t* = 2.901073173, DOF = 5, *p* < 0.05

Table 9 Statistical analysis of Von Mises stress (in MPa) at right sigmoid notch between groups II and III by pooled *t* test

Variables	Group II	Group III	d1	d2	d1 ²	d2 ²
Left molar load with bilateral temporalis	152.5	80	65.42	40.42	4279.7764	1633.776
Right molar load with bilateral temporalis	165	80	77.92	40.42	6071.5264	1633.776
Left molar load without right temporalis	40	25	–47.08	–14.58	2216.5264	212.5764
Right molar load without right temporalis	40	17.5	–47.08	–22.08	2216.5264	212.5764
Left molar load without bilateral temporalis	62.5	17.5	–24.58	–22.08	604.1764	487.5264
Right molar load without bilateral temporalis	62.5	17.5	–24.58	–22.08	604.1764	487.5264
	6	6				
	522.5	237.5			15992.7084	4942.708

Mean 1 = 87.08, mean 2 = 39.58, SD = 45.76, DR = 1.038024, *t* = 1.797911, DOF = 10, *p* < 0.05

From a biomechanical engineering point of view, if the virtual pathology to be treated by osseous resection is only in a part of the mandible, releasing or preservation of a

massive load (masticatory muscle load) over a linearly elastic material like mandible, has considerable biomechanical effects on the surgical site as well as the post

Table 10 Statistical analysis of Von Misses stress (in MPa) at postero-inferior resection margins between groups II and III by pooled *t* test

Variable	Group II	Group III	d1	d2	d1 ²	d2 ²
Left molar load with bilateral temporalis	152.5	100	−7.92	−20.15	62.7264	430.5625
Right molar load with bilateral temporalis	175	155	14.58	34.25	212.5764	1173.0625
Left molar load without right temporalis	152.5	110	−7.92	−10.75	62.7264	115.5625
Right molar load without right temporalis	140	134.5	−20.42	13.75	416.9764	189.0625
Left molar load without bilateral temporalis	160	110	−0.42	−10.75	0.1764	115.5625
Right molar load without bilateral temporalis	182.5	115	22.08	−5.75	487.5264	33.0625
	962.5	724.5			1242.708	2056.875
	<i>n</i> = 6	<i>n</i> = 6				

Mean 1 = 160.42, mean 2 = 120.75, SD = 18.16, DR = 2.184471366, *t* = 3.783615393, DOF = 10, *p* < 0.05

Fig. 10 Eight noded hexahedral solid element used for construction of 3D FE model

surgical residual mandible on the whole. Critical areas of the vertical ramus, the sigmoid notch and the postero-inferior resection corners, basically are junctions of two struts of linearly elastic materials from a FEM's perspective. Sometimes when large lesions of vertical ramus are treated by marginal ramus resections, the post-surgical vertical ramus consists of only a posterior border vertical bony strut and a superior horizontal bony strut. Structural engineering suggests avoiding rectangular 'T' joints and notches to avoid stress concentrations during manufacturing of components or parts of a machine as they increase the chances of failure of material due to fatigue. Wittkamp and Starmans in their biomechanical analysis suggest that resection types with sharper joints induce more than optimal stress in the residual mandible during mastication [11]. Only designs with rounded off borders were hence considered in this study. Murakami et al. in their biomechanical analyses of marginal resections of horizontal ramus have also shown that maximum stress concentration in marginal resections is at the postero-inferior resection corners and hence this area was taken into account during our biomechanical FEA analysis [12].

The ultimate aim of any surgery is long term success of the procedure. This study was an attempt to understand the varying stress concentration patterns of residual mandible after marginal resection of vertical ramus and their influence on fatigue failure. The study also validates and ratifies key mechanical concepts of marginal mandibular resections using a biomechanical mandibular model.

Effect of Temporalis Load on Mandible

Each masticatory muscle contraction is associated with a force which is expressed by three independent variables: its magnitude, its point of application and its orientation. The temporalis muscle generates large forces as it has both increased number pennations and physiological cross-sectional area. The magnitude of temporalis force is accordingly more. The point of application of temporalis force is along its attachment area over the coronoid process and extending onto the anterior ascending ramus. The orientation of the force is along the line of action which extends through the centroid of the muscle (connecting line in between two attachment areas) and is dependent on the position of the lower jaw with respect to the skull. The role of temporalis in the masticatory system is twofold. It is an active elevator and a passive depressor. Even when inactive, temporalis generates passive forces, decelerating the jaw at the end of jaw opening and becomes significant at near maximum mouth opening [13]. Hence, the temporalis always loads mandible during its active and passive phases and induces varying patterns of stress in all phases of mandibular movements.

After marginal resection of a part of ascending ramus (anterior border of vertical ramus), sparing the temporalis attachment at the coronoid, the major load of the temporalis is concentrated on the coronoid and adjoining sigmoid notch, which otherwise would spread along the entire ramus in a normal mandible. Even though during routine marginal resection of vertical ramus the coronoid is also removed simultaneously, the rationale behind removing the

coronoid is ratified with the results of our study, which show that any sort of 3D structural change with ipsilateral temporalis load alone, invariably increased the Von Mises stress of the post-surgical residual mandible with maximal stress in the regions of sigmoid notch and postero-inferior resection corners. There was also an overall increase in the Von Mises stress in both the FE models simulated with resection when compared to the normal mandible (control) which validates the basic principle of stress (force per unit area). If the magnitude of loads distributed over a lesser surface area is not reduced by relieving ipsilateral temporalis load, after marginal vertical ramus resection, force per unit area increases leading to an overall increase in Von Mises stress in both FE models simulated with marginal ramus resection. The notches in a part of a material are proven areas of increased stress on loading [14]. Similarly post-surgical vertical ramus from a mechanistic point of view is considered only as a discontinuity between anterior and posterior ramus and superior and inferior parts of vertical ramus. This leads to progressive localized permanent micro structural changes due to sudden change in masticatory force vectors and loading patterns, producing fluctuating stresses, during different phases of opening and closing. This further culminates to cracks or complete fracture after a sufficient number of fluctuations. This process is called fatigue failure of a material. But once the temporalis load was removed there was a significant reduction in both the overall stress of residual mandible and at the sigmoid notch. Though the stress at sigmoid notch was statistically insignificant between the groups, the pattern of stress reduction after temporalis removal in groups is to be clinically considered.

There is a definite synergy between group III FE model with arc shaped marginal resection design and removal of ipsilateral temporalis load, as the Von Mises stress at both sigmoid notch and postero-inferior resection margins have reduced very significantly when both were combined.

Effect of Arc Shaped and Quadrangular Resection on Residual Mandible

The idea of incorporating rounded borders at the margins of resection is not a new concept [11, 12]. It not only reduces the areas of stress concentration but also allows easy flap cover and mucosalization. As discussed, progressive stress concentration leads to fatigue fractures. The quadrangular resection pattern in comparison to arc resection clearly shows that Von Mises stress concentration is increased at various 'L' junctions of the quadrangle. The study also ratifies the fact that smooth arc pattern marginal resection independent of the site of the marginal resection (horizontal or vertical ramus) produces less stress over the residual mandible when compared to the quadrangular pattern.

Though efforts are made to reduce the assumptions in the created model, models are created manually and hence they are not 100 % anatomically precise unlike modeling using commercial software which directly converts DICOM images into a FE model with accurate anatomic depictions. The teeth and periodontal ligament, the mandibular foramen, mandibular canal and mental foramen were not constructed.

Conclusion

Scientific evidence behind concept of marginal resection of horizontal ramus is available but only scanty biomechanical evidence using FEM is available behind the same when performed in the vertical ramus, as magnitude and direction of loads in this region vary when compared to the horizontal ramus. Our study provides scientific evidence for the common practice of using arc form for marginal resection of vertical ramus of mandible whenever executed. It shows that incorporating arc shaped design pattern and removal of ipsilateral temporalis load by removal of coronoid, an area prone to stress concentration on loading, significantly decreases the post surgical Von Mises stress and hence would reduce the progressive micro-damage of the mandible after marginal resections of the vertical ramus of mandible.

References

1. Watkinson JC, Gaze MN, Wilson JA (2000) *Stell and Maran's head and neck surgery*, 4th edn. Butterworth Heinemann, Oxford, pp 304–305
2. Gold LI, Upton GW, Marx RE (1991) Standardized surgical terminology for the excision of lesions in bone: an argument for accuracy in reporting. *J Oral Maxillofac Surg* 49:1214–1217
3. Frost HM (2000) Does bone design intend to minimize fatigue fractures? A case for the affirmative. *J Bone Min Metab* 28:18
4. Frost HM (2003) Bone's mechanostat: A 2003 update. *Anat Rec A Discov Mol Cell Evol Biol* 275:1081
5. Swasty D, Lee JS, Huang JC, Maki K, Gansky SA, Hatcher D, Miller AJ (2009) Anthropometric analysis of the human mandibular cortical bone as assessed by cone-beam computed tomography. *J Oral Maxillofac Surg* 67:491–500
6. Koriath TWP, Hannam AG (1994) Mandibular force during simulated tooth clenching. *J Orofac Pain* 8:178
7. Wagner A, Krach W, Schico K et al (2002) A 3-dimensional finite element analysis investigating the biomechanical behavior of mandible and plate osteosynthesis in cases of fractures of the condylar process. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 94:678
8. Sundar SS, Nandlal B, Saikrishna D, Mallesh G (2011) Finite element analysis—a maxillofacial surgeon's perspective. *J Maxillofac Oral Surg*. doi:10.1007/s12663-011-0319-5
9. Knudson D (2009) *Fundamentals of biomechanics*, 2nd edn. Springer, New York, pp 173–174

10. Koolstra JH, van Eijden TMGJ (1997) The jaw open-close movements predicted by biomechanical modeling. *J Biomech* 30(9):943–950
11. Wittkamp AR, Starman FJ (1995) Prevention of mandibular fractures by using constructional design principles I. Computer simulation of human mandibular strength after segmental resections. *Int J Oral Maxillofac Surg* 24:306–310
12. Murakami K, Sugira T, Yamamoto K, Kawakami M, Tsutsumi S, Kirita T (2011) Biomechanical analysis of the strength of the mandible after marginal resection. *J Oral Maxillofac Surg* 69: 1798–1806
13. Koolstra JH (2002) Dynamics of human masticatory system. *Crit Rev Oral Biol Med* 13:266–376
14. Yeni YN, Fyhrie DP (2002) Fatigue damage–fracture mechanics interaction in cortical bone. *Bone* 30:509–514