Open Journal of Regenerative Medicine, 2015, 4, 35-45
Published Online December 2015 in SciRes. http://www.scirp.org/journal/ojrm
http://dx.doi.org/10.4236/ojrm.2015.44005

Three-Dimensional Finite Elemental Analysis of Bone Stress near an Implant Placed at the Border between Mandible and Fibular Graft in Mandibular Reconstruction

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Received 11 October 2015; accepted 10 November 2015; published 13 November 2015

Abstract

Purpose: The aim of the present study was to use finite elemental analysis (FEA) to evaluate bone stress near an implant placed at the border between the mandible and fibular graft in mandibular reconstruction. Materials and Methods: A fibular model (FM) and transplantation model (TM) were constructed for FEA. In TM, mandible was on the mesial side and the fibular graft was on the distal side. The implant was positioned at the center of both bone models. In TM, it was placed on the border between the mandible and fibular graft. A 10-mm implant was used in the monocortical model and a 15-mm implant was used in the bicortical model. The loading force was set at 100 N, the angle was set at 90˚, and the loading position was set as center, mesial, or distal on the upper surface of the prosthesis. Von Mises equivalent stress values of the bone near the implant collar and apex at the middle line between buccal and lingual side were measured. Results: In all models, stress values were significantly lower with center loading than with distal loading and mesial loading. In center loading, the stress values were significantly lower in the bicortical model than in the monocortical model. There were no significant differences in stress values between FM and TM in all conditions. Conclusions: Bone stress was least with the center loading position, which was further decreased by bicortical fixation. There was no increase in mechanical stress associated with placing an implant at the border between the mandible and the fibular graft.

Keywords

Finite Elemental Analysis, Mandibular Reconstruction, Fibular Graft, Dental Implant, Stress Analysis

How to cite this paper: Ken, Y., Noriko, T. and Shohei, K. (2015) Three-Dimensional Finite Elemental Analysis of Bone Stress near an Implant Placed at the Border between Mandible and Fibular Graft in Mandibular Reconstruction. *Open Journal of Regenerative Medicine*, **4**, 35-45. http://dx.doi.org/10.4236/ojrm.2015.44005

1. Introduction

Finite elemental analysis (FEA) is used to calculate component displacement, strain, and stress under internal and external loads in 2-dimensional or 3-dimensional (3D) computer models in various fields, including medical applications. In particular, manufacturers of dental devices use FEA to test products used in dental implantation, including the implant body, healing abutment, impression abutment, and drill kit, which are standardized during the production process. However, prosthetic appliances intended for natural teeth are not standardized because of individual differences among patients. Therefore, FEA is better suited for implant assessment; consequently, many studies have reported the standardization of dental implants by FEA [1]-[10].

Cancer treatment includes the resection of healthy tissues to minimize the incidence of recurrence. However, in orthopedic surgery for cancer treatment, the lack of bone continuity results in poor cosmesis, functional failure, and, ultimately, decreased quality of life (QOL) [11]. Autogenous bone grafts have been used to bridge bone gaps, and reconstruction using autogenous bone grafts with implants has been reported to have a good prognosis [12] [13]. Autogenous bone grafting has been applied to reconstruct various bones, including the ilium, scapula, and fibula.

The primary stability of a dental implant is dependent on the rigidity and resistance offered by cortical bone. Iliac bone is primarily composed of cancellous bone, and iliac graft offers less stability for implant placement in mandibular reconstruction [14] [15]. The scapula has a sufficient proportion of cortical bone but it is relatively thin and plate like. Hence, scapula is insufficient as a donor site [16]. In addition, the surgical duration is prolonged with the use of scapular grafts for mandibular construction because surgery is anatomically complex [17]. The fibula also has sufficient cortical bone; however, it has a triangular cross-section, which is smaller than that of the mandible. If a fibular graft is placed in line with the inferior border of the mandible, a large gap will exist between the superior border of fibular graft and the opposing teeth is created. Meanwhile, if the fibular graft is placed in line with the superior border of the mandible, there will be an asymmetry in the facial appearance, resulting in poor cosmesis [18]. Surgeons often place the implant apex in the cortical bone at the inferior border of the mandible. This method is called bicortical fixation, which has been shown to have superior stability than monocoritcal fixation. The use of bicortical fixation with fibular grafts has been reported [19] [20]. However, other studies have reported an increased risk of bone fracture associated with bicortical fixation [21]. Various problems with bicortical fixation have been cited, although there are an insufficient number of cases to arrive at a consensus. Therefore, the efficacy of bicortical fixation for reconstruction continues to be debated.

Kourkouta *et al*. [21] reported that the optimal position of the implant was 2 mm from the tooth using FEA. Yokoyama *et al*. [22] reported that stress to the implant body and bone was increased by the use of mesial cantilever prostheses. In our clinic, we have performed a fibular graft transplantation procedure with implant fixation for mandibular reconstruction, and this reconstruction has lasted for 13 years without any problems. In this case, implant was placed at a distance of 2 mm from the tooth, following the recommendations of a previous report. The implant was positioned at the border between the mandible and the fibular graft, with the mandible forming the mesial border and the fibular graft forming the distal border. Cortical bone, which is important to achieve implant stability, varies among bones. For example, mandible has a cortical bone thickness of 2 mm [23] [24], whereas fibula has a cortical thickness of 3.5 mm [25]. Although there are many reports in the literature about fibular grafts being supported with implants [12] [13] [18] [20] [25], none of them have described the mechanical stress of bone near the implant placed at the border between the mandible and fibular graft.

This report had described both a fibular model (FM) and a transplantation model (TM), in which the implant was placed using bicortical or monocortical fixation at the center of the fibular graft or at the border between the mandible and the fibular graft, respectively. The aim of the present study was to use FEA to evaluate bone stress near the implant placed at the border between the mandible and fibular graft.

2. Materials and Methods

Autodesk Inventor Professional software (version 2013, Autodesk, Inc., Mill Valley, CA, USA) was used to create a digital 3D model to design, visualize, and simulate stress to the implant models Bone models consisted of 2 layers: a cortical layer and a cancellous layer (**Figure 1**). The height of all bone models was set at 15.0 mm (**Figure 2**). The height of fibular cortex was set at 3.5 mm [25] and that of mandibular cortex was set at 2.0 mm [23] [24]. The remaining height of the cancellous bone was set at 8.0 mm for the fibular side and 11.0 mm for the mandibular side. In TM, the mandible formed the mesial border and the fibula formed the distal border. Two

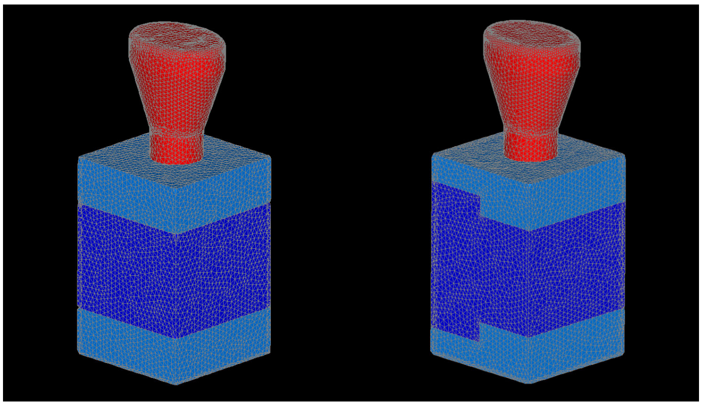


Figure 1. (Left) Fibular model with an implant. (Right) Transplantation model with an implant. The size of both models were width 10 mm × depth 10 mm × high 15 mm.

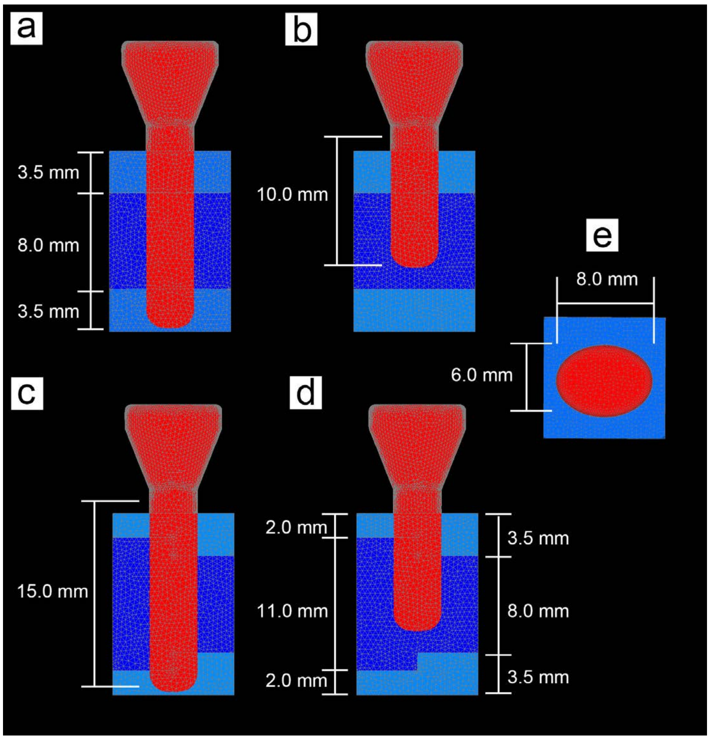


Figure 2. (a)-(d) Mesiodistal cross sections of the 4 simulated models with a prosthesis showing different bone models and implant lengths (a) A fibular model with bicortical fixation and a 15-mm implant (FMB). (b) A fibular model with monocortical fixation and a 10-mm implant (FMM). (c) A transplantation model with bicortical fixation and a 15-mm implant (TMB). (d) A transplantation model with monocortical fixation and a 10-mm implant (TMM). (e) View of the occlusal surface of the prosthesis.

cylinder-type implants, both with a diameter of 4.0 mm and lengths of 10 and 15 mm, were modeled. The occlusal surface of the prosthesis was elliptical with a vertical diameter of 6.0 and a horizontal diameter of 8.0 mm (**Figure 2(e)**). The prosthesis was transitioned from the occlusal surface to the implant collar.

The implant was placed in the center of the bone model, which was at the border between mandible and fibula in TM. The implant length was 10 mm in monocortical models and 15 mm in the bicortical models. Four models were constructed by altering the cortical model and implant positions.

The finalized computer-designed models were discretized into tetrahedral elements with a rectangular base using the FEA software Mechanical Finder Extended Edition (version 6.2; Research Center of Computational Mechanics, Inc., Tokyo, Japan), resulting in finite elemental meshes arranged in a 3D pattern. The elements were set over a range of 0.2 - 0.5 mm. Meshes of 373,848 elements and 66,558 nodes, 374,033 elements and 66,536 nodes, 376,612 elements and 67,126 nodes, and 377,393 elements and 67,190 nodes were generated for FM with bicortical fixation (FMB), FM with monocortical fixation (FMM), TM with bicortical fixation (TMB), and TM with monocortical fixation (TMM), respectively.

The models presented characteristics of linear elasticity. The homogeneity principle was also adopted because the materials were assumed as homogenous and isotropic. The interfaces between the cortical bone, cancellous bone, implant, and prosthesis were assumed to be sufficiently bonded, corresponding to good osseointegration. Input data for the implant and prosthesis were obtained from those made using pure titanium, with a Young's modulus of 105.91 GPa and a Poisson ratio of 0.11. The Young's modulus and Poisson ratio for cortical bone are 14.70 GPa and 0.30, respectively, and those for cancellous boneare 0.49 GPa and 0.30, respectively [22] [26].

The lower surface of each model was completely constrained. Some studies have reported a force of approximately 200 N applied to a molar [27] [28]. In this study, we selected a force of 100 N in order to avoid overstress to the model. The size of force was limited to a diameter of 2.0 mm and loading positions were set as center, mesial, and distal on the upper surface of the prosthesis (**Figure 3**).

Von Mises equivalent stress values at the mesial and distal sides of the cortical bone near the implant border were measured at 4 points on the upper surface to a depth of 2 mm at 0.5-mm increments at the middle line between buccal and lingual side, respectively. The bone near the implant apex was also measured at 4 points from the implant apex, at every 0.5 mm (**Figure 4**). There was a maximum number of 16 points in this model.

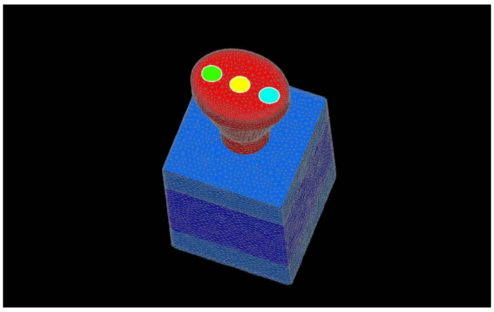


Figure 3. The force was set at 2 mm and loading positions set at the center (yellow), mesial (green), and distal (blue) points on the upper surface of the prosthesis, respectively.

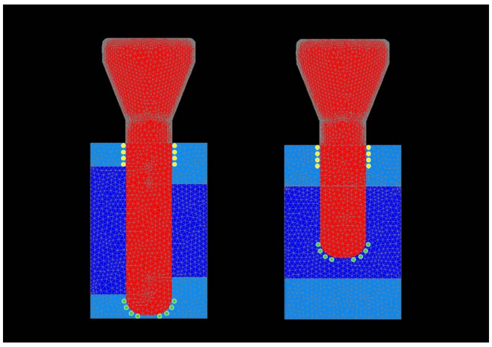


Figure 4. Points for measurement of von Mises equivalent stress. The implant collar is indicated in yellow and the implant apex in green. (left) Fibular model. (right) Transplantation model.

All values are expressed as means ± standard deviation. Statistical analysis was performed by 1-way analysis of variance and Tukey's honestly significant difference test ($p < 0.05$) or the Games-Howell test ($p < 0.05$), where necessary. SPSS software for Windows was used for the analysis (PASW Statistics 18.0; SPSS Inc., Tokyo, Japan).

3. Results

The mean von Mises equivalent stress values of the mesial and distal sides with three loading situations in 4 models are described (**Table 1**; **Figures 5-8**).

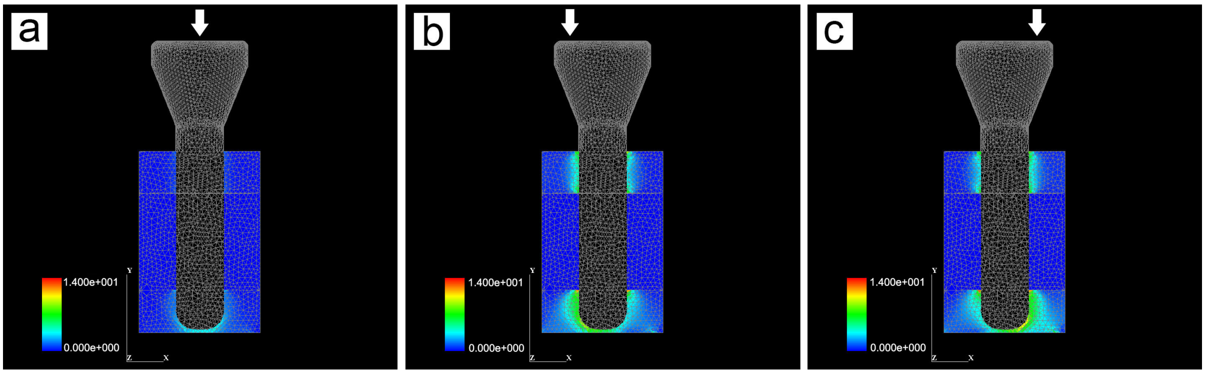


Figure 5. In FMB, the mesiodistal cross sections of von Mises equivalent stress contour patterns with a color bar ranging from 0.000e+000 to 1.4000e+001 MPa (N/mm^2). (a) Center loading. (b) Mesial loading. (c) Distal loading.

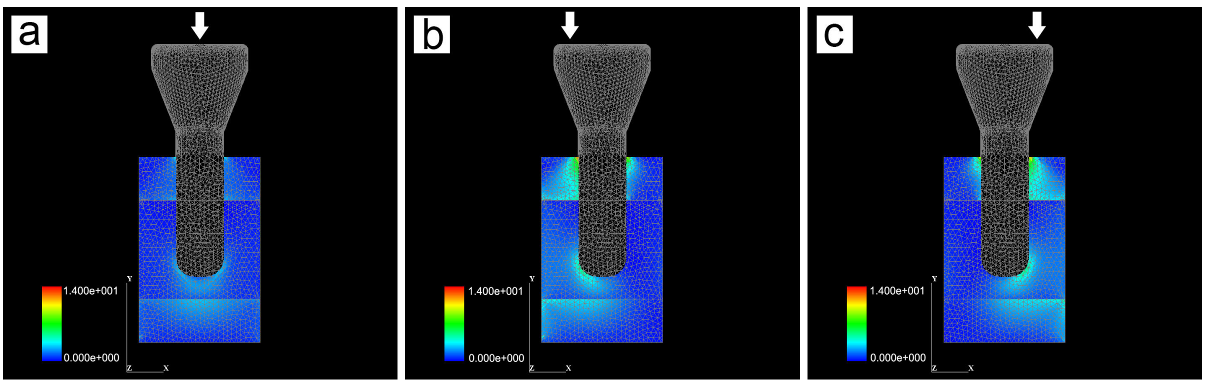


Figure 6. In FMM, the mesiodistal cross-sections of von Mises equivalent stress contour patterns with a color bar ranging from 0.000e+000 to 1.4000e+001 MPa (N/mm^2). (a) Center loading. (b) Mesial loading. (c) Distal loading.

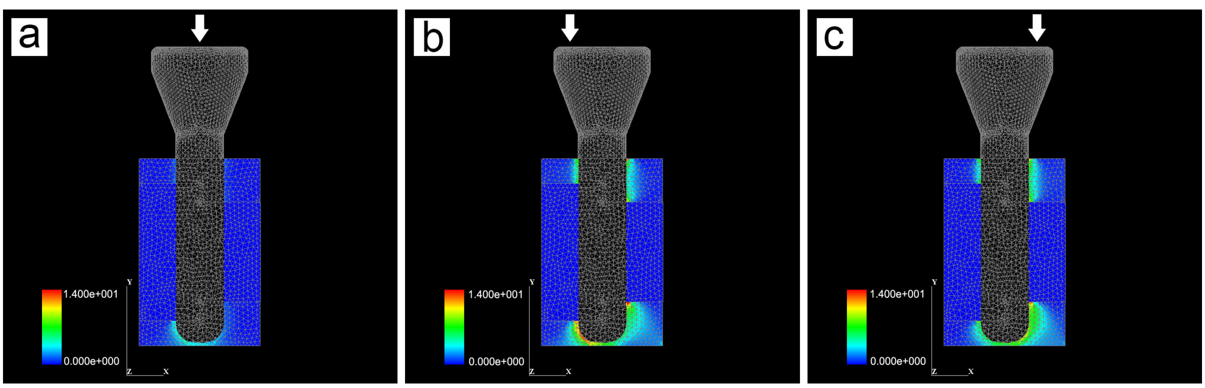
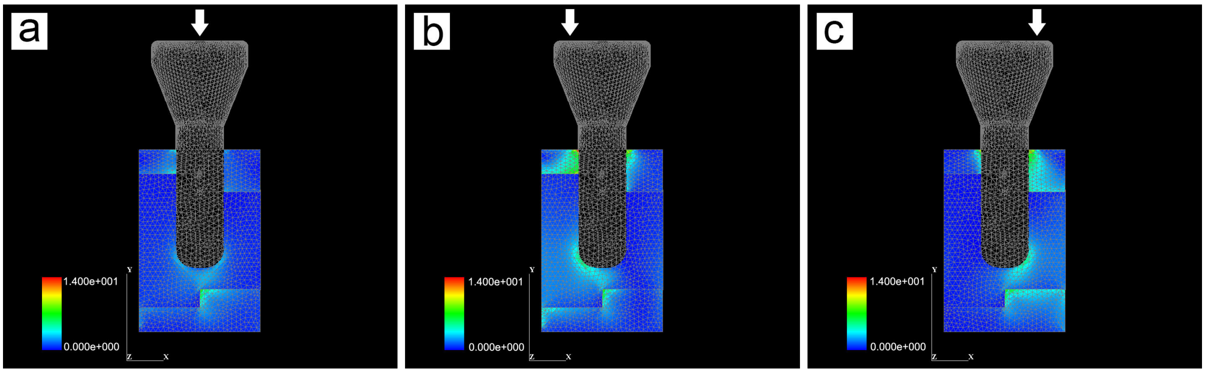


Figure 7. In TMB, the mesiodistal cross-sections of von Mises equivalent stress contour patterns with a color bar ranging from 0.000e+000 to 1.4000e+001 MPa (N/mm^2). (a) Center loading. (b) Mesial loading. (c) Distal loading.



Figures 8. In TMM, the mesiodistal cross sections of von Mises equivalent stress contour patterns with a color bar ranging from 0.000e+000 to 1.4000e+001 MPa (N/mm²). (a) Center loading. (b) Mesial loading. (c) Distal loading.

Table 1. Mean von Mises equivalent stress values for all situations (n = 4).

Bone model	Implant position	Bone	Side	The mean value ± SD [MPa (N/mm²)]		
				Loading position		
				Center	Mesial	Distal
Fibula	Bicortical	Collar	Mesial	0.78 ± 0.10	5.01 ± 0.88	4.44 ± 1.85
			Distal	0.86 ± 0.12	4.79 ± 1.82	5.25 ± 0.84
		Apex	Mesial	3.12 ± 0.47	8.74 ± 0.36	4.25 ± 0.28
			Distal	3.14 ± 0.40	4.48 ± 0.41	9.16 ± 1.34
	Monocortical	Collar	Mesial	1.80 ± 0.47	7.77 ± 2.56	5.94 ± 3.13
			Distal	1.93 ± 0.62	5.89 ± 4.67	7.97 ± 3.06
		Apex	Mesial	2.12 ± 0.26	5.01 ± 1.85	0.77 ± 0.34
			Distal	2.21 ± 0.49	0.66 ± 0.37	5.06 ± 1.91
Transplantation	Bicortical	Collar	Mesial	0.97 ± 0.19	6.26 ± 1.11	4.69 ± 1.31
			Distal	0.84 ± 0.22	4.87 ± 1.08	6.76 ± 1.84
		Apex	Mesial	4.13 ± 0.43	11.67 ± 2.10	6.02 ± 0.55
			Distal	2.15 ± 0.22	5.81 ± 0.62	9.22 ± 0.48
	Monocortical	Collar	Mesial	1.81 ± 0.47	7.43 ± 2.00	4.14 ± 1.48
			Distal	1.74 ± 0.53	5.10 ± 1.87	7.74 ± 3.71
		Apex	Mesial	2.12 ± 0.48	4.33 ± 1.04	0.93 ± 0.69
			Distal	2.33 ± 0.25	0.60 ± 0.42	4.32 ± 0.84

3.1. Loading Position

Differences among loading positions were investigated by comparisons of mean values of the 16 points located on the bone near the collar and apex of the implant (**Table 2**). In all models, the stress values with center loading (**Figure 5(a)**, **Figure 6(a)**, **Figure 7(a)** and **Figure 8(a)**) were significantly lower than those with mesial (**Figure 5(b)**, **Figure 6(b)**, **Figure 7(b)** and **Figure 8(b)**) and distal loading (**Figure 5(c)**, **Figure 6(c)**, **Figure 7(c)** and **Figure 8(c)**).

3.2. Insert Position

Differences among insert positions were investigated by comparisons of mean values at 8 points, which were located along the bone near the implant collar (**Table 3**). The values of bone near the implant apex were excluded because they were outliers in both bicortical and monocortical models. In center loading, the stress values of FMB (**Figure 5(a)**) were significantly lower than those of FMM (**Figure 6(a)**); similarly, stress values of TMB (**Figure 7(a)**) were significant lower than those of TMM (**Figure 8(a)**).

3.3. Bone Model

Differences between the FM and TM under the same conditions were investigated by comparison of mean values of the 16 points on the models, which were located around the bone near the collar and apex of the implant. As shown in **Table 4**, there were no significant differences among all experimental conditions (**Table 4**).

Table 2. Mean von Mises equivalent stress values for bone near the collar and apex of the implant (n = 16). *1: There were significant differences between center loading and mesial loading, and center loading and distal loading. *2: There were significant differences between center loading and distal loading.

Bone model	Implant position	The mean value ± SD [MPa (N/mm^2)]		
		Loading position		
		Center*1,2	Mesial*1	Distal*2
Fibula	Bicortical	1.98 ± 1.22	5.76 ± 2.02	5.77 ± 2.33
	Monocortical	2.02 ± 0.46	4.83 ± 3.69	4.93 ± 3.46
Transplantation	Bicortical	2.02 ± 1.38	7.15 ± 2.99	6.67 ± 2.00
	Monocortical	2.00 ± 0.47	4.36 ± 2.86	4.28 ± 3.10

Table 3. Mean von Mises equivalent stress values for the bone near the implant collar (n = 8). *1: There was a significant difference between FMB and FMM. *2: There was a significant difference between TMB and TMM.

Bone model	Implant position	The mean value ± SD [MPa (N/mm^2)]		
		Loading position		
		Center	Mesial	Distal
Fibula	Bicortical	0.82 ± 0.11*1	4.90 ± 1.33	4.84 ± 1.40
	Monocortical	1.87 ± 0.51*1	6.83 ± 3.63	6.95 ± 3.06
Transplantation	Bicortical	0.90 ± 0.20*2	5.56 ± 1.26	5.73 ± 1.84
	Monocortical	1.77 ± 0.46*2	6.26 ± 2.18	5.94 ± 3.25

Table 4. Mean von Mises equivalent stress values for the bone near the implant collar and apex (n = 16).

Bone model	Implant position	The mean value ± SD [MPa (N/mm^2)]		
		Loading position		
		Center	Mesial	Distal
Fibula	Bicortical	1.98 ± 1.22	5.76 ± 2.02	5.77 ± 2.33
Transplantation		2.02 ± 1.38	7.15 ± 2.99	6.67 ± 2.00
Fibula	Monocortical	2.02 ± 0.46	4.83 ± 3.69	4.93 ± 3.46
Transplantation		2.00 ± 0.47	4.36 ± 2.86	4.28 ± 3.10

4. Discussion

The ideal condition for an implant is a sufficient cortical bone support against the occlusal force [29]. Some studies [30] [31] have reported good long-term prognosis of implants and others [12] [13] [18] [19] [20] [25] have arrived at the same conclusion with fibular grafts. However, there are relatively few reports on the use of implants with fibular grafts; therefore, the efficacy of this treatment option remains controversial.

In some studies, FEA was performed at an acute angle of 45 degrees [19] [32] [33] to duplicate the angle of occlusion. However, reconstruction varies among cases due individual differences. In the present study, the loading angle was set verticality to the upper surface of the prosthesis to exclude phenomena caused by morphological differences among patients. In addition, the following three loading positions were set: center, mesial and distal (**Figure 3**). A single-tooth prosthesis was assumed for all models. However, different loading positions were tested to identify the mechanisms responsible while using a cantilevered prosthesis. Our results showed that stress values were significantly lower with center loading than with mesial and distal loading (**Table 2**). Yokoyama *et al*. [22] reported that bone stress was increased by moving the loading position away from the center of the implant site, which was in accordance with our results, showing that bone stress was lowest at the center loading position under similar conditions in FM and TM.

The use of cortical bone is important to achieve implant stability. Generally, monocortical fixation is used in which the penetration of the cortical bone occurs only near the implant collar. Bicortical fixation involves the use of 2 layers of cortical bone near the collar and apex of the implant. Some studies reported a decrease in bone stress by bicortical fixation [19] [20] [31]. Even by FEA, Holberg *et al*. [34] reported that stress was significantly lower in bicortical fixation than in monocortical fixation. Moreover, other studies [28] [35] reported a decrease in stress levels at the cortical bone near the upper base by the deep positioning of implant and using a longer implant. In this report, the center loading position was associated with significantly lower stress in the cortical bone near the implant collar in the bicortical model than in the monocortical model (**Table 3**); however, there was no significant difference between the mesial and distal loading positions. Another study reported that stress during off-axis loading of the implant was concentrated in the cortical bone near the implant collar [22]. Therefore, the mesial and distal loading positions did not offer the same benefits for decreasing stress levels in the cortical bone near the implant apex in the bicortical model as well.

Huang *et al*. [36] and Haibin *et al*. [37] reported that bone stress levels were increased when the cortical bone is thin. In implant treatment, loading stress was concentrated on the thin cortical bone, which resulted in implant loss [38]. The main difference between the fibula and mandible is the thickness of cortical bone (2.0 and 3.5 mm, respectively) [23]-[25] Chiapasco *et al*. [39] and Kramer *et al*. [40] reported that FEA did not reveal significant differences in stress values between the mandible and fibular graft. In this study, FM and TM were modeled under these same conditions. The thickness of the mesial cortical bone of TM was 2.0 mm and that of the distal cortical bone was 3.5 mm (**Figure 2**). However, this difference did not cause a significant difference in bone stress values at these 2 positions (**Table 4**). In addition, our results are in agreement with those of Huang *et al*. [36], who reported that a cortical bone thickness of 2.0 mm was sufficient to stabilize the implant.

QOL of patients receiving reconstructive treatment can improve with the use of implants compared with that of patients receiving general care [11]. However, no study has investigated the benefits of implants placed at the border between host bone and bone grafts. Hidalgo *et al*. [41] reported that the border between the mandible and transplanted fibular graft was stable. In our clinic, we experienced a case that required tumor resection in which a fibular graft was used for mandibular reconstruction. In this case, the implant was placed at a distance of 2 mm from the tooth on the border between the mandible and fibula using bicortical fixation (**Figure 9**). The reconstruction has lasted for >13 years without any problem. In this study, we simulated a simple implant model and employed FEA to evaluate bone stress. Our results showed that there were not mechanical problems when the implant was placed on the border between the mandible and the fibular graft.

However, there were some limitations associated with the present FEA. Our model did not take into account individual differences, including those in occlusal force, occlusal angle, occlusal muscle strength, bone quality, and bone thickness. Therefore, further studies are necessary to identify appropriate models for FEA.

5. Conclusion

In this study, we constructed a 3D model using FEA for assessing bone stress when an implant was placed at the border between the mandible and fibular graft to investigate bone stress. Our results showed that bone stress was significantly increased by use of a loading position away from the center of the implant. Center loading in a bicortical anchored model was associated with a significant decrease in bone stress. There were no significant differences between FM and TM. The results of this study sufficiently indicated that an implant should not be placed at a more distal position in a mesial cantilever prosthesis in an attempt to avoid a position on the border between

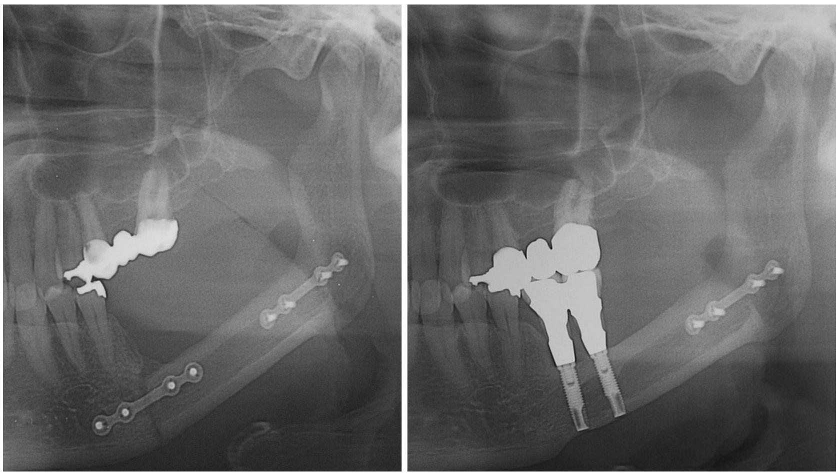


Figure 9. A case of tumor resection and reconstruction surgery (left) 13 years after placement of implants.

the host bone and the graft.

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