Original Article

Optimizing the Insertion Positions And Angles of Implants for All-on-Four Dental Prostheses

Running title: Shape optimization of all-on-four prosthesis

Yung-Chung Chen
Department of Stomatology, Division of Prosthodontics, National Cheng Kung University Hospital, College of Medicine, National Cheng Kung University, Tainan, Taiwan
Institute of Oral Medicine, College of Medicine, National Cheng Kung University, Tainan, Taiwan

Chi-Lun Lin
Department of Mechanical Engineering, National Cheng Kung University, Tainan, Taiwan

Yu-Feng Huang
Department of Mechanical Engineering, National Cheng Kung University, Tainan, Taiwan

Corresponding authors:

Yung-Chung Chen, DDS., M.Dsc, PhD
Assistant Professor, Institute of Oral Medicine, College of Medicine, National Cheng Kung University, Tainan, Taiwan
Email: yc_chen@mail.ncku.edu.tw
Phone: +886-6-2353535 ext. 6713

Chi-Lun Lin, MS., PhD
Assistant Professor, Department of Mechanical Engineering, National Cheng Kung University, Tainan, Taiwan
Email: linc@mail.ncku.edu.tw
Phone: +886-6-2757575 ext. 62190

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Abstract

Objectives: The all-on-four concept is an alternative option of full-arch rehabilitation for fully edentulous patients. However, its structural design and mechanical performance have not been comprehensively investigated. This study was aimed to optimize the placement of dental implants and prosthetic configuration used in all-on-four treatment by a numerical approach in which the finite element analysis (FEA) and design optimization techniques were integrated to minimize the peri-implant strain for reducing the risk of early bone loss.

Methods: In the numerical model, the fixed prosthesis is supported by four implants including two posterior tilt implants and two anterior axial implants over mandible bone, and subject to a distributed force of totally 150N in the occlusal direction. The design variables are the length, diameter, position and two tilt angles of the distal implants. An automated framework was implemented to generate various simulations with given design configurations. The Nelder-Mead method was introduced to iteratively search for the optimal design that minimizes the minimum principal strain in the distal peri-implant region.

Results: Given a clinically used design with [distal implant tilt angle, distal implant length, distal implant diameter] = [30°, 11.5 mm, 4.0mm] as the start point, the search process converged after 200 iterations, which took 52.45 hours of computation time. The total volume of elements in distal peri-implant bone with a minimum principal strain below -0.004 was improved 40.15%, from 7.25 mm^3 to 4.35 mm^3. By adjusting the penalty factor of the optimization algorithm, the computation time was significantly reduced to 16.20 hours.

Conclusion: This research developed an automated framework for optimizing the implants placement based on the FEA and iterative searching algorithm. The results showed that the structural design of prosthesis was improved through the optimization process. The automated framework can be further developed for clinical uses to provide treatment suggestions.

Key words: All-on-four dental prosthesis, automated modeling, finite element analysis, shape optimization

Introduction

Nowadays, implants-supported prosthesis is an alternative treatment option for completely edentulous patients who do not favor wearing removable dentures. Six implants or more are usually used for full-arch rehabilitation. However, it was found in most of edentulous jaws that the resorption in the distal region and poor bone quality are observed[1, 2]. Sufficient and adequate bone quantity is the first requirement to ensure long-term survival of dental implants. To achieve that, bone grafting in mandible and sinus augmentation in maxilla should be conducted in these cases, which would cause a longer procedure time and a higher risk of complication.

The all-on-four treatment concept, which only uses four implants to support prostheses, is a new option for edentulous patients[3, 4]. The surgical principle of the all-on-four treatment concept is to place two axial implants in the anterior region and two tilted implants at the distal end. The tilted distal implants are able to prevent from traumatizing some anatomical structures, for example, the mental foramen in the mandible and maxillary sinus in the maxilla. In addition, some more advanced and complex procedures can also be avoided such as sinus lifting with bone grafting[5]. According to clinical research, cumulative survival rate of all-on-four treatment at follow-up of 12, 24, 36 months is 98.6%, 99.1%, and 99.0% respectively[6]. It can be a cost-effective and time-efficient treatment option for fully edentulous patients.

Although changes in the bone level surrounding the implants of all-on-four treatment were found acceptable in the first few years' follow-up[6-8], many factors can still influence its long-term survival such as peri-implantitis and mechanical failure of prosthesis. More cautious care is required for the surrounding implants tissue health, especially for the tilted implants. Because of using fewer number of implants, it is extremely important to secure each implant's survival. Loss of any implant can reduce the lifetime of the supported prosthesis. In addition, the mechanical factors including occlusal scheme, material selection and stress distribution must be evaluated more carefully. When overloading occurs, resorption of the alveolar bone can be worsen especially in peri-implant region, which further increase the risk of prosthetic failures[9, 10]. For the above reasons, a comprehensively mechanical analysis is necessary to be conducted.

The Finite Elements Method (FEM) is efficient for studying the mechanical structure and has also been widely used in the industry of dental implants. By using FEM, researchers compared mechanical behavior between all-on-four and other fixed prostheses treatments. The results showed that using six or more implants as the fixed prostheses produced smaller peri-implants stress than the all-on-four treatments, however, the maximum stress of all-on-four did not exceed the load resistance of bone[2, 11]. Although the mechanical performance is poorer than other fixed prostheses, the advantages of shorter processing time and lower computing cost make the all-on-four concept an alternative option clinically. It is believed that reducing the peri-implant stress of the structure could make all-on-four prosthesis more reliable. Recent study showed that the configuration and geometry of implants play an important part in the peri-implant stress of all-on-four treatment. By changing tilt angle, length, diameter and cantilever length of implants, it is possible to reduce the stress and strain in peri-implant area[9].

Some researchers proposed that shorter cantilever length results in lower peri-implant stress[12]. Some studies manipulated the tilt angle to obtain different cantilever lengths. The results showed that the model with the tilt angle of 45°, which resulted in the shortest cantilever length, produced the lowest peri-implant stress[13]. In other studies of the all-on-four numerical model, higher peri-implant stress was found around the tilt implants than the axial implants when the positions of the implants were fixed[14, 15]. In other words, increasing tilt angle without varying cantilever length can cause higher peri-implant stress.

According to the researches about all-on-four's parameter, the cantilever length is determined by not only tilt angle but also position of implants[13, 16]. In addition, the length and diameter of implants can affect the mechanical behavior. The study using a multi-parametrical model showed that the matching relation between the parameters should be concerned in order to find the best design for all-on-four treatment[17].

In the present study, a comprehensive mechanical analysis for the all-on-four treatment was conducted to investigate the optimal position and orientation for placing the dental implants.

In addition, an automated modeling framework was proposed to become a part of the treatment evaluation process. The automated modeling enables an automatic process that incorporates the design optimization searching algorithm and finite element analysis to iteratively optimize the alignment of the implants.

MATERIALS AND METHODS

The 3D geometry of an edentulous mandible was imported to construct a finite element model in ABAQUS 6.14 (Simulia by Dassault Systemes, France), and feature points were defined to form the supporting framework of prosthesis. As a result, the framework can be determined by a parabolic curve which fits these given feature points. The implants were positioned along the curve, as shown in Figure 1. The design of the implants was referred from the manufacturer, as shown in Figure 2. To simplify the FEA model, the thread of the implants is neglected. The model was meshed by using tetrahedral elements, and the element size was set as 0.8 mm according to our convergence analysis, which resulted in about 320,000 nodes and 1,600,000 elements. The material properties are shown in Table 1, and the materials are assumed to be homogeneous and isotropic. The materials of the implants and framework used were titanium (Ti). An axial load of 150 N was applied to both sides of the distal end of the framework which can form a larger moment arm.

The model for design optimization includes eight design variables (Figure 3), which are the both sides of the distal implants' tilt angles, lengths, diameters, and positions, and the symbols are chosen as ϕ_{right}, L_{right}, d_{right}, θ_{right}, ϕ_{left}, L_{left}, d_{left} and θ_{left} respectively. The design space is defined by the following constraints:

$0° \leq \phi_{right} \leq 45°$

$8 \leq L_{right} \leq 12 (mm)$

$3 \leq d_{right} \leq 5 (mm)$

$35° \leq \theta_{right} \leq 45°$

$0° \leq \phi_{left} \leq 45°$

$8 \leq L_{left} \leq 12 (mm)$

$3 \leq d_{left} \leq 5 (mm)$

$40° \leq \theta_{left} \leq 50°$

The objective was to minimize the total volume of elements with a minimum principal strain below -0.004[18, 19]. Additional four constraints, interference and mandibular nerve, are derived to avoid the implant constructed by automated algorithm interferes the mandibular nerve. Two interference constraints were then applied to the both sides of the distal implants. An illustration of the constraints is shown in Figure 4, and the equation is shown below, where $t_{tolerance}$ is the distance between distal bound and anterior bound.

$$t - L\sin(\phi) + \frac{d}{2}\cos(\phi) < t_{tolerance}$$

Two mandibular nerve constraints shown in Figure 5 are applied to both sides of the distal implants. The equation of the constraints is shown below, where h_{nerve} is the depth of the mandibular nerve which is set to 6mm for on both sides, and t is the distance between the implant and mandibular nerve

$$\frac{\frac{d}{2}\cos\phi - t}{\tan\phi} < h_{nerve}$$

To search for the optimal solution, the numerical optimization method, the Nelder-Mead method was applied. The exterior penalty method was used to treat the constrained optimization problem of this study. The method introduced a penalty factor to add a penalty value to the objective function of those design points outside the feasible region. A large penalty factor would magnify the penalty more to eliminate infeasible designs. Several penalty factor values were tested, and the values of 100 and 200 were compared and discussed. The flow chart of the automated modeling and mechanical analysis is shown in Figure 6.

To validate the finite element model, an in vitro experiment was conducted to compare the measured and simulated strain values. By using the automated framework developed by present study, another optimization was conducted by using the same material as the experimental model. For the experiment, four implants were placed into two 3D printed mandibular models with the initial prosthesis design and the optimal prosthesis design (Figure 7). For both cases, an axial load of 150 N was applied to the distal end of the prosthesis (Figure 8) and the strain value was measured at 5mm away from the center of the distal implants in the distal direction. The strain value was compared with that probed at the same location of the finite element model.

RESULTS

The optimization process was started with an initial design of 4 mm in diameter, 11.5 mm in length and tilt angle of 30° for the posterior implants and 3.4 mm in diameter, 8.5 mm in length and tilt angle of 0° for the anterior implants, a design currently used in clinical practice. In the first run, the penalty value was set for 100. After 150 iterations of the Nelder-Mead method, the condition of convergence was met. The optimal design point was found in an infeasible region, close to the boundary of the left mandibular nerve constraint. A second run of the Nelder-Mead method was then performed with penalty value of 200. After 150 iterations, the convergent condition was met. The optimal designs obtained by two separate runs of the optimization process are shown in Table 2.

The volume with a minimum principal strain below -0.004 in peri-implant region is shown in Figure 9. The objective value of the optimal design decreased by 40.15% compared to the initial one. The plot of minimum principle strain for the initial design and optimal design was shown in Figure 10. The high strain region, which is close to the lingual side, became smaller after the optimization. In addition, there does not exist elements whose minimum principal strain is below -0.004 in all the anterior peri-implant regions.

In the finite elements model, there might be singular value on the interface between implants and bone, in addition the maximum value of strain or stress in the region is divergence due to the numerical method. To avoid the defect, the total volume summed by the elements with a minimum principal strain below -0.004 is regarded as the indicator of the mechanical structure. And the results showed that using this objective function successfully improved the mechanical performance of the structure.

DISCUSSION

It was observed that the design point searched in each iteration tended to move toward both sides of the mandibular nerve constraints. Therefore, a parametric study was further conducted to investigate the local region around the optimal design point obtained by using the automated framework. The result is shown in Figure 12, Figure 13, Figure 15 and Figure 16.

In our study, the design variables which can directly change the cantilever length are θ_{right} and θ_{left}. By reducing these two variables, the positions of the implants were moved toward the distal end, and the cantilever length was shortened. Since moving the distal implants toward the distal end is restricted by the mandibular nerve constraints (Figure 11 and Figure 14), the distal implants must be placed near the edge of the foramen. However, along with the mandibular nerve constraints, increasing θ resulted in the increase of tilt angle ϕ (Figure 12 and Figure 15). Thus, to avoid the high stress caused by excessive tilt angles, the tilt angle must be considered when reducing the cantilever length.

The result of the experiment is shown in Figure 17 and Figure 18. The error between experiment and simulation resulted from the gap between the implant neck and mandibular in experimental model. Observing the objective values of the optimal and initial designs, the difference of strain between left and right implants in the experiment is similar to the difference found in simulation. As a result, we can consider that the FEM model is able to simulate the mechanical behavior corresponding to design changes.

This study certainly has limitations. First of all, the thread of the implants can be added to simulate more realistic results. However, for the optimization purpose of this study, the thread would not significantly affect mechanical behavior of the bone in the peri-implant area. Secondly, the maximum stress and strain values observed in the FEA results could not be used to compare the performance of designs. The singularities occurred in the computation due to many contacts between geometric parts and at sharp edges of the irregular geometry. This explains partially the reason why we used the total volume of elements with a strain value lower than threshold as the objective function rather than the maximum strain. Finally, the automated modeling framework occasionally stopped in the middle of the process due to an error of auto-meshing, which requires a manual intervention to continue a stopped run. Future improvement can replace the built-in mesh function with a more powerful feature.

CONCLUSION

This research developed an automated framework for optimizing the placement of implants of the all-on-four treatment based on the FEM and optimization searching algorithm. By reducing the volume with a minimum principal strain below -0.004 in peri-implant region, the mechanical performance of the prosthetic structure was improved. With the advance of the computing power, the automated framework can produce optimal designs in a timely manner such that biomechanical analysis of dental implant treatment can be delivered in the surgical planning stage.

To conclude, three findings from the present study should be mentioned. Firstly, the positions and tilt angles of the distal implants on the both sides play an important part in the mechanical performance of the all-on-four treatment. Secondly, when selecting designs along the mandibular nerve constraint, the increase of the strain value in the bone caused by tilting the implant was more significant than the decrease of that caused by shortening the cantilever length. Finally, the implants should be placed close to the mandibular nerve to obtain minimal peri-implant strains, which might not be favored by clinicians. Therefore, further investigation is a must.

Table 1

The material properties of the components used in the FEA model[12]

	Young's modulus (MPa)	Poisson ratio
Cancellous bone	1370	0.3
Cortical bone	13700	0.3
Ti	110000	0.3

Table 2

The configurations of initial and optimal designs with different penalty factor values applied.

	ϕ_{left} (°)	L_{left} (mm)	d_{left} (mm)	θ_{left} (°)	ϕ_{right} (°)	L_{right} (mm)	d_{right} (mm)	θ_{right} (°)
Initial design	30.00	11.50	4.00	140.00	30.00	11.50	4.00	40.00
Penalty factor:100	22.95	11.41	4.87	141.58	21.43	11.71	4.02	38.47
Penalty factor:200	23.15	11.34	4.89	141.47	21.09	11.61	3.99	38.09

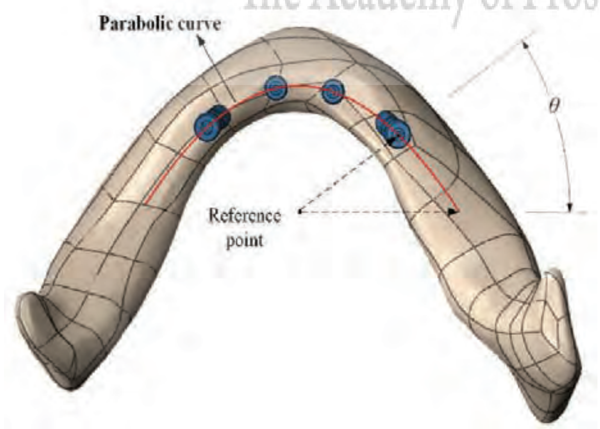


Fig. 1: The positions of implants are defined using a parabolic curve with a reference center point.

Fig. 2: The implant's design contains three parameters: length (L), diameters (d) and tilt angle (Φ).

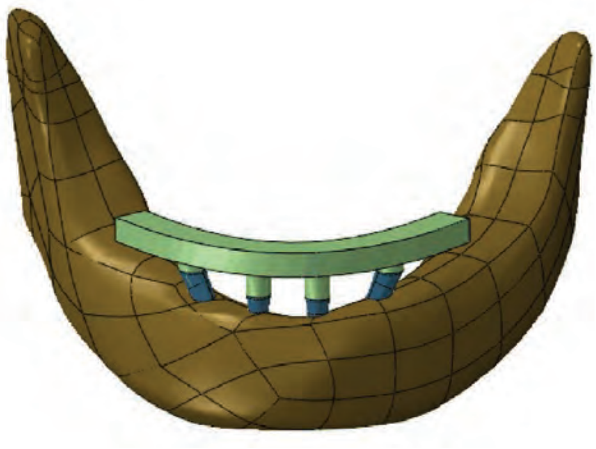
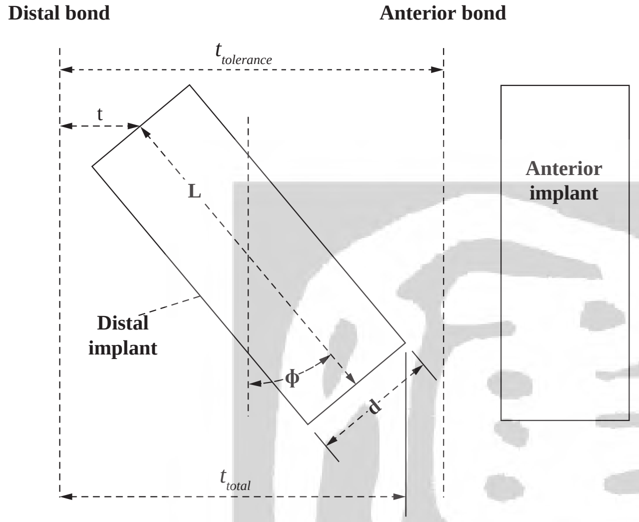


Fig. 3: The geometric model is imported to FEM software.



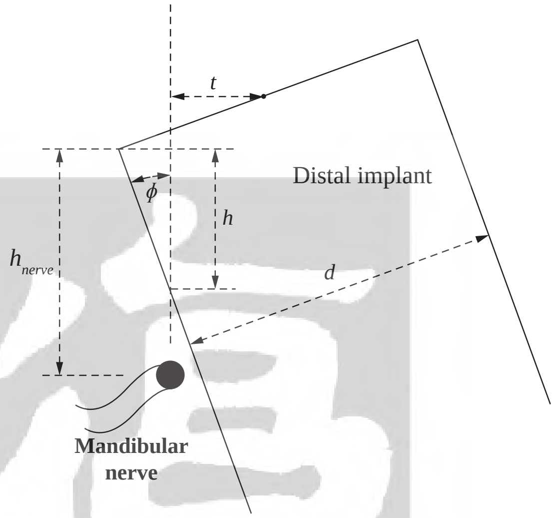


Fig. 4: An illustration of the two interference constraints applied to the both sides of the distal implants, where L is the length, d is the diameter and ϕ is the tilt angle of the implant. Note that the taper and other geometric features are not shown to simplify the illustration.

Fig. 5: The relationship between a distal implant and mandibular.

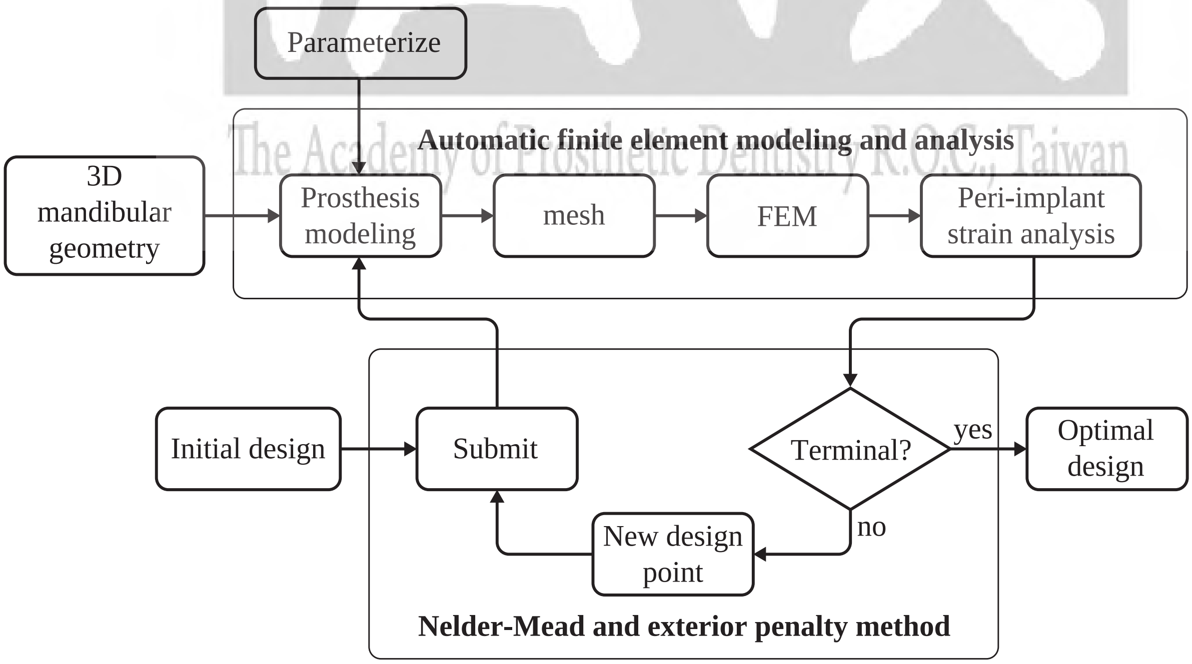


Fig. 6: The flow chart of design optimization combined with automatic modeling for FEA.

Fig. 7: The mandibular model for validation experiment.

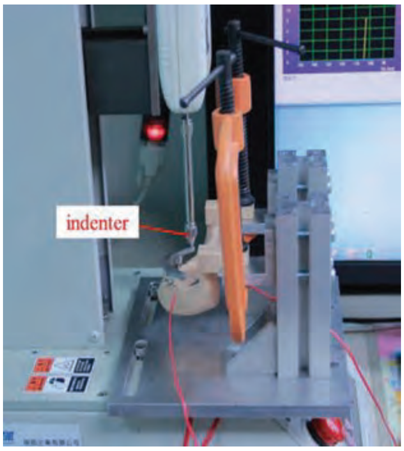


Fig. 8: The experimental setup for loading test, where a mandibular model is fixed by two vises on the frame.

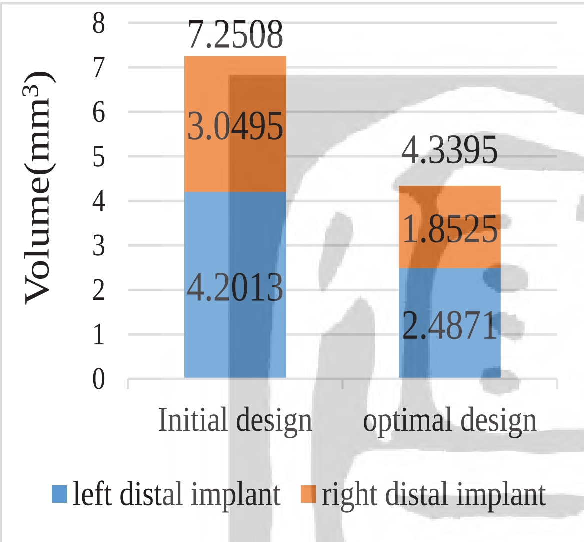


Fig. 9: The total volume of the elements with a minimum principal strain below -0.004 in peri-implant region of distal implants on both sides. The sum of the total volume on both sides is 7.2508 for the initial design and 4.3395 for the optimal design.

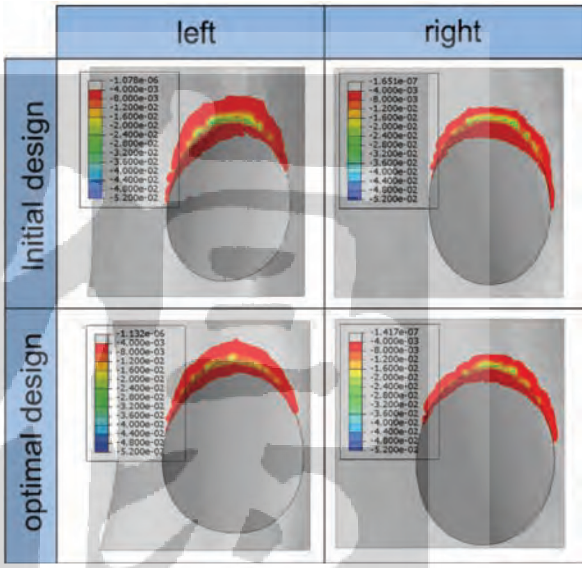


Fig. 10: The top view of the strain contour on the implants. The region with a minimum principal strain below -0.004 is shown in colors.

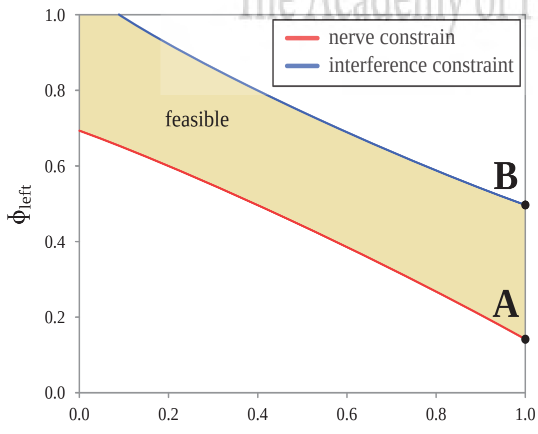


Fig. 11: The feasible region calculated when d_{left} is 5mm.

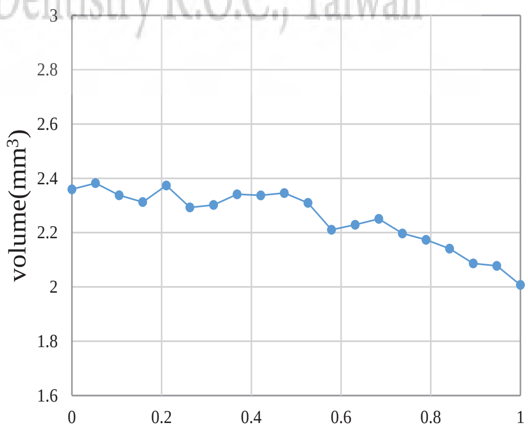


Fig. 12: The implant's design contains three parameters: length (L), diameters (d) and tilt angle (Φ).

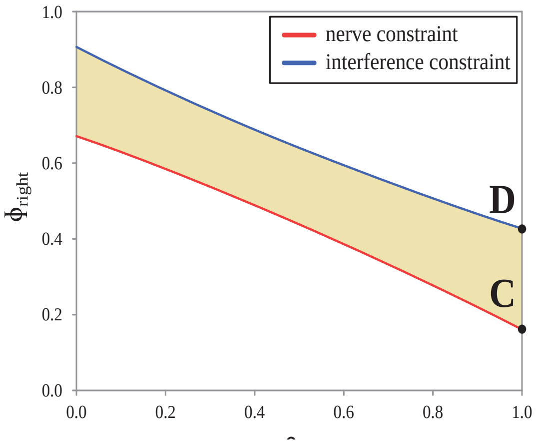


Fig. 13: the positions of implants are defined using a parabolic curve with a reference center point.

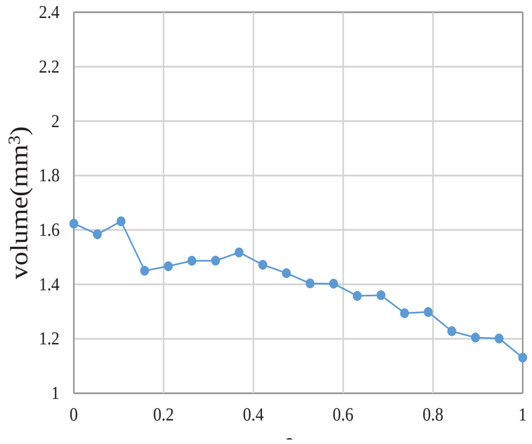


Fig. 14: The value of the objective function versus θ_{right} along the right mandibular nerve constraint.

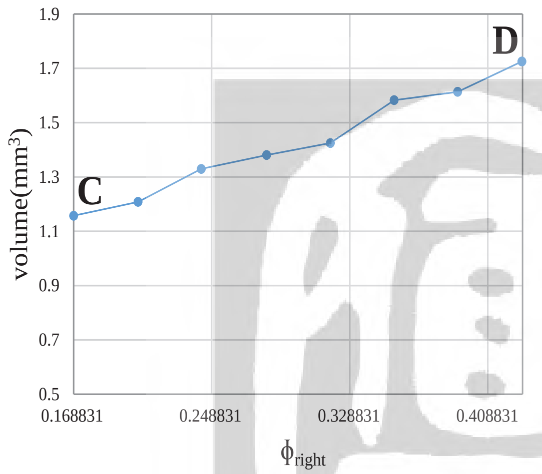


Fig. 15: The value of the objective function evaluated in the range from point C to point D (defined in Figure 12). The minimum is found at point C.

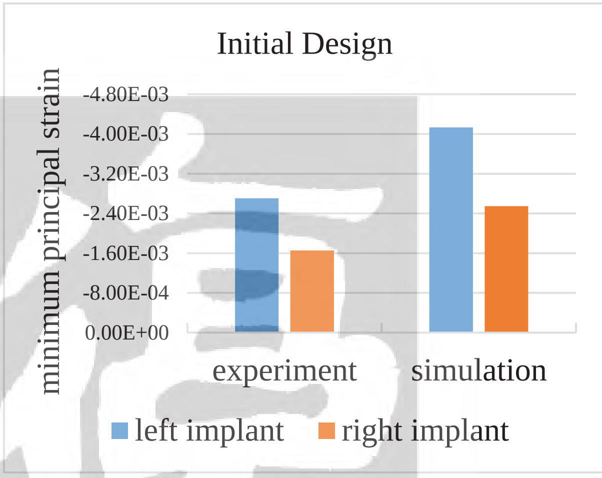


Fig. 16: The minimum principal strain in peri-implant region obtained from simulation and experiment for the initial design.

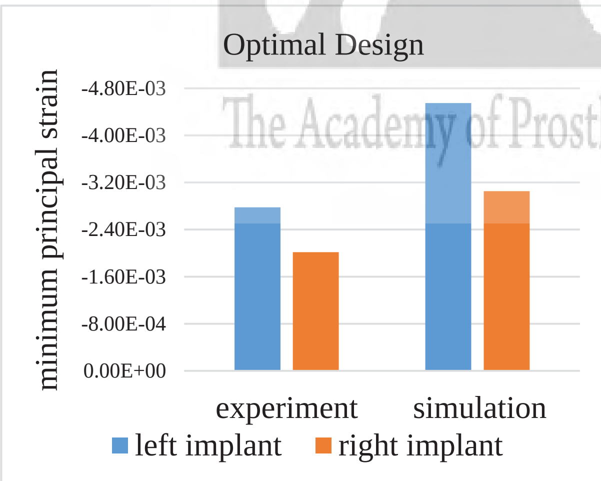


Fig. 17: The minimum principal strain in peri-implant region obtained from simulation and experiment for the optimal design.

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