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Biomechanical effect of length and diameter of a short implant used in splinted prosthesis at the posterior atrophic maxilla of aging patients: A finite element study

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ABSTRACT

The aim of this study was to evaluate the influence of implant diameter, implant length, and cortical bone thickness on the biomechanical behavior of a splinted implant in the posterior atrophic maxilla of aging patients. Eight finite element models for the posterior maxilla bone block were simulated. Each model had two implants with zirconia splinted crowns and varying second pre-molar implant length, first molar implant diameter, and cortical bone thickness. Biomechanical behavior was observed after loading the models with maximum bite force of the elderly patients. The results show that serious biomechanical complications as a consequence of implant displacement and implant fracture were not likely to occur. Additionally, the models with a thicker cortical bone and a larger implant diameter expressed lower elastic strain within the bone. It can be inferred that cortical bone thickness and implant diameter are the dominant factors in improving the biomechanical performance of these implants. Clinicians must not neglect to consider that strain overloading which results from the bite force may lead to peri implant marginal bone loss. Increasing the implant diameter in patients with minimal cortical bone levels can maintain the peri implant marginal bone which is able to result in better long-term outcomes.

Keywords: splint-short dental implant; posterior atrophic maxilla; aging patient; finite element analysis

1. INTRODUCTION

Over the 50 years after dental implants were invented, it has presented good long-term clinical success rates (Jimbo and Albrektsson, 2015). Due to its successful outcomes, dental implants have been used as a standard treatment in both fully and partially edentulous patients (Buser et al., 2017).

After removing the tooth from the socket, the crestal bone naturally and gradually resorbs. In the resorption process, bone which has been left untreated for a long period of time reduces in the vertical and horizontal dimensions and the cortical bone also becomes thinner. This phenomenon increases difficulty when placing implants due to the insufficient amount of bone. Moreover, this complication is usually more complex, especially in the posterior maxilla region. In this region, just after the tooth is extracted the maxillary sinus begins physiologic expansion, which results in a rapid decrease of the vertical bone dimension due to the duo resorption from both crestal resorption and sinus pneumatization (Pramstraller et al., 2011; Tan et al., 2012).

To deal with these problems the surgical procedures, for instance bone block graft, maxillary sinus lifting, and guided bone regeneration, are performed to reestablish an adequate amount of bone height and width to allow for the placement of standard implants (Muchhala et al., 2018). However, these procedures also come with a high risk for both intra-operative and post-operative complications, such as Schneiderian membrane perforation, bleeding, wound infection, and post-operative morbidity (Moreno Vazquez et al., 2014). Furthermore, aging patients may present general health problems, depression, fear, and could also be less able to cope with long and complicated clinical procedures.

To address the issue of bone insufficiency without bone augmentation procedures, short implants with a length not over 6.0 mm were developed and have been widely used as an alternative due to their effectiveness and simple procedure (Lemos et al., 2016; Malmstrom et al., 2016). Nevertheless, some authors mention that short implants have less favorable biomechanical behaviors (Hasan et al., 2010; Pellizzer et al., 2015). Moreover, other authors report that short implants present a significantly reduced survival rate compared to standard implants (Papaspyridakos et al., 2018; Rossi et al., 2016).

In addition, multiple studies suggest that splinting prosthesis improves biomechanics, leading to a higher success rate in splinted posterior short implants, less prosthetic screw loosening, and more protection against overloading forces which may cause crestal bone loss and prosthetic complications (Isidor, 1996; Mendonça et al., 2014; Baggi et al., 2008). Grossmann et al. (2005) proposed a guideline which stated that implant should be splinted in the condition involving edentulous maxilla.

Finite element analysis (FEA) is a computerized method used extensively to predict the biomechanical performance of various components (for instance dental implants, abutment, and bone) and how they will react to force, load transfer, and stress distribution (Geng et al., 2001). The load transfer from implants to the bone induces strain on the surrounding bone. Different strain magnitudes which are exerted on the bone will result in different bone responses. A strain level of 4000 με or more is commonly indexed as the pathologic overload zone, where marginal bone loss is observed due to fatigue failure (Sugiura et al., 2015).

Few studies have analyzed the biomechanical behavior of short splinted dental implants using different lengths, diameters, and cortical bone thicknesses in the atrophic posterior maxilla region. The present study included elderly bite force to study the influence of implant diameter, implant length, and cortical bone thickness to find alternative treatment options which can produce acceptable clinical outcomes.

2. MATERIALS AND METHODS

Computer aided design (CAD) models of splinted short implants were obtained from commercial designs available on the market. The maxilla bone model was derived from computed tomography (CT) data and its shape was modified in CAD software. All the FE analyses were performed using a commercial FE software package.

2.1 Maxilla and splint-implant model construction

The maxilla of a cadaver was scanned via cone beam computed tomography (CBCT). CT images obtained from the scanning process were used to reconstruct the 3D model of the maxilla by the Dolphin 3D imaging software (Patterson Dental Supply, USA). To construct the final 3D model, only the posterior maxilla area was selected. All the teeth and non-involving portions of bone were removed. To simulate the atrophic bone as type IV according to Lekholm and Zarb (1985), CAD software (VISI, Vero Software, UK) was used to modify the cortical layer to thicknesses of 0.5 mm and 1 mm.

Implant models with different diameters and lengths were created using CAD software. The implants used in this study had a diameter of 4.1 mm with a length of 6.0 mm, a diameter of 4.1 mm with a length of 8.0 mm, and a diameter of 4.8 mm with a length of 6.0 mm. All the implants came with a tissue collar height of 1.8 mm. The retained screws and abutments were generated from a commercially available design.

The implants with a diameter of 4.1 mm and lengths of 6.0 mm and 8.0 mm were used with the second premolar, while the implants with diameters of 4.1 mm and 4.8 mm with a length of 6.0 mm were used in first molar. Since there were two differences in the cortical bone thickness, there were a total of eight case studies.

Splinted crown models of the second premolar connected to the first molar with a crown height of 10 mm are shown in Figure 1. The implants were anchored into the cortical and cancellous bone layer. The crowns were obtained from plastic teeth which were scanned using an intraoral scanner (CEREC Omnicam, Sirona Dental Systems, US). The splint crowns were placed on the abutments and attached to the implants using screws.

2.2 Finite element models

FE models were developed from 3D CAD models using automatic mesh generation software (MSC Patran, MSC Software, US). In this study, four-node tetrahedral elements were selected for element generation. A commercial software package (MSC Marc, MSC Software, US) was used for all the FE analyses.

2.3 Material properties

All material properties assigned to the finite element models were assumed to be linearly elastic, homogenous, and isotropic. All values corresponding to the material properties remained constant throughout the testing, which are shown in Table 1.

2.4 Boundary conditions

The cortical bones of the models were fixed in every aspect for all angles. The load value was obtained from the mean maximum bite force of the elderly male patients (Chong et al., 2016). The percentage of force distribution to the second premolar and first molar were from Koos et al., (2010), which were 6.1% and 13.3% of the total bite force, respectively. This produced loading forces of 32 N to the second premolar and 70 N to the first molar. The load was applied on the supporting point of the crowns (Holmes and Loftus, 1997), on a central pit of the second premolar (32 N), and on mesial and distal pits of the first molar (35 N each), as shown in Figure 2.

2.5 Contact conditions

All the bone bodies were fully attached to each another. Implants anchored into bone were set to be osseointegrated, which had no relative translation between bone and implants. Splint-crowns were also set to be non-relative translation to the abutment. The screw securing implants and abutments were set to allow a relative translation without friction.

2.6 Convergence test

A convergence test was performed to determine the suitable number of nodes and elements to be employed in the FE analysis. Five different number of elements between 100,000-160,000 were tested in one of the FE models. The elastic strain on the surrounding bone was used as a parameter to detect the least number of elements which would not affect the FE outcome. The number of elements equal to or greater than this number could then be used for FE analysis.

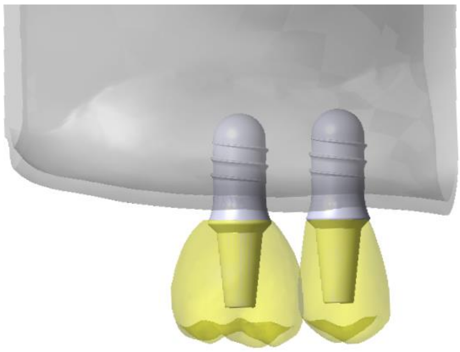

Figure 1. One of the CAD models of splinted short implants in the posterior atrophic maxilla

Table 1. Material properties

Materials	Elastic modulus (MPa)	Possion’s ratio	Reference
Zirconia splinted crown	205,000	0.30	Tanaka et al. (2016)
Titanium CP-4 dental implant	105,000	0.30	Welsch et al. (1993)
Cortical bone	14,000	0.30	Fanuscu et al. (2004)
Trabecular bone	1,100	0.30	Seker et al. (2014)

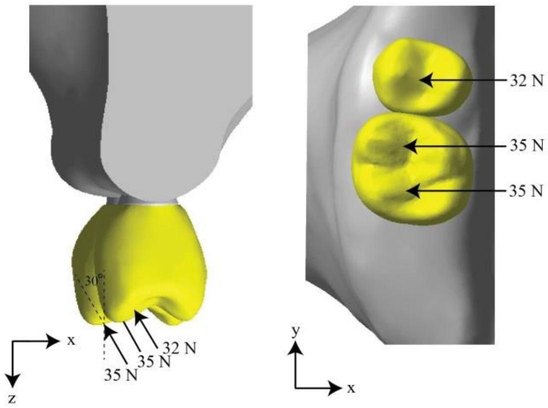

Figure 2. The CAD model with occlusal forces applied on the second premolar and first molar

3. RESULTS AND DISCUSSION

The results report elastic strain distribution of the surrounding bone, implant displacement, and von Mises stress exhibited on the implant system.

3.1 Convergence test

Figure 3 shows the convergence test results. The least number of elements which did not affect the elastic strain magnitude was 135,327. All the FE models in this study used a number of elements that was equal to or higher than 135,327.

3.2 Implant displacement

In descending order, maximum displacement was found at the zirconia splinted crowns, abutments, and implants. Every model expressed the same pattern of displacement towards the buccal direction. From Table 2, the degree of displacements is low and ranges from 15.7-20.3 µm. Thicker cortical bone directly correlates with less translation of the crown. However, longer implants in the second premolar and larger diameter implants in the first molar presented more translation.

3.3 Elastic strain of surrounding bone

The maximum elastic strains from each model were found at the trabecular bone. Table 3 reports the values and Figure 4 shows the distribution pattern. The results showed that model No. 1 (smaller and shorter dental implants with thin cortical bone) demonstrated the highest elastic strain of 9,532 µε. Increasing the cortical thickness and implant diameter reduced the elastic strain. Meanwhile, increasing implant length in the second premolar did not express much influence on elastic strain. Case No. 6 and No. 8 which had cortical thicknesses of 1.0 mm and a wider diameter of the first molar implant had lower elastic strains than the other models.

3.4 Von Mises stress of the implant

In Figure 5, the maximum Von Mises stresses were located on the implant neck and shoulders. The von Mises stress values are presented in Table 4. The von Mises stress values ranged between 248.5-344.7 MPa in all cases. Increasing implant diameter of the first molar implant as well as cortical thickness reduced the stress level.

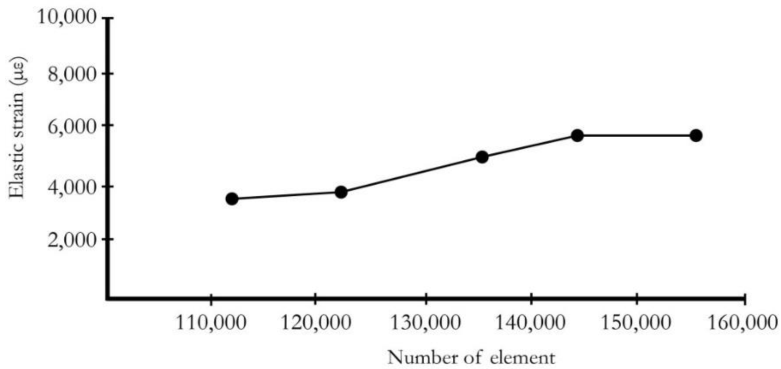

Figure 3. Element convergence test results

Table 2. Implant displacement

No.	Second pre-molar implant (mm)		First molar implant (mm)		Cortical thickness (mm)	Displacement (µm)
	Ø [1]	L [2]	Ø [1]	L [2]		
1	4.1	6.0	4.1	6.0	0.5	19.2
2	4.1	6.0	4.1	6.0	1.0	16.2
3	4.1	8.0	4.1	6.0	0.5	18.8
4	4.1	8.0	4.1	6.0	1.0	16.9
5	4.1	6.0	4.8	6.0	0.5	20.0
6	4.1	6.0	4.8	6.0	1.0	15.7
7	4.1	8.0	4.8	6.0	0.5	20.3
8	4.1	8.0	4.8	6.0	1.0	16.7

Note: [1] Ø is the implant diameter
[2] L is the implant length

Table 3. Elastic strain on surrounding bone

No.	Second pre-molar implant (mm)		First molar implant (mm)		Cortical thickness (mm)	Elastic strain (µε)
	Ø [1]	L [2]	Ø [1]	L [2]		
1	4.1	6.0	4.1	6.0	0.5	9,532
2	4.1	6.0	4.1	6.0	1.0	5,025
3	4.1	8.0	4.1	6.0	0.5	8,546
4	4.1	8.0	4.1	6.0	1.0	3,835
5	4.1	6.0	4.8	6.0	0.5	6,614
6	4.1	6.0	4.8	6.0	1.0	2,926
7	4.1	8.0	4.8	6.0	0.5	7,015
8	4.1	8.0	4.8	6.0	1.0	2,982

Note: [1] Ø is the implant diameter
[2] L is the implant length

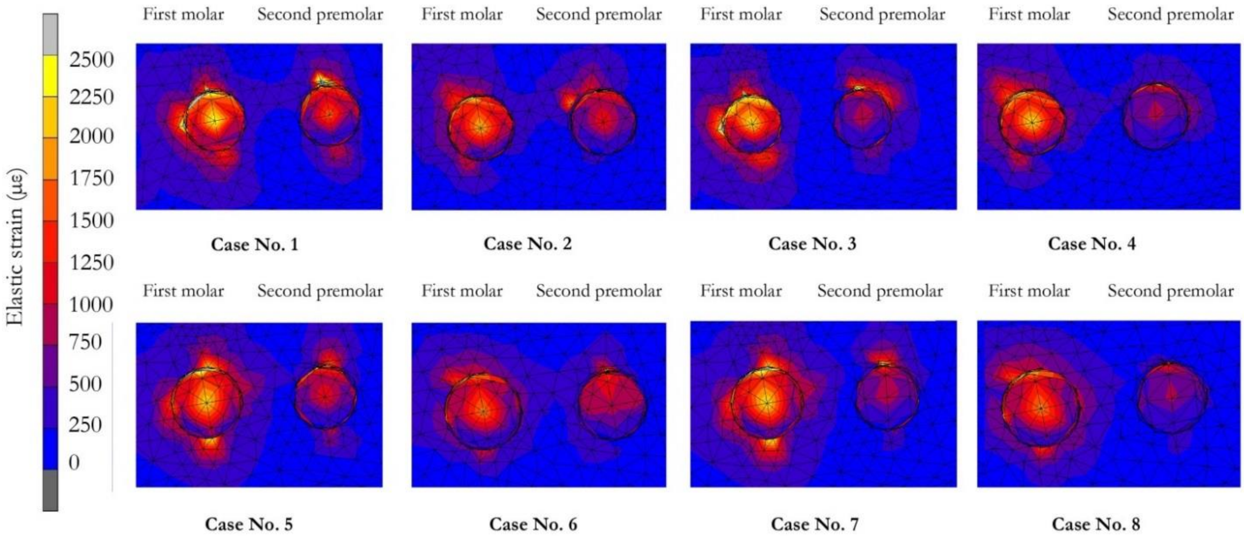

Figure 4. Elastic strain on surrounding bone

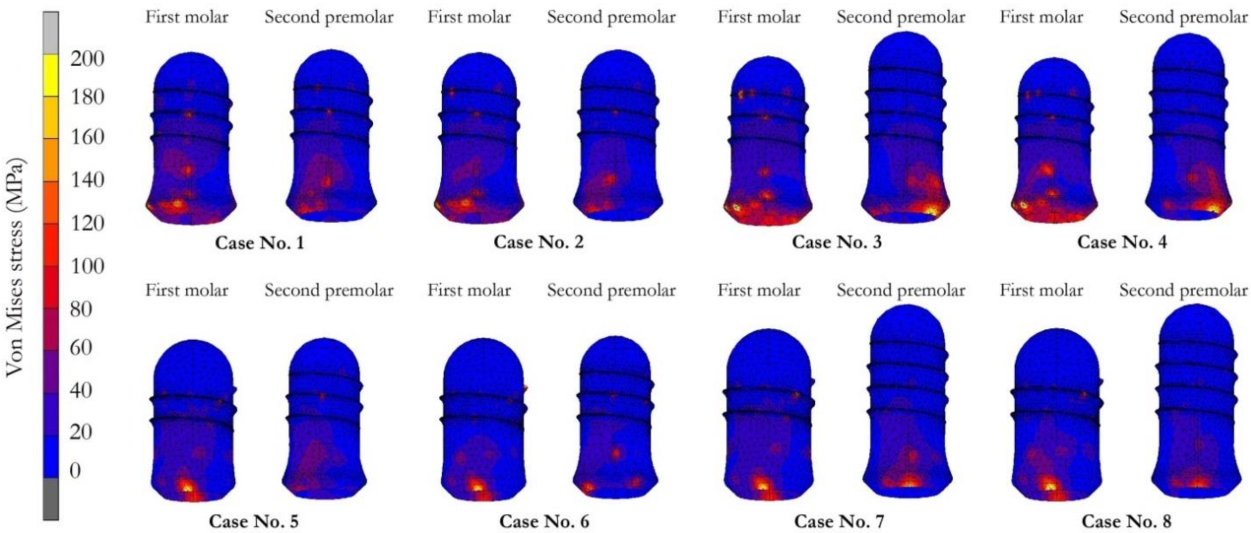

Figure 5. Von Mises stress on the implants

Table 4. Von Mises stress

No.	Second pre-molar implant (mm)		First molar implant (mm)		Cortical thickness (mm)	Von Mises stress (MPa)
	Ø [1]	L [2]	Ø [1]	L [2]		
1	4.1	6.0	4.1	6.0	0.5	344.7
2	4.1	6.0	4.1	6.0	1.0	290.0
3	4.1	8.0	4.1	6.0	0.5	313.8
4	4.1	8.0	4.1	6.0	1.0	326.1
5	4.1	6.0	4.8	6.0	0.5	275.6
6	4.1	6.0	4.8	6.0	1.0	248.5
7	4.1	8.0	4.8	6.0	0.5	278.2
8	4.1	8.0	4.8	6.0	1.0	256.7

Note: [1] Ø is the implant diameter
[2] L is the implant length

4. DISCUSSION

This study created an FE model from CT images together with a commercial implant system. The boundary and contact conditions were generated from actual clinical situations, for example, the bite force, bone model, and implant model. The convergent test was performed to ensure that the number of elements being used in this study would not affect the FE result. According to the test, the selected number of elements were considered appropriate for the analysis.

Bite force was measured using pressure sensitive foils via T-scan III which can measure the bite force in the maximum intercuspation while the mouth is closing (Koos et al., 2010). The percentage force distribution was then calculated using the mean maximum full-arch force acquired from the elderly male patients aged over 60 years old (Chong et al., 2016). T-scan has previously been used in various studies due to its precision, reusability, and user-friendliness (De Prado et al., 2018; Misirlioglu et al., 2014).

The eight analyzed cases were simulated using minimally invasive treatments to address the problems of clinical bone deficiency in posterior maxilla of elderly patients (Ko et al., 2017; Pramstraller et al., 2011). Ko et al. (2017) reported a mean amount of cortical bone thickness of 0.75±35 mm in the posterior maxilla using CBCT from 234 dental implant sites. Additionally, the selection of implant diameter and length used in this study was conducted based on the available bone of 127 patients with at least one tooth loss in the maxillary edentulous area (Pramstraller et al., 2011). The literature reports the mean available bone height at the second premolar and first molar of 9.0 mm and 5.4 mm, respectively, while the mean available bone width at the second premolar and first molar are reportedly 4.8 mm and 5.7 mm, respectively. Pramstraller et al. (2011) also mentioned that at the second premolar site, 60% of the patients had a bone height of more than 8.0 mm. Meanwhile, at the first molar area, 42% had a bone height between 4.1-7.9 mm. This information indicates that the second premolar areas have more bone height but lesser bone width compared to the first molar sites. It is therefore better to use short and wide implants on molars compared to standard implants. However, it is reported that short implants have a significantly reduced survival rate compared to standard-length implants, especially in posterior jaws where poor bone quality can be found (Papaspyridakos et al., 2018). In this case, short implants which can benefit the aging group due to reduced morbidity, fewer complications, and easier procedures were splinted and used in this study (Lemos et al., 2016).

The elastic modulus of the cortical and trabecular bones of elderly persons are not dependent on age (Hoffler et al., 2000), so the present study used data derived from the average person of Fanuscu et al. (2004) and Seker et al. (2014).

Implant micro-movement is one of the most crucial indicators for long term success of implants. Minimizing displacement could decrease the chance of biomechanical related complications. The greatest movement was found at the splinted crown rather than the abutment or the implants. This is due to the force acting at the pits of the crown located further from the crestal bone which acted as a pivot point for bending, and the crown then displaced more than the other parts. Since the cortical bone is a rigid tissue layer, the thicker cortical bone resulted in reduced movement compared to thinner cortical bone. This finding corresponds well with Okumura et al. (2010). In addition, longer implant length in the second pre-molar and larger implant diameter in the first molar presented more translation. When considering the clinical threshold for the displacement, the displacement degree obtained from elderly patients were under 100 µm which is safe for osseointegration rather than fibrous encapsulation (Brunski, 1993).

The area of the retaining screw is a connecting section between implant and abutment. This is a region where the implant system deforms easily. When the suprastructure of implant bends, the abutment presses on the neck of the implant which results in the greatest amount of stress being located at the implant neck and shoulder, which conforms with the findings of Kitagawa et al. (2005). Larger implant diameter showed reduced stress due to the thicker implant materials. All the FE models revealed the maximum equivalent Von Mises stress less than the yield strength of the materials, which is 483 MPa for titanium grade 4 (CP-4) (Elias et al., 2008). This showed a low risk of implant deformation.

Another key parameter for the success of dental implants is the strain on the surrounding bone created by force transferred from the implant. Different magnitudes of strain results in different bone responses. Bone regeneration can only be induced by an appropriate range of strain, which is around 1,000-3,000 µε. Conversely, bone resorption is seen whenever strain reaches above 4,000 µε, as mentioned in Harold Frost's mechanistat hypothesis (Geng et al., 2001).

The result shows that elastic strain is mostly located on the buccal region of marginal bone since the occlusal force is directed towards the buccal side. All models with a 0.5 mm cortical bone thickness presented elastic strain over 4,000 µε. Conversely, two models in the cortical bone thickness 1.0 mm group with a 4.8 diameter molar implant resulted in the elastic strain were under the limit. Narrow and short dental implants with thin a cortical bone demonstrated high elastic strain. Meanwhile, in descending order, increasing the cortical thickness, implant diameter, and implant length reduced the elastic strain in the surrounding bone. Wider implant diameters presented a larger contact area between implant and bone which resulted in greater resistant to deformation, which finally leads to lower elastic strain. This situation would be beneficial for bone remodeling.

It can be inferred that cortical thickness and implant diameter have tremendous effects on elastic strain in the alveolar bone. These findings agree well with a number of previous clinical studies (Chou et al., 2010; Holmes and Loftus, 1997; Sevimay et al., 2005; Ueda et al., 2017). However, implant length in the second pre-molar did not express much influence on elastic strain, which can be clearly seen in case No. 6 and No. 8 in which implant length only slightly influenced elastic strain.

The present study focused on the splinted implant technique to guide clinicians in the selection of dental implant lengths and diameters to be placed in the posterior atrophic maxilla of aging patients. For further investigation, other techniques such as cantilever prosthesis or single unit should be biomechanically compared with the splint technique.

5. CONCLUSION

This research performed FE analysis to study the effect of splinted short implant diameter, implant length, and cortical thickness in posterior atrophic maxilla of aging patients. The results of this study are beneficial in the selection of implant diameter and length for placing in this region. It can be seen that without sufficient cortical bone thickness, clinicians should be aware of marginal bone loss due to strain overload from the bite force of elderly patients. Cortical thickness and implant diameter have dominant effects on implant system stability, while little effect was observed for implant length. Increasing implant diameter and implant length, respectively, in poor cortical bone condition can maintain the peri implant marginal bone level which leads to long-term success.

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