Journal of Zhejiang University-SCIENCE B (Biomedicine & Biotechnology)
ISSN 1673-1581 (Print); ISSN 1862-1783 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Report:

Effect of proximal contact strength on the three-dimensional displacements of implant-supported cantilever fixed partial dentures under axial loading

Zhen-zhen PENG, Xin-min CHEN†‡, Jun WANG, Ai-jie LI, Zu-jie XU

(*State Key Laboratory of Oral Diseases, West China Hospital of Stomatology, Sichuan University, Chengdu 610041, China*)

†E-mail: chenxinmin218@163.com

Received Sept. 26, 2012; Revision accepted Mar. 5, 2013; Crosschecked May 17, 2013

Abstract: Objective: This study investigated the effect of proximal contact strength on the three-dimensional displacements of cantilever fixed partial denture (CFPD) under vertically concentrated loading with digital laser speckle (DLS) technique. Methods: Fresh mandible of beagle dog was used to establish the implant-supported CFPD for specimen. DLS technique was employed for measuring the three-dimensional displacement of the prosthesis under vertically concentrated loading ranging from 200 to 3000 g. The effect of the contact tightness on the displacement of CFPD was investigated by means of changing the contact tightness. Results: When an axial concentrated loading was exerted on the pontic of the implant-supported CFPD, the displacement of the CFPD was the greatest. The displacement of the prosthesis decreased with the increase of contact strength. When the contact strength was 0, 0.95, and 3.25 N, the displacement of the buccolingual direction was smaller than that of the mesiodistal direction but greater than that of the occlusogingival direction. When the force on the contact area was 6.50 N, the mesiodistal displacement of the prosthesis was the biggest while the buccolingual displacement was the smallest. Conclusions: The implant-supported CFPD is an effective therapy for fully or partially edentulous patients. The restoration of the contact area and the selection of the appropriate contact strength can reduce the displacement of the CFPD, and get a better stress distribution. The most appropriate force value is 3.25 N in this study.

Key words: Cantilever fixed partial denture, Digital laser speckle technique, Contact strength, Three-dimensional displacement

doi:10.1631/jzus.B1200264 **Document code:** A **CLC number:** R783.4; R783.6

1 Introduction

Dental implants were introduced in the late 1960s for rehabilitation of completely edentulous patients (Branemark *et al.*, 1986; Adell *et al.*, 1990). The use of osseointegrated implants as abutments for fixed partial dentures (FPDs) has become a treatment option for the rehabilitation of completely or partially edentulous patients over the last three decades (Adell *et al.*, 1981; 1990). The use of implants has revolutionized dental treatment modalities and provided excellent long-term results (Esposito *et al.*, 1998). Long-term success rates as high as 95% for mandibular implants and 90% for maxillary implants have been reported (Sevimay *et al.*, 2005). Despite high success rates provided by a great number of clinical studies, early or late implant failures still exist (Kohavi, 1993). A key factor for the success or failure of a dental implant is the mobility of the implant after loading. Weinberg (1993) compared the mobilities of natural tooth and implant, and the results showed that the movement of natural teeth is more than 500 μm in both horizontal and vertical directions and is easily observed, while on the contrary, the mobility of implant is below 100 μm and not observable. The

---

‡ Corresponding author

proximal contact strength and the type of restorations are responsible for the mobility of the implant after loading, which have a great influence on the success of dental implants in this study. In normal dentitions, natural teeth are integrated by contact areas which may keep them in balance and avoid their abnormal movement, and are helpful for the self-cleaning of gingival papilla. Dörfer *et al.* (2000) had studied the contact strength of normal natural dentition. It is a common view that contact area plays an important role in stress transmission and dispersion for decreasing implant mobility; however, there is limited research studying the effect of proximal contact strength on the three-dimensional displacements of implant-supported cantilever fixed partial denture (CFPD).

The implant-supported CFPD, which is supported by implant abutment at one end and unsupported at the other end, is one kind of FPD restoration. Forces transmitted through the cantilevered pontic could cause tilting and rotational movements of the implant abutments and can be detrimental to the health of the periodontium to some extent (Becker and Kaiser, 2000; Becker, 2004; Eskitascioglu *et al.*, 2004; Aglietta *et al.*, 2009; Salvi and Brägger, 2009; Zurdo *et al.*, 2009). So the restoration of the proximal contact area is crucial to the success of implant-supported CFPD.

When dealing with a complex stress analysis problem in which a complete theoretical solution may prove impractical with respect to time, cost, or degree of difficulty, experimental techniques are often used. Current techniques employed to evaluate the biomechanical loads on implants comprise the use of photoelastic stress analysis, two or three-dimensional finite element stress analysis, and holographic interferometry. At home and abroad, holographic interferometry method and beagles had been widely used to study displacement of implants or the stress distribution under static load (Batista *et al.*, 2003; van Leeuwen *et al.*, 2003; Chorres *et al.*, 2005; Campos *et al.*, 2006); however, this method is time-consuming and two-dimensional. Digital laser speckle (DLS) technique, developed from the holographic interferometry method, is real-time and easier to manipulate, but its use in the implant biomechanics area is rare. Accordingly, the purpose of this study was to research the displacement of implant-supported CFPD under vertically concentrated loading by means of DLS technique. Furthermore, the effect of proximal contact strength on the displacement of implant-supported CFPD was investigated.

2 Materials and methods

2.1 Manufacture of experimental animal models of implant-supported CFPD

The experiment was carried out in accordance with the guidelines issued by the Ethical Committee of Sichuan University, China. A healthy adult male beagle, aged at 12 months, weighing 12.4 kg, was provided by and housed in the Animal Center of West China School of Medicine, Sichuan University. The general health of the dog was checked daily by a veterinarian, who was also responsible for general anesthesia and euthanasia at the surgical procedure.

Firstly, under axenic conditions, the first and second premolars of the right mandible in the beagle dog were extracted with general anesthesia, and then two Straumann Tapered Effect implants (diameter 4.1 mm, length 8 mm) were immediately installed in the edentulous premolar regions. The primary stability of implants was evaluated after the implantation. After four months of healing, an X-ray plate of the implant was taken, which showed the secondary stability was well. Then the dog was euthanized and the implant-supported CFPD was fabricated in the in vitro fresh mandible of the beagle dog. The morphology of the abutments (C5) far from the pontic was the same as that of the first premolar of human beings; the morphology of the abutments (C6) near to the pontic was the same as that of the second premolar of human beings; and the morphology of the pontic (C7) was the same as that of the first molar of human beings.

2.2 DLS technique

The DLS technique applies a charge-coupled device (CCD) instead of the traditional holographic plate to get objective images before and after the loadings. Then the pictures of the CCD were taken by the conjoint computer and the speckle grams exposed before and after the loadings were analyzed (Chen *et al.*, 2000). The displacements of the fixed bridge are observed only in the plane of the CCD observation direction rather than the spatial orientation through single CCD in this study. Two CCDs that are in the same horizontal plane are arranged in a certain angle α. The spatial displacement of the fixed bridge was obtained from the vector synthesis of the respective measurements of the denture displacement by two CCDs.

The main components of the DLS system include a He-Ne laser, INFINITY3-1 typed CCDs, microscope tube, loading devices, computer, and so on (Fig. 1). The computer outputs the displacement directly. The procedures were as shown in Fig. 2.

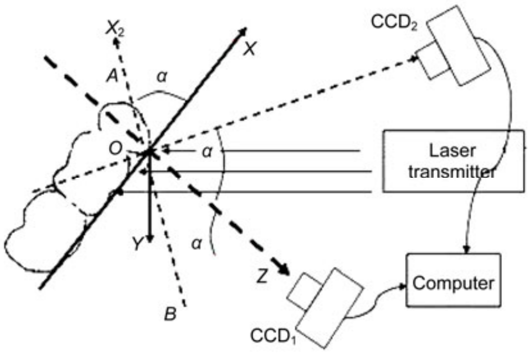


Fig. 1 Schematic representation of experimental setup
With one CCD can only get in-plane displacement *OX* and *OY*. In the present study, this technique was improved. With two CCDs, through formulation $OZ=(OX\cos\alpha-OX_2)/\sin\alpha$, we could get three-dimensional displacement (Xu *et al.*, 2013)

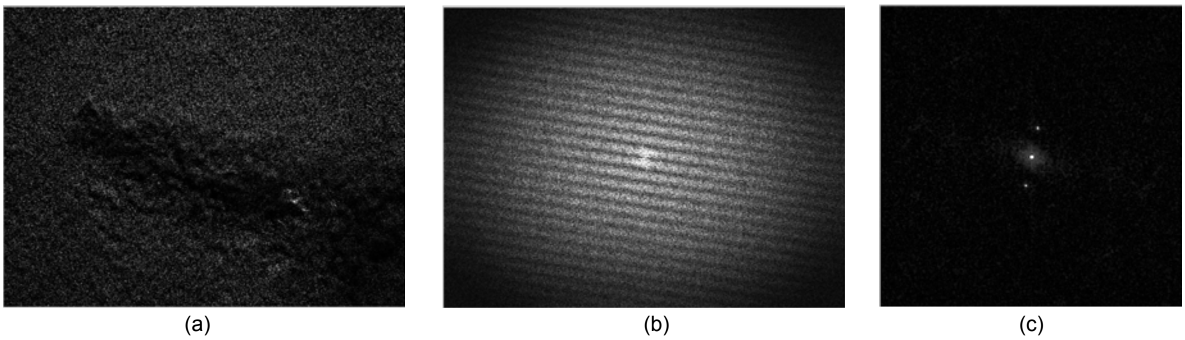
2.3 Proximal contact area restoration system

Several components, including cylindrical compression springs (outside diameter 3 mm, wire diameter 0.5 mm), orthodontic band (thickness 0.2 mm), and spring dynamometer (Jinan Second Machine Factory), were employed to restore the proximal contact area.

The conventional Au-Pt porcelain fused to metal (PFM) was made after the preparation of the beagle left mandible canine, with a cavity of 3 mm in depth and 2.5 mm in diameter, in the distal proximal surface. The orthodontic band strip was prepared into 2.5 mm diameter circular and welded to one end of the spring to replace the proximal contact area. The contact area was located in the junction of mesial 1/3 and buccal 1/3. The springs were in different lengths.

The elastic coefficient of the stainless steel cylindrical helical spring was measured by spring tension and compression testing machine.

We placed the springs in the cavity of the crown to simulate four kinds of contact tightness. The original length of the spring (x) was measured when the elastic value (F) was 0, 0.95, 3.25, and 6.50 N according to the formula $F=k\cdot\Delta x$, where k is elastic coefficient. Data are shown in Table 1.



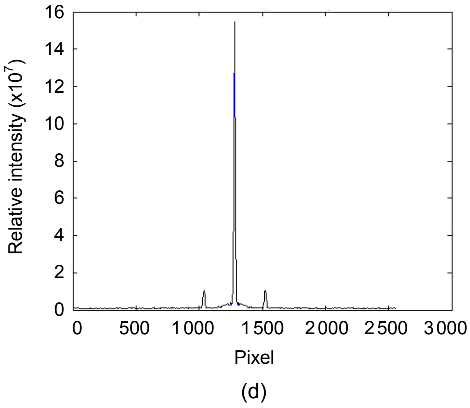


Fig. 2 Procedure of digital laser speckle (DLS) technique
(a) Overlying of two speckle patterns before and after loading by MATLAB; (b) Through one-step fast Fourier before transform, young fringes were formed; (c) The second-step fast Fourier transform achieved fringes diffraction spots (the direction of the spots implied displacement direction); (d) Spectrum two-dimensional curve was generated by two-step fast Fourier (the single peak in the spectral domain resolved the displacement vector)

Table 1 Coefficients of the springs

No.	Original length (mm)	Elastic coefficient (N/m)	Elastic value (N)
1	3.95	1.0×10^3	0.95
2	6.25	1.0×10^3	3.25
3	6.25	2.0×10^3	6.50

2.4 Loading test

Firstly, a die stone foundation was made, the CFPD of which was straight when viewed from the horizontal direction. Then the animal model of the CFPD was fixed on the loading devices, and the light path of the DLS was adjusted (Fig. 1) to attain a real-time and clear picture in the conjoint computer. After that, an axial loading of 200, 500, 1500, and 3000 g was respectively exerted on the central fossa of the pontic, the abutments near to the pontic, and the abutments far from the pontic. Meanwhile, the CCDs' pictures were taken, and the conjoint computer analyzed the speckle grams exposed before and after the loadings. Finally, the software MATLAB and the relevant programs were used for calculating the three-dimensional displacements of the pontic and the abutments. The measurement of the pontic or the abutments was repeated three times, and the average value of the displacements was achieved. It might also be noted that the X-axis was in the mesiodistal direction (distal direction was minus; mesial direction was plus), the Y-axis was in the occlusogingival direction (occlusal direction was minus; gingival direction was plus), and the Z-axis was in the buccolingual direction (buccal direction was plus; lingual direction was minus).

3 Results

The displacement of CFPD increases with the increasing of loads, but the displacements' variation trend of implant-supported CFPD remains unchanged (Fig. 3).

When an axial concentrated loading was exerted on the abutment, the displacement tends to the mesial, buccal, and gingival directions. When an axial concentrated loading was exerted on the pontic, the displacement tends to the distal, buccal, and gingival directions. When the contact tightness was 0, 0.95, and 3.25 N, the displacement of the buccolingual direction was smaller than that of the mesiodistal direction but greater than that of the occlusogingival direction. After the force reached 6.50 N, the displacements' variation trend changed. The mesiodistal displacement of the prosthesis was the biggest while the buccolingual displacement was the smallest. The displacement decreased dramatically when the contact value changed from 0.95 to 3.25 N, which means 3.25 N is the most appropriate force value.

4 Discussion

The aim of this study was to investigate the effect of proximal contact strength on the three-dimensional displacements of implant-supported CFPD with the DLS technique.

One characteristic of this study was the introduction of the DLS technique. The DLS technique, which is developed on the basis of the laser

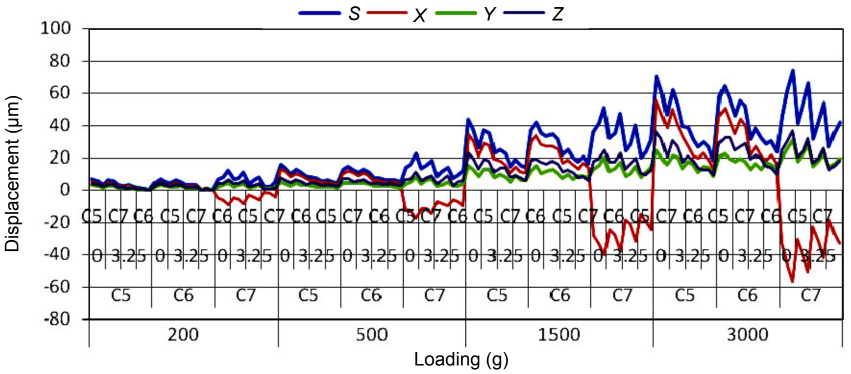


Fig. 3 Three-dimensional displacements of implant-supported CFPDs under different loading and proximal contact strengths

C5: abutments far from the pontic; C6: abutments near to the pontic; C7: pontic. X-axis was in the mesiodistal direction (distal direction was minus; mesial direction was plus); Y-axis was in the occlusogingival direction (occlusal direction was minus; gingival direction was plus); Z-axis was in the buccolingual direction (buccal direction was plus; lingual direction was minus); S was the total displacement holography method, applies a CCD to get objective images immediately before and after the loadings. It is more accurate than manual calculation. The DLS technique is an up-to-date technique of phonology which can be performed under atrocious conditions. As compared with holographic interferometry (Zhang *et al*., 2007), the DLS technique has more advantages, such as high accuracy, real time, ease of operation, and time-savings. Compared with the finite element method (Wang, 2009), DLS overcomes the disadvantages of the finite element method about the simplification and approximation of the subject's geometry and mechanical properties, and avoids error and effect of the experimental results.

It must be assumed that the sustained external force applied to the teeth led to periodontal tissue creep. The elastic recovery of periodontal tissue, which is crucial to the measurement of denture displacement, was incomplete (Parfitt, 1960). Thus, a further significant effect that could be demonstrated with the DLS technique is the fact that it can observe whether the elasticity and stability of the abutment periodontal membrane are fully recovered after loading in time through the comparative analysis of the two speckle images in different periods. Therefore, the DLS technique guarantees that the abutments are in the same physiological condition, which increases the comparability and reproducibility of the experimental results.

As for the results of the experiment, when an axial concentrated loading was exerted on the pontic of the implant-supported CFPD, the displacement of the CFPD was greatest. Stress concentration usually exists in the connector of the CFPD, which is consistent with the findings of most scholars (Wang *et al.*, 1998; Romeed *et al.*, 2004). So it is advisable for clinicians to pay attention to the design of the connector of the abutment near to the pontic. Manda *et al.* (2010) reported that the connector with the highest risk of failure is the 3-mm connector distal to the retaining abutment. The forces transmitted through the cantilevered pontic could cause tilting and rotational movements of the abutments. Therefore, it is reasonable for clinicians to avoid premature contact, especially premature contact of the pontic when the CFPD is used. Huang *et al.* (2011) revealed that both loading type and implant position were crucial for the stress distribution in bone.

About the selection of loads, Chorres *et al.* (2005) chose 100 g in their experiment. Some researchers chose 500, 1000, or 3000 g to conduct their experiment (Chen *et al.*, 1995; Çehreli and Iplikçioglu, 2002; Sevimay *et al.*, 2005). According to these references, dynamic loads of 100, 150, 200, 300, 500, 1000, 1500, 2000, 2500, 3000, 3500, and 4000 g were exerted on the models in this experiment. However, we found that the young fringes were too sparse when the load was lower than 200 g and too compact when the load was greater than 3000 g. For this reason four representative loads (200, 500, 1500, and 3000 g) were selected in the experiment. Under these loads, the interference fringes were clear and stable.

Another characteristic of this study was the introduction of the effect of proximal contact strength on the three-dimensional displacements of implant-supported CFPD. It is important to clinical research to some extent. The displacement of implant-supported CFPD, which is crucial to implant success and periodontal tissue health, decreased after the restoration of the proximal contact area. However, the displacements' variation trend of implant-supported CFPD remains unchanged and is characterized by the displacement of the buccolingual direction which was smaller than that of the mesiodistal direction but greater than that of the occlusogingival direction when the contact tightness was 0, 0.95, and 3.25 N. The proximal contact area has little effect on the displacement of CFPD under small loads (200 and 500 g). With increasing loads (1500 and 3000 g), the function of the proximal contact area increased. The displacement decreased dramatically when the contact value changed from 0.95 to 3.25 N and the total displacement of the CFPD was reduced to less than 50 μm, but after the contact value reached 6.50 N, no mesial and buccal displacements were detected under small loads (200 and 500 g). The displacements' variation trend of the implant-supported CFPD changed, and the mesiodistal displacement of the prosthesis was the biggest while the buccolingual displacement was the smallest under large loads (1500 and 3000 g). At this level of contact strength, the normal mobility of implants was restricted under small loads and the movement tendency was changed under large loads, which means the contact value of 6.50 N was too tight. Dörfer *et al.* (2000) had found the contact strength between the first and second premolars to be

(3.48±1.80) N, greater than the range of the force that will cause irreversible damage of periodontal tissue. In conclusion, the most appropriate contact force value is 3.25 N.

The implant-supported CFPD model was established on the mandible of a beagle dog in this study. Many scholars at home and abroad have chosen the beagle dog to fabricate FPD models (Arısan *et al*., 2010; Coelho *et al*., 2010a; 2010b). Andersen and Good (1970) contended that the histomorphology of the mandible and alveolar bones of beagle dogs was similar to that of humans. The strain condition of teeth and alveolar bone after loading was also similar to that of humans. In addition, many researchers select the beagle dog as an animal model to study the biomechanical behavior of teeth and alveolar bone after loading. Combined with the research of Dörfer *et al*. (2000), we draw the conclusion that 3.25 N is also applicable in humans.

The experiment was carried out under static vertically concentrated loading. The implant suffers from different kinds of non-axial loading during chewing; however, there is no animal model that could precisely simulate the masticatory behavior. Therefore, further research about the influence of non-axial loading during chewing on implants is still required.

5 Conclusions

An in vitro study was constructed to investigate the effect of contact strength on three-dimensional displacement of the implant-supported CFPD by means of DLS technique. Within the limitations of this study, the following conclusions were drawn:

1. DLS technique successfully measured the three-dimensional displacement and was illustrated as a fast, effective, and safe method.

2. Recovering contact reduced the displacement of implants, mainly in the mesial and buccal parts.

3. It is advisable for clinicians to avoid premature contact, especially premature contact of the pontic.

4. Contact should be recovered to a proper strength which can effectively reduce the movement without changing the displacement distribution regularity.

Acknowledgements

We sincerely thank Associate Professor Yi LIU (University of Electronic Science and Technology of China) for his expert technical assistance in the loading test for this study.

Compliance with ethics guidelines

Zhen-zhen PENG, Xin-min CHEN, Jun WANG, Ai-jie LI, and Zu-jie XU declare that they have no conflict of interest.

All institutional and national guidelines for the care and use of laboratory animals were followed.

References

Adell, R., Lekholm, U., Rockler, B., Brånemark, P.I., 1981. A 15-year study of osseointegrated implants in the treatment of the edentulous jaw. *Int. J. Oral Surg.*, **10**(6):387-416. [doi:10.1016/S0300-9785(81)80077-4]

Adell, R., Eriksson, B., Lekholm, U., Brånemark, P.I., Jemt, T., 1990. Long-term follow-up study of osseointegrated implants in the treatment of totally edentulous jaws. *Int. J. Oral Maxillofac. Implants*, **5**(4):347-359.

Aglietta, M., Siciliano, V.I., Zwahlen, M., Brägger, U., Pjetursson, B.E., Lang, N.P., Salvi, G.E., 2009. A systematic review of the survival and complication rates of implant supported fixed dental prostheses with cantilever extensions after an observation period of at least 5 years. *Clin. Oral Implants Res.*, **20**(5):441-451. [doi:10.1111/j.1600-0501.2009.01706.x]

Andersen, A.C., Good, L.S., 1970. The beagle as an experimental dog. *Science*, **170**(3959):723. [doi:10.1126/science.170.3959.723]

Arısan, V., Anıl, A., Wolke, J.G., Özer, K., 2010. The effect of injectable calcium phosphate cement on bone anchorage of titanium implants: an experimental feasibility study in dogs. *Int. J. Oral Maxillofac. Surg.*, **39**(5):463-468. [doi:10.1016/j.ijom.2010.01.004]

Batista, L.R., Muramatsu, M., Campos, T.N., 2003. Stress analysis of fresh, fixed and macerated dog mandibles—holographic interferometric double exposition method. *Proc. SPIE*, **4829**:1012-1013. [doi:10.1117/12.530479]

Becker, C.M., 2004. Cantilever fixed prostheses utilizing dental implants: a 10-year retrospective analysis. *Quintessence Int.*, **35**(6):437-441.

Becker, C.M., Kaiser, D.A., 2000. Implant-retained cantilever fixed prosthesis: where and when. *J. Prosthet. Dent.*, **84**(4):432-435. [doi:10.1067/mpr.2000.110259]

Branemark, P.I., Zarb, G.A., Albrektsson,, T., Rosen, H.M., 1986. Tissue-integrated prostheses. osseointegration in clinical dentistry. *Plastic Reconstruc. Surg.*, **77**(3): 496-497.

Campos, T.N., Adachi, L.K., Chorres, J.E., Campos, A.C., Muramatsu, M., Gioso, M.A., 2006. Holographic interferometry method for assessment of static load stress distribution in dog mandible. *Brazilian Dent. J.*, **17**(4): 279-284. [doi:10.1590/S0103-64402006000400003]

Çehreli, M.C., Iplikçioglu, H., 2002. In vitro strain gauge analysis of axial and off-axial loading on implant supported fixed partial dentures. *Implant Dent.*, **11**(3): 286-292.

Chen, F., Brown, G.M., Song, M., 2000. Overview of three-dimensional shape measurement using optical methods. *Opt. Eng.*, **39**(1):10-22. [doi:10.1117/1.602438]

Chen, T.Y., Chang, G.L., Wu, S.H., 1995. Holographic evaluation of the marginal fits of complete crowns loaded at the central fossa. *Opt. Eng.*, **34**(5):1364-1368. [doi:10.1117/12.199877]

Chorres, J.E., Uono, C., Gioso, M.A., Batista, L., Muramatsu, M., Campos, T.N., 2005. Qualitative analysis of stress distribution in tooth-implant and implant-supported prosthesis by means of holography interferometry method. *RPG Rev. Pos. Grad.*, **12**(4):412-416.

Coelho, P.G., Granato, R., Marin, C., Bonfante, E.A., Janal, M.N., Suzuki, M., 2010a. Biomechanical and bone histomorphologic evaluation of four surfaces on plateau root form implants: an experimental study in dogs. *Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod.*, **109**(5):e39-e45. [doi:10.1002/jbm.b.31298]

Coelho, P.G., Marin, C., Granato, R., Bonfante, E.A., Lima, C.P., Suzuki, M., 2010b. Surface treatment at the cervical region and its effect on bone maintenance after immediate implantation: an experimental study in dogs. *Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod.*, **110**(2): 182-187. [doi:10.1016/j.tripleo.2010.01.027]

Dörfer, C.E., von Bethlenfalvy, E.R., Staehle, H.J., Pioch, T., 2000. Factors influencing proximal dental contact strengths. *Eur. J. Oral Sci.*, **108**(5):368-377. [doi:10.1034/j.1600-0722.2000.108005368.x]

Eskitascioglu, G., Usumez, A., Sevimay, M., Soykan, E., Unsal, E., 2004. The influence of occlusal loading location on stresses transferred to implant-supported prostheses and supporting bone: a three-dimensional finite element study. *J. Prosthet. Dent.*, **91**(2):144-150. [doi:10.1016/j.prosdent.2003.10.018]

Esposito, M., Hirsch, J., Lekholm, U., Thomsen, P., 1998. Biological factors contributing to failures of osseointegrated oral implants. (I) Success criteria and epidemiology. *Eur. J. Oral. Sci.*, **106**(1):527-551. [doi: 10.1046/j.0909-8836..t01-2-.x]

Huang, C.C., Lan, T.H., Lee, H.E., Wang, C.H., 2011. The biomechanical analysis of relative position between implant and alveolar bone: finite element method. *J. Periodontol.*, **82**(3):489-496. [doi:10.1902/jop.2010.100388]

Kohavi, D., 1993. Complications in the tissue integrated prostheses components: clinical and mechanical evaluation. *J. Oral Rehabil.*, **20**(4):413-422. [doi:10.1111/j.1365-2842.1993.tb01625.x]

Manda, M., Galanis, C., Georgiopoulos, V., Provatidis, C., Koidis, P., 2010. Effect of varying the vertical dimension of connectors of cantilever cross-arch fixed dental prostheses in patients with severely reduced osseous support: a three-dimensional finite element analysis. *J. Prosthet. Dent.*, **103**(2):91-100. [doi:10.1016/S0022-3913(10)60012-1]

Parfitt, G.J., 1960. Measurement of the physiological mobility of individual teeth in an axial direction. *J. Dent. Res.*, **39**(3):608-618. [doi:10.1177/00220345600390032201]

Romeed, S., Fok, S., Wilson, N.H.F., 2004. Finite element analysis of fixed partial denture replacement. *J. Oral Rehabil.*, **31**(12):1208-1217. [doi:10.1111/j.1365-2842.2004.01354.x]

Salvi, G.E., Brägger, U., 2009. Mechanical and technical risks in implant therapy. *Int. J. Oral Maxillofac. Implants*, **24**(Suppl):69-85.

Sevimay, M., Turhan, F., Kiliçarslan, M.A., Eskitascioglu, G., 2005. Three-dimensional finite element analysis of the effect of different bone quality on stress distribution in an implant-supported crown. *J. Prosthet. Dent.*, **93**(3): 227-234. [doi:10.1016/j.prosdent.2004.12.019]

van Leeuwen, E.J., Maltha, J.C., Kuijpers-Jagtman, A.M., van't Hof, M.A., 2003. The effect of retention on orthodontic relapse after the use of small continuous or discontinuous forces. An experimental study in beagle dogs. *Eur. J. Oral Sci.*, **111**(2):111-116. [doi:10.1034/j.1600-0722.2003.00024.x]

Wang, C.H., Lee, H.E., Wang, C.C., Chang, H.P., 1998. Methods to improve a periodontally involved terminal abutment of a cantilever fixed partial denture—a finite element stress analysis. *J. Oral Rehabil.*, **25**(4):253-257. [doi:10.1111/j.1365-2842.1998.00234.x]

Wang, Q., 2009. Stress distribution of rigid fixed bridge in abutments with mandibular 56 deletion—a three-dimensional finite element analysis. *J. Clin. Rehabil. Tissue Eng. Res.*, **13**(17):3361-3364 (in Chinese). [doi:10.3969/j.issn.1673-8225.2009.17.035]

Weinberg, L.A., 1993. The biomechanics of force distribution in implant-supported prostheses. *Int. J. Oral Maxillofac. Implants*, **8**:19.

Xu, Z.J., Chen, X.M., Li, A.J., Chen, Y., Peng, Z.Z., Wang, J., 2013. Measuring three-dimensional displacement of tooth-supported rigid fixed bridge under oblique concentrated loading using digital laser speckle photograph. *J. Sichuan Univ. (Med. Sci. Ed.)*, **44**(1): 99-103 (in Chinese).

Zhang, Y.Z., Zhou, Y.C., Liu, L., Lu, Y., Hirofumi, Y., 2007. Stabilization of an abutment under a rigidly fixed bridge by holographical-speckle interferometry. *J. Zhejiang Univ.-Sci. B*, **8**(6):416-421. [doi:10.1631/jzus.2007.B0416]

Zurdo, J., Romao, C., Wennström, J.L., 2009. Survival and complication rates of implant-supported fixed partial dentures with cantilevers: a systematic review. *Clin. Oral Implants Res.*, **20**(s4):59-66. [doi:10.1111/j.1600-0501.2009.01773.x]