Effect of alternative framework designs on stresses in zirconia-ceramic dental crowns

Liliana Porojan, Florin Topală, Sorin Porojan, Cristina Savencu

Abstract**—**Advances in CAD/CAM technology have enabled the dental applications of zirconia ceramics, which become increasingly popular as frameworks of dental prosthetic restorations. Because the strength of all-ceramic restorations depends not only on the fracture resistance of the material, but also on a suitable design and adequate material thickness, the objective of this study was to provide alternative framework designs of zirconia-ceramic crowns. Three different framework designs were found to be possible to create using the soft of the CAD/CAM system. The framework design modifications have been suggested by the soft, in order to improve strength by providing support to veneering porcelain and also to improve aesthetics without compromising strength. The finite element analysis (FEA) was used to understand and predict the biomechanical behavior of the prosthetic restored teeth, related to the shape of the zirconia substructure. Based on computational methods, different framework designs for zirconia-ceramic crowns can be chosen in order to provide adequate support for the veneering material. Recent advances in CAD/CAM technology and simulation platforms offer a wide range of tools to investigators, the decision to provide an adequate individual design during modeling and simulation involves interdisciplinary and skilled developers.

Keywords**—**zirconia-ceramic crown, CAD/CAM, framework design, FEA.

I. Introduction

ADVANCES in CAD/CAM technology have enabled the dental applications of zirconia ceramics, which become increasingly popular because of the excellent esthetics of anterior and posterior teeth. Recently, yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) have been introduced to the dental professionals. These materials have to be fabricated in CAD/CAM (Computer- Aided Design/ Computer-Aided Manufacturing) procedures. The partially stabilized zirconia shows high fracture strength and structural reliability when fabricated into prostheses framework. However, due to their low translucency of the light, all zirconia frameworks have to be veneered with glass-ceramics aesthetic reasons [1].

In its specific form of "yttria-stabilized zirconia polycrystal (Y-TZP)", zirconia is a high-strength ceramic. The much higher mechanical performances of this material (flexure strength, fracture toughness) compared to most of the other metal-free materials, make framework bulk fractures quite unlikely [2, 3]. On the other hand, a major concern is the chipping of the aesthetic ceramic veneer, showing a high incidence, as demonstrated by the majority of clinical trials and systematic reviews [4-12]. The problem is specific to the bilayer nature of these restorations, and is multifactorial. To date, many factors have been reported to be related to the prosthetic complications in zirconia restorations: pressing and structural defects of the frameworks, grinding damages, improper cooling rates, not compatible coefficients of Thermal Expansion, incorrect surface treatment procedures, wrong framework design and thickness, type of finishing margins, incorrect luting procedures, material aging [13-15].

The framework design is an important factor, which can significantly influence the mechanical performance of all the bilayered restorations, like the zirconia–ceramic ones [16]. An improperly modeled coping substructure, in fact, can lead to a sensible increase of the failure rates, strongly conditioning the fracture modes of final restorations [17-22]. The relevance of the framework design for porcelain veneer restoration has been addressed in various studies. According to different studies, the chipping of the veneering ceramics is strongly related to the shape of the zirconia substructure. Other authors speculated that if the ceramic structure is adequately supported, reducing also the thickness of the veneering porcelain, the damage could be fairly limited [1,23,24].

Regarding the preparation guidelines and design parameters there are no defined limits. A minimum thickness of 0.4 mm, respective 0.5 mm is recommended for Y-TZP ceramic crown frameworks in the anterior or posterior region.

In principle, tooth preparation for zirconia-ceramic crown restorations with conventional Y-TZP frameworks requires a shoulder finish line with rounded internal angles. However, a light chamfer can also be prepared. This would allow less reduction for tooth preparation and help to preserve the tooth structure without damaging the remaining pulp in vital teeth, which is preferable in terms of the minimal intervention concept [25]. The slight chamfer, pronounced deep chamfer, and beveled shoulder preparations did not differ significantly with regard to breaking load. This could be attributed to the adequate strength attained with preparation designs that require minimal removal of sound tooth structure, such as

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slight chamfer preparation. In light of this result, consideration should be given to these designs from a prophylactic point of view with emphasis on conserving tooth structure and preventing preparation trauma. The strength of an all-ceramic restoration depends not only on the fracture resistance of the material, but also on a suitable preparation design with adequate material thickness. The assumption that increased material thickness automatically produces greater strength was disproved by different studies [26].

Nowadays, frameworks for all-ceramic crown design by CAD/CAM have been based upon empirical machine guidelines rather than clinical scientific data. Most of all CAD/CAM systems, the frameworks of the crowns are design to arbitrary thicknesses of 0.4 to 0.6 mm [27]. This is leading to non-uniform thicknesses of veneering porcelains. Like porcelain fused to metal restorations, zirconia frameworks should be designed to provide the appropriate veneering porcelain thickness and support to minimize internal stress, reduce mechanical failures, and optimize aesthetics of the veneering porcelains [28].

Stress analysis is a useful tool for predicting the physical responses restored teeth, for example, the most likely fracture location. Much has been reported on the magnitude and distribution of stress associated with various types of restorations [29-30]. Simulation-based medicine and the development of complex computer models of biological structures is becoming ubiquitous for advancing biomedical engineering and clinical research. Finite element analysis (FEA) has been widely used in the last few decades to understand and predict biomechanical phenomena [31].

II. Purpose

The objective of this study was to provide alternative framework designs of molar zirconia-ceramic crowns and to predict the biomechanical behavior of the prosthetic restored teeth using finite element analysis.

III. Materials and Method

A plaster die was replicated from a plastic maxillary right first molar prepared for all ceramic crowns. A chamfer finishing line, an occlusal convergence angle of 6° were chosen for the preparation, anatomical occlusal reduction, and the palatal surface of the functional cusp was reduced in two planes. The master die was scanned using the Cercon Eye scanner (Degudent, Hanau, Germany). Scanned data were computed (Fig. 1) and then designed for all-ceramic crown framework using the Cercon Art 3.2 software (Degudent, Hanau, Germany).

Three different framework designs were found to be possible to create using the soft of the system.

First, a uniform thickness of 0.5 mm was chosen for the framework (Fig. 2).

Second, a cutback design was prepared as same as for metal-ceramic crowns in order to obtain uniform, adequate thickness and support for the veneering ceramics (Fig. 3).

Third, a reduction of the framework was made only in the buccal area, in order to achieve aesthetics (Fig. 4).

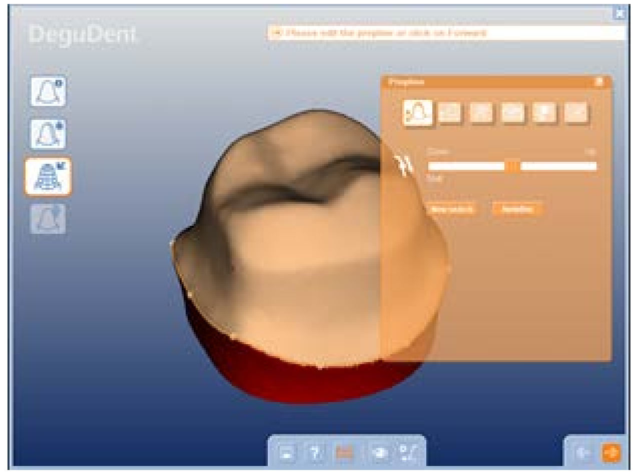

Fig. 1. Virtual model of the die

Fig. 2. Design of a standard form framework (uniform thickness of 0.5 mm)

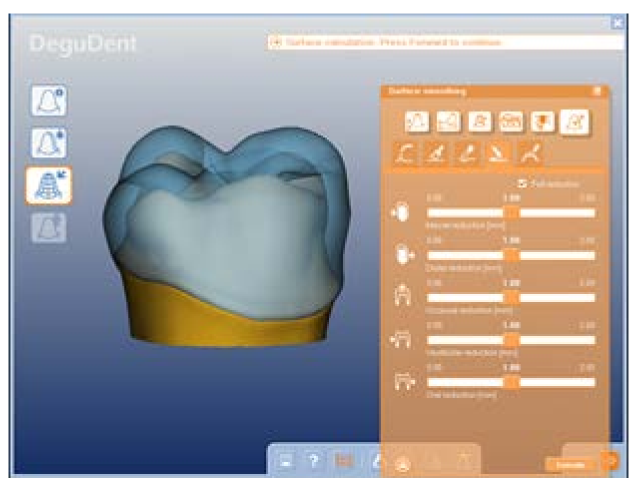

Fig. 3. Design of a framework with full uniform reduction (1 mm) from the full anatomic contour

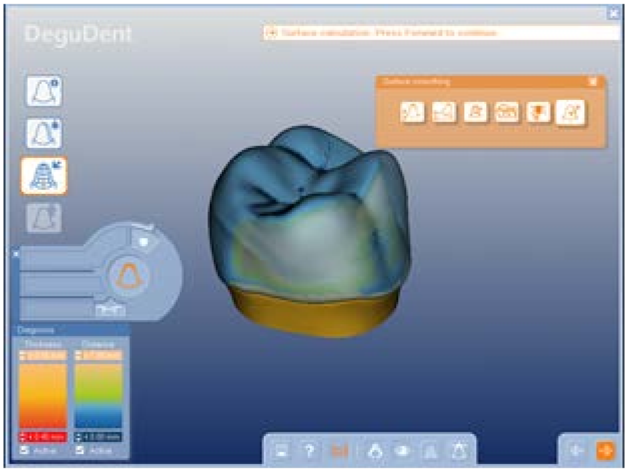

Fig. 4. Design of a framework with buccal uniform reduction (1 mm) from the full anatomic contour

On the other hand a nonparametric modeling software (Blender 2.57b) was used to obtain the 3D tooth shape (Fig. 5-8). At first the external surface was finished. The collected data were used to construct three dimensional models using Rhinoceros (McNeel North America) NURBS (Nonuniform Rational B-Splines) modeling program. In order to obtain a 3D solid model of the tooth, a surface following the cervical line was achieved, to close the surfaces.

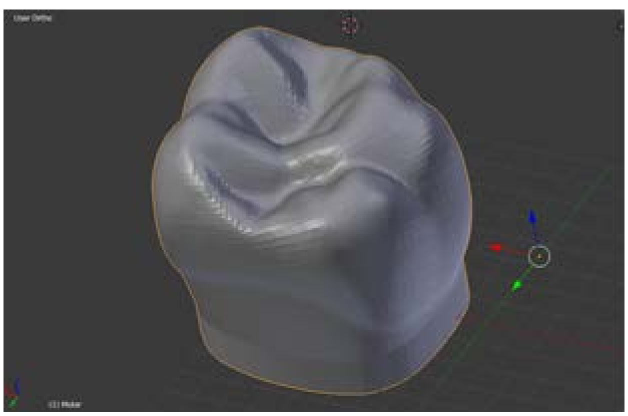

Fig. 5. Surface finishing for the molar

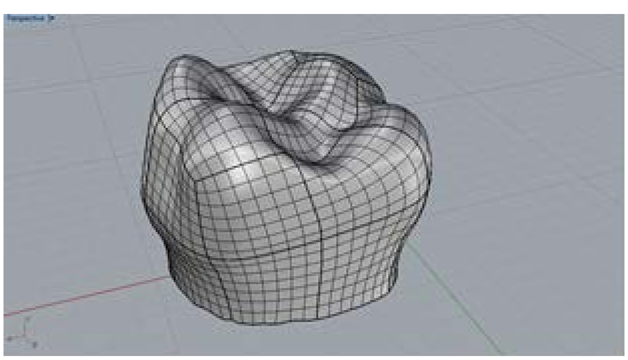

Fig. 6. NURBS surfaces modeled in Blender

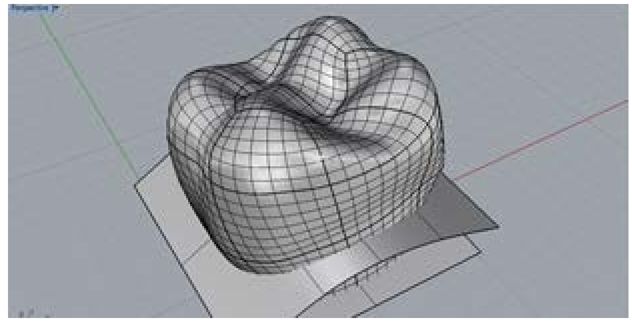

Fig. 7. Modeling of the cervical surface

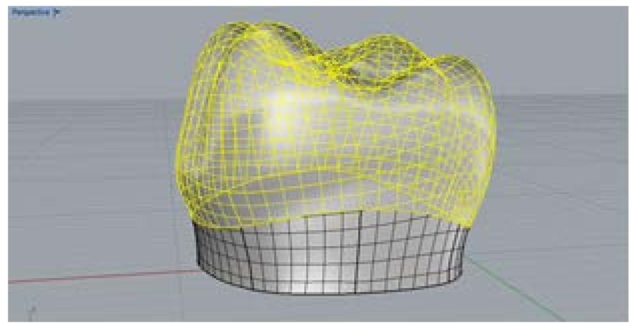

Fig. 8. 3D solid model of the molar

From the anatomic contour of the crown, the prepared tooth prepared for all-ceramic crowns was modeled (Fig. 9).

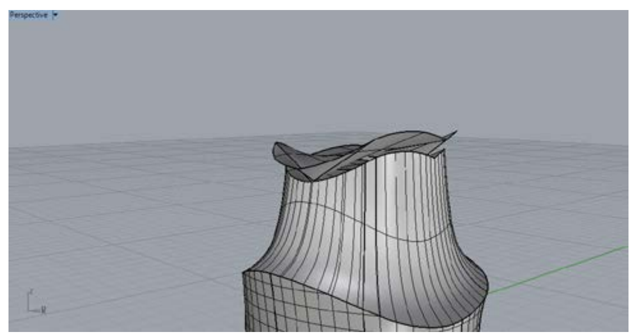

Fig. 9. 3D model of a molar prepared for all-ceramic crowns

Beginning from this model, the three different framework designs suggested by the CAD/CAM system were 3D modeled (fig. 10-12).

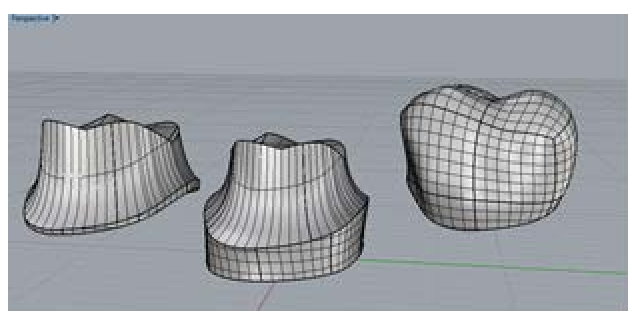

Fig. 10. 3D models of the prepared tooth, framework with uniform thickness of 0.5 mm, and properly veneer

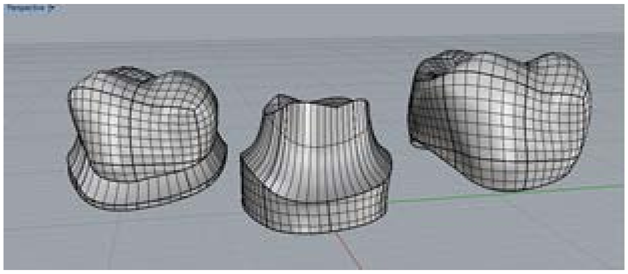

Fig. 11. 3D models of the prepared tooth, framework with total cutback design, and veneer with uniform thickness

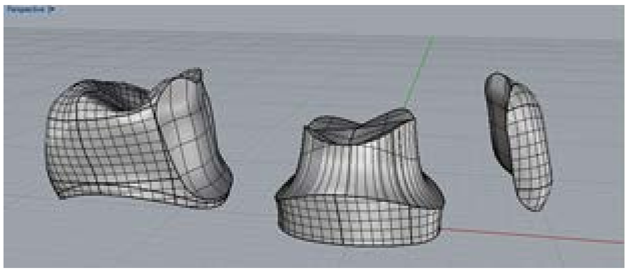

Fig. 12. 3D models of the prepared tooth, framework with buccal cutback design, and partial veneer with uniform thickness

For all cases a digital model of the bilayer crown was designed to occupy the space between the original tooth form and the prepared tooth form.

The geometric models were imported in the finite element analysis software ANSYS (Fig. 16) and meshed (Fig. 17). 47205 respective 55434 and 43085 tetrahedral elements were generated for each model, connected in 80720 nodes for the first model and in 93924 and 72002 nodes for the second and third one. Finite element calculations were carried out.

In order to simulate the influence of different framework designs, the Young's module and Poisson's ratios were introduced: Young's modulus (GPa) 18 for dentin, 64 for veneering ceramics, and 205 for zirconia and Poisson's ratio 0.27 for dentin, 0.21 for veneering ceramics, and 0.31 for zirconia.

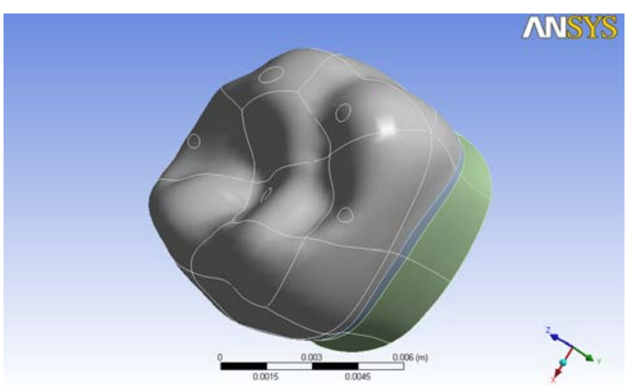

Fig. 16. Geometric model imported in the FEA software

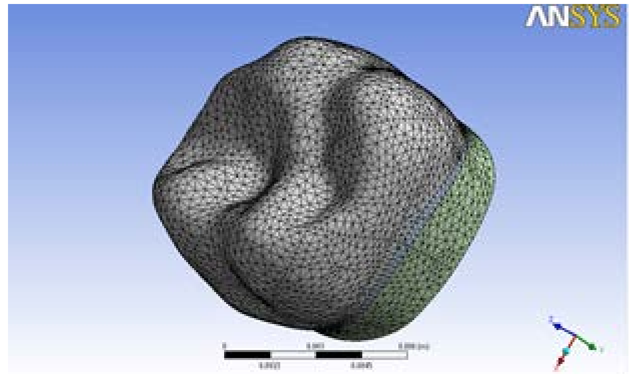

Fig. 17. Mesh structure of the model

To simulate physiological mastication behavior five loading areas were defined on the occlusal surface. Each defined loading area had a diameter of 0.5 mm. A total force of 250 N was allocated to these areas as pressure load normal to the surfaces in each point (Fig. 18). The bottom of the abutment teeth model was fully constrained for all simulations. A static structural analysis was performed to calculate the stress distribution for different designs using the computer-aided engineering software.

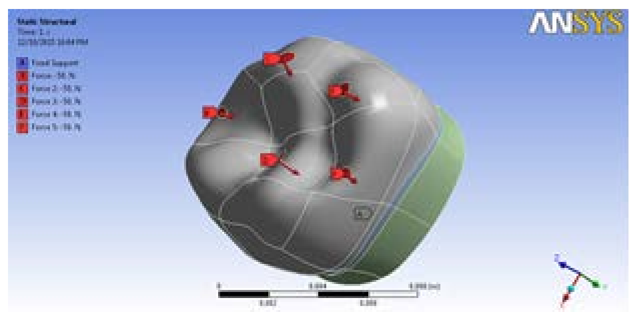

Fig. 18. Surfaces selected for loading.

IV. Results and Discussions

Three framework design modifications have been suggested by the soft (Degudent, Hanau, Germany), in order to improve strength by providing support to veneering porcelain and also to improve aesthetics without compromising strength (Fig. 19-21).

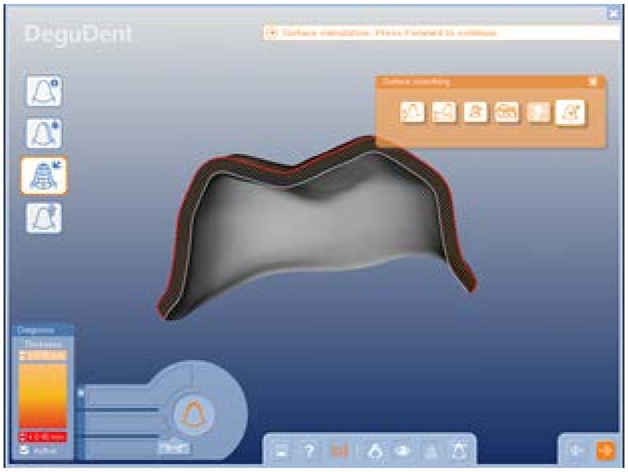

Fig. 19. Design of the framework with uniform thickness

Fig. 20. Design of the framework with anatomical contour

Fig. 21. Design of the framework with buccal reduction

Using FEA maximal equivalent stresses were recorded in the tooth structures and in the restoration for all these designs (Table 1, Fig. 22-24).

Table 1. Maximal Von Mises equivalent stress values in the teeth and restorations.

Compound	Max. equivalent stress in model 1[Pa]	Max. equivalent stress in model 2 [Pa]	Max. equivalent stress in model 3 [Pa]
dentin	1.70E+07	1.86E+07	1.85E+07
zirconia	4.78E+07	1.10E+08	2.26E+08
veneering ceramics	2.07E+08	2.04E+08	3.83E+06

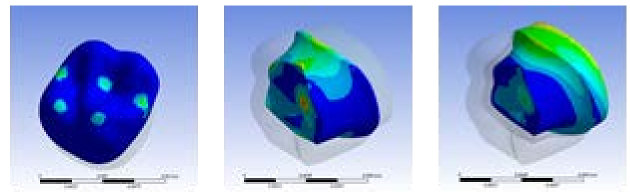

Fig. 22. Von Mises Stress distribution in the veneer, zirconia framework and dentin for the design with uniform framework thickness

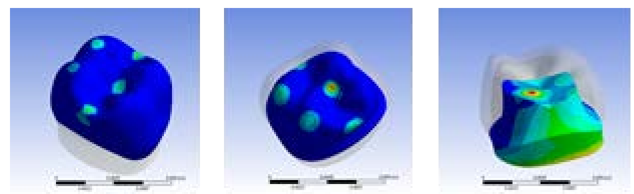

Fig. 23. Von Mises Stress distribution in the veneer, zirconia framework and dentin for the design with uniform veneer thickness

Fig. 24. Von Mises Stress distribution in the veneer, zirconia framework and dentin for the design with buccal veneer

For the first two cases the values were higher in the veneers. There stresses were distributed around the contact areas with the antagonists. The values of the maximal equivalent stress in the frameworks were higher for cutback design, but it have to be correlated also with the higher thickness. On the other hand the values and location of the maximal stresses represent areas of weakness and starting points for crack propagation. For the model with buccal veneer of the framework, maximal stress values are higher in the framework than for the other cases, but in the veneer are recorded the lowest stress values. The maximal stress values in the dentin are similar regardless of the restoration type.

The individual design of a crown will, of course, influence the stability and the longevity of the final dental restoration. Especially an anatomically reduced crown framework possesses, in comparison to a simple coping design, several advantages [32]. Anatomic core design modification significantly increased the reliability and resulted in reduced chip size of either veneering techniques [33]. Anatomically guided zirconia frames resisted significantly higher loads than flat and PFM-like frame designs [34]. A cusp supporting framework design can significantly decrease the maximum tensile stresses in the veneering material of single crowns [35]. Different studies showed that one of the reasons for porcelain fracture is improper framework design. This causes the improper support for the porcelain veneer layer and also the nonappropriate thickness of the veneering layer. The modification of the framework design by creating an appropriate support and allowing the proper veneering thickness has been proved to reduce the porcelain chipping rates. Different framework designs have influence on the failure load and failure characteristics of all ceramic zirconia crowns [36].

Deterministic computational methods are widely accepted in ceramic restorations as an important tool used in the design and analysis of all-ceramic crowns and other prostheses [37]. The finite element method (FEM) is the most general and widely accepted technique in this field. Many studies have been performed to determine when stress convergence exists in the loading surfaces and cervical margin of the crown [38].

Modeling and simulation approaches in biomechanics are highly interdisciplinary, involving novice and skilled developers in all areas of biomedical engineering and biology. While recent advances in model development and simulation platforms offer a wide range of tools to investigators, the decision making process during modeling and simulation has become more opaque [39].

V. Conclusion

Within the limitations of the present study because of the multitude of parameters involved in the design, the following conclusions can be drawn:

1. Different framework designs for zirconia-ceramic crowns can be chosen in order to provide adequate support for the veneering material.
2. The cutback design allows the control of the veneering material thickness in order to ensure proper aesthetics, without compromising strength of the veneering material.
3. The finite element analysis (FEA) can be used to understand and predict the biomechanical behavior of the prosthetic restored teeth.
4. Recent advances in CAD/CAM technology and simulation platforms offer a wide range of tools to investigators.
5. The decision to provide an adequate individual design during modeling and simulation involves interdisciplinary and skilled developers.

References

[1] M. Rosentritt, D. Steiger, M. Behr, G. Handel, C. Kolbeck "Influence of substructure design and spacer settings on the in vitro performance of molar zirconia crowns". *J Dent*.;37:978-83, 2009.

[2] MC. Cehreli, AM. Kokat, K.Akca "CAD/CAM zirconia vs.slip-cast glass-infiltrated alumina/zirconia all-ceramic crowns: 2-year results of a randomized controlled clinical trial" *J Appl Oral Sci*;17:49–55, 2009.

[3] Ortorp A, Kihl ML, Carlsson GE. "A 3-year retrospective and clinical follow-up study of zirconia single crowns performed in a private practice" *J Dent* 37:731–6, 2009.

[4] Choi JE, Waddell JN, Torr B, Swain MV. "Pressed ceramics on to zirconia. Part 1: Comparison of crystalline phases present, adhesion to a zirconia system and flexural strength. *Dent Mater* 27:1204–12, 2011.

[5] JE. Choi, JN. Waddell, MV. Swain. "Pressed ceramics ontozirconia. Part 2: Indentation fracture and influence ofcooling rate on residual stresses" *Dent Mater* 27:1111–8, 2011.

[6] K. Nakamura, E. Adolfsson, P. Milleding, T. Kanno, U. Örtengren. "Influence of grain size and veneer firing process on the flexural strength of zirconia ceramics" *Eur J Oral Sci* 120:249–54, 2012.

[7] B. Stawarczyk, M. Ozcan, CH. Hämmerle, M. Roos "Thefracture load and failure types of veneered anterior zirconia crowns: an analysis of normal and Weibull distribution of complete and censored data" *Dent Mater* 28:478–87, 2012.

[8] Y. Zhang, BR. Lawn "Fatigue sensitivity of Y-TZP to microscale sharp-contact flaws" *J Biomed Mater Res B: Appl Biomater* 15(72):388–92, 2005

[9] J. Fischer, P. Grohmann, B. Stawarczyk "Effect of zirconia surface treatments on the shear strength of zirconia/veneering ceramic composites" *Dent Mater J* 27:448–54, 2008.

[10] M. Cattani Lorente, SS. Scherrer, J. Richard, R. Demellayer, M. Amez-Droz, HW. Wiskott "Surface roughness and EDS characterization of a Y-TZP dental ceramic treated with the Co Jet TM Sand" *Dent Mater* 26:1035–42, 2010.

[11] KJ. Anusavice "Standardizing failure, success, and survival decisions in clinical studies of ceramic and metal–ceramic fixed dental prostheses" *Dent Mater* 28:102–11, 2012.

[12] SD. Heintze, V. Rousson "Survival of zirconia- and metal-supported fixed dental prostheses: a systematic review" *Int J Prosthodont* 23:493–502, 2010.

[13] JR. Kelly, I. Denry "Stabilized zirconia as structural ceramic: an overview" *Dent Mater* 24:289–98, 2008.

[14] I. Denry, JR. Kelly "State of the art of zirconia for dental applications" *Dent Mater* 24:299–307, 2008.

[15] M. Ferrari, A. Vichi, F. Zarone "Zirconia abutments and restorations: from laboratory to clinical investigations" *Dent Mater*.31(3):e63-76 , Mar 2015.

[16] NR. Silva, E. Bonfante, BT. Rafferty, RA. Zavanelli, LL. Martins, ED. Rekow, et al. "Conventional and modified veneered zirconia vs. metallo ceramic: fatigue and finite element analysis" *J Prosthodont* 21:433–9, 2012.

[17] Y. Kokubo, M. Tsumita, T. Kano, S. Fukushima "The influence of zirconia coping designs on the fracture load of all-ceramic molar crowns" *Dent Mater J* 30:281–5, 2011.

[18] T. Sornsuwan, A. Ellakwa, MV. Swain "Occlusal geometrical considerations in all-ceramic pre-molar crown failure testing" *Dent Mater* 27:1127–34, 2011.

[19] T. Sornsuwan, MV. Swain "Influence of occlusal geometry on ceramic crown fracture; role of cusp angle and fissure radius" *J Mech Behav Biomed Mater* 4:1057–66, 2011.

[20] PC. Guess, EA. Bonfante, NR. Silva, PG. Coelho, VP. Thompson "Effect of core design and veneering technique on damage and reliability of Y-TZP-supported crowns" *Dent Mater* 29:307–16, 2013.

[21] BT. Rafferty "Biomechanical evaluation of an anatomically correct all-ceramic tooth-crown system configuration: core layer multivariate analysis incorporating clinically relevant variables" *J Biomech Eng* 132:15–9, 2001.

[22] BT. Rafferty, MN. Janal, RA. Zavanelli, NR. Silva, ED. Rekow, VP. Thompson, et al. "Design features of a three-dimensional molar crown and related maximum principal stress. A finite element model study" *Dent Mater* 26:156–63, 2010.

[23] JW. Kim, S. Bhowmick, I. Hermann, BR. Lawn "Transverse fracture of brittle bilayers: relevance to failure of all-ceramic dental crowns" *J Biomed Mater Res B: Appl Biomater* 79:58–65, 2006.

[24] A. Sundah, G. Sjögren "Fracture resistance of all-ceramic zirconia bridges with differing phase stabilizers and quality of sintering" *Dent Mater* 22:778–84, 2006.

[25] S. Omori, W. Komada, K. Yoshida, H. Miura "Effect of thickness of zirconia-ceramic crown frameworks on strength and fracture pattern" *Dent Mater J*. 32(1):189-94, 2013.

[26] F. Beuer, D. Edelhoff, W. Gernet, M. Naumann "Effect of preparation angles on the precision of zirconia crown copings fabricated by CAD/CAM system" *Dent Mater J*. 27(6):814-20, Nov 2008.

[27] PG. Coelho, NR. Silva, EA. Bonfante, PC. Guess, ED. Rekow, VP. Thompson "Fatigue testing of two porcelain-zirconia allceramic crown systems" *Dent Mater*. 25:1122-7, 2009.
[28] BW. Marchack, Y. Futatsuki, CB. Marchack, SN. White "Customization of milled zirconia copings for all-ceramic crowns: a clinical report" *J Prosthet Dent*. 99:169-73, 2008.
[29] P. Oyar, M. Ulusoy, G. Eskitaşçıoğlu "Finite element analysis of stress distribution in ceramic crowns fabricated with different tooth preparation designs" *J Prosthet Dent*. 112(4):871-7 Oct 2014.
[30] S. Shahrbaf, R. van Noort, B. Mirzakouchaki, E. Ghassemieh "Effect of the crown design and interface lute parameters on the stress-state of a machined crown-tooth system: a finite element analysis" *Dent Mater* 29:e123-31, 2013.
[31] A, Erdemir, TM. Guess, J. Halloran, SC. Tadepalli, TM. Morrison "Considerations for reporting finite element analysis studies in biomechanics" *J Biomech*. 23;45(4):625-33 Feb 2012.
[32] S. Cramer von Clausbruch, A. Faust "Advanced crown and bridge design" *Int J Comput Dent*.6(3):293-302 Jul 2003.
[33] PC. Guess, EA. Bonfante, NR. Silva, PG. Coelho, VP. Thompson "Effect of core design and veneering technique on damage and reliability of Y-TZP-supported crowns" *Dent Mater*. 29(3):307-16 Mar 2013.
[34] M. Ferrari, A. Giovannetti, M. Carrabba, G. Bonadeo, C. Rengo, F. Monticelli, A. Vichi "Fracture resistance of three porcelain-layered CAD/CAM zirconia frame designs" *Dent Mater*. 30(7):e163-8 Jul 2014.
[35] A. Kirsten, D. Parkot, S. Raith, H. Fischer "A cusp supporting framework design can decrease critical stresses in veneered molar crowns" *Dent Mater*. 30(3):321-6 Mar 2014.
[36] S. Urapepon, P. Taenguthai "The effect of zirconia framework design on the failure of all-ceramic crown under static loading" *J Adv Prosthodont*. 7(2):146-50 Apr 2015.
[37] N. De Jager, P.Pallav, A.J. Feilzer, "The influence of design parameters on the FEA-determined stress distribution in CAD-CAM produced all-ceramic dental crowns" *Dental Materials* 21,242–251, 2005.
[38] B. Dejak, A. Mlotkowski, M. Romanowicz "Finite element analysis of stresses in molars during clenching and mastication" *The Journal of Prosthetic Dentistry* 90, 591–597, 2003.
[39] A. Erdemir, TM. Guess, J. Halloran, SC. Tadepalli, TM. Morrison "Considerations for reporting finite element analysis studies in biomechanics" *J Biomech*. 23;45(4):625-33, Feb 2012.