EGYPTIAN
DENTAL JOURNAL
www.eda-egypt.org

VOL. 71, 523:532, JANUARY, 2025

PRINT ISSN 0070-9484 • ONLINE ISSN 2090-2360

FIXED PROSTHODONTICS AND DENTAL MATERIALS

Submit Date : 15-06-2024 • Accept Date : 02-10-2024 • Available online: 10-01-2025 • DOI : 10.21608/edj.2024.297791.3082

REGRESSION MODEL ANALYSIS OF MANDIBULAR LOCATOR CAD/CAM-MILLED BAR IMPLANT OVERDENTURE: BIO-SIMULATION FINITE ELEMENT STUDY

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ABSTRACT

Objective: To compare the performances of various materials used in mandibular locator CAD/CAM-milled bar implant overdentures based on biomechanics using finite element analysis and regression modeling.

Materials and Methods: Four materials were analyzed, Titanium Alloy Type IV, Polyether Ether Ketone (PEEK), Cobalt Chromium Alloy Type III, and High Strength Zirconia. A 3D model of an edentulous mandible with four implants was created with Solidworks software. FEA was run to determine von Mises stress, resultant displacement, and equivalent strain using static load study under applied loads from 0 to 200 N. Linear regression analysis was performed to build models to predict equivalent strain.

Results: Maximum resultant displacement and equivalent strain were shown by the PEEK followed by Titanium Alloy Type IV, Cobalt Chromium Alloy Type III, and High Strength Zirconia. Regression analysis showed an excellent linear relationship for all the materials. Thus, regression values can be used to predict equivalent strain.

Conclusion: Material choices greatly affect stress distribution and deformation within implant-supported restorations. While PEEK was more deformable, it may have produced the highest stress on the prosthetic components. Titanium Alloy Type IV and Cobalt Chromium Alloy Type III had the most similar patterns of stress in the supporting bone. High Strength Zirconia demonstrated the least stress on implant assemblies compared to titanium.

KEYWORDS: Bar, PEEK, Titanium, Zirconia, Cobalt-Chrome, Simulation

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INTRODUCTION

Predictable and successful treatment options for implant-supported or implant-retained overdentures have been introduced for rehabilitating edentulous arches by providing higher performance, aesthetics, and residual bone preservation. [1] However, conventional dental implants can cause complications with atrophied mandibular arches. So, the implant/prosthesis system involves placing four implants in the anterior mandibular region between the mental foramina and the material used for constructing this framework plays an essential role in the biomechanical success of the prosthesis. [2]

High tensile strength and elastic modulus of metallic alloys prevent deformation and cantilever fractures. [3] The higher mechanical properties and biocompatibility of titanium have made it the preferred material in dentistry. Nevertheless, there is an aesthetic problem with it because of its metallic grayish color and lack of light transmission that can cause prosthesis discoloration.[4]

Zirconia is a good choice for dental implants and frameworks as it has a natural shade, excellent mechanical properties, biocompatibility, and the same survival rate as metal. [5] Polyether ether ketone (PEEK) is a polymeric material that can be used in prosthetic frameworks advanced with higher esthetics, thermo-mechanical properties, and biocompatibility. [6]

Several methods like photoelastic analysis, strain gauges, and finite element analysis (FEA) are utilized to evaluate stress distribution analysis. An accurate technique of three-dimensional FEA is used to assess the amount and stress distribution in dental structures. [7] It has higher reproducibility, and repeatability and is non-invasive, capable of simulating biological conditions pre-, intra-, and post-operatively. Linear and nonlinear, solid and fluid structural interactions can be simulated and analyzed. [8]

Regression analysis is a statistical method that greatly aids in determining the association of the dependent variable with independent variables. It has been used in dentistry to predict and approximate treatment outcomes for different dental procedures and treatments. [9]

Various forms of regression models such as simple linear regression and multivariate regression were discussed by the authors. Simple linear regression involves having a continuous dependent variable that replaces a continuous or discrete independent variable where you establish a best-fit straight line that relates to these variables on a linear basis. In addition, multivariate regression includes multiple independent variables understanding their relationship with the dependent %. [10]

This study aims to utilize finite element analysis to design models of an implant-supported locator CAD/CAM-milled bar overdenture for edentulous mandibles to develop predictive models relating stress and design parameters.

MATERIALS AND METHODS

Model Design

Using Solidworks 3D mechanical CAD and simulation software (***DS Solidworks Corp, 2024, USA),*** (.sldprt) model of a completely edentulous mandible prepared for four implant insertion with corresponding overdenture, Figure (1). The dental implants were designed as threaded implants with 8 mm in length and 4 mm in diameter (***Tri® Performance Line, Bone Level Matrix Implant***) with 38 mm distance between each two central implants and 20.5 mm distance between central and peripheral implants. The framework was created and standardized as a solid bar following the curvature of the mandibular arch with 8.5 mm in width and 4.8 mm in thickness placed 2 mm away from the crest of the ridge, Figure (2).

According to the type of material, the models were divided into ***Model A;*** Titanium Alloy Type IV, ***Model B;*** Poly Ether Ether Ketone (PEEK), ***Model C;*** Cobalt Chromium Alloy Type III and ***Model D;***

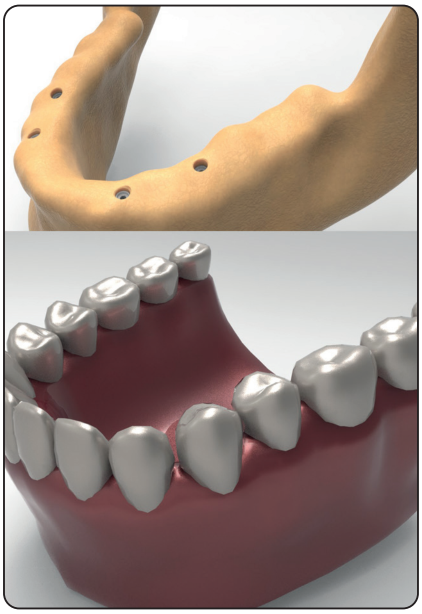

Fig. (1) Solid part model of completely edentulous mandible prepared for four implant insertions with corresponding overdenture.

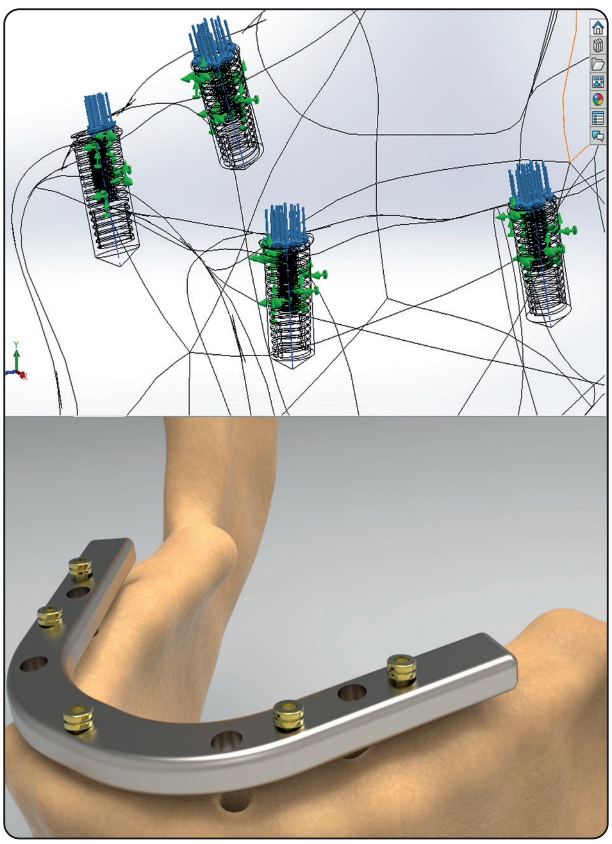

Fig. (2) Model Design of Locator CAD/CAM-Milled Bar Implant Overdenture

High Strength Zirconia with 40 readings for each model during the analysis.

Nodes and Elements

In the present FEA model simulation, the models with total nodes (18500) and total elements (11171) under (310.15) Kelvin zero strain temperature were meshed using a mixed mesh model with linear elastic isotropic model type, Figure (3).

Material Properties

It was assumed that the mandibular bone and the other materials that were simulated in the study were homogenous, isotropic, and linearly elastic. The attributes given to each material utilized in the simulation are displayed in Table (1).

Loads and Fixtures

The model's movements within the 6-degree of freedom were restricted through fixation at predetermined implant positions of the assembly. On the overdenture attached to the bar by locator attachment, axial static stress ranging from zero to 200 newtons was applied with sequential step values of 5 newtons. Following the application of load, the von Mises stress distribution pattern, resultant displacement (mm), and equivalent strain were computed at the bar/implant interface, Figure (4).

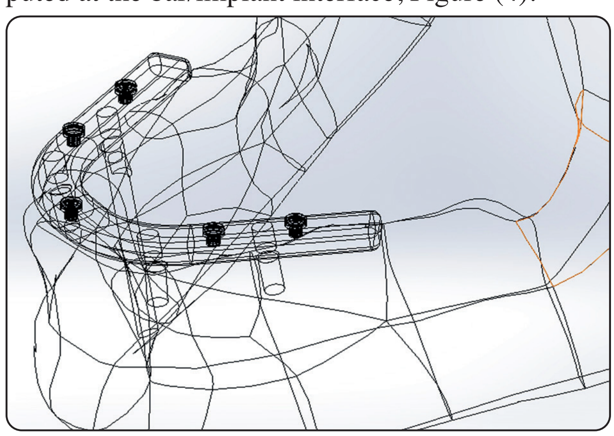

Fig. (3) Mixed mesh model with linear elastic isotropic model type of Locator CAD/CAM-Milled Bar Implant Overdenture

TABLE (1) Material Properties Used for Bar Simulation

	Cortical Bone	**Titanium Alloy Type IV**	**Poly Ether Ether Ketone (PEEK)**	**Cobalt Chromium Alloy Type III**	**High Strength Zirconia**
Model type	Linear Elastic Isotropic				
Default failure criterion	Max von Mises Stress				
Yield strength	151 N/m^2	8.32e+008 N/m^2	1.25e+008 N/m^2	3.2e+008 N/m^2	1.2e+009 N/m^2
Elastic modulus	13.7 N/m^2	1.2e+011 N/m^2	3.81e+009 N/m^2	2.02e+011 N/m^2	2.05e+011 N/m^2
Poisson's ratio	0.3	0.36	0.375	0.28	0.19
Mass density	1.6 kg/m^3	4300 kg/m^3	1300 kg/m^3	8500 kg/m^3	5850 kg/m^3
Commercial Specifications		rematitan® blank Ti5, TiAlV - Dental alloy based on titanium (grade 5)	Techno-polymer polyetheretherketone (Smile PEEK)	remanium® star MD II CoCrW – Dental alloy	DDBioZWiso high strength 3Y-TZP-A

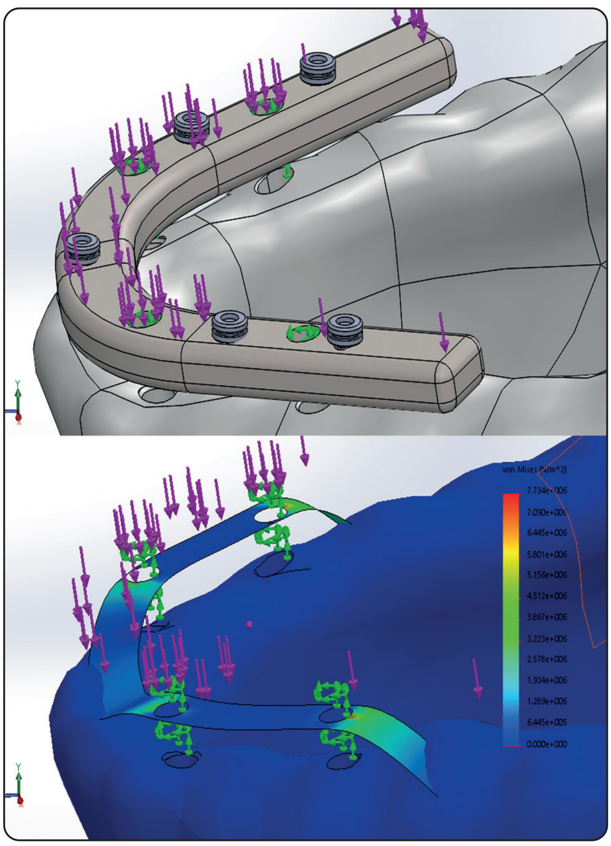

Fig. (4) Loads and Fixtures on Locator CAD/CAM-Milled Bar Implant Overdenture

Statistical Analysis

Von Mises stress, resultant displacement, and equivalent strain for four different materials: Titanium Alloy Type IV, Polyether Ether Ketone (PEEK), Cobalt Chromium Alloy Type III, and High Strength Zirconia were analyzed and evaluated through provided descriptive statistics such as mean, standard deviation, and percentiles. In addition, analysis through linear regression was performed on the equivalent strain using best-fit values, standard errors, confidence intervals, goodness-of-fit measures, and regression equations using (GraphPad Prism, Graphpad Software, Boston, MA 02110).

RESULTS

The CAD/CAM milled bar overdenture used four different materials: Type IV Titanium Alloy, Poly Ether Ether Ketone (PEEK), Type III Cobalt Chromium Alloy, and High Strength Zirconia. There were 40 readings for each material and measure. The highest mean values across all three measures are consistently shown by PEEK, particularly in terms of displacement and strain where it significantly exceeds the others.

Table (2) evaluated the mechanical simulation data of different materials for locator CAD/CAM-milled bar implant overdenture systems under simulated loading conditions. Von Mises stress, measuring the overall stress by the material, the highest maximum values of 76.9 MPa and 77.5 MPa were represented in Titanium Alloy Type IV and Polyether Ether Ketone (PEEK), respectively, which were higher than those observed for Cobalt Chromium Alloy Type III (74.3 MPa) and High Strength Zirconia (72.5 MPa).

TABLE (2) Descriptive Statistics of von Mises Stress, Resultant Displacement and Equivalent Strain for Locator CAD/CAM-Milled Bar Overdenture

	Titanium Alloy Type IV			**Poly Ether Ether Ketone (PEEK)**		
	von Mises Stress N/m²	**Resultant Displacement mm**	**Equivalent Strain**	**von Mises Stress N/m²**	**Resultant Displacement mm**	**Equivalent Strain**
N	40	40	40	40	40	40
Min	1920000	0.0004028	7.500e-006	1940000	0.01263	0.0002347
25% Percentile	19700000	0.004129	7.690e-005	19875000	0.1293	0.002408
Med	39450000	0.008257	0.0001538	39750000	0.2590	0.004810
75% Percentile	59125000	0.01239	0.0002308	59625000	0.3880	0.007220
Max	76900000	0.01611	0.0003002	77500000	0.5051	0.009388
Range	74980000	0.01571	0.0002927	75560000	0.4925	0.009153
M	39426250	0.008257	0.0001538	39692000	0.2586	0.004805
SD	22483552	0.004709	8.774e-005	22589761	0.1471	0.002735
SEM	3554962	0.0007445	1.387e-005	3571755	0.02326	0.0004324
Lower 95% CI	32235661	0.006751	0.0001258	32467444	0.2115	0.003931
Upper 95% CI	46616839	0.009763	0.0001819	46916556	0.3056	0.005680
	Cobalt Chromium Alloy Type III			**High Strength Zirconia**		
	von Mises Stress N/m²	**Resultant Displacement mm**	**Equivalent Strain**	**von Mises Stress N/m²**	**Resultant Displacement mm**	**Equivalent Strain**
N	40	40	40	40	40	40
Min	1860000	0.0002446	4.600e-006	1810000	0.0002460	4.650e-006
25% Percentile	19050000	0.002510	4.715e-005	18550000	0.002520	4.768e-005
Med	38050000	0.005015	9.440e-005	37200000	0.005039	9.540e-005
75% Percentile	57125000	0.007520	0.0001418	55750000	0.007559	0.0001431
Max	74300000	0.009784	0.0001842	72500000	0.009833	0.0001861
Range	72440000	0.009540	0.0001796	70690000	0.009587	0.0001815
M	37934000	0.004996	9.404e-005	37164750	0.005039	9.539e-005
SD	21698017	0.002857	5.379e-005	21194597	0.002874	5.439e-005
SEM	3430758	0.0004518	8.506e-006	3351160	0.0004544	8.600e-006
Lower 95% CI	30994638	0.004083	7.683e-005	30386389	0.004120	7.799e-005
Upper 95% CI	44873362	0.005910	0.0001112	43943111	0.005958	0.0001128

PEEK revealed the highest resultant displacement and equivalent strain value (0.5051 mm, 0.009388), followed by Titanium Alloy Type IV (0.01611 mm, 0.0003002), Cobalt Chromium Alloy Type III (0.009784 mm, 0.0001842), and High Strength Zirconia (0.009833 mm, 0.0001815).

For example, respectively around 0.2586mm and 0.004805 PEEK's resultant mean displacement and equivalent strain were nearly 50 times higher than the other materials; however, the average total displacement for all other materials is about 0.005mm. Also, PEEK's mean equivalent strain (0.004805) is almost 31 times that of the rest. This is not the case as Titanium Alloy, Cobalt Chromium Alloy, and High Strength Zirconia exhibit comparable performance among themselves whereby; Zirconia in general has slightly lower stress, displacement, and strain values.

Linear regression analysis of the equivalent strain results is represented in Table (3). Regarding titanium Alloy Type IV, it has a very strong fit (R-square = 1.000) with a highly significant

TABLE (3) Linear Regression Analysis for Equivalent Strain Results for Titanium Alloy Type IV, Polyether Ether Ketone (PEEK), Cobalt Chromium Alloy Type III and High Strength Zirconia

		Titanium Alloy Type IV	**Poly Ether Ether Ketone (PEEK)**	**Cobalt Chromium Alloy Type III**	**High Strength Zirconia**
Best-fit values	**Slope**	1.501e-006	4.678e-005	9.199e-007	9.306e-007
	Y-intercept	-1.310e-008	1.030e-005	-2.497e-007	2.838e-009
	X-intercept	0.008727	-0.2202	0.2715	-0.003050
	1/slope	666197	21377	1087085	1074611
Std. Error	**Slope**	5.002e-011	1.000e-007	4.489e-009	5.604e-011
	Y-intercept	5.884e-009	1.177e-005	5.281e-007	6.592e-009
95% Confidence Intervals	**Slope**	1.501e-006 to 1.501e-006	4.658e-005 to 4.698e-005	9.108e-007 to 9.290e-007	9.305e-007 to 9.307e-007
	Y-intercept	-2.501e-008 to -1.189e-009	-1.352e-005 to 3.412e-005	-1.319e-006 to 8.194e-007	-1.051e-008 to 1.618e-008
	X-intercept	0.0007920 to 0.01666	-0.7321 to 0.2879	-0.8985 to 1.421	-0.01739 to 0.01129
Goodness of Fit	**R square**	1.000	0.9998	0.9991	1.000
	Sy.x	1.826e-008	3.651e-005	1.639e-006	2.046e-008
Significance	**F**	900605430	218730	41984	275769566
	DFn, DFd	1, 38	1, 38	1, 38	1, 38
	P value	<0.0001	<0.0001	<0.0001	<0.0001
	Deviation from zero	Significant	Significant	Significant	Significant
Equation		Y = 1.501e-006*X - 1.310e-008	Y = 4.678e-005*X + 1.030e-005	Y = 9.199e-007*X - 2.497e-007	Y = 9.306e-007*X + 2.838e-009

(p<0.0001) slope of 1.501e-006 (very small positive slope) and Y-intercept -1.310e-008 (close to zero).

While Polyether Ether Ketone (PEEK), has a very strong fit (R-square = 0.9998) with a highly significant (p < 0.0001) slope of 4.678e-005 (largest positive slope among the materials) and Y-intercept 1.030e-005. Cobalt-Chromium Alloy Type III has a strong fit (R-square = 0.9991) with a highly significant (p < 0.0001) slope of 9.199e-007 (small positive slope) and -2.497e-007 (close to zero).

High Strength Zirconia has a very strong fit (R-square = 0.9991) with a highly significant (p<0.0001) slope of 9.306e-007 (small positive slope) and 2.838e-009 (very close to zero).

Titanium Alloy Type IV, PEEK, Cobalt Chromium Alloy Type III, and High Strength Zirconia are linear regressions analyzed for strong linear relationships between variables. For all models, these models show high statistical significance (p<0.0001) as well as excellent goodness of fit (R-square 0.9991-1.000). A unique equation is set for each material to estimate equivalent strain from the independent variable. As compared to other materials, it has been noted that PEEK has the largest slope; on the other hand, some materials have smaller positive slopes with almost zero Y-intercepts. These models give reliable predictions on equivalent strain for any of the materials used, Figure (5).

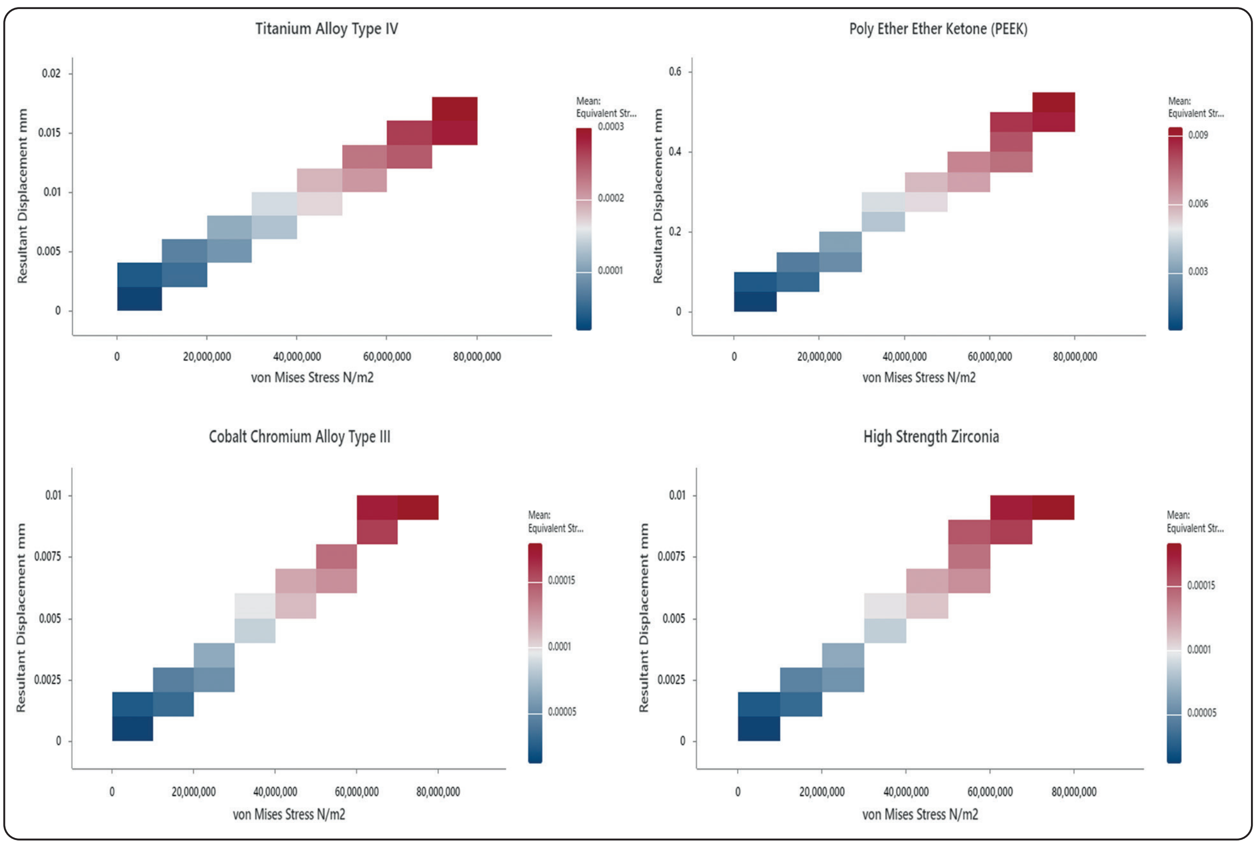

Fig. (5) Binned Scatterplot of Resultant Displacement mm vs von Mises Stress N/m2

DISCUSSION

In this study, von Mises stress, resultant displacement, and equivalent strain were assessed in mandibular locator CAD/CAM-milled bar Implant overdenture using four framework materials. This introduced detailed findings of stress distribution and material performance, which can be expensive and time-wasting. FEA is particularly useful in dental biomechanics as it can provide insights into stress patterns that would be difficult or impossible to observe in vivo. [11]

Regression models help predict the performance of different materials under various loading conditions. Evaluating four different framework materials under the same conditions provides a direct comparison of their biomechanical properties. The simulation of loads up to 200 N reflects realistic biting forces. It makes the results clinically relevant. Material optimization: Understanding stress distribution and yield points of various materials can guide the development of optimized implant overdenture designs. [11]

Bio-mechanical performance was simulated using 3D modeling and FEA under vertical loads up to 200 N along the milled bar. Throughout the linear regression model, deformation and von Mises stress were introduced to predict material performance in addition to von Mises yield criterion was used to determine when materials would yield under load. By this method, relationships between applied loads and material responses are determined to generate more reliable predictions of long-term performance as well as failure points. The determination of when materials would yield under load is particularly significant and specific use of the von Mises yield criterion indicates as to what level of material may fail in clinical service. [12]

Researchers found higher stress on prosthetic screws through PEEK frameworks caused compared to stiffer materials and prosthetic screw loosening occurs in 8-13% of cases, potentially due to increased stress. However, other studies proved PEEK as a treatment option for full-arch implant-supported prostheses. This may be credited to the flexibility of the PEEK framework bending during function. [13]

The material's bending capacity during function could suggest several advantages including more even distribution of occlusal forces and a shock-absorbing effect. This theoretically decreases stress on the bone-implant interface and advances patient comfort. This flexibility while potentially increasing stress on individual screws, may contribute to better overall performance of prosthesis. The conflicting findings highlight the complex nature of material selection in implant prosthodontics. Trade-offs between different properties must be carefully considered. [13]

High Strength Zirconia frameworks exhibited Von Mises stress values near yield points of Titanium Alloy Type IV and Cobalt Chromium Alloy Type III. [14] A higher elastic modulus resulted in less stress of high-strength Zirconia on implant or bone assemblies than Titanium Alloy Type IV. Both remained within physiological limits. [15]

The observation that Zirconia exhibits Von Mises stress values near the yield points of metallic alloys challenges traditional perceptions of ceramics as inherently less stress-resistant than metals. Furthermore, Zirconia's higher elastic modulus resulting in less stress on implant or bone assemblies compared to Titanium Alloy Type IV suggests potential advantages in stress distribution. This also benefits long-term implant stability. Importantly, both Zirconia and Titanium Alloy frameworks remained within physiological limits. This indicates their suitability for clinical use. [14-15]

This study compared Titanium Alloy Type IV and Cobalt Chromium Alloy Type III frameworks for implant-supported restorations. [16] The comparison of Titanium Alloy Type IV and Cobalt Chromium Alloy Type III frameworks for implant-supported restorations illustrated in this study presented beneficial data of the materials` biomechanical performance. The finding that both materials exert similar stress on the surrounding bone due to rigidity is noteworthy. This rigidity is beneficial for overall prosthesis stability. However, it has important implications. These include stress distribution throughout the implant-prosthesis system. [17]

The observation that these rigid materials cause more stress to be absorbed within the framework itself leads to higher stress values in denture bases. This could potentially impact the longevity and performance of the prosthesis. Additionally, higher stress concentration at the implant-abutment connection is critical. This interface often represents a weak point in implant-supported restorations. [17]

Titanium Alloy Type IV frameworks caused slightly higher implant stresses than Cobalt Chromium Alloy Type III. This was due to lower rigidity. This allowed more stress dissipation into denture bases and implants. [18] Higher elastic modulus in frameworks reduced stress transmission to implants and surrounding bone. The study highlights the importance of material properties in stress distribution. This impacts implant restoration performance. [19]

CONCLUSION

Based on the finite element analysis and regression model study of mandibular locator CAD/CAM-milled bar implant overdentures, several conclusions can be drawn. Material selection significantly impacts stress distribution. Deformation in implant-supported restorations is also affected. PEEK frameworks exhibited the highest resultant displacement. Equivalent strain suggested more flexibility but potentially higher stress on prosthetic components.

Titanium Alloy Type IV and Cobalt Chromium Alloy Type III, being rigid materials showed similar stress patterns in supporting bone. This makes them suitable for preserving supporting structures. High Strength Zirconia demonstrated lower stress on implant assemblies compared to titanium due to its higher elastic modulus.

All materials showed strong linear relationships in regression analysis. This allows for reliable predictions of equivalent strain. While each material has its advantages, careful consideration should be given to the specific clinical requirements. These include stress distribution biocompatibility and aesthetics.

Limitations

However, the FEA simulations were only used to represent idealized conditions and they did not necessarily account for all complexities that existed in the oral environment. Material Homogeneity Assumptions are likely modeled as homogenous in the study, with probably poor agreement to reality (at least when it comes to biological tissues).

ACKNOWLEDGMENT

We wish to offer our deepest gratitude to ***Eng. Mahmoud Hassan El-Garhy*** and ***Eng. Khaled Mohamed Zaghloul*** for their incomparable technical support in the Finite Element Simulation. Their expertise and availability substantially helped this project see the light. They provided valuable insights and guidelines throughout the implementation and interpretation of the finite element analyses that formed a backbone for the success of this research.

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