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Faculdade de Odontologia de Piracicaba

Leticia Del Rio Silva

A APLICAÇÃO DE CERÂMICA, ELETROEROSÃO E CICLAGEM MECÂNICA INFLUENCIAM O COMPORTAMENTO BIOMECÂNICO DE INFRAESTRUTURAS DE PRÓTESES TOTAIS IMPLANTOSSUPORTADAS USINADAS EM ZIRCÔNIA, COBALTO-CROMO E TITÂNIO?

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Orientador: Prof. Dr. Marcelo Ferraz Mesquita

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"A tarefa não é tanto ver aquilo que ninguém viu, mas pensar o que ninguém ainda pensou sobre aquilo que todo mundo vê."

Arthur Schopenhauer.

Resumo

A tecnologia CAD-CAM (*computer-aided design and computer-aided manufacturing*) de usinagem é um método bem estabelecido para fabricar infraestruturas protéticas. Contudo, ainda são escassas informações sobre a influência da cobertura cerâmica e da eletroerosão sobre o comportamento biomecânico de infraestruturas totais fixas *all-on-six* fabricadas em diferentes tipos de materiais. O objetivo nesse estudo foi comparar o comportamento biomecânico de infraestruturas totais usinadas em zircônia (Zr), cobalto-cromo (Co-Cr) e titânio (Ti), em diferentes fases do processo de fabricação da prótese. Adicionalmente, avaliar a influência da ciclagem mecânica sobre as próteses finalizadas. Foram confeccionadas 15 infraestruturas usinadas em Zr, Co-Cr e Ti (n=5). A adaptação foi mensurada por meio do protocolo do parafuso único. A tensão foi quantificada por análise fotoelástica. Os valores de torque de afrouxamento (TA) foram obtidos torqueando os parafusos protéticos, com 10-Ncm de torque, retorqueando após10 minutos, e avaliando a força de destorque após 24 horas. Em seguida, todas as infraestruturas receberam cobertura cerâmica e todos os testes foram repetidos. As infraestruturas confeccionadas em Co-Cr e Ti receberam o tratamento de eletroerosão após aplicação de cerâmica, e todos os testes foram repetidos novamente. Após ciclagem mecânica, foi avaliado o torque de afrouxamento. Os resultados foram submetidos ao ANOVA 2-fatores com medidas repetidas e as comparações múltiplas foram realizadas pelo teste de Bonferroni (α=,05). Antes da aplicação de cerâmica, o Ti apresentou os menores valores de adaptação (média ±desvio padrão µm) (Zr: 62,39 ±33,72, Co-Cr: 78,25 ±31,34, Ti: 99,86 ±19,03, *P*<,05). A cobertura cerâmica diminuiu os níveis de adaptação para Zr (121,15 ±69,62, *P*=,001) e Co-Cr (144,36 ±125,90, *P*=,008). O Ti apresentou maiores valores médios de tensão (média ±desvio padrão MPa) (Zr: 365,22 ±80,65, Co-Cr: 350,10 ±76,07, Ti: 463,66 ±72,55, *P*<,05) independente do tempo avaliado. Antes da aplicação de cerâmica, todos os materiais apresentaram valores médios de tensão mais baixos: 327,06 ±73,73, após aplicação de cerâmica: 405,57 ±80,84, após eletroerosão: 447,34 ±72,36 (*P*<,05). Antes da aplicação de cerâmica, o grupo Ti apresentou valores médios de TA mais elevados (média ±desvio padrão Ncm) (Zr: 7,36 ±0,35, Co-Cr: 7,31 ±0,29, Ti: 8,74 ±0,22, *P*<,05), como também após (Zr: 6,82 ±0,61, Co-Cr: 6,43 ±0,54, Ti: 8,47 ±0,42, *P*<,05). A eletroerosão melhorou os valores de adaptação (82,44 ±22,87) e TA (8,14 ±0,20) apenas para o Co-Cr (*P*<,05). A ciclagem mecânica não influenciou os valores de TA (Zr: 6,61 ±0,57, Co-Cr: 7,99 ±0,57, Ti: 8,11 ±0,27, *P*>,05). Os resultados obtidos permitem concluir que no tempo inicial as infraestruturas totais fixas em

Ti apresentaram os piores valores de adaptação e os maiores valores de torque de afrouxamento. A aplicação de cerâmica diminuiu os níveis de adaptação das infraestruturas em Zr e Co-Cr e diminuiu o TA apenas para o Co-Cr, além de elevar os níveis de tensão transmitidas ao sistema implantossuportado. A eletroerosão pode ser útil para melhorar a adaptação e o TA das infraestruturas em Co-Cr. A ciclagem mecânica simulando um ano de uso das próteses não afetou a estabilidade dos parafusos protéticos.

Palavras-chave: Próteses e Implantes. Projeto Auxiliado por Computador. Adaptação Marginal Dentária. Estresse Mecânico. Torque. Cerâmica.

Abstract

The computer-aided design and computer-aided manufacturing (CAD-CAM) technology is a well-established method for manufacturing prosthetic frameworks. However, information about the influence of ceramic coverage and spark erosion on the biomechanical behavior of the all-on-six full-arch fixed (FAF) framework design manufactured by using different materials is still lacking. This study aimed to compare the biomechanical behavior of milled FAF frameworks with zirconia (Zr), cobalt-chromium (Co-Cr), and titanium (Ti), at different steps of their manufacturing process and the influence of mechanical cycling thereon. Fifteen milled FAF frameworks were made with the all-on-six implant design: Zr, Co-Cr, and Ti (n=5). The fit was measured by the single-screw test protocol. Stress was measured by photoelastic analysis. The loosening torque (LT) was evaluated by tightening the screws, retightening them after 10 minutes, with 10-Ncm torque, and then evaluating the LT 24 hours later. Thereafter, all frameworks received ceramic coverage, and the previous tests were repeated. Co-Cr and Ti frameworks received spark erosion after ceramic coverage, and all analyses were repeated. Before and after mechanical cycling, LT was evaluated. The results were subjected to 2-way repeated-measures ANOVA and Bonferroni's test (α=.05). Ti presented lower fit values at baseline (mean ± standard deviation in µm) (Zr, 62.39 ±33.72; Co-Cr, 78.25 ±31.34; Ti, 99.86 ±19.03, *P*<.05). Ceramic coverage decreased fit levels for Zr (121.15 ±69.62, *P*=.001) and Co-Cr (144.36 ±125.90, *P*=.008). Ti showed higher stress values (mean ± standard deviation in MPa) (Zr, 365.22 ±80.65; Co-Cr, 350.10 ±75.04; Ti, 463.66 ±72.55, *P*<.05) regardless of time. Baseline for all materials presented lower stress values (baseline, 327.06 ±73.73; after ceramic coverage, 404.57 ±80.84; after spark erosion, 447.34 ±72.36, *P*<.05). Higher LT values (mean ± standard deviation in Ncm) were found for the Ti group at baseline (Zr, 7.36 ±0.35; Co-Cr, 7.31 ±0.29; Ti, 8.74 ±0.22, *P*<.05) and after ceramic coverage (Zr, 6.82 ±0.61; Co-Cr, 6.43 ±0.54; Ti, 8.47 ±0.42, *P*<.05). Spark erosion improved fit (82.44 ±22.87) and LT values only for Co-Cr (8.14 ±0.20) (*P*<.05). Mechanical cycling did not influence LT (Zr, 6.61 ±0.57; Co-Cr, 7.99 ±0.57; Ti, 8.11 ±0.27, *P*>.05). The obtained results allow to conclude that in baseline the FAFs Ti milled frameworks presented the worst adaptation levels and the highest loosening torque values. Ceramic coverage decreased the fit levels for Zr and Co-Cr, decreased the LT values for Co-Cr, and enhanced stress levels transmitted to the implant-supported system. Spark erosion can be a reliable technique to improve fit and LT for Co-Cr frameworks. Mechanical cycling simulating one year of prosthesis use did not affect the stability of the prosthetic screws.

Keywords: Prostheses and Implants. Computer-Aided Design. Dental Marginal Adaptation. Stress Mechanical. Torque. Ceramics.

Sumário

1 Introdução

Com o advento da osseointegração foi aberto um leque de possibilidades para a reabilitação de pacientes parcial ou totalmente edêntulos (Pjetursson *et al*., 2012; Block, 2018). Os implantes dentários tem apresentado altas taxas de sucesso (Moraschini *et al*., 2015), além disso maior conforto e qualidade de vida são relatados pelos pacientes reabilitados com próteses implantossuportadas (Oh *et al*., 2016). Entretanto, limitações anatômicas podem comprometer o posicionamento dos implantes e o design das infraestruturas de próteses, comprometendo o resultado do tratamento (Chiapasco e Zaniboni, 2009; Moraschini *et al*., 2015). Reabsorção óssea, tipo de osso (III ou IV) e pneumatização do seio maxilar são exemplos de situações que tornam desafiadora a reabilitação total de maxilas edêntulas (Chiapasco e Zaniboni, 2009; Agliardi *et al*., 2014).

Para minimizar ou até mesmo evitar cirurgias de levantamento de seio e enxerto ósseo, procedimentos associados a maior custo, tempo e morbidade, surgiu o conceito de reabilitação *all-on-four* (Maló *et al*., 2005). Esta técnica preconiza o uso de dois implantes na região anterior e outros dois inclinados distalmente na região posterior (entre 30 e 45 graus). A inclinação possibilita a utilização de implantes mais longos instalados em região de pilar canino que possui bom volume e qualidade óssea, além disso o aspecto biomecânico da prótese também é favorecido com a redução do *cantilever* posterior e da distância interimplantar (Pomares, 2009). Apesar da literatura relatar altas taxas de sucesso para esta técnica (Maló *et al*., 2011; Lopes *et al*., 2017), estudo prévio reportou que a inclinação dos implantes pode promover acúmulo de tensão na região peri-implantar (Çağlar *et al*., 2006). Com o intuito de evitar esse tipo de complicação surgiu posteriormente o conceito *all-on-six*. Nesta técnica são instalados seis implantes: dois implantes na região de incisivos, dois na região de pré-molares e dois curtos na região de molares (Bhering *et al*., 2016a). Esse conceito, além de evitar cirurgias complexas, apresenta comportamento biomecânico favorável. Isto por que nesse tipo de reabilitação não é necessário o uso de *cantilever* posterior, propiciando melhor distribuição de tensões com reflexo direto na longevidade da prótese (de Souza Batista *et al*., 2017). Finalmente, a literatura demonstra altas taxas de sucesso em maxila atrófica dos implantes curtos (<10mm) que são similares as dos implantes convencionais (Sierra-Sánchez *et al*., 2016).

Além do design da infraestrutura da prótese, outro fator associado à longevidade é o nível de adaptação marginal (Abduo e Judge, 2014). Nesse sentido, a técnica convencional de fundição tem sido substituída devido as várias etapas de fabricação e consequente incorporação de distorções ao longo do processo (Papadiochou e Pissiotis, 2018). Na tentativa de melhorar a adaptação surgiu a tecnologiD-CAM (*computer-aided design and computer-aided manufacturing*) de usinagem (Strub e Witkowski, 2006) que utiliza brocas e blocos pré-fabricados do material desejado que são usinados em fresadoras CNC (*computer numeric control*) a partir de um desenho prévio (CAD) realizado em computador (Beuer *et al*., 2008). Essa tecnologia permite a utilização de diversos materiais para a usinagem de infraestruturas. A zircônia (Zr) tem sido amplamente utilizada devido às propriedades estéticas e mecânicas (Saito *et al*., 2009; Spies *et al*., 2018); o cobalto-cromo (Co-Cr) apresenta boa resistência de união à cerâmica, alta resistência à flexão, além de bom desempenho clínico (Rocha *et al*., 2006; Svanborg *et* al.,2018); e as ligas (Ti-6Al-4V) de titânio (Ti) apresentam biocompatibilidade, baixo custo e alta resistência à corrosão, o que as tornam apropriadas para confecção de infraestruturas extensas (Katsoulis *et al*., 2015; Yilmaz *et al*., 2018).

Qualquer que seja o material, a aplicação de cobertura estética em cerâmica é uma fase obrigatória quando se pretende reproduzir uma situação clínica em ensaios *in vitro*. Fatores como contração, ciclos de cocção, design da infraestrutura e diferentes coeficientes de expansão térmica entre cerâmica e material da infraestrutura são associados às distorções que podem ocorrer durante o recobrimento estético (Nakaoka *et al*., 2011; Presotto *et al*., 2018). Além da adaptação, deve-se levar em consideração a quantidade de tensão transmitida ao sistema implantossuportado. Reabsorção óssea, sobrecarga, afrouxamento ou fratura do parafuso, pilar e/ou implante são complicações biomecânicas que podem ser evitadas com próteses bem adaptadas e com baixos níveis de tensão (Bhering *et al*., 2016b).

Quando se considera próteses com adaptação clinicamente aceitável, imediatamente se reporta ao termo adaptação passiva (Jemt, 1991) que foi definido como o nível de desajuste marginal que não causaria complicações biomecânicas ($<150\mu m$). Próteses que apresentassem esse nível de adaptação não induziriam quantidade significativa de tensão sobre os implantes, diminuindo a probabilidade de ocorrer adversidades ao longo do tempo (Al-meraikhi *et al*., 2017). Apesar de toda a evolução tecnológica envolvendo a confecção de infraestruturas de próteses sobre implantes ainda podem ocorrer situações em que se observa valores de desajustes inaceitáveis, com todas as consequências possíveis apresentadas anteriormente. Quando isso ocorre, o profissional dispõe de diversas técnicas que possibilitam melhorar o nível de adaptação marginal, como a soldagem (Rodrigues *et al*., 2017). Contudo, essa técnica apresenta desvantagens: 1- os pontos de solda na infraestrutura enfraquecem a resistência; 2- maior número de sessões clínicas; e 3- devem ser realizadas antes da cobertura estética da prótese para não danificá-la (Rodrigues *et al*., 2017; Presotto *et al*., 2018). Além da soldagem, a técnica de eletroerosão permite o refinamento das margens da prótese, melhorando os níveis de adaptação sem solda da infraestrutura, podendo ser aplicada mesmo após a cobertura estética sem provocar nenhum dano (Nakaoka *et al*., 2011). Dessa forma, as possíveis distorções oriundas dos ciclos de queima da cerâmica podem ser corrigidas sem prejuízo a estética e resistência mecânica. Contudo, a Zr apresenta como desvantagem não aceitar estas técnicas de correção de desajustes.

Levando em consideração a importância da distribuição de tensões e sua associação com a menor ocorrência de complicações biomecânicas foi avaliado os níveis de tensão ao redor dos implantes por fotoelasticidade (Presotto *et al*., 2017). Essa técnica é baseada na passagem de luz polarizada (fenômeno de interferência óptica) através de um modelo de resina fotoelástica, o qual quando submetido a tensões produz padrões de franja (De Medeiros *et al*., 2017). A análise fotoelástica é largamente utilizada em estudos de biomecânica e permite relacionar a resposta do osso circunjacente aos materiais da prótese e dos implantes (Assunção *et al*., 2009; Pereira *et al*., 2015).

Outros fatores importantes que podem afetar a longevidade das próteses por meio do afrouxamento dos parafusos protéticos são a localização e a magnitude das forças oclusais transmitidas aos componentes do sistema implantossuportado (Farina *et al*., 2012). Quando a prótese está em função, forças oclusais atuam em diferentes eixos o que afeta a estabilidade do parafuso (Bhering *et al*.,2016b). A ciclagem mecânica é um teste *in vitro* que simula o processo dinâmico de mastigação e está relacionada com a estabilidade do parafuso e com a durabilidade dos componentes do sistema implantossuportado (Gomes *et al*., 2014).

Apesar de estudos prévios analisarem o comportamento biomecânico de próteses totais fixas maxilares nenhum deles avaliam todas as variáveis descritas nesse trabalho. O conceito de reabilitação *all-on-six* ainda não foi utilizado na literatura como alternativa à realização de cirurgias de enxerto e para confeccionar infraestruturas de próteses totais fixas implantossuportadas sem *cantilever*. Permanece sem elucidação na literatura como a aplicação de cerâmica influencia na distribuição de tensões e infraestruturas tridimensionalmente complexas de arco acentuado. Além disso, ainda não foi avaliado como a eletroerosão influencia na adaptação, tensão e torque de afrouxamento em infraestruturas usinadas.

Dessa forma, os objetivos nesse estudo *in vitro* foram (1) comparar o comportamento biomecânico de infraestruturas totais implantossuportadas com design de implantes *all-on-six* confeccionadas pela tecnologia de usinagem em Zr, Co-Cr e Ti; (2) avaliar os efeitos da aplicação de cerâmica e da eletroerosão sobre a adaptação das infraestruturas, distribuição de tensões e torque de afrouxamento dos parafusos, e (3) investigar o efeito da ciclagem mecânica sobre o torque de afrouxamento dos parafusos. As 4 hipóteses do estudo foram: (1) o material da infraestrutura, (2) a aplicação da cerâmica, e (3) a eletroerosão não teriam efeito na adaptação, distribuição de tensões e torque de afrouxamento dos parafusos; e (4) a ciclagem mecânica não teria influência sobre o torque de afrouxamento dos parafusos.

2 Artigo

Can ceramic coverage, spark erosion, and mechanical cycling affect the biomechanical behavior of milled zirconia, cobalt-chromium, and titanium full-arch implant-supported fixed frameworks?

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Can ceramic coverage, spark erosion, and mechanical cycling affect the biomechanical behavior of milled zirconia, cobalt-chromium, and titanium full-arch implant-supported fixed frameworks?

ABSTRACT

Statement of problem. Milling is a well-established method for manufacturing prosthetic frameworks. However, information about the influence of ceramic coverage and spark erosion on the biomechanical behavior of the all-on-six full-arch fixed (FAF) framework design manufactured by using different materials is still lacking.

Purpose. This study aimed to compare the biomechanical behavior of milled FAF frameworks with zirconia (Zr), cobalt-chromium (Co-Cr), and titanium (Ti), at different steps of their manufacturing process and the influence of mechanical cycling thereon.

Material and methods. Fifteen milled FAF frameworks were made with the all-on-six implant design: Zr, Co-Cr, and Ti (n=5). The fit was measured by the single-screw test protocol. Stress was measured by photoelastic analysis. The loosening torque (LT) was evaluated by tightening the screws, retightening them after 10 minutes, and then evaluating the LT 24 hours later. Thereafter, all frameworks received ceramic coverage, and the previous tests were repeated. Co-Cr and Ti frameworks received spark erosion after ceramic coverage, and all analyses were repeated. Before and after mechanical cycling, LT was evaluated. The results were subjected to 2-way repeated-measures ANOVA and Bonferroni's test (α=.05).

Results. Ti presented lower fit values at baseline (mean ±standard deviation in µm) (Zr, 62.39 ±33.72; Co-Cr, 78.25 ±31.34; Ti, 99.86 ±19.03, *P*<.05). Ceramic coverage decreased fit levels for Zr (121.15 ±69.62, *P*=.001) and Co-Cr (144.36 ±125.90, *P*=.008). Ti showed higher stress values (MPa) (Zr, 365.22 ±80.65; Co-Cr, 350.10 ±75.04; Ti, 463.66 ±72.55, *P*<.05) regardless of time. Baseline for all materials presented lower stress values (baseline, 327.06

±73.73; after ceramic coverage, 404.57 ±80.84; after spark erosion, 447.34 ±72.36, P<.05). Higher LT values (Ncm) were found for the Ti group at baseline (Zr, 7.36 ±0.35; Co-Cr, 7.31 ±0.29; Ti, 8.74 ±0.22, P<.05) and after ceramic coverage (Zr, 6.82 ±0.61; Co-Cr, 6.43 ±0.54; Ti, 8.47 ±0.42, P<.05). Spark erosion improved fit (82.44 ±22.87) and LT values only for Co-Cr (8.14 ±0.20) (P<.05). Mechanical cycling did not influence LT (Zr, 6.61 ±0.57; Co-Cr, 7.99 ±0.57; Ti, 8.11 ±0.27, P>.05).

Conclusions. Ti milled FAFs presented lower fit values and higher LT values at baseline. Ceramic coverage decreased the fit levels for Zr and Co-Cr, decreased the LT values for Co-Cr, and enhanced stress levels. Spark erosion can be a reliable technique to improve fit and LT for Co-Cr frameworks. Mechanical cycling did not decrease screw stability.

Clinical Implications

Zirconia, cobalt-chromium, and titanium milled frameworks showed acceptable levels of fit, stress, and loosening torque values. The use of these materials should depend on the limitation of each clinical situation.

INTRODUCTION

Despite the reliability and high survival rates of implant-supported rehabilitations, the anatomic limitations of patients may affect implant positioning and thereafter the final framework design.[1–4] For the prosthetic rehabilitation of an atrophic maxilla, anatomic limitations such as posterior bone resorption[5] and maxillary sinus pneumatization[2] pose a clinical challenge.[4] The all-on-six concept appears to overcome these limitations, with short implants in the posterior region to decrease prosthesis cantilever, bone grafting, and sinus elevation.[2,6] In addition, the final two surgeries are associated with higher cost, increased time, and increased postoperative morbidity.[2,4,6] Moreover, the framework design, material, and technique used to manufacture prosthesis frameworks can affect fit and stress distribution to the implant-supported system.[7,8,9] Biomechanical complications such as bone resorption, overload, screw-loosening, and fracture of the screw, abutment, and/or implant can be avoided with well-fitting prostheses.[10,11]

Different techniques and materials may be used to rehabilitate edentulous patients. In terms of the techniques used for the construction of dental prostheses, computer-aided design and computer-aided manufacturing (CAD-CAM) technology reduces the steps and distortions incorporated from conventional casting technique.[7,12-15] With regard to materials, zirconia (Zr) has been increasingly used due to its esthetic features and mechanical properties.[16-19] Cobalt-chromium (Co-Cr) has a strong bond to ceramics, good mechanical properties, and good clinical performance.[20-22] Finally, suitable properties such as biocompatibility, low density, high mechanical strength, high corrosion resistance, and high ductility make titanium (Ti) alloys (Ti-6Al-4V) applicable for the construction of full-arch fixed (FAF) frameworks.[23-27]

Regardless of the framework material, it is necessary for esthetic coverage to be applied.[28,29] Inherent distortions by this process are associated with ceramic contraction, differences in the coefficient of thermal expansion (CTE), and framework design.[11,28,29] The improvement of fit levels after ceramic coverage, without framework sectioning, may be achieved with spark erosion.[30,31] This technique improves marginal adaptation levels without damaging the esthetic coverage and impairing the mechanical strength.[31-33] Thus, frameworks that show acceptable fit levels would reduce stress around implants and result in fewer mechanical complications.[34,35]

The location and magnitude of occlusal forces can also affect the stress transmitted to the implant-supported system components.[35,36] In addition, when the prosthesis is in function, occlusal forces act in different axes which affect the screw stability.[35] Mechanical cycling is an in vitro fatigue test that simulates the dynamic process of masticatory function and is related to the durability of implant-supported components, as the properties of materials may be changed by the cycles.[34]

Therefore, the aims of this study were: (1) to compare the biomechanical behavior of milled FAF frameworks in Zr, Co-Cr, and Ti; (2) to evaluate the effects of ceramic application and spark erosion on fit, stress, and loosening torque; and (3) to investigate the effect of mechanical cycling on the loosening torque of the screws. The 4 null hypotheses were: (1) the framework material, (2) ceramic coverage, and (3) spark erosion would have no effect on fit, stress, and loosening torque of the screws; (4) and mechanical cycling would have no influence on the loosening torque of the screws.

MATERIAL AND METHODS

A fully edentulous maxilla prototype (master model) was created from the computed tomography database of the Renato Archer Information Technology Center (Campinas, Brazil). The master model received 6 implants (all-on-six concept) by means of a parallelometer: 2 implants (Easy Grip Porous EH 4.1×11.5 mm; Conexao Prosthesis System) positioned in the lateral incisor region; 2 implants in the premolar region (Easy Grip Porous, EH 4.1×11.5 mm; Conexao Prosthesis System); and 2 short implants (Easy Grip Porous, EH 5.0×7 mm; Conexao Prosthesis System) positioned in the molar region. Each implant received a mini-abutment (4.8×4.0 mm; Conexao Prosthesis System), tightened with a 20-Ncm torque (Fig.1).

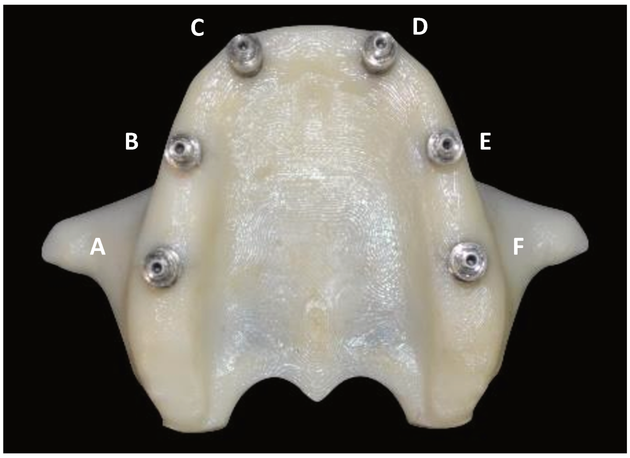

Figure 1. Master model.

A FAF framework was waxed on the master model. The set was digitally scanned (Ceramill map 400+; Amann Girrbach). The .stl file of the 3D model obtained (Ceramill Mind; Amann Girrbach) was sent for the respective milling machines: Zr (Ceramill Motion 2; Amann Girrbach), Co-Cr and Ti (CNC D15W; Yenadent) (n=5). After being milled, the Zr frameworks were sintered at 1530°C for 12 hours in a sintering box (Ceramill Therm S; Amann Girrbach) (Fig. 2). Afterward, the fit evaluation of the frameworks was performed by means of a microscope with 1.0-µm accuracy at 120× magnification (VMM 100 BT; Walter Uhl), and an analyzer unit (QC 220 HH Quadra-Check 200; Metronics Inc.), following the single-screw test protocol that is based on tightening one screw at an extremity and measure the gaps formed between the framework and all the mini-pillars.[14,15,37] The fit evaluation was performed by a calibrated examiner (L.D.R.S.) [intraclass correlation coefficient of 0.987 (P<.001)] three times on the abutment/framework interface (buccal and lingual surfaces). An average value was obtained for each framework.

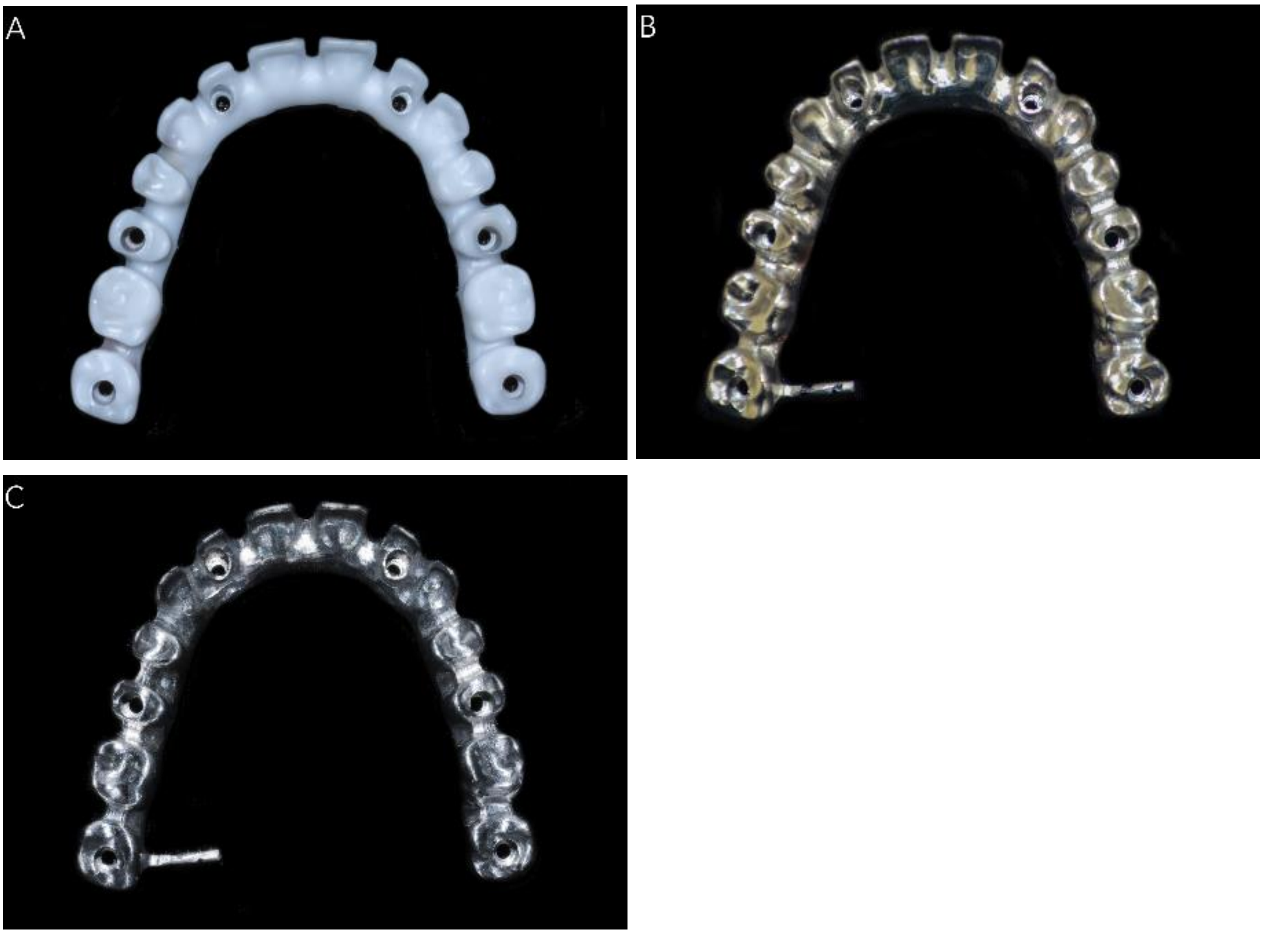

Figure 2. Frameworks. A, Zr. B, Co-Cr. C, Ti. Zr, zirconia; Co-Cr, cobalt-chromium; Ti, titanium.

The methodology for obtaining the photoelastic models strictly followed a previous study.[38] The photoelastic resin (Araldite GY 279 BR; Araltec Chemicals Ltd.) and the catalyst (Aradur HY 2963; Araltec Chemicals Ltd.) were manipulated and poured into a silicone impression according to a previously published protocol.[15,38] The photoelastic model and the frameworks were positioned in a circular polariscope of horizontal transmission[39,40] (Mechanical Design Lab, FMEC, Federal University of Uberlandia) coupled with a digital camera (EOS Rebel T6; Canon). The frameworks were tightened to the photoelastic models (10-Ncm) following the sequence of a previous study: A, F, B, E, C, D.[35] The isochromatic fringes were photographed and quantified by means of the Fringes® program (Mechanical Design Lab, FMEC, Federal University of Uberlandia).

To accomplish the loosening torque evaluation and mechanical cycling, working models were manufactured. A digital torque meter with 0.1-Ncm precision (TQ-8800; Lutron) was used to measure the loosening torque values. The same tightening sequence was performed, and the screws received 10-Ncm torque, following the manufacturer's recommendation. After 10 minutes, the screws were retightened, and after 24 hours the loosening torque was obtained.[41,42]

An experienced dental technician performed the ceramic coverage according to the manufacturer's recommendation. The layering procedure was standardized by means of a pachymeter. The frameworks thickness was measured in the prosthetic equator after the application of each ceramic layering. The difference between the thickness of the framework before and after ceramic coverage was between 1.5 and 2.5mm according to the dental element. The ceramic used for Zr and Ti frameworks was InSync ceramic (Jensen Dental), while feldspathic ceramic (InSync MC; Jensen Dental) was applied to Co-Cr (Fig. 3). Fit, photoelastic, and loosening torque analyses were evaluated again following the same protocol.

Figure 3. Illustration of a framework after ceramic coverage.

The spark erosion process was performed by means of an electrical discharge machine (Form 2-LC ZNC; Charmilles Technologies) on the Co-Cr and Ti frameworks. Zr frameworks are not eligible for the process because they are not metallic. A dental stone index

(Herostone; Vigodent) containing copper implant replicas (interconnected by a copper wire) was manufactured (Fig. 4).[28] The Co-Cr and Ti frameworks were fixed with low shrinkage acrylic resin (GC Pattern Resin; GC America Inc) and immersed in a dielectric fluid insulator, conductor, and coolant.[31,32] A hydraulic cylinder moved toward the framework until sequential sparks could be seen around all copper analogs.[32] Afterward, all frameworks were re-evaluated for fit, photoelastic analysis, and loosening torque, following previously described methodology.

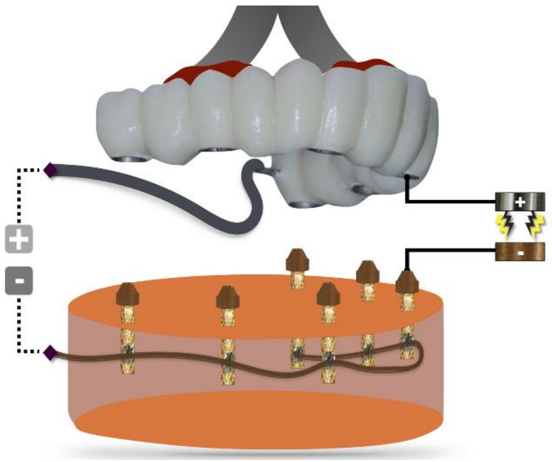

Figure 4**.** Spark erosion scheme. Framework and model connected by Cu wire to the positive and negative poles of spark erosion electrical discharge machine. Between the framework and the electrode are created electrical discharges that by means of ion exchange refines the marginal edges of the framework.

The mechanical fatigue simulator (ER11000 Plus; Erios) was calibrated for 1×10^6 cycles to simulate one year in function.[35,43] The pistons were placed on the occlusal surface of the first right molar with a 150-N compressive load at 2-Hz frequency.[10,35] The frameworks were angled 30° to the long axis[44] and immersed in artificial saliva (1.5 mM Ca, 3.0 mM P, 20.0 mM $NaHCO_3$, pH 7.0) at room temperature.[10] After mechanical cycling, the loosening torque values were measured again.

The data were subjected to normality analysis by the Kolmogorov-Smirnov method. Two-way repeated-measures ANOVA was used to investigate the influence of the framework material (Zr, Co-Cr and Ti), and the time (baseline, after ceramic coverage, and after spark erosion) on fit, stress, and loosening torque values; and the influence of mechanical cycling on loosening torque. All data were evaluated with SPSS software (IBM SPSS Statistics, v21.0; IBM Corp.). Pairwise multiple-comparisons were assessed by the Bonferroni test (α=.05). Statistical power was calculated (β>.9; α=.05) by specific software (G*Power; Universität Heinrich-Heine) with the partial eta-squared (η_p^2=.497) obtained by the interaction between framework×time and the main variable (fit).

RESULTS

The time (within-subjects P<.001) and interaction of framework×time (within-subjects P=.002) influenced fit values (Fig. 5). Loosening torque values showed an influence on time (within-subjects P=.002), framework material (between-subjects P<.001), and their interaction (within-subjects P<.001) (Fig. 6). At baseline, Zr and Co-Cr groups showed similar fit (P=.298) and loosening torque values (P=.785). Conversely, these groups showed statistically significant differences from the Ti group, which presented lower fit values and higher loosening torque values (P<.05). After ceramic coverage, all groups showed no statistically significant differences among them (P>.05) for fit values, while for loosening torque the values significantly decreased for the Co-Cr (P=.012) group. After spark erosion, the Co-Cr group showed improved fit similar to baseline values (P=.427) and loosening torque values (P<.001) similar to those of the Ti group (P=.252). After mechanical cycling, the Zr group presented the lowest statistically loosening torque values (Co-Cr, P=.001; Ti, P<.001), whereas no statistically significant differences were found between Co-Cr and Ti groups (P=.691). Regarding stress values, time (within-subjects P<.001) and framework material (between-subjects P=.002) affected the results (Fig. 7). Regardless of the material framework, baseline showed significantly lower stress values (P<.05). Regardless of time, lower stress was observed for the Co-Cr and Zr groups, with no statistically significant differences between them (P>.05) (Table 1).

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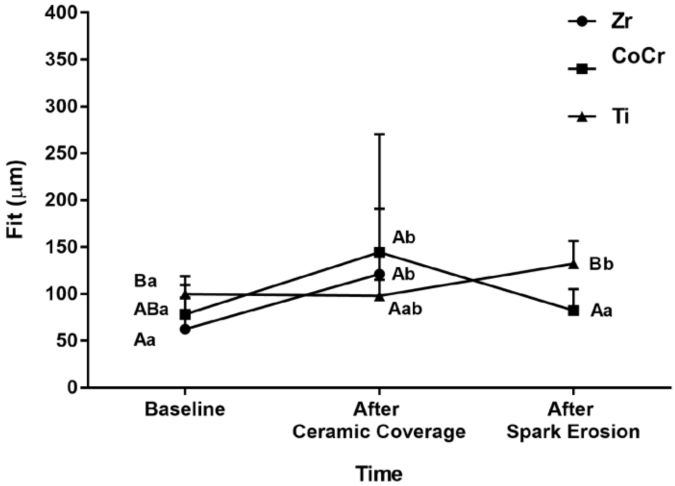

Figure 5. Fit values (μm) for Zr, Co-Cr, and Ti frameworks according to time. Different uppercase letters indicate differences among the framework materials at the same time, and different lowercase letters indicate differences over time. Zr, zirconia; Co-Cr, cobalt-chromium; Ti, titanium

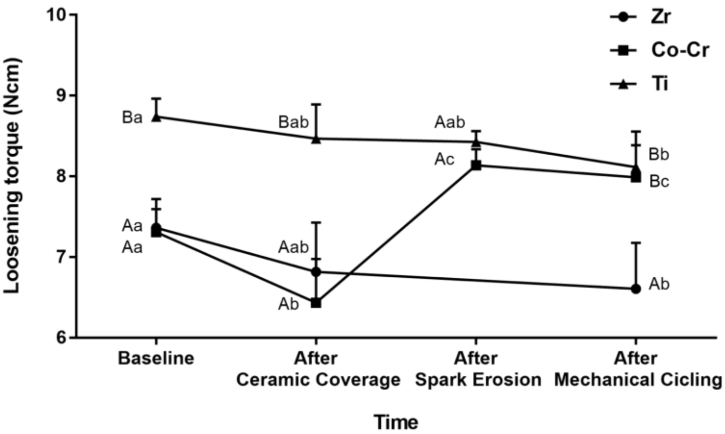

Figure 6. Loosening torque (Ncm) for Zr, Co-Cr, and Ti frameworks according to time. Different uppercase letters indicate differences among the framework materials at the same time, and different lowercase letters indicate differences over time. Zr, zirconia; Co-Cr, cobalt-chromium; Ti, titanium.

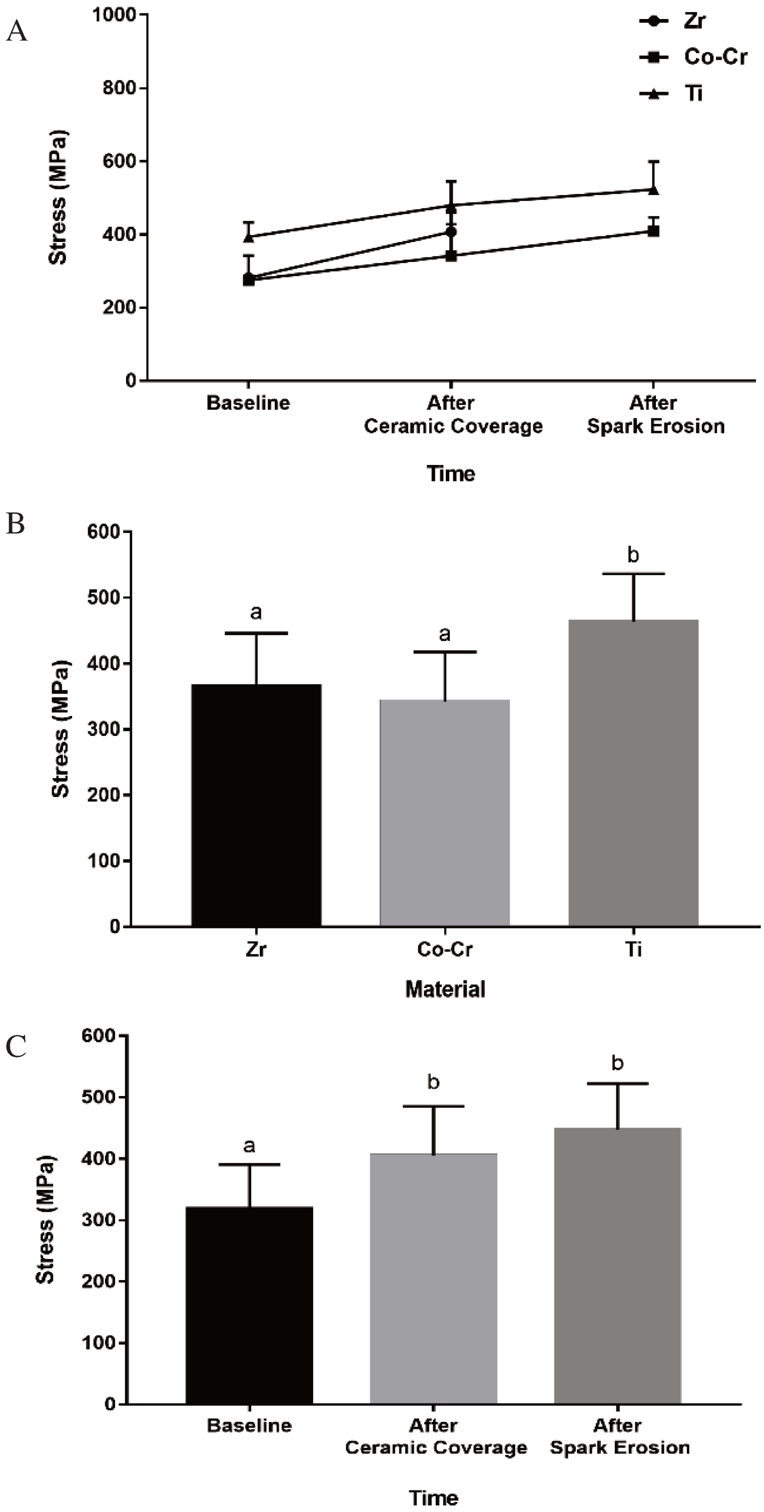

Figure 7. A, Stress values (MPa) for Zr, Co-Cr, and Ti frameworks according to time. B, Stress values (MPa) independent of time. C, Stress values (MPa) independent of framework material. Different lowercase letters indicate statistically significant differences. Zr, zirconia; Co-Cr, cobalt-chromium; Ti, titanium.

DISCUSSION

The biomechanical behavior of milled FAFs fabricated in Zr, Co-Cr, and Ti was compared and evaluated. The first null hypothesis tested was rejected, because framework material influenced fit, stress, and loosening torque values of the screws. Although clinically acceptable[12,15,19,37] the FAF Ti frameworks showed the worst fit levels at baseline. Moreover, higher stress levels were found for the Ti group regardless of evaluation time. The lower Ti elastic modulus (110 GPa) compared with that of Zr (200 GPa) and Co-Cr (191 GPa), as reported by the manufacturers, could explain this finding. Framework materials with lower elastic modulus are less resistant to deformation during screw-tightening, and consequently transmit more stress to the implant-supported system,[8] which could also explain the significantly higher loosening torque values for the Ti group compared with the Zr and Co-Cr groups. Lower elastic deformation can be observed when the screw is in contact with more flexible materials,[10] which could facilitate the preload maintenance.[42,43]

From the clinical scenario, a more accurate framework can be related to the higher stability of the implant-supported system, and also offers lower risk for biomechanical complications over time.[14,38] Earlier publications[19,24] found no fit differences between Zr and Ti frameworks. However, the methodology used to estimate fit was an industrial CT scanner that may incorporate bias during transfer to stereolithography files.[24] In addition, a previous study[30] reported no significant differences between 2D and 3D fit-reading techniques, with the benefit of the 2D method being simple and affordable for in vitro measurements.

The behavior of a FAF is a complex phenomenon. Three-dimensional changes caused by ceramic contraction and firing cycles might induce distortion patterns, acting positively or negatively on framework dimensional precision.[11,29] Therefore, the second null hypothesis was rejected, because the ceramic application did have an effect on fit, stress, and loosening torque of the screws. The ceramic coverage showed an insignificant effect on the fit of FAF Ti frameworks. These results are supported by those of other studies[25,26] that evaluated the effect of ceramic coverage by using the one-screw test. Likewise, previous investigations reported no significant differences on the fit of Zr[12] and Co-Cr[21] FAFs supported by six implants after ceramic coverage. However, the present results showed an influence of ceramic coverage on the fit of Zr and Co-Cr FAFs, and this can be supported by differences in fit-reading methodology. These previous studies[12,21] evaluated the fit level tightening four screws, keeping two in the anterior region, and then loosening the extremities ones, followed by fit measurement with a coordinate measuring machine (CMM). Thus, methodological differences among the studies may explain the variability of the outcomes.

Even after ceramic coverage the frameworks presented eligible fit.[37] This result demonstrates the accuracy and consistency of milling technology, regardless of the material used, even after ceramic application.[13] After ceramic coverage, only the Co-Cr group showed a significant decrease in loosening torque values. The CTE variation between the framework materials and the ceramics used supports these results.[28] As reported by the manufacturers Zr (CTE, 10.6 x 10^{-6}/ºC) and Ti (CTE, 10.3 x 10^{-6}/ºC) presented lower CTE compared with Co-Cr (CTE, 14.3 x 10^{-6}/ºC). Higher framework distortions might be attributed to higher CTE values. Regardless of the material, higher stress was observed after ceramic coverage and this can be supported by the firing cycles and the differences in CTE between the material framework and the ceramic.[11,28]

The passive fit of FAF frameworks can be improved by fit-corrective methods.[11,29,30] The spark erosion technique allows for the refinement of edges after ceramic coverage without sectioning, keeping the framework resistance.[11] In line with this, the third null hypothesis was rejected, because spark erosion influenced fit and loosening torque. The Co-Cr group showed improved fit and loosening torque values with spark erosion application, while no significant differences were found for the Ti group. Moreover, the alloy-dependency of the spark erosion technique has already been demonstrated in the literature.[31,32] Different electrochemical potentials between Co-Cr and Cu and between Ti and Cu,[28] as well as lower Ti thermal conductivity,[20] may explain favorable outcomes for the Co-Cr alloys, particularly in more fitted frameworks. Regardless of material, no statistically significant difference was verified on stress distribution before and after spark erosion. This might be explained because the spark erosion process only improves the fit levels on the vertical plane, while the stress is quantified in an 3D model.[35] Therefore, the angular misfits were not corrected with this technology explaining the similar stress levels found. Studies comparing the fit values in mandibular casted Co-Cr and Ti frameworks supported by 5 implants before and after spark erosion process found that this technology improved the fit values.[11,28] However, future research is still required to investigate its influence on milled FAF frameworks especially those with higher adaptation levels, and to develop refined protocols based on alloy type for each material framework.

Besides the fit and stress distribution evaluation, the assessment of screw stability after mechanical cycling is an important biomechanical analysis when the goal is to obtain long-lasting prostheses. No statistically significant difference in loosening torque values was observed for Zr, Co-Cr, and Ti groups before and after mechanical cycling. Therefore, the fourth null hypothesis was accepted, because mechanical cycling had no influence on the loosening torque values of the screws. Non-decreased torque values may be associated with passive fit frameworks (fit <150 μm).[10,37] Nonetheless, adequate contact between the screw and framework surface increases the friction coefficient and subsequent stability and loosening torque.[34] After mechanical cycling, lower loosening torque values were found for the Zr group. The contact of the screw with a framework of higher elastic modulus may induce screw wear due to its higher malleability. Furthermore, Zr frameworks are not susceptible to corrective methods such as spark erosion, which reaffirms the lower loosening torque values found.

The non-differentiation between cortical and cancellous bone,[39] and the inability to quantify framework stress are limitations of the methodology applied in this study to evaluate the stress distribution.[40] Therefore, finite element analysis could provide data complementary to this study. Also, the non-use of an opposite arch in the mechanical cycling test can be considered as a limitation.

There are several situations that the clinician faces during dental practice. Nonetheless, the physical mechanical properties inherent to restorative materials should be well-known by the clinician. Regardless of the material, ceramic application is mandatory. Zr restorations are often associated with low-temperature degradation[17] and chipping of veneer material,[18] so they should be used with caution.[12] Ti frameworks have been associated with lower ceramic bond strength compared with that of Co-Cr frameworks.[23] In addition, future research comparing other CAD-CAM technologies and materials as well as randomized controlled trials with long-term follow-up are needed to elucidate the influence of the analyzed variables on the biomechanical behavior of implant-supported prostheses.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. At baseline the Ti FAF frameworks presented the worst fit values, the higher loosening torque values, and lower stress was transmitted to the implant-supported system.

2. Ceramic coverage decreases the fit levels for Zr and Co-Cr FAF frameworks, decreases the loosening torque values only for Co-Cr FAF frameworks, and increases the stress levels for all groups.

3. Spark erosion technology improved fit and loosening torque of Co-Cr FAF frameworks, but it did not influence stress levels transmitted to the implant-supported system.

4. Mechanical cycling did not influence the loosening torque of the screws of FAF frameworks.

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TABLES

Table 1. Two-way repeated-measures ANOVA results of fit, stress, and loosening torque as a function of framework material, time, and their interaction (framework × time)

	Sum of Squares	***df***	**Mean Squares**	**F value**	***P****
Fit					
Within-subjects					
Time	0.232	2	0.116	14.095	0.000
Framework × time	0.196	4	0.049	5.932	0.002
Error	0.198	24	0.008		
Between-subjects					
Framework	0.077	2	0.038	0.495	0.622
Error	0.932	12	0.078		
Stress					
Within-subjects					
Time	111525.932	2	55762.966	25.591	0.000
Framework × time	11219.669	4	2804.917	1.237	0.322
Error	54421.857	24	2267.577		
Between-subjects					

Framework	114071.390	2	57035.695	10.300	0.002
Error	66450.325	12	5537.527		
Loosening torque					
Within-subjects					
Time	3.150	3	1.050	5.785	0.002
Framework × time	8.473	6	1.412	7.780	0.000
Error	6.535	36	0.182		
Between-subjects					
Framework	24.162	2	12.081	58.424	0.000
Error	2.429	12	0.202		

*Significant at $P < .05$.

3 Conclusão

Baseados nos resultados encontrados e dentro das limitações deste estudo *in vitro*, foram elaboradas as seguintes conclusões:

A tecnologia CAD/CAM de usinagem produziu infraestruturas com níveis de adaptação marginal considerados satisfatórios independentemente dos materiais avaliados.

Antes da aplicação de cerâmica as infraestruturas em Ti apresentaram piores níveis de adaptação e maiores valores de torque de afrouxamento.

Menores valores de tensão foram encontrados antes da aplicação de cerâmica.

A aplicação da cerâmica diminuiu os valores de adaptação marginal para as infraestruturas em Zr e Co-Cr e diminuiu os valores de torque de afrouxamento apenas para as infraestruturas confeccionadas em Co-Cr.

Maiores valores de tensão foram encontrados para as infraestruturas em Ti independentemente do tempo avaliado.

A aplicação da cerâmica aumentou a tensão ao redor dos implantes, independentemente dos materiais utilizados.

A tecnologia de eletroerosão melhorou a adaptação marginal e o torque de afrouxamento apenas para as infraestruturas em Co-Cr, não apresentando influência sobre a tensão transmitida ao sistema implantossuportado.

A ciclagem mecânica não teve influência sobre o torque de afrouxamento dos parafusos.

De maneira geral, as infraestruturas em Zr, Co-Cr e Ti apresentaram comportamento biomecânico satisfatório tanto para os níveis de adaptação, tensão e torque de afrouxamento. Dessa forma a escolha do material a ser utilizado na prática deve estar associada as limitações do caso clínico.

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