SERVIÇO PÚBLICO FEDERAL
MINISTÉRIO DA EDUCAÇÃO
UNIVERSIDADE FEDERAL DE UBERLÂNDIA
FACULDADE DE ODONTOLOGIA
PROGRAMA DE PÓS-GRADUAÇÃO

Fabiane Maria Ferreira

Avaliação dos efeitos da placa estabilizadora de oclusão na distribuição de tensões no disco da articulação temporomandibular, pelo método de elementos finitos

Tese apresentada ao Programa de Pós-Graduação em Odontologia da Faculdade de Odontologia da Universidade Federal de Uberlândia, como parte dos requisitos para obtenção do título de Doutor em Odontologia.

Área de Concentração: Clínica Odontológica Integrada.

Uberlândia-MG
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Área de concentração: Clínica Odontológica

Orientador: Prof. Dr. Alfredo Júlio Fernandes Neto

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Prof. Dr. Alfredo Júlio Fernandes Neto
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FOUFU

Ata da defesa de TESE DE DOUTORADO junto ao Programa de Pós-graduação em Odontologia da Faculdade de Odontologia da Universidade Federal de Uberlândia.

Defesa de: Tese de Doutorado nº 021- COPOD
Data: 29/08/2017
Discente: Fabiane Maria Ferreira **(11313ODO004)**
Título do Trabalho: Avaliação computacional do efeito da placa estabilizadora de oclusão na distribuição de tensões no disco da articulação temporomandibular
Área de concentração: Clínica Odontológica Integrada.
Linha de pesquisa: Tratamento das deformidades dento-faciais e dos distúrbios da ATM
Projeto de Pesquisa de vinculação: Tratamento das deformidades dento-faciais e dos distúrbios da ATM
As **oito horas** dia **vinte e nove de agosto de 2017** no Anfiteatro Bloco 4L Anexo A, sala 23 Campus Umuarama da Universidade Federal de Uberlândia, reuniu-se a Banca Examinadora, designada pelo Colegiado do Programa de Pós-graduação em junho de 2017, assim composta: Professores Doutores: Paulo Cézar Simamoto Júnior (UFU); Marlete Ribeiro da Silva (UFU); Dauro Douglas Oliveira (PUC Minas); Germana de Villa Camargos (UNIFAL); Alfredo Júlio Fernandes Neto (UFU) orientador(a) do(a) candidato(a) **Fabiane Maria Ferreira.**

Iniciando os trabalhos o(a) presidente da mesa Dr. Alfredo Júlio Fernandes Neto apresentou a Comissão Examinadora e o candidato(a), agradeceu a presença do público, e concedeu ao Discente a palavra para a exposição do seu trabalho. A duração da apresentação do Discente e o tempo de argüição e resposta foram conforme as normas do Programa.

A seguir o senhor(a) presidente concedeu a palavra, pela ordem sucessivamente, aos (às) examinadores (as), que passaram a argüir o(a) candidato(a). Finalizada a argüição, que se desenvolveu dentro dos termos regimentais, a Banca, em sessão secreta, atribuiu os conceitos finais.

Em face do resultado obtido, a Banca Examinadora considerou o(a) candidato(a) a provado(a).

Esta defesa de Tese de Doutorado é parte dos requisitos necessários à obtenção do título de Doutor. O competente diploma será expedido após cumprimento dos demais requisitos, conforme as normas do Programa, a legislação pertinente e a regulamentação interna da UFU.

Nada mais havendo a tratar foram encerrados os trabalhos às 12 horas e 20 minutos. Foi lavrada a presente ata que após lida e achada conforme foi assinada pela Banca Examinadora.

Prof. Dr. Dauro Douglas Oliveira – PUC Minas

Profª Dra. Germana de Villa Camargos - UNIFAL

Prof ª Drª Marlete Ribeiro da Silva – UFU

Prof. Dr. Paulo Cézar Simamoto Júnior– UFU

Prof. Dr. Alfredo Júlio Fernandes Neto – UFU
Orientador (a)

PPGO

DEDICATÓRIA

Dedico este trabalho e este título aos meus pais, Pedro e Maria Carolina, que nunca mediram esforços para me dar a oportunidade de hoje chegar até aqui!

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"Estou semeando as sementes da minha mais alta esperança. Não busco discípulos para comunicar-lhes saberes. Busco discípulos, para neles plantar minhas esperanças."

Rubem Alves

SUMÁRIO

LISTA DE ABREVIATURAS E SIGLAS

ATM: Articulação Temporomandibular

CT: Computed Tomography

DTM: Disfunção Temporomandibular

FE: Finite element

FEA: Finite Element Analysis

GAGs: Glycosaminoglycans

mm: milímetro

Mpa: Megapascal

MIMICS: Materialise Interactive Medical Image Control System

TMD: Temporomandibular Disorders

TMJ: Temporomandibular Joint

Resumo

RESUMO

Disfunção temporomandibular (DTM) é um termo que se refere a sinais e sintomas funcionais e estruturais que acometem o sistema mastigatório, especialmente músculos, articulação temporomandibular (ATM) e tecidos circundantes. É considerada causa mais freqüente de dor orofacial crônica, cerca de 40 a 75% dos indivíduos saudáveis apontam ao menos um sinal, e 33% já manifestaram ao menos um sintoma de DTM. Abordagens conservadoras, incluindo o uso de placas oclusais, são as primeiras opções de tratamento da DTM, devido à sua alta eficácia associada à possibilidade de reversibilidade e baixa morbidade. O mecanismo de ação das placas no espaço intra-articular ainda é bastante discutido, mas há indícios de que há diminuição das tensões no disco em decorrência da mudança na posição mandibular. Diante disso, o objetivo geral desse estudo foi verificar a influência da placa de estabilização oclusal na distribuição de tensões e deformações geradas no disco da articulação temporomandibular (ATM), em condições de normalidade e paatológicas, utilizando para isto o método de elementos finitos. Este estudo envolveu três objetivos específicos. **Objetivo Específico 1:** Analisar o efeito da placa oclusal sobre a distribuição de tensões no disco da articulação temporomandibular, em diferentes posições. **Objetivo Específico 2:** Conhecer por meio de revisão da literatura as propriedades mecânicas aplicáveis ao disco articular em análises de elementos finitos, e desenvolver um modelo tridimensional de ATM normal utilizando o software MIMICS. **Objetivo Específico 3:** Desenvolver modelos tridimensionais do aparelho estomatognático, incluindo as ATMs esquerda e direita, e avaliar a distribuição de tensões e deformações em ambos os discos articulares na presença e ausência de placa estabilizadora de oclusão. As metodologias empregadas foram análises de elementos finitos 2D e 3D, com análise das tensões pelo critério de von Mises, e revisão da literatura. Frente aos resultados destes objetivos conclui-se que em todas as situações testadas a superfície inferior do disco exibiu maior concentração de tensões e deformações, e na análise antero-posterior a região mais afetada foi a zona intermediária do disco. Quando o disco apresenta-se deslocado anteriormente, embora a placa não

promova grande redução na magnitude das tensões, observou-se uma tendência de redução que deve ser mais bem investigada em estudos futuros. A análise bilateral e 3D das ATMs revelou que embora a placa não proporcione uma redução relevante das tensões e deformações que incidem sobre os discos articulares, ela promove melhor estabilização da oclusão refletindo em melhor estabilização das articulações, fazendo com que elas trabalhem de forma mais simétrica e as tensões estejam distribuídas entre os dois discos homogeneamente. Por fim, a revisão da literatura sobre propriedades mecânicas do disco articular revelou que apesar de ele ser predominantemente viscohiperelástico, existem muitas formas de caracterizar o disco e que cada representação tem suas particularidades e limitações que devem ser consideradas no momento de interpretar os resultados.

Abstract

ABSCTRAT

Temporomandibular disorder (TMD) is a term that refers to signs and symptoms associated with pain and functional and structural disturbances of the masticatory system, especially muscles, temporomandibular joints (TMJs) and surrounding tissues. This disorder is considered the most frequent cause of chronic orofacial pain, 40% to 75% of healthy individuals point out at least one sign and 33% observed at least one symptom of TMD. Conservative approaches, including occlusal splint therapy, is the first option to treat temporomandibular disorders (TMD), due to its high efficacy associated with the possibility of reversibility and low morbidity.The action of the splints in the intra-articular space is still discussed, but is considered that the occlusal splints leads to reduction of stress in the temporomandibular joint secondary to change in the position of the mandible. Thus, the general objective of the present study was to evaluate the influence of occlusal stabilization splint on stress and strain generation in the temporomandibular joint disc, under conditions of normality and anterior disc displacement, using the finite element analysis. This study involved three specific objectives. **Objective 1:** analyze the effect of the occlusal splint on stress distribution on the temporomandibular joint disc, in different positions. **Objective 2:** to know the properties used for articular disc in other FEA studies by means of a bibliographic survey of the literature, and based on this, develop an accurate 3D computational model of a normal TMJ, by the Materialise Interactive Medical Image Control System (MIMICS). **Objective 3:** develop 3D computational models, of normal TMJ, in order to simulate mandibular closure in the presence or absence of an occlusal splint to evaluate the distribution of stress and strain in both situations. The methods used were 2D and 3D finite element analysis and stress evaluation by von Mises criterion, and literature review. Based on the results of these objectives is possible to conclude that in all tested situations the lower surface of the disc exhibited the higher concentration of stresses and strain, and in the anteroposterior analysis the most affected region was the intermediate zone of the disc. When the disc is displaced anteriorly, although the splint does not promote a great reduction in the stress magnitude, a tendency of reduction has been observed that should be better investigated in future studies. Bilateral and

3D analysis of the TMJs revealed that although the splint does not provide a significant stress and strain reduction, it promotes better occlusion stabilization reflecting in better stabilization of the joints. Thus, they work more symmetrically and the stresses are distributed between the two discs homogeneously. Finally, the literature review on the mechanical properties of the articular disc revealed that although it is predominantly viscohiperelastic, there are many ways to characterize the disc and that each representation has its particularities and limitations that must be considered when interpreting the results.

Introdução e Referencial Teórico

1. Introdução e Referencial Teórico:

A articulação temporomandibular (ATM) é um tipo de articulação sinovial, que funciona como dobradiça modificada. Entre as várias funções, desempenha papel chave no sistema orofacial. Como articulação ginglimo artroidal realiza movimentos em um plano principal, e, ao mesmo tempo, movimentos de deslizamento num segundo plano. A ATM é a única articulação do corpo humano, que abriga um centro de crescimento, resultando na necessidade permanente de cooperação entre as articulações esquerda e direita (Fanghanel et al., 2007; Stankovic et al. 2013).

As superfícies articulares envolvidas na ATM são fossa mandibular e tubérculo articular do osso temporal, bem como o côndilo. Ao contrário da maioria das articulações sinoviais, cujas superfícies articulares são cobertas com cartilagem hialina, os ossos que formam a ATM são cobertos por camada de cartilagem fibrosa. Entre o côndilo mandibular e a fossa mandibular há um disco articular fibrocartilaginoso oval denso denominado disco da ATM ou disco articular. Este disco divide a cavidade articular em dois compartimentos separados: o superior e o inferior (Tanaka et al., 2008), e a parte anterior e posterior do disco são espessas, delimitando um centro mais fino. O mesmo serve como osso não calcificado, permitindo os movimentos complexos do ATM ao mesmo tempo em que desempenha papel importante na função mandibular, proporcionando distribuição de tensões e lubrificação na ATM. Cargas mecânicas patológicas, como o aumento de atrito entre as superfícies em movimento, estão entre as principais causas de deslocamento de disco da ATM (Stankovic et al. 2013).

Como resultante dos músculos que estão inseridos na ATM, a força de apoio cria uma pressão no momento da oclusão, que é transmitida para o tubérculo articular através do disco articular. Há muitas posições geométricas específicas das superfícies articulares durante a oclusão, que pode levar à forma mais ou menos excêntrica das distribuições de tensões nas ATM. Existem três tipos de carregamento a que o disco é submetido: compressão, tensão e cisalhamento. Naturalmente, durante o movimento existem muitas combinações destes tipos básicos de carregamento. Além disso, a carga sobre o disco pode ser classificada em carga estática (apertamento, ranger de dentes e bruxismo) e carga dinâmica (mastigar, falar) (Tanaka & Eijden, 2003). O comportamento biomecânico do disco ainda não foi completamente identificado, e, por essa razão, ainda não há valores universalmente acordados para condições de carga da ATM, quer para manutenção ou risco (Tanaka et al., 2008; Stankovic et al. 2013).

A magnitude da deformação e tensões geradas no disco é determinada principalmente pela natureza da aplicação da carga e propriedades biomecânicas do disco, como rigidez e resistência (Tanaka & Eijden, 2003). As propriedades mecânicas são dependentes da composição do disco no que diz respeito à quantidade e orientação das fibras colágenas, composição e organização de proteoglicanos e a interação dessas moléculas com os fluidos.

Para manter a integridade do disco durante a função, suas fibras colágenas estão dispostas circunferencial e antero-posteriormente, o que resulta em um tecido com característica anisotrópica sob tensão e cisalhamento (Sight e Detamore, 2009). Devido à alta viscosidade das moléculas de proteoglicanos, elas conferem maior rigidez e resistência às cargas compressivas, e por isso tendem a se concentrar em regiões de maior carregamento (Tanaka & Eijden, 2003). Assim o disco é capaz de atuar na absorção e distribuição das tensões prevenindo, em condições fisiológicas, doenças degenerativas.

Estudos experimentais para medir tensões e deformações no disco articular durante seu funcionamento são difíceis de serem realizados (Comisso et al., 2015), devido ao risco de danos biológicos à articulação. Portanto, a análise por elementos finitos é uma boa metodologia para simular a distribuição de tensão e deformação na ATM durante a mastigação (Comisso et al., 2015). Alguns estudos simularam movimentos mandibulares fisiológicos, enquanto outros simularam apertamento dental prolongado. Os resultados indicam que o aumento do coeficiente de atrito entre as superfícies articulares podem ser a causa principal do deslocamento de disco (Tanaka et al., 2008), e o movimento lateral contínuo da mandíbula pode resultar em perfurações de ambos os discos na sua parte lateral, e danificar os ligamentos laterais do disco (Pérez Del Palomar & Doblare, 2006).

Geração de um modelo do sistema mastigatório com características anatômicas próximas da realidade não é uma tarefa fácil. A literatura não é clara sobre os valores de referência das propriedades estruturais, e isso faz a definição do método mais difícil. Outra dificuldade é decidir sobre o grau de simplificação do modelo, porque as limitações de software e de tempo não permitem a modelagem do sistema mastigatório em toda a sua complexidade conhecida. Portanto, não surpreende que estudos prévios que aplicaram análise por elementos finitos ao aparelho mastigatório diferem significativamente quanto a variáveis básicas, tais como: propriedades dos materiais, restrições e forças aplicadas (Grooming et al., 2013). No entanto, nos últimos anos, uma melhoria na representação da ATM para aperfeiçoar a avaliação de tensões fisiológicas e patológicas no disco articular tem sido observada (Savoldelli et al., 2012), resultando em dados mais confiáveis.

As propriedades biomecânicas podem mudar em decorrência de traumas e patologias na ATM, muitas vezes provocadas por danos que excedem a capacidade de reparo dos tecidos articulares (Tanaka & Eijden, 2003). De forma geral as condutas terapêuticas requeridas para tratamento de DTM envolvem abordagens conservadoras e cirúrgicas (Lee et al, 2013). Dentre os métodos conservadores estão: placas oclusais, fisioterapia, *biofeedback*, acupuntura e medicamentos de curta duração. Este tipo de abordagem é a primeira escolha de tratamento para disfunções articulares devido ao seu caráter reversível (Oz et al., 2010). Placas oclusais são frequentemente utilizadas para tratamento de desarranjos internos de ATM e dores miofasciais (Lee et al., 2013), e seu mecanismo de atuação está baseado no reflexo neuromuscular (Miernik et al., 2015) e diminuição da pressão intra-articular (Nitzan et al., 1994). Contudo, registros sobre o efeito do uso de placas na geração de tensões e deformações no disco articular são ainda desconhecidos.

Neste contexto, o presente estudo se dedicou a desenvolver modelos computacionais de ATM normal e com deslocamento de disco, aptos para aplicação do método de elementos finitos, com objetivo de simular movimentos mandibulares na presença ou ausência da placa oclusal, a fim de compreender a distribuição de tensões no disco articular em diferentes situações.

Objetivos

2- Objetivos:

2.1: Objetivo Geral:

Verificar a influência da placa de estabilização oclusal na distribuição de tensões e deformações geradas no disco da articulação temporomandibular, em condições de normalidade e deslocamento de disco anterior, utilizando para isto o método de elementos finitos.

2.2: Objetivos Específicos:

2.2.1: Objetivo específico1:

Analisar o efeito da placa oclusal na distribuição de tensões no disco da articulação temporomandibular, em diferentes posições.

Este objetivo específico está contido no Capítulo 1 desta tese, intitulado: Effect of occlusal splints on the stress generation on the temporomandibular joint disc stress.

2.2.2: Objetivo específico 2:

Conhecer por meio de revisão da literatura as propriedades mecânicas aplicáveis ao disco articular em análises de elementos finitos, e desenvolver um modelo tridimensional de ATM normal utilizando o software MIMICS.

Este objetivo específico está contido no Capítulo 2 desta tese, intitulado: Temporomandibular joint disc biomechanical behavior: a literature review and 3D FEA.

2.2.3: Objetivo específico 3:

Desenvolver modelos tridimensionais do aparelho estomatognático, incluindo as articulações temporomandibulares esquerda e direita, e avaliar a distribuição de tensões e deformações em ambos os discos articulares na presença e ausência de placa estabilizadora de oclusão.

Este objetivo específico está contido no Capítulo 3 desta tese, intitulado: Can occlusal splint influence the stress and strain distribution on temporomandibular joint disc?

Capítulos

3. Capítulos:

Serão apresentados nesta sessão três artigos separadamente sendo que cada um corresponde a um capítulo.

Capítulo 1

3.1. Capítulo 1: Artigo aceito para publicação pelo periódico Brazilian Dental Journal

Title: Effect of occlusal splints on the stress generation on the temporomandibular joint disc stress

Short title: Occlusal splint's effect on the articular disc

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SUMMARY:
Conservative approach, including occlusal splint therapy, is the first option to treat temporomandibular disorders (TMD), because of its reversibility. The present study analyzed the effect of the articular disc position and occlusal splints use on the stress distribution on this disc. A two-dimensional (2D) finite element (FE) model of the temporomandibular joint with the articular disc at its physiologic position was constructed based on cone-beam computed tomography. Three other FE models were created changing the disc position, according to occlusal splint use and anterior disc displacement condition. Structural stress distribution analysis was performed using Marc-Mentat package. The equivalent von Mises stress was used to compare the study factor. Higher stress concentration was observed on the intermediate to anterior zone of the disc, with maximum values over 2MPa. No relevant difference was verified on the stress distribution and magnitude comparing disc positions and occlusal splint use. However, there was stress reduction arising from the use of the occlusal splints in cases of anterior disc displacement. In conclusion, based on the generated FE models and established boundary conditions, the stress increased at the intermediate zone of the TMJ disc during physiological mandible closure. The stress magnitude was similar in all tested situations.

KEY WORDS: temporomandibular joint, temporomandibular joint disc, occlusal splints, finite element analysis.

INTRODUCTION

Anatomically, between the condyle and the articular fossa of the temporomandibular joint (TMJ) there is the articular disc, a fibrocartilage that facilitates movement between the mandible and temporal bone (1). The main function of the articular disc is absorbers and distributes the load effect over a larger contact area to prevent damage to the articulating surfaces (1). This is important to maintain the stomatognathic system healthy, preventing articular disc alterations thar can lead to the temporomandibular disorders (TMD) (1).

The therapeutic approach required for TMJ treatment involves two categories: the conservative and surgical methods (2). Conservative methods are first choice for TMJ treatment, because of their reversible nature. This category includes occlusal splints, physical therapy, feedback, acupuncture, and short-term pharmacotherapy (3). Occlusal splint therapy has frequently been used for internal derangement and myofascial pain treatment (2). The performance of the occlusal splint is based on the mechanism of neuromuscular reflex (4) and decrease in intra-articular pressure in TMJ (5).

Mandibular movement analysis has shown that sliding and rotating with slight lateral excursion occur simultaneously between articulating surfaces, the articular disc is subjected to many different loading regions (6). Compression, tension and shear loads can be observed, but combinations of these basic types of loading during physiologic function of the joint are more common (6-7). The TMJ disc consists of circumferentially and antero-posteriorly aligned collagen fibers, resulting in a tissue that is anisotropic under tension and shear stress and strain (8). The biomechanical behavior of the TMJ disc has not yet been understood completely, and for this reason, there are still no universally agreed values for TMJ loading conditions, for either maintenance or hazard (7,9). Studies have characterized the articular disc, on Finite Element Analysis (FEA) of the TMJ, as isotropic elastic material, porohyperelastic, hyperelastic and viscoelastic materials (10-13)

Experimental studies for measuring stresses and strains in the articular disc during loading are very difficult to conduct, due to the risk of biological damage to the joint (1). The FEA is nowadays the more appropriated method for investigating stress and strain distributions in the TMJ during mastication (1,9-14). Some studies have simulated physiological mandibular movements or simulated prolonged teeth clenching. Increase in the frictional coefficient between the articular surfaces may be a major cause of the onset of disc displacement (9). Continuous lateral movement of the jaw may lead to perforations in the lateral part of both discs, and may damage the lateral attachments of the disc to the condyle (12).

Generating a model of the masticatory system with anatomic characteristics close to reality is not simple process. The literature is not clear about reference values for tissues properties, due to the diversity of characterizations found to articular disc (10-13). The degree of simplification of the model is difficult to establish, because computational and time limitations do not allow the masticatory system to be modeled in all its known complexity (13). Nevertheless, in recent years an improvement has been noted in TMJ representation for optimizing assessment of the physiological and pathologic strains in the joint disc (15), however further developments are still necessary.

In this context, the aim of this study was to develop 2D computational models, of normal TMJ, and with anterior disc displacement, in order to simulate mandibular closure in the presence or absence of an occlusal splint. The null hypothesis of this study was that the stress in the articular disc would be the same in all situations.

MATERIAL AND METHODS:

- *Finite element model generation:*

This study was approved by ethics committee (83073/2014), prior to study initiation. The TMJ geometry was obtained from the cone-beam computed tomography (CT) of the right TMJ of an adult female volunteer (aged 28 years) with no history of present or past TMJ disorders. The 432 slices of the skull and mandible, and images with a resolution of 0.2X 0.2X0.2mm voxels were obtained. From these images, the mandibular condyle and articular fossa–eminence of temporal bone contours, were delimitated, and the upper and lower boundaries of the disc were modeled according to the upper and lower articular surfaces (Figure 1). In this image, it was possible to identify the three parts of the articular disc: posterior zone, intermediate zone and anterior zone. The contours of the TMJ components were entered into MSC.Marc (MSC Software Corporation, Santa Ana, CA, USA) and 2D quadric elements with four nodes were used. Bones and articular disc were discretized into 3841 and 160 elements respectively. The mesh adaptive procedure was applied after each step 0.1s.

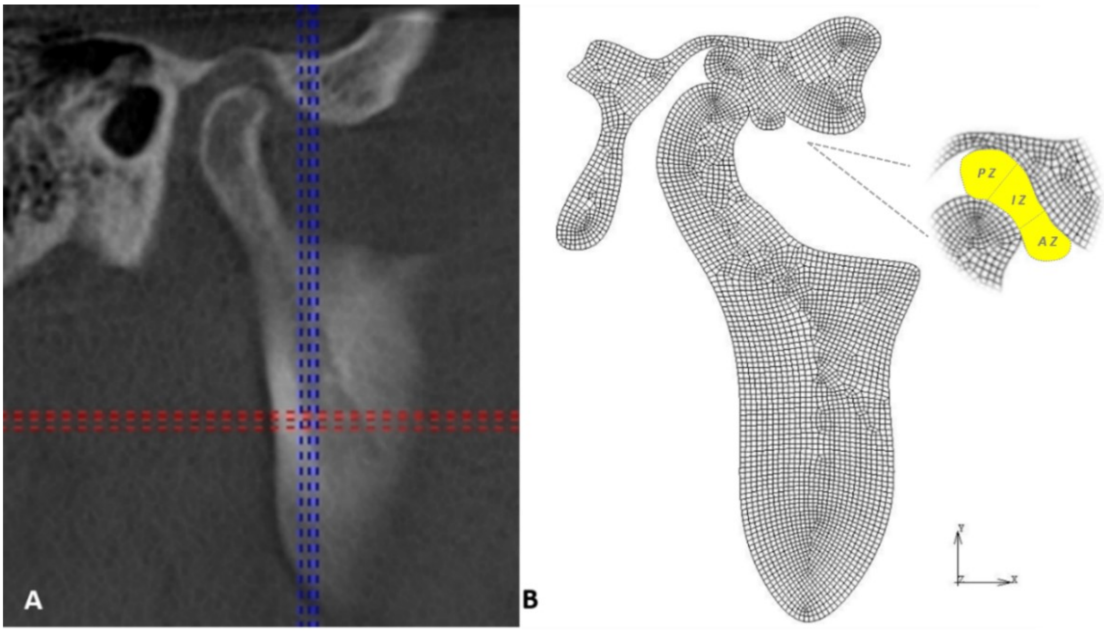

Figure 1: A- CT scan image of section; B- Numerical model and division of the articular disc into three parts: posterior, intermediate and anterior zones.

From this model of normal TMJ, three other models were designed, considering the presence or absence of occlusal splints, and presence or absence of anterior displacement of the articular disc. For this, the volunteer also was submitted to a CT scan wearing occlusal splints. The images of this CT scan were analyzed for measuring the upper distance (D1) and anterior distance (D2) of the joint space between the condyle surface and fossa (Figure 2). The following changes were identified: a small increase in the upper joint space; and decrease in the distance previously measured; accompanied by slight rotation of the condyle, due to 2mm thickness of occlusal splints in the molar.

These changes were in agreement with another study that found similar changes in joint space during the use of mouthguards (16). Thus, compared with the original model, the condyle was moved downward and forward 0.4mm and 0.2mm, respectively, for create models with occlusal splint use.

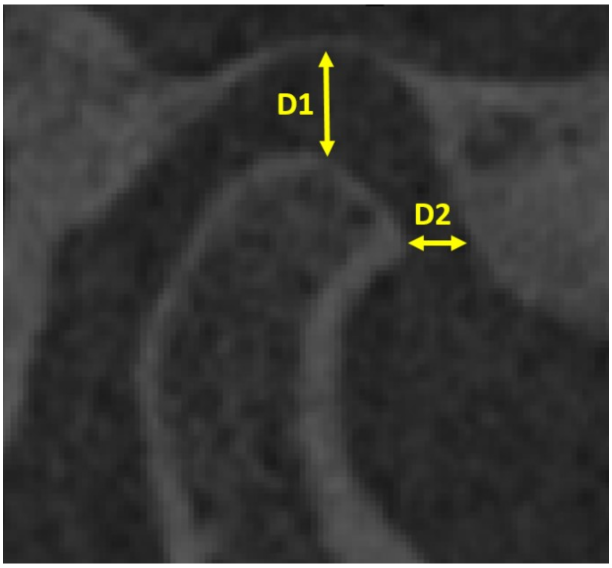

Figure 2: Measurement of the intra-articular spaces between surface of the condyle and the roof of the fossa-articular eminence. D1: upper distance; D2: anterior distance.

For create models with anterior disc displacement, the authors were based on the concept that when the disc posterior band assumes an anterior position to the top of the mandibular condyle in the closed-mouth position, and the limit between disc and retrodiscal tissue is located anterior to the 11:30 clock position, this is considered anterior displacement of the disc (17). Based on this principle, in this study the disc was displaced anteriorly, when compared with the original model.

The total of the four FE TMJ models were created: (A) TMJ with normal disc position and without occlusal splint use; (B) TMJ with normal disc position and with occlusal splint use; (C) TMJ with anterior disc displacement and without occlusal splint use; (D) TMJ with anterior disc displacement and with occlusal splint use.

- Boundary conditions

The model of the temporal bone was restrained for all degrees of freedom, and all structures were modeled as deformable bodies. The mechanical behavior of the bone structures was described with a linear isotropic elastic model. The material properties used in this study were taken from the literature (Table 1) (11). Cortical bone properties were considered for temporal and mandibular bones. The articular disc was treated as incompressible hyperelastic material, and the classical Mooney–Rivlin form was used in this study. Thus, the strain energy equation was given by:

$$U = C_1 (I_1 - 3) + C_2 (I_2 - 3)$$

where U was the strain energy density, I_1 and I_2 were the first and second deviatory strain invariants, and C_1 and C_2 were material constants that were determined from the non-linear stress–strain curves (18).

Table 1: Material properties of FEA models.

Material Properties	*V*	*E (Mpa)*	C_1 *(Mpa)*	C_2*(Mpa)*
Bones	0.3	13700	_	_
Articular Disc	_	_	$9X10^{-1}$	$9X10^{-4}$

The joint was also considered well lubricated, so a friction coefficient of 0.0001 was considered between the disc and the two bone structures (12). Simulation began with a closure of the mandible against the temporal bone in a direction corresponding to the estimated direction of the joint reaction force (19). For a mandibular closure simulation, a displacement of 0.2mm was applied in 1 second in the vertical direction (Axis Y). The present simulation was focused on the response of the articular disc during clenching, similar to the previous study

(20), corresponding to the simplest loading condition of the temporomandibular joint.

The mesh remodeling function was activated for the disc to perform the geometry of the bone in the fossa and in the condyle. The stress distribution in the disc was analyzed by Equivalent von Mises Stress, during 0.2mm of mandibular closure, in 1, 5 and 10 increments. Other stress and strain were performed on the superior and inferior surfaces of the articular disc, considering twenty-seven nodes in the direction from posterior to anterior zone, on each surface after complete mandibular closure.

RESULTS:

The stress distribution on normal disc position and without occlusal splint use is presented in Figure 3A. The Equivalent von Mises Stress in the disc, showed stress concentration in the intermediate to anterior zone of the disc with maximum values of over 2Mpa.

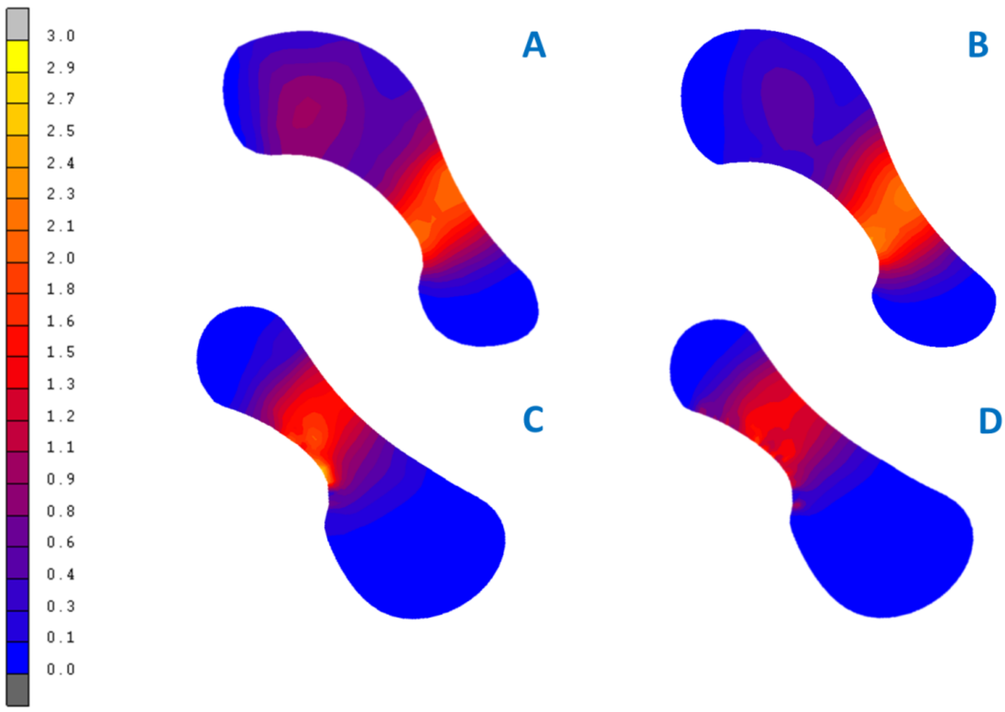

Figure 3: Von Mises Stress distribution in the temporomandibular joint after mandibular closure, in the last increment and in the different models. (A) TMJ

with normal disc position and without occlusal splint use; (B) TMJ with normal disc position and with occlusal splint use; (C) TMJ with anterior disc displacement and without occlusal splint use; (D) TMJ with anterior disc displacement and with occlusal splint use.

Analysis of the disc behavior during all mandibular closure showed different stress distribution in the anterior, intermediate and posterior zone of the disc, subdivided as shown in Figure 1. The von Mises Stress variation (Figure 4) is shown in representative nodes in each of these regions; the most critical region was the intermediate zone, showing values exceeding 2 Mpa.

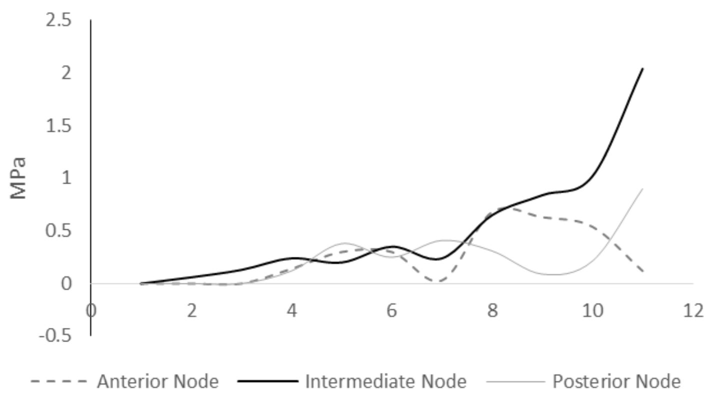

Figure 4: Von Mises Stress variation in representative nodes in the disc during mandibular closure.

The distribution of total strain and equivalent Von Mises stress on both surfaces (inferior and superior) are presented four situations in Figures 3 to 6. The strain distribution on the inferior surface and superior surface was analyzed in the last step (Figure 5). The Equivalent of Total Strain was recorded in these nodes after complete mandibular closure, and the strain values are shown. The strain on the inferior surface was more critical than it was on the superior surface.

The results of the other three models showed no differences in the amount and location of stress when the normal disc position was compared with and without the occlusal splint. The model showed lower stress values in the

TMJ with anterior disc displacement associated with occlusal splint use. In models with disc displacement, the highest stress was shown in the region between the intermediate and posterior zones of the disc (Figure 6).

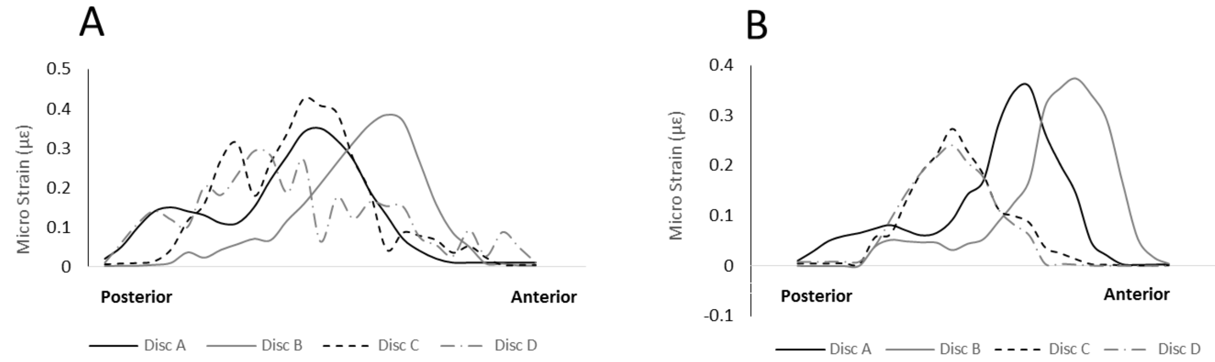

Figure 5: Equivalent of Total Strain distribution on the inferior (A) and superior (B) surfaces of the articular disc, by after complete mandibular closure.

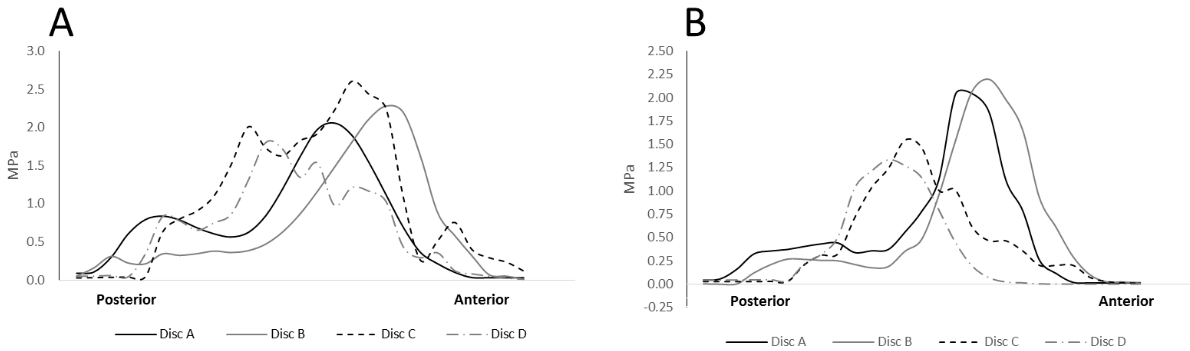

Figure 6: Equivalent von Mises Stress distribution on the inferior (A) and superior (B) surfaces of the articular disc, after complete mandibular closure.

DISCUSSION:

Equivalent von Mises Stress values found in this study (shown in Figure 3A) are similar to those found in a previous study (11), in which the disc was treated as incompressible hyperelastic material, in the classical Mooney–Rivlin form. This indicated that the model was a good representation of the TMJ structures, since it presented feasible results.

Different models have been used to characterize the mechanical properties of the disc. Poroelastic and biphasic models are widely used to represent hyaline cartilages and some studies have used them to describe the articular disc (12,20). However, these may not be the best options for modeling the mechanical response of the TMJ disc, because the concentration of glycosaminoglycans (GAGs) in this fibrocartilaginous soft tissues is lower, which may result in reduced drag between the fluid and solid matrix (21).

The articular disc has been shown to have both viscoelastic and hyperelastic properties and undergoes large deformation (22). Therefore, another form of representation is to consider soft tissues as viscoelastic structures. While it may be an oversimplification to assume the behavior of cartilaginous tissue to be viscoelastic only, for the purpose of a quantitative analysis of TMJ stress, it can allow a good qualitative study to be conducted (14). In this study, the hyperelastic Mooney–Rivlin material model was applied because it behaves most reliably under large deformations. Its hyperelasticity, however, is mainly directed to stretching. On the other hand, the compressive hyperelasticity exhibited by cartilage continues to be underrated (11). In this context, it is observed that there are many ways to represent the disc, but each has limitations that should be carefully considered when interpreting the results.

Maximum peak of the von Mises Stress observed in the intermediate zone has also been mentioned in the previous studies (10-11,14,22). And an anatomical study with a cadaver showed maximum pressure signals in discs located in the intermediate zone during mandibular movements (23). Von Mises analysis may represent predominantly shear stress (14), and this type of stress probably occurs because the joint surfaces and disc are not parallel during compression. As a result, not all areas of the disc are deformed in the same direction, leading to local shear stress (24). Another reason why shear stress occurs in the disc is its non-homogeneous structure (7). In the long-term, the mechanical properties of the disc may be impaired, since excessive shear stresses can cause fatigue and structural damage to the disc (24).

The anterior zone showed stress decreasing at the end of the mandibular closure. The maximum stress (0.68MPa) in this region occurred at the increment 7, reducing at each step. The stress decreasing has been reported (11,14). An explanation for this is the stress relaxation that occurs during progressive mandibular closure, which resulted in a reduction in the peak stress within the disc and in the dissipation of strain energy (10). After stress relaxation, physiological loads allow a biomechanical equilibrium which results in balance between the stress applied and the disc resistance to the generated stress. This behavior explains the performance of the articular disc to absorb and to dissipate the stress generated at the TMJ. Without the dissipation of the stress/strain, the concentration of the excessive energy can lead to breakage the disc and cause damage on the other TMJ components (24).

Stabilization occlusal splints allow bilateral, simultaneous and homogeneous occlusal contacts, and slightly increase the vertical occlusal dimension. A recent literature review stated that the success of occlusal appliances is due to the basic mechanism of neuromuscular reflex and stress reduction in the TMJ (4). The result of the present study agrees with this statement. Although the stress reduction arising from the use of occlusal splints in the cases of disc displacement was small, it should not be overlooked, because the time of analysis was also short. This analysis simulated only mandibular closure, corresponding to the simplest loading condition of the temporomandibular joint. Future studies with time variations are required to simulate the condition of teeth clenching. The limitation of this study was absence of temporal and condylar cartilage layers and retrodiscal tissues, although this simplification did not impair accuracy of the data when compared with other studies in the literature. However, futures studies should simulate these structures, and it is necessary to test other masticatory movements, such as parafunction habits.

Although good clinical outcomes have been observed with use of occlusal splints (2,4), sometimes these devices are not able to correct the disc position (25). The improvement of the signs and symptoms appear to be due to the loss of elasticity, remodeling and adaptation of the posterior disc attachment. The articular disk is a firm but flexible structure, and its morphology can be altered. If the disk is chronically anteriorly displaced, it probably undergoes irreversible morphologic changes losing the elasticity of the posterior band (25). The reduction in stress and strain noted in this study and described by up-to-date literature about use of occlusal splints, suggest that these devices can be a good alternative to protect the articular disc and prevent structural damage or progressive disorders, especially when there is disc displacement in the anterior position.

In conclusion, the null hypothesis of this study was accepted, because the stress in the articular disc was similar in all situations tested. The results presented in this study demonstrated than the FEA model generated and boundary conditions established were suitable for physiological mandibular closure simulations. The stress increased at the intermediate zone of the TMJ disc. The use of occlusal splints tends to reduce stress on the disc anteriorly displace.

RESUMO:

Abordagens conservadoras, incluindo o uso de placas oclusais, são as primeiras opções de tratamento para disfunção temporomandibular (DTM), devido à sua natureza reversível. O presente estudo analisou distribuição de tensões no disco articular variando a posição do disco e o uso de placa oclusal. Um modelo bidimensional (2D) de articulação temporomandibular (ATM) foi desenvolvido para análise por método de elementos finitos, através de imagens de tomografia computadorizada do tipo cone-bean. A partir deste primeiro modelo, em que o disco estava em posição fisiológica, três outros modelos foram criados alterando a posição do disco para simulação do uso de placa oclusal e deslocamento anterior do disco. Uma análise estrutural da distribuição de tensões foi realizada no software Marc-Mentat, e Equivalente de von Mises foi usado para comparar os fatores de estudo. Maior concentração de tensão foi observada na zona intermediária para a zona anterior do disco, atingindo valores máximos acima de 2Mpa. Nenhuma diferença relevante foi verificada na localização e magnitude das tensões quando comparadas as posições dos

disco e presença ou ausência de placa oclusal. No entanto, observou-se uma pequena redução das tensões no modelo que simulou uso de placa em casos de deslocamento anterior do disco, o que deve ser mais bem investigado em estudos futuros. Diante disso, conclui-se que mediante os modelos criados e condições de contorno estabelecidas, as tensões na zona intermediária do disco, de forma geral, aumentam durante o fechamento mandibular.

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Capítulo 2

3.2. Capítulo 2: Artigo será encaminhado para o periódico Journal of Oral Maxillofacial Surgery para publicação.

Title: Temporomandibular joint disc biomechanical behavior: a literature review and 3D FEA.

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Abstract:

Creating a good temporomandibular joint (TMJ) model for finite element analysis (FEA) is challenging due to its complexity. Many biomechanical properties are used by articular discs, which reflect on their behavior when subjected to different loads. However, is necessary to understand when and how these properties should be applied in the best way. In this study a bibliographic search was conducted about articular disc properties applicable to Finite Element Analysis (FEA), and a general approach to three-dimensional (3D) TMJ model generation was described. In the search to find the reviewed manuscripts, the combined MeSH and Entry terms and the Pubmed / MEDLINE filter for experimental studies or FEA were used. Inclusion and exclusion criteria were used to select only relevant manuscripts. A 3D-finite element model of the temporomandibular joint, with the articular discs in their physiologic positions, was constructed based on cone-beam computed tomography. The model geometry and mesh were obtained by MIMICS software, and structural stress distribution analysis was performed using the Marc-Mentat package. At the end of the review, 63 articles published between 1994 and 2015 were included, 42 were studies that developed FEA, 18 were experimental tests and 3 literature reviews. Different properties, models and values were identified in FEA studies that treated the disc as linear elastic (43%), nonlinear (12%), hyperelastic (12%), viscoelastic (21%) and poro-hyperelastic material (12%). The 3D-FEA showed higher stress concentration on the lower surface of the articular disc. The zones more affected were intermediate zone in the anteroposterior direction and the central zone in the mediolateral direction. In conclusion, many ways of representing the disc were observed, but each has limitations that should be carefully considered when interpreting the results. The FEA model

generated and boundary conditions established were suitable for physiological mandibular closure simulations.

Key words: temporomandibular joint, temporomandibular joint disc, finite element analysis.

Introduction:

Composed of the mandibular condyle and articular fossa–eminence, the Temporomandibular Joints (TMJ) have the peculiarity of being the only bilateral linked joints of the human body. Both TMJs are necessary for mastication, swallowing, speech and facial expressions,[1] and must function at the same time.[2] Between the condyle and the articular fosse, there is the articular disc, a fibrocartilage that facilitates the movement between the mandible and the temporal bone. It acts as a load absorber and distributing it load over a larger contact area in order to prevent damage to articulating surfaces. This is important for maintaining the stomatognathic system healthy, because articular disc alterations can lead to temporomandibular disorders (TMD).[3, 4]

Rotating with slightly lateral excursion occur simultaneously between articulating surfaces during mandibular movements, so the articular disc is subjected to different loading regions.[5] Although compression, tension and shear loads can be observed, the combination of these types of loading is what happens in physiological TMJ movements.[5, 6] The loads can also be classified as dynamic and static, where clenching and grinding represent static loads, and talking and chewing represent dynamic loads.[7]

The type of load and biomechanical properties, such as stiffness and strength, directly influence the magnitude of the strain and resulting stress on disc.[7] The mechanical properties are dependent on the composition of the disc with respect to the amount and orientation of the collagen fibers, composition and organization of proteoglycans and interaction of these molecules with the fluids.[7] To maintain the integrity of the disc during function, its collagen fibers are arranged circumferentially and antero-posteriorly, which results in a tissue with anisotropic characteristic under tension and shear.[8] The high viscosity of the proteoglycan molecules gives this disc greater stiffness and resistance to the compressive loads. For this, these loads tend to concentrate in regions of higher loading.[7] Thus, under physiological conditions the disc is able to act in the absorption and distribution of stresses, thereby preventing degenerative diseases.

Analysis of stresses and strains in the articular disc in vivo it is not advisable, because the use of experimental devices, such as strain gauges within the joint would introduce damage to its tissues.[9] Therefore, computational studies of the TMJ have been shown to be a powerful tool to predict the biomechanical behavior of this joint.[4, 9-15] Although, some authors have simulated physiological mandibular movements and prolonged tooth clenching [10,13], the biomechanical behavior of the TMJ disc has not yet been completely understood. In this context, there are still no universally agreed values for TMJ loading conditions for maintenance or hazard, [6, 10] being the articular disc characterized as isotropic elastic, poro-hyperelastic, hyperelastic and viscoelastic material.[11-14]

Creating a replicated biomechanical model of the masticatory system is a challenge. The degree of simplification of the model is difficult to establish, because computational and time limitations do not allow the masticatory system to be modeled in all of its known complexity.[14] Nevertheless, in recent years an improvement in TMJ representation has been noted for optimizing assessment of the physiological and pathologic strains on the joint disc,[16] and several models have been used to generate more realistic behavior. However further developments are still necessary. In this context, the aim of this study was to know the properties used for articular disc in other FEA studies by means of a bibliographic survey of the literature, and based on this, develop an accurate 3D computational model of a normal TMJ, by the Materialise Interactive Medical Image Control System (MIMICS).

Material and methods:

- Literature search strategy:

The PubMed-Medline database (United States National Library of Medicine, National Institutes of Health, Bethesda, Maryland) was electronically searched for articles published up until April 7, 2016. The search strategy included MeSH terms and Entry terms related to biomechanical properties and behavior of the articular disc. The terms were combined with the Pubmed / MEDLINE filter for experimental studies or finite element method. There were no restrictions about the date of publication. Manual search was also designed to add other relevant articles.

The inclusion criteria were:

(a) Articles with reference values for biomechanical properties of articular disc for application in FEA;

(b) Literature review that discussed the composition and biomechanical behavior of the articular disc;

(c) Experimental studies based on human or porcine disc.

The exclusion criteria applied were:

(a) Articles published in a language other than English;

(b) Studies about other soft tissues of TMJ, such as cartilage or retrodiscal tissues;

(c) Clinical studies;

(d) Studies based on tissue engineering, and

(e) Studies that did not have a clear methodology.

All titles and abstracts obtained in this search were independently analyzed by two reviewers based on the inclusion criteria. Disagreements were resolved by a third expert reviewer, and then the full versions of all articles considered suitable for review were obtained. These were read in full, and the data of those that met the inclusion criteria were collected for qualitative analysis.

-Finite element model generation:

This study was approved by Ethics Committee of the Federal University of Uberlândia (83073/2014), before the study began. A three-dimensional TMJ model was obtained from the cone-beam computed tomography (CT) image of the right TMJ of an adult female volunteer (aged 28 years) with no present or past history of TMJ disorders. The 432 slices of the skull and mandible, and images with a resolution of 0.2X 0.2X0.2mm voxels were obtained. The bone structures of the TMJ were identified using an interactive medical image control system (MIMICS 16.0, Materialise, Leuven, Belgium), and segmentation of these structures was achieved with a tool based on image density thresholding. The bone structures were individualized by Boolean operations, and three masks were generated (temporal bone, mandibular cortical and mandibular medullary bone). The upper and lower boundaries of the disc were shaped according to the upper and lower articular surfaces, because they were not visible in the images for segmentation. A disc mask was created and for each mask, a stl* file was generated.

A mesh was generated and improved by the Remesh component present in MIMICS software, and an advanced stl* design and meshing software (3-Matic 8.0; Materialise, Leuven, Belgium). Each stl* file was individually improved and later a single definitive stl* file was obtained with volumetric meshes. This file was entered into MSC.Marc (MSC Software Corporation, Santa Ana, CA, USA) for analysis (Figure 1).

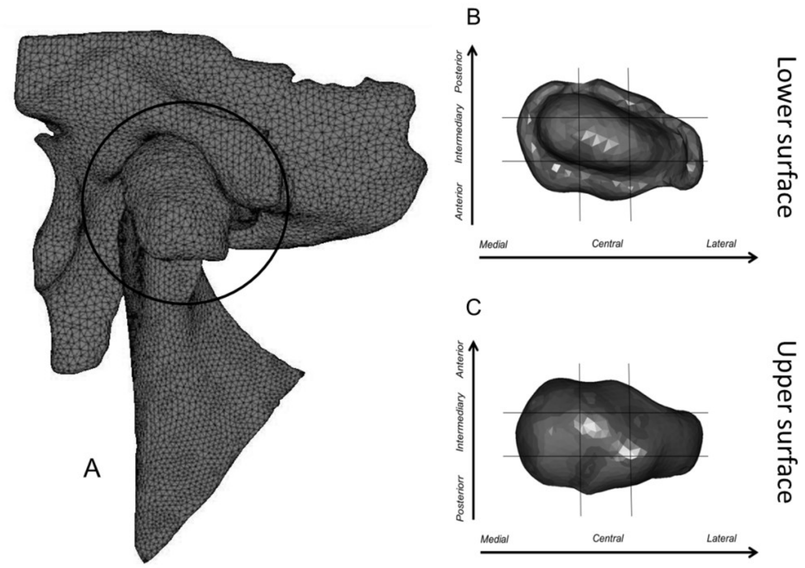

Figure 1: A- Numerical model; B and C- division of the articular disc into three zones in antero-posterior direction (anterior, intermediary and posterior) and three zones in the mediolateral direction (medial, central and lateral), on the lower and upper surface, respectively.

-Boundary conditions

The model was restrained in the area of the temporal bone at all degrees of freedom, and all structures were modeled as deformable bodies. The mechanical behavior of the bone structures was described as a linear isotropic elastic model. The material properties used in this study were taken from the literature (Table 1).[12] The articular disc was treated as incompressible hyperelastic material, and the classical Mooney–Rivlin form was used in this study. Thus, the strain energy equation was given by:

$$U = C_1 (I_1 - 3) + C_2 (I_2 - 3)$$

where U was the strain energy density, I1 and I2 were the first and second deviatory strain invariants, and C1 and C2 were material constants that were determined from the non-linear stress–strain curves.[12] Retrodiscal tissues were not modeled, but their function was simulated by springs positioned with similar orientation to those of the tissues and equivalent stiffness 6,5N / mm.

Table 1: Mechanical Properties of the materials:

PROPERTIES	ν	E(Mpa)	C_1(Mpa)	C_2(Mpa)
Mandibular cortical bone	0,3	13700	_	_
Mandibular medullary bone	0,3	7900		
Articular disc	_	_	$9X10^{-1}$	$9X10^{-4}$

The joint was also considered well lubricated, so a friction coefficient of 0.0001 was considered between the disc and the two bone structures.[13] Simulation began with closure of the mandible against the temporal bone in a direction corresponding to the estimated direction of the joint reaction force.[17] For a mandibular closure simulation, a displacement of 0.2mm was applied in 1 second in the vertical direction (Axis Y). The present simulation was focused on the response of the articular disc during clenching, similar to the situation in a previous study,[19] corresponding to the simplest loading condition of the temporomandibular joint.

For the disc, the mesh remodeling function was considered to adapt the disc geometry to the bone in the fossa and condyle. The stress distribution on the disc was analyzed by Equivalent von Mises Stress after mandibular closure. To facilitate stress visualization, the disc was subdivided into 3 zones in antero-posterior direction (anterior, intermediary and posterior) and 3 zones in the mediolateral direction (medial, central and lateral) (Figure 1).

Results:

-Review of articular disc properties used in FEA:

The electronic search with MeSH and Entry terms resulted in 209 articles, and another 6 studies found by manual search were added, totaling 215 articles. After reading the titles and abstracts, 97 articles met the inclusion criteria, but the full version of only 90 was available in the database. After reading the articles, 27 were excluded. Among the 63 that remained in the research, 42 were studies that developed the FEA (Table 2), 18 were experimental tests, and 3 reviews of the literature.

Among the studies that carried out FEA (published between 1994 and 2015), different properties, models and values were identified in articles that treated the disc as linear elastic (43%), nonlinear (12%), hyperelastic (12%), viscoelastic (21%) and poro-hyperelastic material (12%).

-Finite element model generation:

The highest stress magnitude observed in this study was approximately 1.34Mpa on the lower surface of the disc (Figure 2). The stress was prevalent in the intermediate zone of the disc in antero-posterior direction on the lower surface, and in anterior zone on the upper surface. In the mediolateral direction, high stress values were observed in the central zone on both surfaces.

Table 2: Disc articular properties used in previous FEA studies.

Reference	*Disc articular properties*	*Model details and reference values*
Linear elastic models		
Tanne et al. (1996) 20 Nagahara et al. (1999) 21 Tanaka et al. (2000) 22 Tanaka et al. (2001) 23 del Pozo et al. (2003) 24 Tanaka et al. (2004) 25 Sun etal. (2015) 26	Isotropic	E= 44.1 MPa / *v*=0.4
DeVocht et al. (1996) 27	Isotropic	E= 1.8 a 100 MPa / *v*=0.4
Beek et al. (2000) 9 Kim et al. (2012) 28	Isotropic	E= 6 MPa / *v*=0.4
Beek et al. (2001) 29	Homogeneous, Isotropic	E= 0.068; 0.68; 68.0; 6.80MPa/ *v*=0.4
Pileicikiene et al. (2007) 30	Isotropic	E= 30.9MPa / *v*=0.4
Jirman et al. (2007) 31	Homogeneous, Isotropic	E= 16MPa / *v*=0.45
Gupta et al. (2009) 32 Shrivastava et al. (2015) 33	Isotropic	E= 10MPa (anterior zone); 10.73MPa (intermediate zone); 9 (posterior zone) / *v*=0.4
Savoldelli et al. (2012) 16 Murakami et al. (2013) 34	Isotropic	E= 40 MPa / *v*=0.4
El-Zawahry et al. (2015) 35	Homogeneous, Isotropic	E= 6.82MPa / *v*=0.4
Nonlinear elastic models		
Tanaka et al. (1994) 36 Tanne et al. (1995) 37 Hu et al. (2003) 38 Liu et al. (2007) 39 Cheng et al.(2013) 40	Nonlinear	E= 44.1 MPa (stress<1.5Mpa); E= 92.4MPa (stress>1.5Mpa) / *v*= 0.4
Hyperelastic models		
Chen et al. (1998) 17	Nonlinear; Hyperelastic material	Modelo Mooney-Rivlin: C1= 27.91MPa ; C2= -20.81MPa
Koolstra & van Eijden (2005) 12	Nonlinear; Incompressible hyperelastic material	Modelo Mooney-Rivlin: C1= $9X10^5$Pa ; C2= $9X10^4$Pa
Palomar & Doblare (2008) 41	Nonlinear; Incompressible hyperelastic material	Modelo Mooney-Rivlin: C1= $9X10^5$MPa ; C2= $9X10^4$MPa
Jaisson et al. (2012) 42	Nonlinear; Hyperelastic material	Green-Lagrange/Piola-Kirchoff c_0= 1; c_1= 0; c_2=10^4; c_3=10^4

Savoldelli et al. (2012B) 43	Nonlinear; Incompressible hyperelastic material	Modelo Neo-Hookean C= 7.14
Viscoelastic models		
Koolstra & van Eijden (2007) 44	Nonlinear, viscoelastic	Modelo Maxuell com Mooney-Rivlin de 2ª ordem: G_0=0.65MPa. G_1=0.33MPa. G_2=0.3MPa. G_3=0.42MPa. G_4=0.9MPa. τ_1=10s. τ_2=1s. τ_3=0.1s. τ_4=0.01s.
Tanaka et al. (2008) 10	Linear, viscoelastic	Modelo Kelvin: v=0.4; E_R= 16.1Kg/mm^2; τ_ε=31.2s; E_0= 31.5Kg/mm^2
Koolstra & Tanaka (2009) 45	Nonlinear, viscoelastic	Modelo Maxuell com Mooney-Rivlin de 2ª ordem: G_0=0.4MPa. G_1=0.5MPa. G_2=0.5MPa. G_3=0.72 MPa. G_4=2.5MPa. τ_1=50s. τ_2=5s. τ_3=0.2s. τ_4=0.005 s.
Hirose et al. (2006) 11 Nishio et al. (2009) 46 Mori et al. (2010) 15 Abe et al. (2013) 47 Hattori-Hara et al. (2014) 48	Linear, viscoelastic	Modelo Kelvin: v=0.4 E_0= 30.9Mpa; E_R= 15.8Mpa; τ_ε =31.2s
Commisso et al. (2014) 49	Quasi-linear, viscoelastic	Modelo Fung: g_1=0.20; g_2=0.37; g_3=0.27; g_4=0.08; τ_1=0.01s. τ_2=0.1s. τ_3=1s. τ_4=10s. A=0.16Mpa; B=4.18; D_1=0.01MPa^{-1}
Porohyperelastic Models		
del Palomar & Doblaré (2006a) 13 del Palomar & Doblaré (2006b) 19 del Palomar & Doblaré (2007a) 50 del Palomar & Doblaré (2007b) 51 del Palomar et al. (2008) 52	Nonlinear Fiber-reforced Porohyperelastic	C_1= 0.77MPA; k_1=0.6Mpa; K_2= 79.8; D= 1.41MPa^{-1}; k=7.51E-15m^4/Ns; φ_0^f=0.2; M=4.638; L=0.0848

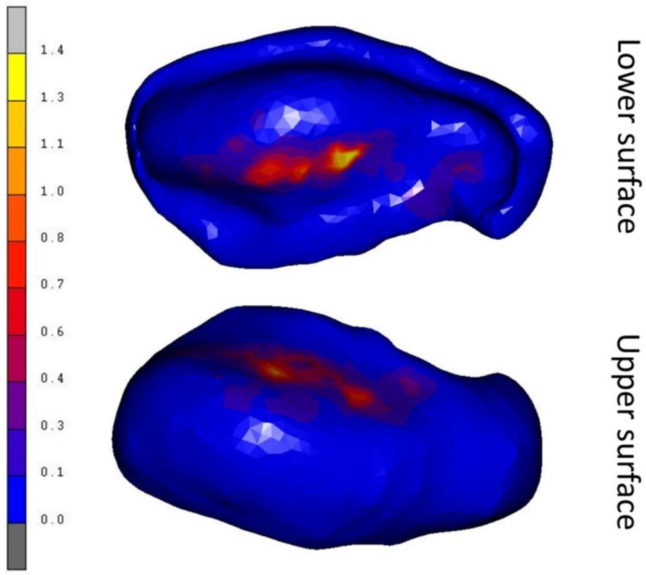

Figure 2: Von Mises Stress distribution in lower and upper surface of the temporomandibular joint disc, after mandibular closure simulation.

Discussion:

Extracting reference values from the experimental studies for application in FEA became difficult due to the variability of methodological conditions used by each author. Several study factors were identified, such as: treatment of specimens;[53] indentation frequency;[5] disc characteristics and behavior resulting from shearing, compression, tension and friction tests;[2-3,54-66] porosity; solute transport and electrical conductivity.[67] However, these studies in conjunction with the literature review studies provided an understanding of disc behavior in different situations, and interaction of the behavior with its constitution.

Considering the articular disc as linear elastic material was the simplest way to characterize it. When the influence of the velocity and subsequent cycles were not investigated, and small deformations on the disc were assumed, using a linear law behavior could be appropriate. Whereas, in analyses involving large deformations, the use of non-linear elastic behavior would be required.[16] An evolution in disc characterization was the development of a model that represented the interaction between fluid and solid constituents as a biphasic or poro-elastic model that accounted for the shock-absorbing properties of the disc.[7] This type of model was also used to represent hyaline cartilages, however, it was not the best option for modeling the mechanical response of the

TMJ disc, because the concentration of glycosaminoglycans (GAGs) in this fibrocartilaginous soft tissues was lower, which could result in reduced drag between the fluid and solid matrix.[68] Another representation was the fiber-reinforced poro-hyperelastic model, but this also had limitations, since the collagen fibers of the disc were not uniformly arranged. This reflected on the behavior of the disc when subjected to traction or shearing loads, because it did not react in the same way in all regions.[42]

Perhaps, the ideal for TMJ disc would be to obtain a viscohyperelastic model. Thus, it would associate hyperelasticity, which would provide a good description of the disc behavior to a large scale of strain; and viscoelasticity for describing time-dependent characteristics.[69] As a viscoelastic material, the disc showed immediate strain after loading, followed by a time-dependent creep or stress relaxation phase, which enhanced the strain and decreased the stress. Creep was defined as the strain over time with constant stress; stress-relaxation was the decrease in stress over time with constant strain.[7] Although most of the authors of the articles included in the present review considered the discs only as viscoelastic structures, this could be a simplification for the purposes of a quantitative TMJ stress analysis, but it allowed good qualitative analysis. In this study, the hyperelastic Mooney–Rivlin material model was applied because it behaved most reliably under large deformations. Its hyperelasticity, however, was mainly directed to stretching. On the other hand, the compressive hyperelasticity exhibited by cartilage continued to be underrated.[12] In this context, many ways of representing the disc were observed, but each had limitations that should be carefully considered when interpreting the results.

In this study, the maximum stress value of 1.34MPa was observed on the lower surface of the articular disc Figure 2. This value was slightly lower, but within the same order of magnitude as that found in a previous study which also considered the disc as incompressible hyperelastic material by applying the classic form of Mooney-Rivlin.[12] Ain in-depth quantitative comparison with previous FEA studies was difficult because the simulation conditions varied among models.

Qualitative von Mises analysis showed higher stresses on the lower surface than on the upper surface. The exact point of stress concentration was found in the intermediate zone in the anteroposterior direction, and in the central zone in the mediolateral direction. This was also described in previous studies,[1, 4, 11-12, 15, 29] and was in agreement with an anatomical study conducted with cadavers that showed signs of maximum pressure on the disc exactly in this region, during mandibular movements.[70] Von Mises analysis may predominantly represent shear stress,[15] and this type of stress probably occurred because the joint surfaces and disc were not parallel during compression. As a result, not all areas of the disc were deformed in the same direction, leading to local shear stress.[7] Another reason why shear stress occurred on the disc was because of its non-homogeneous structure.[6]

The orientation of the collagen fibers in the disc was determined by the type of load to which the zones were submitted. In the intermediate zone, the collagen fibers were oriented anteroposteriorly, which provided the disc with higher tensile strength in this direction than in the mediolateral direction.[7] Proteoglycans contributed to the viscoelasticity of the TMJ disc,[6] and provided more resistance to compression. The large proteoglycan molecules were predominant in the central part of the intermediate zone, while in the lateral and medial regions of the intermediate zone, where the compressive modulus was smaller, there was predominance of small proteoglycans. Thanks to this constitution, the disc was capable of adapting its shape between the articular surfaces, when it was not deformed beyond the physiologic strain range.[6-7]

A limitation of this study was absence of temporal and condylar cartilage layers. However, the presence of cartilage promoted little stress reduction on the disc when the situation was simulated in a previous study.[38] Nevertheless, future studies should simulate these structures and test other masticatory movements, such as parafunction habits. In conclusion, this study demonstrated than the FEA model generated and boundary conditions established were suitable for physiological mandibular closure simulations. The increased stress in the intermediate zone was representative of the physiological behavior of the TMJ disc under this loading condition. In addition, the bibliographic survey about articular disc properties was enlightening with regard to the development of this and future studies by FEA.

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Capítulo 3

3.3. Capítulo 3: Artigo será encaminhado para o periódico Jornal of Oral Rehabilitation para publicação.

Title: Can occlusal splint influence the stress and strain distribution on temporomandibular joint disc?

Running head: Occlusal splint effect on the articular disc

Original research

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Abstract

Clinically, occlusal stabilization splints are indicated to maintain or restore the health of the stomatognathic system in cases of parafunction and temporomandibular disorders (TMD). Biomechanically, their action and effect on the temporomandibular joint (TMJ) disc are still unclear. The present study analyzed the effect of occlusal splints on stress and strain distribution on TMJ disc after simulating mandibular closure. A three-dimensional finite element model of the skull and jaw bones, with interposition of both articular discs was created based on cone-beam computed tomography. Arigid occlusal splint was simulated by creating three rigid elements between the maxillary and mandibular central incisor teeth. Afterwards, the mandibular closure was induced by muscle forces, with and without splint. Structural stress and strain distribution analysis was performed using the Marc-Mentat package. Higher stress concentration was observed on the right disc without occlusal splint, with maximum values of 9Mpa. The discs presented different behaviors considering use of the occlusal splint. On the right disc there was a slight decrease in stress and strain magnitude, while the left disc showed higher values with splint. However, the differences were small; stress localization followed the same distribution pattern, and the discs showed similar stress and strain values with occlusal splint use. In conclusion, although the splint did not significantly reduce the stress and strain generated on the disc after mandibular closure, it promoted a better distribution of loading between the right and left articular discs.

Keywords:

temporomandibular joint, temporomandibular joint disc, occlusal splints, finite element analysis.

Introduction:

With the purpose of maintaining or restoring the health of the stomatognathic system health, the use of occlusal splints is indicated for several situations such as: to promote a harmonious maxillomandibular relationship; redistribute occlusal forces; prevent mobility and accentuated dental wear; treat different manifestations of temporomandibular disorders (TMD); change the relationship between temporomandibular joint (TMJ) components, and parafunctional control (1-3). These appliances make patients aware of their parafunctional habits and promote a more comfortable mandibular position, with elevator muscle relaxation and joint stabilization (1,4-5).

The use of occlusal stabilization splints results in rotation of the condyle towards the mandibular opening, associated with a condylar displacement in an anteroinferior direction (6,7). Previous studies have suggested that the stabilization splint raised the occlusal plane uniformly, shifted the vector of the bite force distally, and decreased the length of the resistance arm relative to the effort arm, thereby sharply reducing the force directed on the TMJ (1,8). As result, such splints could act to decompress the TMJ (1).

Although many studies have been conducted about the mechanism of action of occlusal splints (1,6,7,9-13), there is still insufficient scientific evidence to explain their action in the intra-articular space. The interocclusal appliance reduces intra-articular pressure in the upper compartment of the TMJ, and intra-articular pressure is an important determinant of joint maintenance and performance (8). Studies that have evaluated the use of occlusal stabilization splints in TMD cases identified pain relief in some type of manifestation of this disorder, and increase in the ranges of condylar translation. The authors attributed these results to different factors such as: increased blood supply due to the widening of joint space and elastic tissues in the deeper layer that expanded the internal space of the plexus (7,15); neuromuscular balance, lowering disc adhesion; adaptive remodeling of the posterior attachment and shifting the range of disc mobility (9,13).

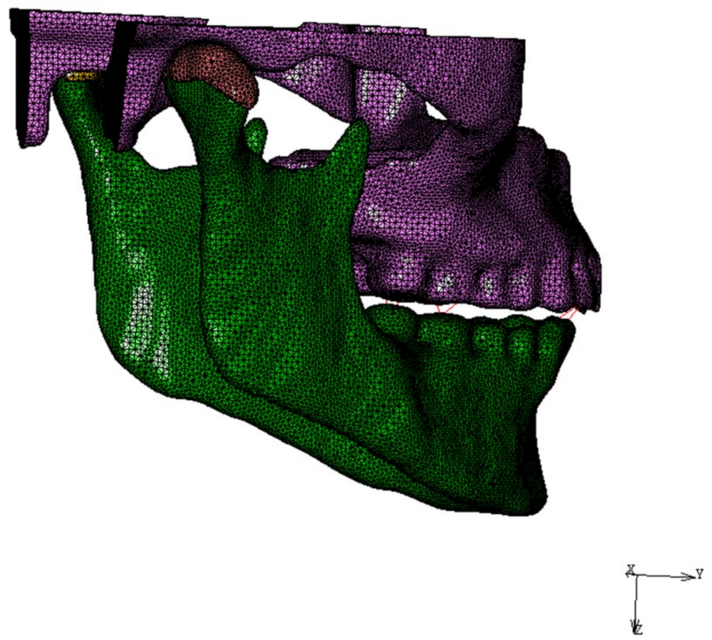
Occlusal splints have been considered to reduce stress in the temporomandibular joint secondary to change in the position of the mandible (12,13). Analysis of stresses and strains on the articular disc in vivo it is not advisable, because the use of experimental devices, such as strain gauges, inside the joint would introduce damage to its tissues and biomechanical behavior (16). Therefore, computational studies of the TMJ have been shown to be a powerful tool to predict the load on this joint (16-22). Some authors have simulated physiological mandibular movements and prolonged tooth clenching (17,20). However, no previous research that evaluated the efficacy of occlusal splints on reducing TMJ stress was found in the literature search of the present study. In this context, the aim of this study was analyzed the effect of occlusal splints on stress and strain distribution on TMJ disc after simulating mandibular closure. The hypothesis was that the stress and strain in the articular disc would be the same in all cases.

Material and Methods:

Finite element model generation:

This study was approved by Ethics committee (83073/2014),before the study began. The TMJ model was obtained from a cone-beam computed tomography (CT) image of an adult female volunteer (aged 28 years) with no present or past history of TMJ disorders. The 432 slices of the skull and mandible, and images with a resolution of 0.2X 0.2X0.2mm voxels were obtained. The bone structures of the TMJ were identified using software for processing 3D image data that offers image visualization, analysis, segmentation and quantification tools (ScanIP, Simpleware, Exeter, UK), and the segmentation of these structures was done with a tool based on image density thresholding. The individualization of the bone structures was performed by boolean operations, and three masks were generated (skull bone, mandibular cortical and mandibular medullary bone). The upper and lower boundaries of the discs were shaped according to the upper and lower articular surfaces, because these were not visible in the images for segmentation. Two disc masks were created and for each mask, a stl* file was generated.

A mesh was generated and improved by the Scan FE software (Simpleware, Exeter, UK). Subsequently, the final mesh was entered into MSC.Marc (MSC Software Corporation, Santa Ana, CA, USA) for analysis (Fig. 1). Altogether, bones and articular discs were discretized into 707229 elements.



Three-dimensional finite element model of skull and mandible, including temporomandibular joints and articular discs, obtained by ScanIP and ScanFE software programs.

Boundary conditions

The model was restrained in the area of the skull at all degrees of freedom, and all structures were modeled as deformable bodies. The mechanical behavior of the all structures was described with a linear isotropic elastic model. The material properties used in this study were taken from the literature (Table 1) (19, 23).

Table 1: Material properties of FEA models.

Material Properties	ν	E *(Mpa)*
Mandibular cortical bone	0,3	13700
Mandibular medullary bone	0,3	7900
Articular Disc	0,4	44,1

The joint was considered well lubricated, so a friction coefficient of 0.0001 was determined between the disc and the two bone structures (20). The actions of the masseter, temporalis, and medial pterygoid muscles were applied to the model at their insertion points for the mandibular closure simulation. The masseter was divided into deep and superficial parts, and temporalis muscles were divided into anterior and medial parts, depending on the direction of their fibers. The load magnitudes in each direction are shown in Table 2. The intensities of the muscle actions applied were calculated in previous in vivo study (24). The insert regions of the muscles were almost symmetrical and have been described in previous studies (23).

Table 2: Muscular actions in FEA models.

Muscles	Load (N)		
	X	*z*	*Y*
Deep masseter	7,78	-127,23	22,68
Superficial masseter	12,87	-183,50	12,11
Medial pterygoid	140,38	-237,80	-77,30
Anterior temporalis	0,06	-0,37	-0,13
Medial temporalis	0,97	-5,68	-7,44

Two simulations were performed: model with splint and without splint. Although the occlusal splint was not modeled, three rigid elements were interposed between the maxillary and mandibular molars bilaterally and between the maxillary and mandibular central incisor teeth. These elements formed a stability triangle that prevented mandibular closure during the application of muscle forces. This condition acted as a rigid acrylic occlusal splint. For simulation of mandibular closure without splint, these rigid elements were removed, allowing contact between maxillary and mandibular teeth.

The mesh remodeling function was considered for the discs to adapt the geometry of discs to the bone in the fossa and condyle. The stress distribution in the disc was analyzed by Equivalent von Mises Stress, and strain was analyzed by Normal Total Strain after mandibular closure. To facilitate visualization of the stress and strain, the disc was subdivided into 3 zones in the antero-posterior direction (anterior, intermediary and posterior) and 3 zones in the mediolateral direction (medial, central and lateral).

Results:

In this study, a maximum stress value of approximately 9MPa was observed on the lower surface of the right articular disc, without occlusal splint use (Fig. 2). The stress was prevalent in the posterior zone of the disc in the antero-posterior direction, with additional points of concentration in anterior and intermediary zones. In the mediolateral direction, high stress values were observed in the medial, central and lateral zones of the right disc without splint use, while in the presence of the splint, the stress concentration was prevalent in the lateral zone. The left disc showed higher stress values in the posterior and intermediary zones in the antero-posterior direction, and in the medial zone In the mediolateral direction.

The discs presented different behaviors considering use of the occlusal splint. The right articular disc presented a slight decrease in stress magnitude with the use of splint, while the left disc showed higher stress values on the lower surface with occlusal splint use, according to Equivalent von Mises Stress. However, the differences were small and the stress localization followed the same distribution pattern. The discs showed more homogeneous stress and strain generation with use of the occlusal splint, therefore, its use had no significant influence on the magnitude of stress on the disc surfaces, but it promoted better stress distribution between the discs.

The strain values on the lower and upper surfaces were analyzed on conclusion of mandibular closure (Fig. 3). The strain on the lower surface was more critical than it was on the upper surface. The strain values decreased with use of the occlusal splint, when the right articular disc was analyzed. For the left disc, a small increase in strain was observed with use of the splint.

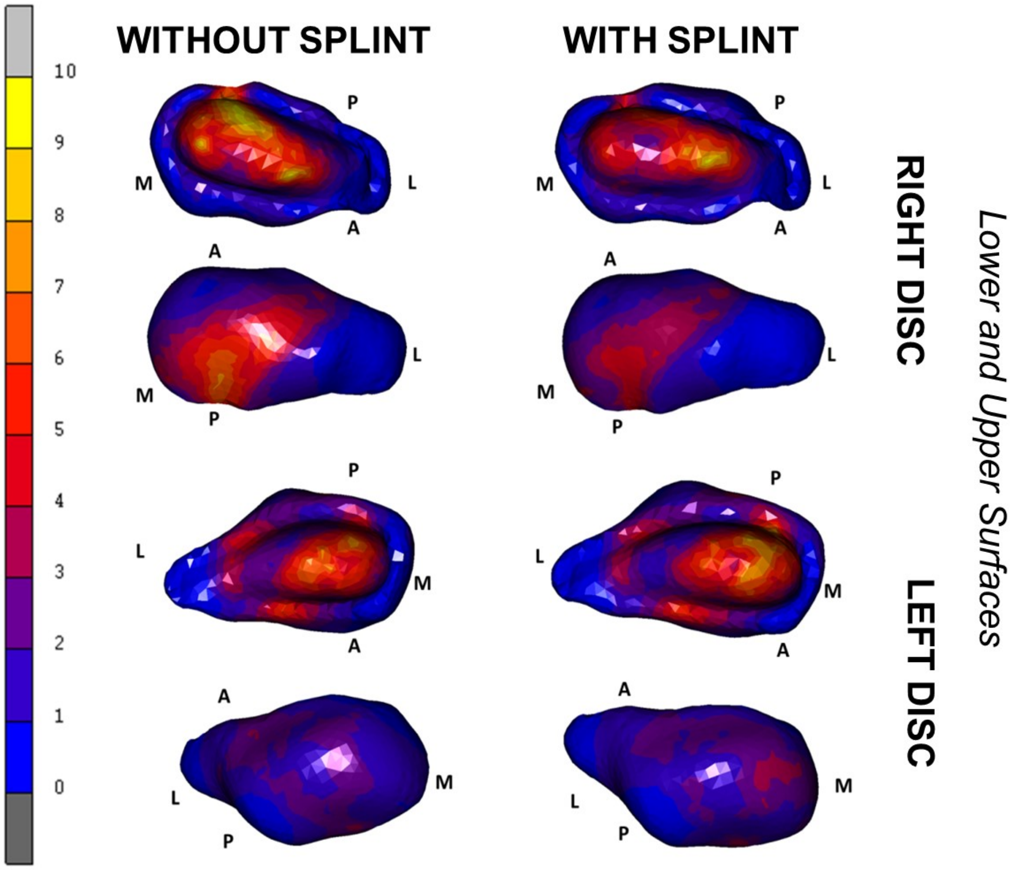


Fig. 2: Equivalent von Mises Stress distribution on the lower and upper surfaces of the articular discs, with and without occlusal splint use, after complete mandibular closure.

The strain values on the lower and upper surfaces were analyzed at the final of the mandibular closure (Fig. 3). The strain on the lower surface was more critical than it was on the superior surface. The strain values decreased with use of the occlusal splint, when the right articular disc was analyzed. In the left disc, was observed a small increased of the strain with splint use.

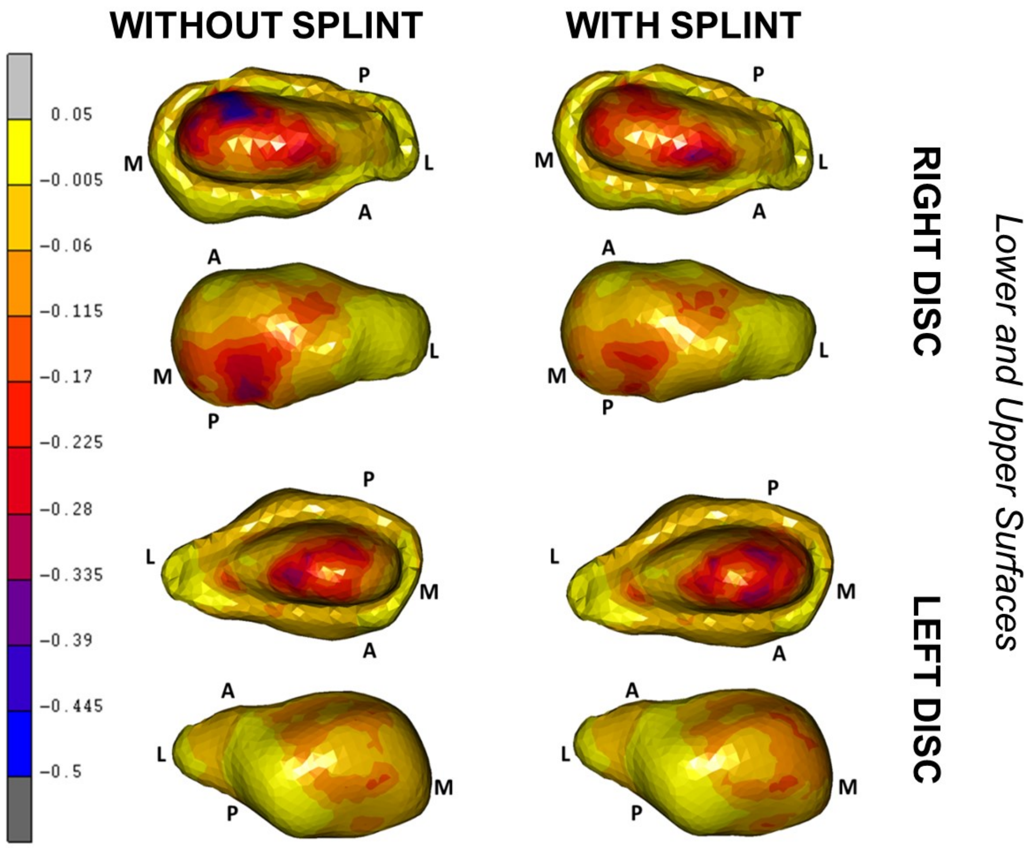


Fig. 3: Normal Total Strain distribution on the lower and upper surfaces of the articular discs, with and without occlusal splint use, after complete mandibular closure.

Discussion:

The hypothesis of this study was rejected, because although the articular discs presented divergent behaviors relative to occlusal splint use, the splint promoted a more homogeneous stress and strain distribution when left and right discs were compared.

As far as we know, the present study is a precursor in finite element analysis of the temporomandibular joint with simulation of occlusal splint use. Thus, to compare the results of this study with previous studies is difficult, because different types of models, joint component properties and boundary conditions could be found. This reflects the wide variety of stress and strain values obtained by different criteria (16-22). However, the literature allows us to understand the results when stress localization and joint disc behavior are analyzed. In general, higher stress values are found on the lower surface of the articular disc [18,19,22]. A study conducted with cadavers showed signs of maximum pressure on the lower surface of the disc during mandibular movements (25), in agreement with the most critical strain values found in this region, in the present study.

The medio-lateral and antero-posterior analysis of both articular discs showed that without occlusal splint use they did not follow a pattern of stress and strain distribution, characterizing an asymmetric function. The higher the magnitude of stress, the more were the stress points localized on the right disc. The three-dimensional model generated in the present study was obtained from real images of a healthy individual. The TMJ anatomy is complex and naturally asymmetric, so the stress and strain on the surface of each articular disc were expected to be slightly different. This heterogeneous result has previously been described by other authors (26-28), and one of the causes indicated for this is the application of non-symmetrical forces, which may be associated with functional asymmetries, such as muscular function asymmetry or unilateral chewing habits that may induce morphological asymmetry (28). In this study, as in a similar previous study, the results did not suggest functional asymmetry, since the muscular actions applied to the models were of the same intensity on both sides, but rather to possible morphological asymmetry inherent to the volunteer.

Although the articular discs behaviors differed with and without occlusal splint use, with reduced stress on the right disc, and greater stress on the left disc, a more homogeneous stress and strain distribution was observed on both the upper and the lower surfaces when the articular discs were compared.

Successful therapy with the occlusal stabilization splint is due to the occlusal stability that promotes better distribution of abnormal forces, reducing the risk of overload on the masticatory muscles and TMJ (7). The use of occlusal stabilization splint leads to changing the condylar position, resulting in decompression of the TMJ, and reestablishing the ideal disc-condyle relationship (1,6,7,12). Thus, the splint seemed to stabilize the joint while simultaneously stabilizing the occlusion, causing a more symmetrical stress and strain distribution on the discs, than the situation occurring in the absence of splint. If this does occur, the splint may prove more protection and keep the articular discs healthy, especially in patients with parafunctional habits. However, in this study only the mandibular closure was simulated, additional analyses of other movements need to be performed in the future to substantiate the conclusions on this issue.

Biomechanical model generation of the masticatory system is challenging. The degree of simplification of the model is difficult to establish, because computational and time limitations do not allow the masticatory system to be modeled in all of its known complexity (21). Over the years, advancements have been noted in TMJ representation for improving analysis of the physiological and pathologic strains on the joint disc (28), and several models have been developed to create more realistic behavior. In the present study a three-dimensional model, with both TMJ and a high level of anatomical accuracy, was constructed from images that allowed visualization of the real geometries. Cortical and medullary bones were considered for the mandible and the mechanical behavior of the all structures was described with linear isotropic elastic materials. Although the disc has a more visco-hyperelastic behavior (29), the present simulation did not consider a large scale of strain and the time-dependent characteristics of the disc. Thus, the linear behavior law was appropriate. The simplification assumed in this model was the absence of temporal and condylar cartilage layers, but a low-friction coefficient was established between upper and lower surfaces of the discs and their bones, as was done in similar previous study (28).

In the future, further studies should be conducted to simulate other movements of the stomatognathic system in situations of function and parafunction, as well as healthy and pathological joint conditions. These studies may be better able to clarify the role of the occlusal splint, as a means of preventing or treating possible temporomandibular disorders.

Conclusions:

The findings of this computational study showed that the occlusal stabilization splint did not promote significant stress and strain reduction on the articular disc surface after mandibular closure, but it promoted a better distribution of these factors between the right and left articular discs. This result may indicate that both temporomandibular joints work more symmetrically in the presence of the splint, but to confirm this trend, further studies should be performed with other mandibular movements.

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Conclusões gerais

4-Conclusões gerais

Considerando as limitações deste estudo, pode-se concluir que em todas as situações testadas a superfície inferior do disco, que é a região de contato com o côndilo da mandíbula, exibiu maior concentração de tensões e deformações, assim como a zona intermediária do disco analisando-o no sentido ântero-posterior. Quando o disco apresenta-se deslocado anteriormente, embora a placa não promova grande redução na magnitude das tensões, observou-se uma tendência de redução que deve ser mais bem investigada em estudos futuros. A análise bilateral e tridimensional das ATMs sugere que embora a placa não proporcione uma redução relevante das tensões e deformações que incidem sobre os discos articulares, ela promove melhor estabilização da oclusão refletindo em melhor estabilização das articulações, fazendo com que elas trabalhem de forma mais simétrica e as tensões estejam igualmente distribuídas nos dois discos bilateralmente. Por fim, a revisão da literatura sobre propriedades mecânicas do disco articular revelou que apesar de ele ser predominantemente viscohiperelástico, existem muitas formas de caracterizar o disco e que cada representação tem suas particularidades e limitações que devem ser consideradas no momento de interpretar os resultados.

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