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Finite element analysis of stabilization splint pressure distribution in a patient with disc displacement without reduction: A preliminary study

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ABSTRACT

Purpose: This study was performed to investigate the pattern of condylar pressure distribution in the discs of a patient diagnosed with disc displacement without reduction.

Materials and Methods: This research consisted of a pre- and post-test observational clinical study. A patient diagnosed with disc displacement without reduction underwent treatment with an occlusal splint for 3 months. Finite element analysis employed a 3-dimensional model constructed from magnetic resonance images of the patient, taken both before the application of the splint and 3 months after its use.

Results: The post-test model demonstrated a decrease in condylar pressure on the disc, with measurements dropping to 72 MPa from the pre-test level of 143 MPa. In the pre-test, the pressure distribution pattern was concentrated on the lateral posterior border, whereas in the post-test, it shifted toward the intermediate zone of the disc.

Conclusion: Utilization of a stabilization splint for 3 months resulted in decreased pressure and a marked change in the pressure distribution pattern on the temporomandibular disc. ***(Imaging Sci Dent 2024; 54: 251-6)***

KEY WORDS: Temporomandibular Joint Disorders; Occlusal Splints; Finite Element Analysis; Magnetic Resonance Imaging

Introduction

Jaw joint disorders, or temporomandibular disorders (TMDs), encompass a range of conditions that affect the temporomandibular joint (TMJ), masticatory function, and muscle integrity, and can lead to headaches and issues with related structures.[1] The global prevalence of TMD with symptoms is 41%, while the rate is 56% for those with at least 1 clinical sign. In Indonesia, the prevalence of TMD-related pain is 23.4% among children and 36.9% among adults.[2,3]

Clinical signs and symptoms of TMDs present in the jaw muscles and joints, causing pain and dysfunction that can impact quality of life if left untreated. Prolonged excessive pressure on these joints can induce changes in the position and anatomy of the disc, potentially resulting in abnormalities. For instance, disc displacement without reduction (DDwoR) occurs when the disc is displaced in the anterior direction within the condylar area. This displacement can result in the elongation of ligaments and prevent the disc from returning to its original position when the jaw closes.[4] These conditions can be accurately diagnosed using magnetic resonance imaging (MRI).[5]

Therapeutic approaches for patients with joint disorders typically include pharmacological interventions, such as non-steroidal anti-inflammatory drugs, and non-pharma-

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cological methods, which encompass patient self-management, physiotherapy, acupuncture, counseling, and occlusal therapy.[6] Among these, the preferred treatment for TMD is the use of a stabilization splint, usually a flat occlusal plate made of hard acrylic or polycarbonate. The purpose of such a splint is to increase occlusal stability, reduce muscle tension, and relieve pain.[7]

A study by Zhang et al.[8] concluded that the use of stabilization splints is clinically effective in reducing the frequency of pain and improving the range of mouth opening in patients with an opening of less than 45 mm, thus restoring jaw function. Furthermore, research by Al-Moraissi et al.[9] demonstrated that a hard acrylic stabilization splint is more effective in promptly alleviating pain originating from the joint (arthralgia) compared to a soft stabilization splint. Finite element analysis (FEA) is a numerical method widely used to solve complex mechanical problems regarding intricate structures. Recently, FEA has become increasingly popular in medical biomechanics research, especially in the study of orthopedic devices under various pressure application scenarios.[10] The application of FEA to joints includes both static and dynamic analyses. Static analysis relates to the load exerted by the masticatory muscles on the disc during centric occlusion. In contrast, dynamic analysis involves simulating jaw movements to evaluate dynamic conditions.

Extensive research has been conducted on the motion of the TMJ using dynamic analysis. Tanaka et al.[11] examined TMJ pressure dynamics during mouth-opening movements, while del Pozo et al.[12] explored the effects of friction coefficients on the articular surface and its effects on articular disc pressure. Shao et al.[13] analyzed pressure contact points in patients with TMD during mastication. Many similar studies were carried out from 2000 to 2023. However, these studies did not explore the distribution patterns under specific conditions. Consequently, this study aimed to investigate the pattern of condylar pressure distribution in the discs, particularly in cases of DDwoR.

Materials and Methods

A patient presented with a chief concern of pain in the right TMJ, clicking, rightward deviation of the jaw upon opening, and limited maximum jaw opening. The patient was diagnosed with TMD, which was further classified as DDwoR using the Diagnostic Criteria for Temporomandibular Disorders diagnostic decision tree. MRI scans were performed prior to the application of an occlusal splint—specifically, a stabilization splint—and again 3 months later. These scans were processed using zero-time echo (ZTE) in bone MRI to sharpen the distinction between the bone structure and the articular disc. Using the MRI data, a 3-dimensional (3D) model was generated and analyzed using FEA. This analysis was performed to assess the changes in pressure distribution exerted by the condyle on the articular disc before and after the use of the stabilization splint. The study protocol was reviewed and approved by the Ethical Board of Hasanuddin University Dental Hospital, under approval number UH 17120882.

MRI and data collection

MRI examination was conducted using a 3T Signa Pioneer device (GE HealthCare, Milwaukee, WI, USA) with a 21-channel head-array coil. The imaging protocol utilized software designed to capture the cortical bone surface, specifically the radial zero-time echo (oZTEo) program. The images were acquired in the coronal plane, with oZTEo providing 3D isotropic imaging. The parameter specifications included a field of view of 24 × 24 cm, a repetition time of 445 ms, a matrix size of 200 × 200 mm, a bandwidth of 62.5 kHz, 180 slices, a slice thickness of 1.2 mm without spacing, and a number of excitations of 7.

Construction of the TMJ model in FEA

The body surface model derived from MRI results was processed in the Standard Tessellation Language (STL) format. This transformation was designed to refine the model's surface by eliminating errors introduced during the MRI model tracing process. Subsequently, the model was converted into the Standard for the Exchange of Product (STEP) format to facilitate its use in FEA simulations. For the solid body model, a C3D10M mesh was used, configured with a 1-mm condyle and eminence and a 0.5-mm disc.

The materials used in this study were divided into 2 categories: cartilage, which constitutes the condyle and eminence, and the disc material, representing the disc. The cartilage was characterized as an isotropic, homogeneous, and linear elastic material. Meanwhile, the Mooney-Rivlin approach modeled the disc as hyperelastic. The material constants applied in this simulation were obtained from previous research (Table 1).[13]

Table 1. Material constants for each component used in the simulation

Parts	Young modulus (MPa)	Poisson ratio
Articular condyle	13900	0.3
Articular eminence	13900	0.3
Articular disc	30.9	0.4

In the interaction among components, friction arises from the contact between the condyle and the disc, as well as between the eminence and the disc. The magnitude of this friction is quantified by a friction coefficient of 0.001.[14]

Dynamic explicit loading was applied by imposing specific boundary conditions on each component of the TMJ. The eminence component was fixed in place, while the behavior of the condyle was governed by the biomechanical displacement of the patient's jaw. The disc was permitted to move freely between the condyle and the eminence, with its movement dependent on interactions with both structures. The simulation spanned a 2-second duration, representing the average time required to open the mouth.

Results

In the present context, biomechanics are characterized by the movements involved in opening and closing the mouth. During this process, the maxillary region remains stationary, while the mandible moves both translationally and rotationally relative to a specific reference point. This point is the center of rotation and displacement of the jaw, which is determined by the position of the sphenomandibular ligament. By establishing these biomechanics, the present analysis was focused on the interactions of the condyle, eminence, and disc, as depicted in the MRI results (Fig. 1). Subsequent data demonstrate the distribution of pressure on the disc resulting from condylar movement (Fig. 2).

The comparison illustrates the pressure distribution on the disc for both pre-test and post-test simulations. The resulting graphs depict distinct curves with varying characteristics. In the pre-test curve, the peak pressure was recorded at 143 MPa, occurring 1.38 seconds into opening. The post-treatment curve shows a maximum pressure of 72 MPa, which occurred at a mouth-opening interval of 1.15 seconds (Fig. 3). Figure 4 presents a curve demonstrating the pressure absorption by the disc in both scenarios.

Discussion

This study analyzed the patient's MRI data using oZTEo software, which was further interpreted with the oZTEo

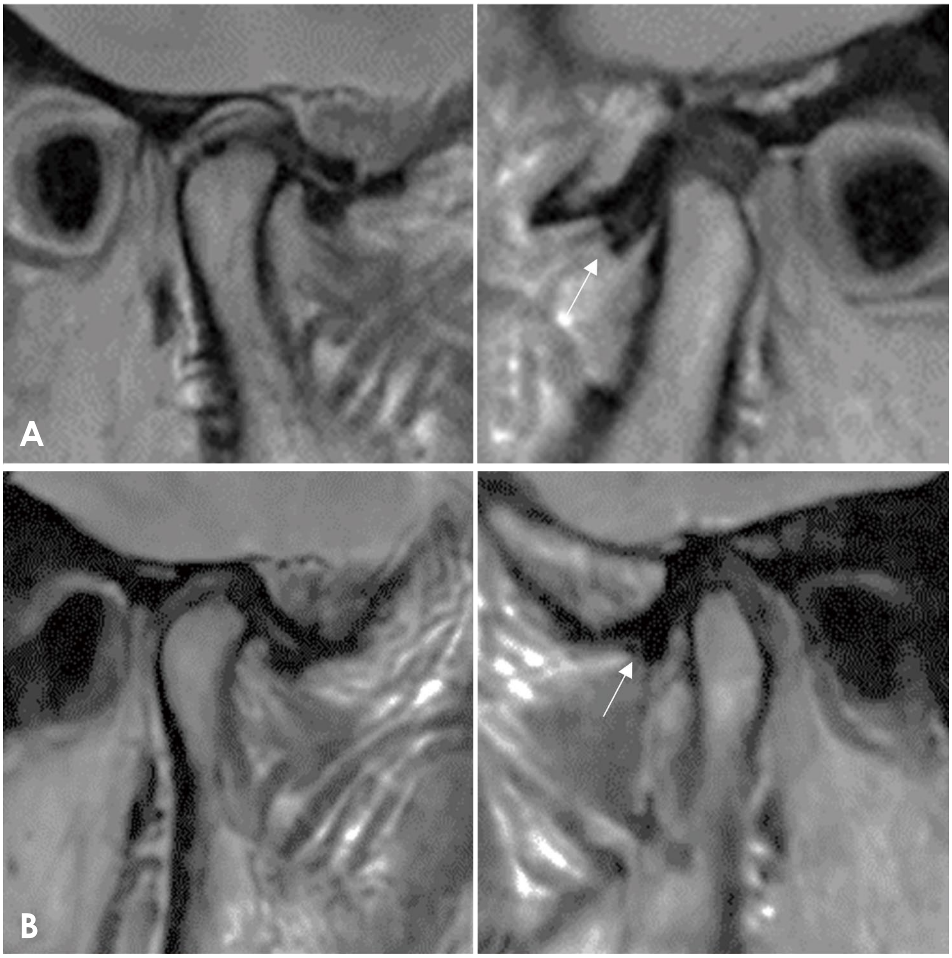

Fig. 1. A. Pre-treatment: sagittal magnetic resonance image (MRI) of the right condyle reveals disk displacement in the closed-mouth condition, with the posterior band of the disk positioned anterior to the condyle (white arrow). The disk on the left condyle is in the normal position. B. Post-treatment: sagittal MRI of the right condyle taken 3 months after treatment shows the articular disk has returned to its normal, centric position atop the condyle (white arrow).

radial application to generate a comprehensive 3D solid body model. This combination provides clinically reliable images for bone assessment in TMJ disorders, offering numerous clinical benefits due to the precise registration of soft tissue and bony structures. The study closely simulates the patient's condition through FEA and identifies the distribution pattern of condylar pressure on the disc. The simulation was based on the definition of biomechanical motion, specifically dynamic analysis, and was derived from a recorded 2-second video that captures mouth opening. Material constants and friction coefficients used in this study were obtained from prior research.[14-16]

In this study, both MRI and clinical findings confirmed unilateral DDwoR in the left joint. This condition, identified as a joint disorder, is known to induce pain, making the alleviation or elimination of pain a crucial factor in determining suitable treatment options.[17] Lee et al.[18] previously demonstrated that utilizing stabilization splint therapy among patients with DDwoR could effectively reduce pain.

MRI performed during the pre-test phase revealed anterior displacement of both the right and left discs toward the condyle. The extent of displacement was classified as mild for the right disc and moderate for the left disc, according to the criteria outlined by Takahara et al.[19] Pain intensity measurements, assessed using a visual analog scale (VAS), yielded a score of 60 prior to treatment with a stabilization splint.

The post-test MRI, conducted after 12 weeks of treatment, showed that the right disc had repositioned toward a normal alignment relative to the pre-test MRI. However, no change was observed in the position of the disc on the affected side (left joint). The decrease in VAS score was likely indicative of reduced pressure on the disc. Figure 2 illustrates a notable reduction in condylar pressure on the disc, which decreased from 143 MPa to 72 MPa during mouth opening. The variability in VAS scores merits further investigation, as pain is a subjective experience and its assessment can be complex.

The FEA simulation results reveal a distinct impact of stabilization splint use on the pressure distribution between the condyle and the disc, as shown in Figure 1. In the pre-test results, the stress contour was primarily focused on the posterior region of the disc, while in the post-test phase, it clearly shifted toward the intermediate zone. Notably, the post-test pressure distribution demonstrated a more uniform dispersion, with an absence of extreme pressure points, especially when the mouth was fully opened.

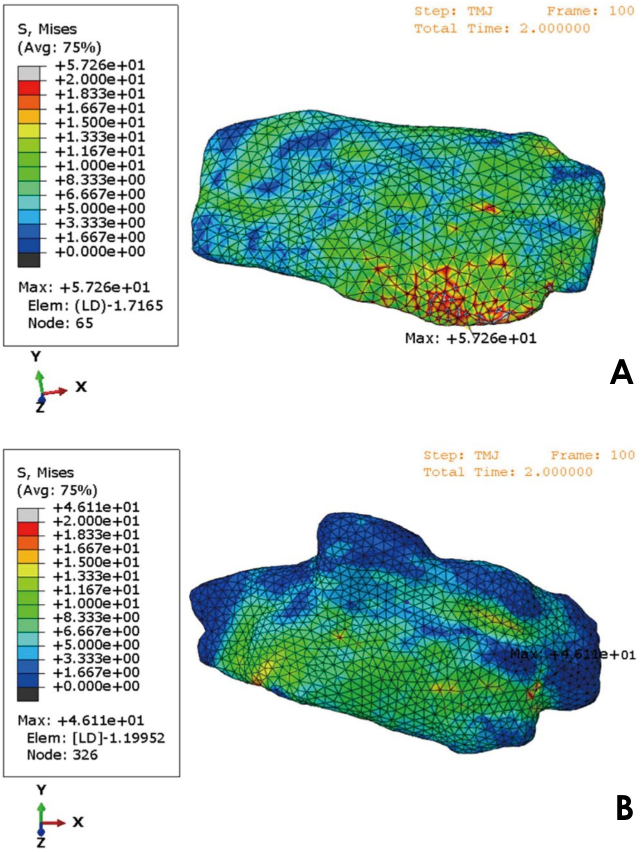

Fig. 2. Comparison of stress contours and pressure distribution patterns on the condyle and against the disc before (A) and 3 months after (B) use of a stabilization splint.

The FEA simulation conducted in this study also evaluated the likelihood of treatment success by correcting leftward deviations in the process of defining biomechanics. This correction normalized the mouth opening movement and extended the distance between the condyles and the glenoid fossa by 3 mm, corresponding to the initial thickness of the splint. As illustrated in Figure 2, treatment success was predicted to be indicated by a reduction in pressure to 39 MPa from the initial level of 143 MPa. Tanaka et al. reported that the ultimate tensile strength—the maximum pressure the disc can withstand—is 37.4 MPa in the intermediate zone, 46.7 MPa at the anterior border, and 67.7 MPa at the posterior border. Pressures exceeding these values suggest that the disc is at risk of damage or perforation.[11]

A study by Vrbanovic and Alajbeg[20] found that the use of a stabilization splint for 6 months effectively reduced pain and significantly alleviated limitations in mouth opening. However, after 3 months of splint use in the present investigation, the pressure applied to the disc remained above the threshold for the disc's ultimate tensile strength, measuring 72 MPa. This indicates that study participants should continue to use the splint and undergo re-evaluation after

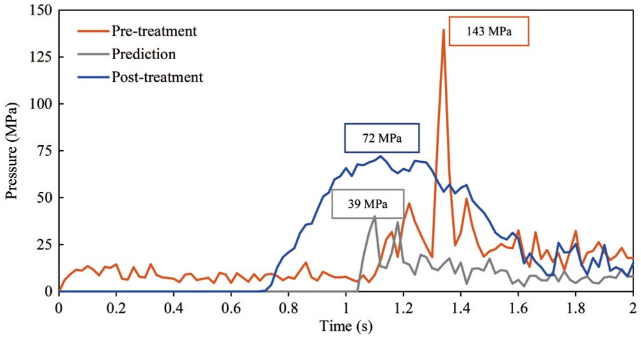

Fig. 3. Graph comparing pre-treatment, predicted, and post-treatment pressure.

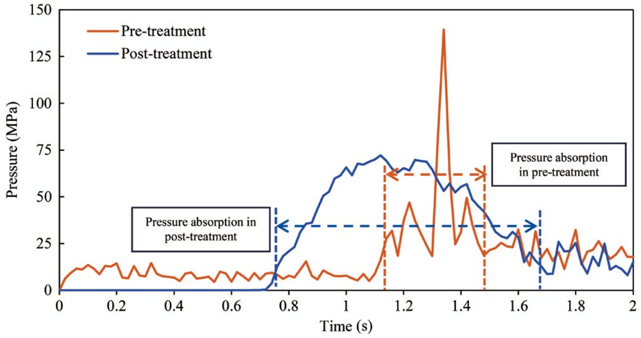

Fig. 4. Graph comparing pressure absorption in pre-test and post-test scenarios.

6 months. The aim was to align the pressure exerted on the disc to 39 MPa or less, the level predicted by the analysis to indicate successful treatment (Fig. 2).

The articular disc plays a key role in the biomechanics of the TMJ by functioning as both a shock absorber and a pressure distributor. Figure 3 depicts the extent of the pressure absorption process.[16] In the pre-test phase, the results indicated a pressure absorption duration of 0.37 seconds, while in the post-test period, this duration increased to 0.92 seconds. Notably, the pressure absorption process began earlier in the post-test phase, starting at 0.75 seconds, compared to 1.13 seconds in the pre-test phase.

One limitation of this study was that the analysis focused exclusively on the joint diagnosed with DDwoR, without simultaneous analysis of the contralateral joint. Therefore, for future studies, it is recommended to analyze both joints concurrently to achieve a more thorough analysis.

In conclusion, this study revealed a shift in the distribution pattern of condylar pressure after 3 months of stabilization splint usage in a patient with DDwoR. The condylar pressure exerted on the disc decreased following the use of a stabilization splint.

Conflicts of Interest: None

Acknowledgments

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