https://doi.org/10.14368/jdras.2025.41.3.169
ISSN 2384-4353 eISSN 2384-4272

Original Article

Mouth opening limitation induced by scarring in the supporting ligaments of the temporomandibular joint following maxillectomy: a 3D simulation study

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Purpose: Mouth opening limitation following maxillectomy significantly has great influence on the quality of life. The purpose of this study was to analyze the effect of scarring in the supporting ligaments of the temporomandibular joint that is recognized as one of the causes of mouth opening limitation using a three-dimensional computer simulation. **Materials and Methods:** Based on the CT data from a healthy adult, a computer musculoskeletal model with a maxillary palatal defect was developed. The geometry from patient's CT data was imported into the biomechanical simulation platform Artisynth to reproduce mandibular movement. Four simulations including scar tissue in the capsular and temporomandibular ligament were established. Forty and 60 percent of the maximum voluntary muscle contraction (MVC) were applied to evaluate the mouth opening limitation. Distance between maxillary and mandibular central incisors were evaluated. **Results:** In all simulations, the model that had scarring in the capsular ligament showed the most significant mouth opening limitation. The simulation with scarring only in the temporomandibular ligament also showed reduced mouth opening compared to the non-scarred condition. However, the effect was less than that of the capsular ligament. **Conclusion:** When the capsular ligament that plays a great role in mandibular movement is scarred, it might be the one of the most important factors in mouth opening limitation. Therefore, in the surgical treatment around the temporomandibular joint, the biomechanical characteristics of the joint supporting ligaments has to be considered. **(J Dent Rehabil Appl Sci 2025;41(3):169-76)**

Key words: mouth opening limitation; maxillectomy; capsular ligament; scar tissue; biomechanical simulation; temporomandibular joint

Introduction

The incidence of cancer in oral and maxillofacial region in South Korea has increased steadily over the past years. It reflects a global trend that cancer increases in head and neck region. According to the data from the National Cancer Center, the annual number of new oral and pharyngeal cancer in Korea has grown significantly, particularly among middle-aged and elderly populations.[1] Contributing factors include tobacco use, alcohol consumption, poor oral hygiene, and human papillomavirus (HPV) infection, and advanced age. The incidence of the cancer in oral and maxillofacial region increases significantly in

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Received: May 29, 2025/Last Revision: June 20, 2025/Accepted: June 26, 2025

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individuals over the age of 50.[2] For the management of these cancers, surgical resection, radiotherapy, and chemotherapy are commonly used.[3] Among surgical treatments, maxillectomy is a principal approach in eliminating malignant tumors in the oral and maxillofacial structures.[4]

Although maxillectomy is essential for cancer treatment, it is associated with a wide range of postoperative complications. The procedure involves partial or total resection of the maxilla. In addition, it often include the removal of adjacent soft tissues, and in some extreme cases the procedure involves orbital or nasal structures.[4,5] As a result, patients frequently experience complex functional problems including difficulties in mastication, swallowing, phonation, and prosthetic rehabilitation.[6] One of the most frustrating and functionally disabling result from maxillectomy is mouth opening limitation, which refers to a significant reduction in the maximal interincisal distance. This complication can be originated from a direct result of surgical tissue removal, fibrosis from postoperative radiation, or mechanical restriction due to scar formation in the temporomandibular joint (TMJ) region.[7,8]

Mouth opening limitation, often called trismus, arises multiple problems in oral functions. They include mastication, speech articulation, and prosthodontic treatment. Mouth opening limitation also has a profound negative impact on daily functioning, social interaction, and overall quality of life.[9] Patients with mouth opening limitation often struggle with maintaining oral hygiene, undergoing dental procedures, and receiving prosthodontic treatment. In addition, with restricted mouth opening oral examinations and diagnostic imaging become difficult procedure. For cancer survivors, the quality of life decreases with these difficulties.[10] Therefore, it is crucial to understand the underlying mechanisms contributing to limited mandibular movement following resective surgeries in oral and maxillofacial regions. In this context, scar formation following surgery or radiation therapy, which is often characterized histologically as fibrosis, can lead to increased stiffness of involved structures, including the temporomandibular ligaments.[11,12]

Among the various etiological factors contributing to mouth opening limitation, one of the important mechanisms is the development of postsurgical scar or scar after radiation therapy in the supporting ligaments of the temporomandibular joint. The expected area includes the capsular and temporomandibular ligaments. These ligaments play a central role in stabilizing the mandibular condyle and guiding its movement during mandibular movements.[13] When these ligaments become fibrotic or inelastic due to scar formation, the condylar movement during mandibular movements may be restricted. Consequently, it can lead to a decrease in mouth opening range.[11] Although some clinical and histological studies have suggested this connection, there is a lack of quantitative evidence that clearly establishes the biomechanical impact of ligament scarring on mandibular kinematics.

Computer simulation can offer a valuable tool in analyzing the complex dynamics of mandibular motion under various clinical conditions. Three-dimensional (3D) musculoskeletal simulations have been successfully used in biomechanical research to investigate temporomandibular joint disorders, muscle activation patterns in oral and maxillofacial region, and temporomandibular joint loading.[14] Such simulations allow various clinical situations, including ligament stiffness and damping properties. How specific changes in ligament properties influence mandibular movement can be analyzed using computer simulations without the ethical concerns.

The purpose of this study was to analyze the effect of scarring in the supporting ligaments of the temporomandibular joint, which is considered one of the causes of mouth opening limitation, through a three-dimensional computer simulation.

Materials and Methods

Model Construction

This study was approved by the Seoul National University Dental Hospital institutional review board (approval no. CRI12016). A three-dimensional computer musculoskeletal model of the craniofacial

region was constructed based on computed tomography (CT) data obtained from a healthy 30-year-old male subject who voluntarily participated in the study. The CT data were segmented using Mimics software (Mimics 19.0; Materialise NV, Leuven, Belgium), and the geometry of the segmented structures were imported into the Artisynth biomechanical simulation platform (Artisynth; University of British Columbia, Vancouver, Canada) for dynamic biomechanical analysis. The skeletal components included the maxilla, mandible, maxillary and mandibular teeth, and hyoid bone. To make a postmaxillectomy situation, an Aramany Class I defect was virtually created in the maxilla by removing half of the maxilla and maxillary teeth.[15] The removal includes teeth from the right central incisor to the right second molar, and the hard palate on the right side. Following the modeling of hard tissue, muscles and ligaments were added.

Muscle attachment sites were determined based on standard anatomical references[13] and implemented using Hill-type line muscles.[16] The modeled muscles included the major masticatory muscles (masseter, medial pterygoid, and anterior, middle, and posterior portions of the temporalis), as well as the suprahyoid muscle group (digastric, mylohyoid, and geniohyoid).

Ligaments were added based on anatomical literature.[13,17] Two bilateral ligament groups were modeled: the temporomandibular (TMJ) ligament and the capsular ligament surrounding the condylar head and glenoid fossa. All ligaments were modeled as linear elastic, and stiffness and damping values assigned based on previous biomechanical studies.[13,17] A visual representation of the completed computer model is shown in Fig. 1.



Fig. 1. Three-dimensional musculoskeletal model of postmaxillectomy situation which was constructed in Artisynth biomechanical platform. The model includes the maxilla, mandible, hyoid bone, teeth, major masticatory muscles, suprahyoid muscles, temporomandibular joint (TMJ) ligament, and capsular ligament. The model was used to simulate mandibular motion and the biomechanical effects of ligament scarring.

Simulation Protocol

The initial mandibular position of the model was set to a slightly open-mouth posture, reflecting the position that was comfortable for the subject during CT imaging to minimize motion-related artifacts. Total simulation time was 5 seconds. During the first 2 seconds, the opening muscles were activated to induce maximal opening, and from 3 seconds, the closing muscles were activated to simulate the closing phase. During each activation, muscle activations increased linearly from 0% to a target percentage. Two levels of muscle activation were used: 40% and 60% of maximum voluntary contraction (MVC). MVC is the maximum force that a muscle can produce during voluntary isometric contraction under standardized conditions. The 40% activation level was selected based on previous studies to represent physiological chewing forces,[18] while the 60% level was used to analyze the effect of increased muscle effort on mandibular motion under ligament scarring.[19]

In the simulations, four distinct ligament configurations were modeled: no scarring (Simulation 1), scarring limited to the TMJ ligament (Simulation 2), scarring limited to the capsular ligament (Simulation

3), and scarring affecting both the TMJ and capsular ligaments (Simulation 4). To replicate the biomechanical effects of scarring, the stiffness and damping coefficients of the affected ligaments were increased according to values reported in previous studies. In this study, the mechanical properties of the ligaments were defined in terms of stiffness and damping. To simulate fibrotic ligaments, both coefficients were increased by 50% based on the previous studies.[20-22] The specific values are listed in Table 1.

Analysis

To evaluate the effect of scarring on ligaments, virtual markers were placed at the incisal edge of the right mandibular and right maxillary central incisors. The distance between the two markers was measured during mouth opening. The maximum values were obtained for each simulation and were evaluated.

Results

The mandibular model demonstrated smooth and physiologically plausible motion throughout the simulations. The mandible opened gradually and returned to a position consistent with the maximum intercuspal position (MIP) during the late stage of the closing phase. In addition, there was no significant left and right deviation at the end of the simulations. The models showed opening and closing movement without noticeable lateral shifting. Under dynamic conditions the models showed stable movements.

The primary outcome was maximum mouth opening distance between maxillary and mandibular central incisors. Table 2 summarizes the maximum interincisal distances measured at 40% and 60% MVC under four different ligament conditions. Fig. 2 summarizes the results of all simulations. In both activation levels, the control simulation consistently showed the greatest interincisal distance. Scarring in the ligaments was associated with varying degrees of mouth opening limitation. Among the experimental groups, capsular ligament scarring (Simulation 3) produced the most pronounced restriction in both 40% and 60% MVC simulations. The combined scarring condition (Simulation 4) did not show additive limitation beyond that of capsular scarring alone.

Increasing muscle activation from 40% to 60% led to greater mouth opening across in all simulations. However, the pattern of mouth opening limitation remained consistent across simulations, underscoring the dominant role of capsular ligament in mandibular motion during opening and closing movements.

Table 2. Maximum interincisal distances under varying ligament scarring situations with a muscle activation level of 40% and 60% of maximum voluntary contraction (MVC)

Simulation	Maximum interincisal distance	
	40% of MVC	60% of MVC
Simulation 1	28.56	31.84
Simulation 2	27.73	31.37
Simulation 3	27.35	31.06
Simulation 4	27.66	30.62

MVC: maximum voluntary contraction.

Table 1. Description of the four simulation conditions used to evaluate the impact of ligament scarring on mandibular motion. Each condition involves a distinct pattern of ligament modification to simulate scar-induced changes

Simulation	Target ligament	TMJ ligament		Capsular ligament	
		Stiffness (N/m)	Damping (Ns/m)	Stiffness (N/m)	Damping (Ns/m)
Simulation 1	None	80,000	90	40,000	90
Simulation 2	TMJ ligament	120,000	135	40,000	90
Simulation 3	Capsular ligament	80,000	90	60,000	135
Simulation 4	TMJ and capsular ligaments	120,000	135	60,000	135

TMJ: Temporomandibular joint.

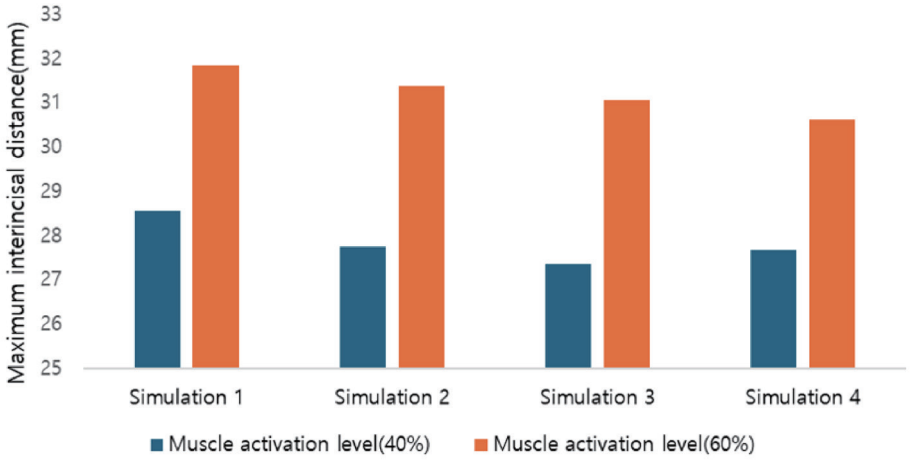

Fig. 2. Maximum interincisal distances under two muscle activation levels (40% and 60% MVC) across four ligament conditions. Increased muscle activation led to greater mouth opening, while capsular ligament scarring consistently caused the greatest mechanical restriction. Simulation with combined scarring did not produce an additive restrictive effect compared to the that with capsular ligament scarring.

Discussion

This study analyzed the biomechanical effects of stiffness from scarring in temporomandibular joint (TMJ) supporting ligaments on mouth opening capacity using 3D computer simulations. The simulation assumed a clinical situation in which unilatereal maxillectomy resulted in postmaxillectomy scarring in the TMJ-supporting ligaments due to proximity of surgery site and radiation exposure. How scarring of the capsular and TMJ ligaments influenced mandibular motion was analyzed with a maxillectomy computer model under two levels of muscle activation. The results showed that capsular ligament scarring consistently caused the greatest reduction in mouth opening, regardless of whether muscle activation was set at 40% or 60% of maximum voluntary contraction (MVC). These findings demonstrate the dominant role of the capsular ligament during mandibular movements. To conduct these simulations, the Artisynth simulation platform was utilized to implement a biomechanical model that incorporates the properties of muscles and ligaments. As Artisynth supports the integrated analysis of both rigid and soft tissues and offer features such as time-based dynamic motion simulation, muscle modeling, and adjustable ligament stiffness, the simulation of human body mechanics can be easily performed.

The combined scar condition (Simulation 4) at 40% of MVC resulted in slightly greater mouth opening than the scarring condition in the capsular ligament alone (Simulation 3), as shown in Table 2. However, the magnitude of this difference was small, and the overall pattern across activation levels remained consistent. This suggests that the scarring in TMJ ligament does not produce an additive effect. One possible explanation lies in complex joint mechanics, where dual stiffness may stabilize the temporomandibular joint in a way that limits further restriction. Another explanation might be the simplified computer model used in this study, which did not consider complex structures such as connective tissue, muscles, skin and surrounding other anatomical components. The pronounced limitation observed in the capsular scarring condition (Simulation 3) is likely attributable to its anatomical orientation and mechanical function. The capsular ligament surrounds the TMJ capsule and serves as a key restraint against anterior and inferior condylar translation, movements essential for wide mouth opening.[13]

When stiffened, even modest reductions in its elasticity can substantially affect condylar mobility, leading to measurable decrease in interincisal distance.[11] In contrast, the TMJ ligament is primarily oriented to prevent posterior and lateral displacement and may have limited influence on anterior-inferior motion during normal opening ranges.[17]

The comparison between the 40% and 60% MVC conditions showed that higher muscle activation consistently improved mouth opening in all simulations. This result suggested that therapeutic exercise and patient's voluntary activation of the muscles are necessary. In addition, the results demonstrated that the scarring of capsular ligament is critical in controlling mandibular movements. The results suggest that scarring of the underlying structures may play a dominant role in mandibular movement although muscle force is increased to produce greater mouth opening. These analyses offer a biomechanical explanation related to clinical observations that mouth opening limitation is often more severe when post-maxillectomy scarring affects the capsular region. Early identification and targeted rehabilitation strategies in patients at risk following maxillectomy or head and neck cancer treatment is necessary.

From a clinical and biomechanical perspective, these findings emphasize the importance of preserving capsular ligament in maxillectomy procedure. Rehabilitation efforts aiming at improving mandibular range of motion, including stretching, physical therapy, or medication, may be helpful when specifically focused on the capsular region. Furthermore, understanding the anatomy around temporomandibular joint can be critical in the planning of surgery and radiation therapy. It can lead to conservative approach or preventive interventions in patients with high risk of joint scarring.[9,10]

Despite these implications, this study has several limitations. First, although the simulations reproduced overall biomechanical trends, the predicted reduction in mouth opening was relatively small, likely due to the simplified computer model. In clinical situations, tissues including skin, muscles, and connective tissue play significant roles in the range of mouth opening. In terms of biomechanical analysis, nonlinear modeling and the inclusion of anatomically detailed structures, such as the temporomandibular disc, are also required for more realistic simulations.[14,17] Second, ligaments were represented with linear elastic properties, and muscle activation was modeled using a linearly increasing Hill type profile. Although this linear approach does not fully reflect the intricate and nonlinear activation patterns observed in vivo, it was considered appropriate for the objective of this study, given that muscle activation in the human body typically begins progressively from rest rather than occurring abruptly. Furthermore, radiation induced fibrosis and dose distribution effects, which are clinically relevant in post maxillectomy patients, were not considered. Future research may consider including additional structures such as the pterygoid muscles and pterygomandibular ligaments, and adopting EMG based muscle activation and anisotropic material properties.

Conclusion

This computer simulation demonstrated that scarring of the capsular ligament was closely related to a biomechanical limitation on mouth opening both under moderate (40%) and increased (60%) muscle activation levels. In contrast, the temporomandibular ligament played a limited role in mouth opening limitation. The findings emphasize the biomechanical importance of the capsular ligament during mandibular movements. Furthermore, the absence of an additive effect in the combined scarring condition suggests that the changes in capsular ligament mainly determine the extent of mouth opening limitation.

Acknowledgements

This study was supported by grant no 04-2020-0109 from the SNUDH Research Fund.

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상악절제술 후 반흔화된 측두하악관절 지지 인대에 의한 개구 제한: 3차원 시뮬레이션 연구

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목적: 상악절제술 후 발생하는 개구제한은 삶의 질에 큰 영향을 미친다. 이 연구의 목적은 개구제한의 원인 중 하나로 알려진 측두하악관절(TMJ) 지지인대의 반흔화가 개구제한에 미치는 영향을 3차원 컴퓨터 시뮬레이션을 통해 분석하는 것이다.

연구 재료 및 방법: 건강한 성인의 CT 데이터를 이용하여 상악 구개부 결손이 있는 컴퓨터 근골격 모형을 제작하였다. 제작된 형상을 생체역학 시뮬레이션 플랫폼인 Artisynth에 불러와 하악 운동을 재현하였다. 관절낭 인대와 측두하악인대에 반흔조직이 형성된 상태를 포함하는 4가지 조건을 설정하였고, 근수축은 최대 수의적 수축력(MVC)의 40%와 60% 수준으로 적용하여 상하악 중절치 사이의 개구량을 평가하였다.

결과: 모든 실험에서 관절낭 인대에 반흔이 형성된 경우가 가장 큰 개구제한이 발생하였다. 측두하악인대에만 반흔이 있는 경우는 반흔이 없는 경우에 비해 개구량이 작았으나 관절낭인대에 비해 영향이 작았다.

결론: 개구 시 하악의 전하방 이동을 생체역학적으로 지지하는 관절낭인대는 반흔화 시 개구제한에 영향을 크게 미치는 것으로 보인다. 그러므로 관절낭 주위를 포함하는 외과적 치료 시 관절낭의 생체역학적 특징에 대한 고려가 필요하다.

(구강회복응용과학지 2025;41(3):169-76)

주요어: 개구 제한; 상악절제술; 관절낭 인대; 섬유화; 생역학 시뮬레이션; 측두하악관절

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접수일: 2025년 5월 29일 | 수정일: 2025년 6월 20일 | 채택일: 2025년 6월 26일