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OPTIMUM DESIGN METHOD FOR ARTIFICIAL EAR OSSICLES BASED ON A HIGH-PRECISION VIBRATION ANALYSIS MODEL

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Abstract. In this study, we propose a topology optimization approach aimed at designing an optimal artificial auditory ossicle to enhance hearing restoration in the sound conduction reconstruction of a damaged human middle ear. The primary objective of our design is to maximize the vibration displacement of the stapes footplate by employing the concept of mutual mean compliance. Using this method, we can determine the optimal topology configurations of the artificial component based on topology sensitivity, which we theoretically derive in this paper. To demonstrate the effectiveness and practical utility of our proposed approach, we present a design example of artificial auditory ossicles utilized in tympanoplasty procedures.

1 INTRODUCTION

Hearing loss is a significant problem in everyday life, and conductive hearing loss is the most common type, often resulting from issues in the middle ear or outer ear. The human middle ear comprises three small bones called the auditory ossicles (malleus, incus, and stapes) and the tympanic membrane. The primary function of the middle ear is to transmit sound energy from the air to the inner ear. The process of hearing begins at the tympanic membrane, which vibrates upon receiving sound energy. These vibrations are then amplified by the auditory ossicles as they pass through the malleus, incus, and stapes. Finally, the stapes transfers the vibrations into the cochlear fluid of the inner ear, enabling the hair cells to generate neuronal signals. Conductive hearing loss occurs when the middle ear is damaged by various ear diseases, hindering sound conduction through the eardrum and ossicles to the inner ear.

Tympanoplasty is often performed to reconstruct the damaged ossicular chain and improve sound conduction efficiency. In this procedure, an artificial component called a ”columella” is used to replace the typically damaged incus. The sound conduction efficiency during this operation depends on the shape, material, and mounting position of the columella. Currently, the procedure relies heavily on the surgeon's skill and experience. In our previous studies [1, 2], we investigated the dynamic characteristics of the middle ear in sound conduction using a three-dimensional finite element method. Based on our analysis, we proposed that hearing restoration effectiveness can be estimated by comparing the displacement of the stapes footplate in a healthy model to that in an operative model. This suggests that designing a suitable artificial auditory ossicle before the operation may be feasible. However, most research has focused on the analytical aspects, such as the shape or mounting positions of the columella, without exploring optimization through numerical methods.

In this study, we propose a topology optimization approach to design an optimal artificial auditory ossicle to enhance hearing restoration in sound conduction reconstruction of the damaged human middle ear. Our design objective is to maximize the vibration displacement of the stapes footplate using the concept of mutual mean compliance [3]. With this method, optimal topology configurations of the artificial part can be determined based on topology sensitivity, which we theoretically derive in this paper. To demonstrate the effectiveness and practical utility of our proposed approach, we present several design examples of artificial auditory ossicles used in different types of tympanoplasty operations.

2 HUMAN MIDDLE EAR AND ITS FUNCTION

The ear functions as the organ responsible for both hearing and balance, and it comprises three distinct sections: the outer ear, the middle ear, and the inner ear, as illustrated in Figure 1. The middle ear connects the eardrum of the outer ear and the oval window of the inner ear. Its primary function is to effectively transform the vibrations from the eardrum into fluid waves within the cochlea. As depicted in Figure 2, the middle ear houses three small ossicles: the malleus, incus, and stapes. These ossicles are interconnected by joints and supported by ligaments and muscles. The rotary motion of the auditory ossicles amplifies the vibrations received by the tympanic membrane and transmits them to the stapes footplate. This action moves the labyrinthine fluid within the inner ear, leading to the generation of electrical signals. These electrical signals are then conveyed directly to the brain, where they are interpreted as sound.

3 DYNAMIC ANALYSIS OF MIDDLE EAR

3.1 Geometric modeling

A precise geometric model of the ossicles can be constructed through CT scanning of the human head. As illustrated in Figures 3-5, the two-dimensional slice images obtained from the CT scan data were converted into three-dimensional solid geometries using post-processing software, allowing the extraction of the region containing the three ossicles.

Subsequently, these 3D geometries were refined and converted into DICOM data, which were then transformed into STL data. These STL files were imported into general-purpose structural analysis software to create a finite element analysis (FEA) model. The FEA model of a healthy subject is depicted in Figure 6, encompassing the tympanic membrane, the auditory

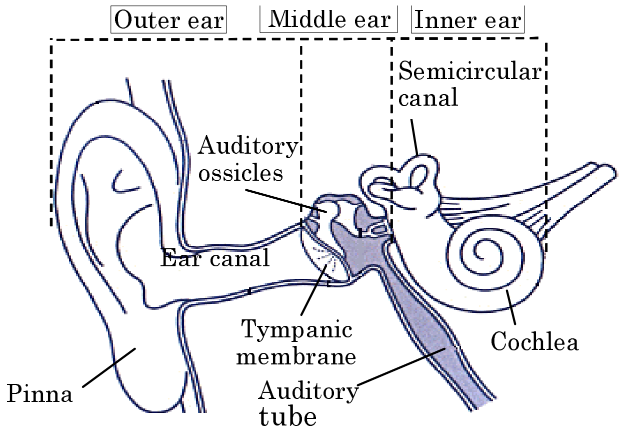

Figure 1: Structure of the human ear.

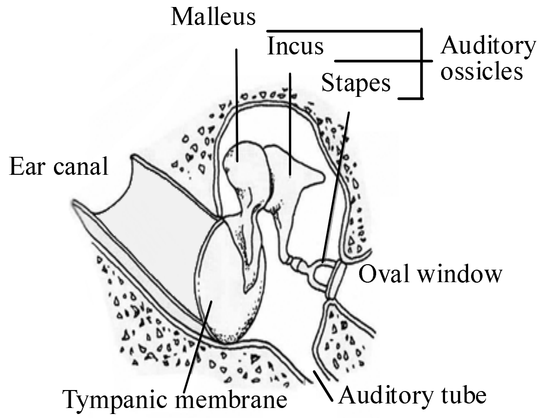

Figure 2: Structure of the middle ear.

ossicles chain (malleus, incus, and stapes), ligaments, joints, the stapedial muscle, and other relevant structures. The anatomical nomenclature for each part shown in Figure 6 is provided in Table 1.

Subsequently, dynamic characteristics of a healthy model have been investigated by the harmonic vibration analysis using a general-purpose finite element method code.

3.2 Material properties and boundary conditions

Material properties used in the analysis model were determined by referring to other researches [4, 5, 1, 2]. The interaction between the stapes footplate and the cochlea labyrinthine fluid was modelized with a set of translational springs installed between the stapes footplate and a virtual base plate (a rigid body). The spring constant was given as 40N/m by considering the research of Gan et al [6]. In addition, the damping matrix $[C]$ of the solid elements was expressed in equation (1).

$$[C] = \zeta[I] + \alpha[K] + \beta[M] \tag{1}$$

where, $[I]$ was the unit matrix, $[M]$ was the mass matrix, and $[K]$ was the stiffness matrix. ζ, α, β express the damping coefficients. Rayleigh damping was only considered in this study, ie., $\zeta = 0$, and $\alpha = 0, \beta = 7.5 \times 10^{-5}$ were used for the coefficients of Rayleigh damping.

As the boundary conditions, outer circumferences of the tympanic membrane and the stapedial muscle, ends of the six ligaments, and the inner side of the base plate were clamped. In the harmonic vibration analysis, a uniform pressure p was applied at the whole surface of the tympanic membrane, and the applied pressure p=0.632 Pa can be calculated from the definition equation of the sound pressure level (SPL) expressed in equation (2).

$$L_p = 20log_{10}(p/p_0) \tag{2}$$

where, $L_p = 90$dB was set as the sound pressure level. $p_0 = 20 \times 10^{-6}$Pa denotes the reference value or hearing threshold of the sound pressure.

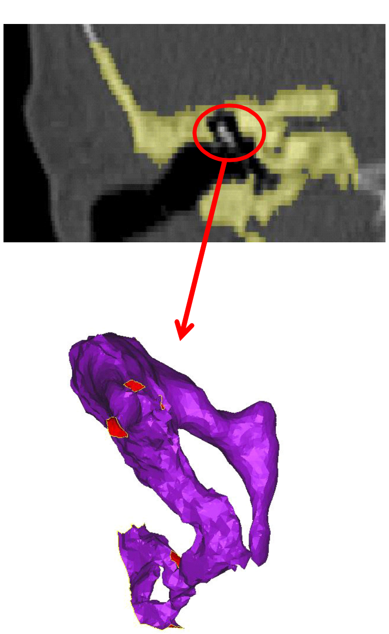

Figure 3: Extracting 3D model from CT.

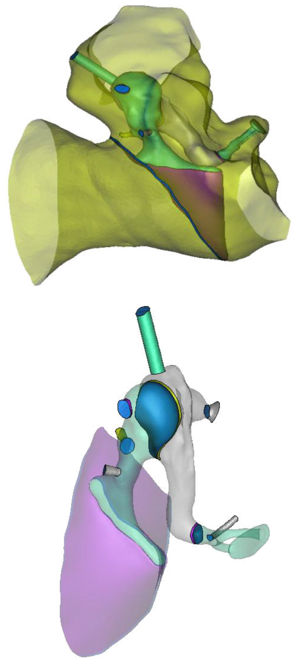

Figure 4: Refine, design and prepare model for FEM.

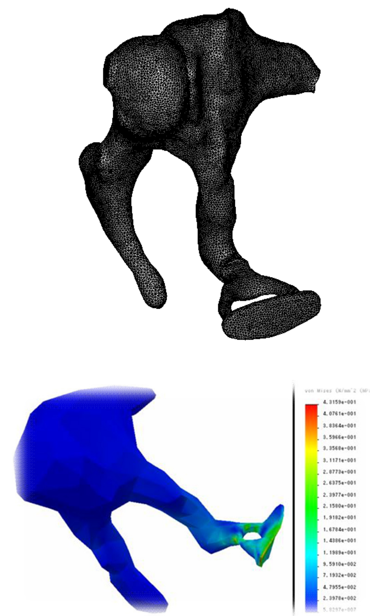

Figure 5: Vibration analysis by FEM.

3.3 Analysis results of the healthy model

The results of the analysis are depicted in Figure 7, which illustrates the frequency response curve of the healthy model. In this figure, the vertical axis represents the peak displacements of the stapes footplate and the tympanic membrane, while the horizontal axis indicates the input frequency. As shown in Figure 7, a resonance region emerges within the frequency range of 0.5 to 2 kHz, commonly referred to as the ”conversation range.” The peak displacement of the stapes footplate occurs at approximately 1.3 kHz, with the response diminishing steadily beyond 2 kHz. Furthermore, it is evident that the displacements of both the tympanic membrane and the stapes footplate align closely with empirical measurements reported in previous studies [7, 8, 9]. In this research, the frequency response curve of the healthy model serves as a baseline for comparison with that of an operative model, wherein the damaged auditory ossicles are replaced by a columella (a medical device). This comparison facilitates the identification of an optimal surgical technique for sound conduction reconstruction.

4 TOPOLOGY OPTIMIZATION METHOD FOR ARTIFICIAL EAR OSSICLES

Let us consider the formulation of the topology optimization for finding the maximum Z-direction displacement of the stapes footplate using the concept of the mutual mean compliance [4]. Consider the columella as a linear elastic body occupying a three-dimensional domain Ω and suppose that the body is subjected to pressure p^1 at the surface of the tympanic membrane Γ_1 denoted as case (1), and unit dummy load p^2 in the direction vetical to the footplate of stapes

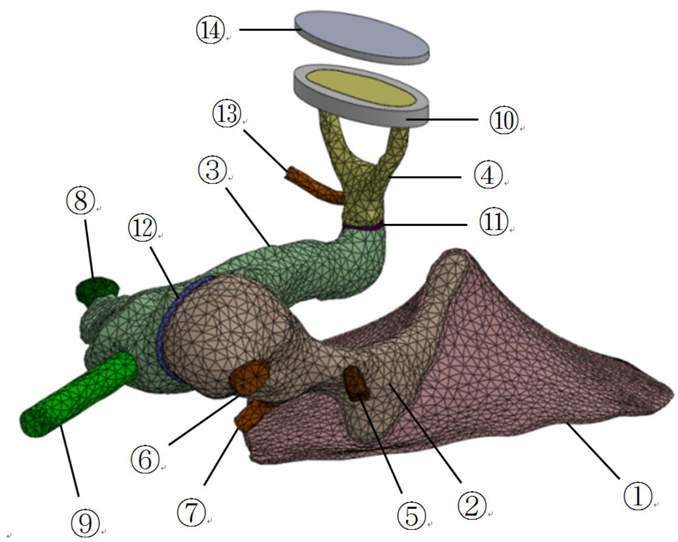

Figure 6: Geometric model of the healthy middle ear

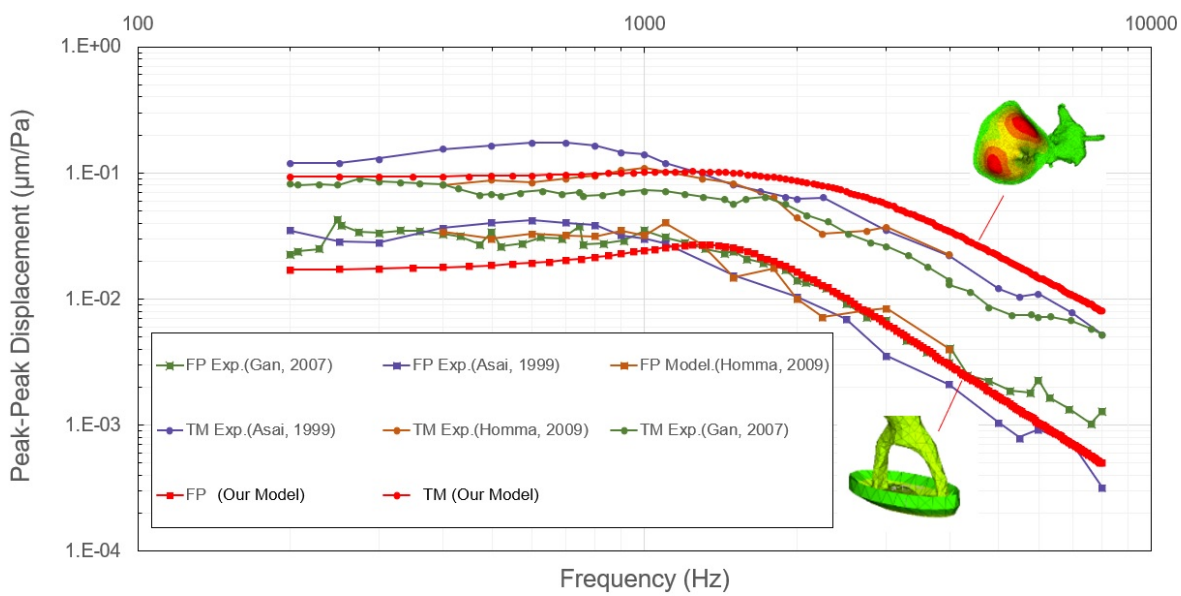

Figure 7: Comparison of harmonic vibration analysis results with reference measurement values

Γ_2 denoted as case (2). Body forces applied to the elastic body are ignored for simplicity in the formulation. The displacement field is $u^1 = \{u_1^1, u_2^1, u_3^1\}^T$ in case (2), and $u^2 = \{u_1^2, u_2^2, u_3^2\}^T$ in case (2). The mutual mean compliance of the structure, $l^2(u^1)$ is defined by the following load linear form:

$$l^2(u^1) = \int_{\Gamma_2} p^2 \cdot u^1 d\Gamma. \tag{3}$$

Eq. 3 shows the measurement of displacement u^1 at Γ^2 along Z-direction of stapes when p^1 is applied at Γ^1. Hence, the maximum displacement of stapes can be obtained by maximizing the mutual mean compliance. The topology optimization problem can be formulated as shown below:

$$\text{Minimizing} \quad -l^2(u^1), \tag{4}$$

$$\text{Subject to} \quad \text{Case (1): } a(u^1, v^1) = l^1(v^1), \quad \text{for all } u^1, \forall v^1 \in U, \tag{5}$$

$$\text{Case (2): } a(u^2, v^2) = l^2(v^2), \quad \text{for all } u^2, \forall v^2 \in U, \tag{6}$$

$$M = \int_{\Omega} dV \leq \hat{M} \tag{7}$$

where $l^1(u^1)$ and $l^2(u^2)$ represent the average compliance of case (1) and case (2), respectively. $v^1 = \{v_1^1, v_2^1, v_3^1\}^T$ and $v^2 = \{v_1^2, v_2^12, v_3^2\}^T$ express adjoint variables of the variational governing equations for case (1) and case(2), respectively. $\hat{M}$ denotes constraint value of the volume. In addition, the bilinear forms $a(u, v)$ and the linear form $l(v)$ are defined as follows using tensor representation.

$$a(u, v) = \int E_{ijkl} u_{k,l} v_{i,j} d\Omega, \tag{8}$$

$$l(u) = \int_{\Gamma} p_i v_i d\Gamma \tag{9}$$

where E_{ijkl} is the elasticity tensor and $E_{ijkl} = E_{jikl} = E_{ijlk} = E_{klij}$.

Letting v and Λ denote the Lagrange multipliers for the state equation and volume constraint, respectively, the Lagrange functional $\mathscr{L}$ associated with the topology optimization problem can be expressed in Eq. (10).

$$\mathscr{L} = -l^2(u^1) + a(u^1, v^1) - l^1(v^1) + \Lambda(\int_{\Omega} \rho d\Omega - \Omega_0) \tag{10}$$

Then, the derivative of the Lagrange functional is derived as shown in Eq. (11).

$$\frac{\partial \mathscr{L}}{\partial \rho} = -\int_{\Gamma_2} p^2 \frac{\partial u^1}{\partial \rho} d\Gamma + \int_{\Omega} \frac{\partial u_{k,l}^1}{\partial \rho} E_{ijkl} v_{i,j}^1 d\Omega + \int_{\Omega} u_{k,l}^1 \frac{\partial E_{ijkl}}{\partial \rho} v_{i,j}^1 d\Omega + \Lambda \int_{\Omega} 1 d\Omega \tag{11}$$

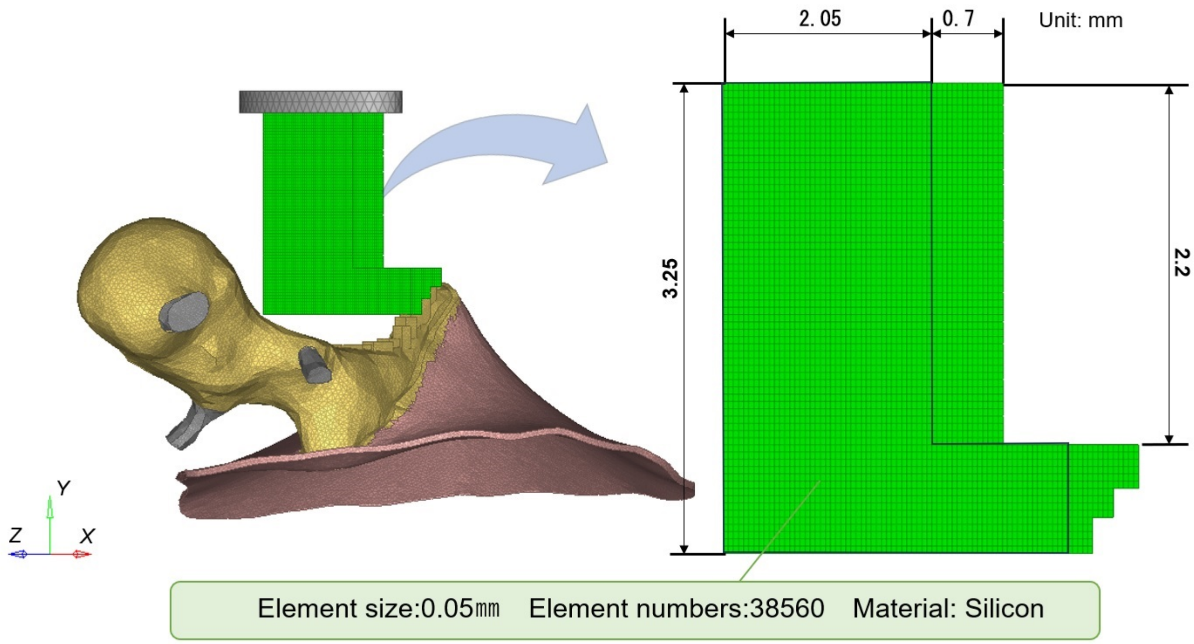

Figure 8: Design domain for the application example in the type-Ⅳ tympanoplasty operation

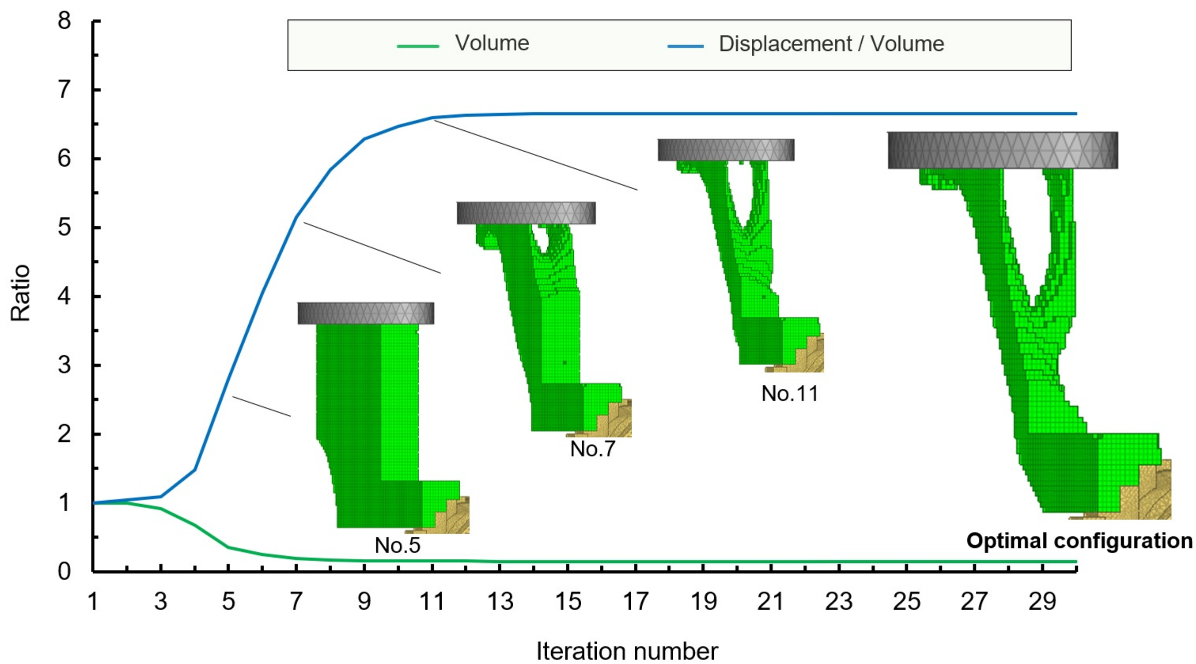

Figure 9: Optimal configuration and convergence histories

Since $v_{i,j}^1$ is arbitrary variables, the first two terms in Eq. (11) can be cancelled by considering $v_{i,j}^1 = u_{i,j}^2$. Therefore, the sensitivity of the mutual mean compliance with respect to ρ is obtained as follows:

$$\frac{\partial \mathscr{L}}{\partial \rho} = \int_\Omega u_{k,l}^1 \frac{\partial E_{ijkl}}{\partial \rho} u_{i,j}^2 d\Omega + \Lambda \int_\Omega 1 d\Omega \tag{12}$$

To validate the effectiveness and practical utility of the proposed approach, topology optimization of an artificial ear ossicle used in type-IV tympanoplasty was conducted to maximize the displacement of the stapes footplate. The operational model of the human middle ear, including the design domain, is depicted in Fig. 8. In this model, only the footplate remains intact in the stapes damaged by ear diseases, and the artificial ear ossicle is positioned between the footplate and the malleus.

Figure 9 presents the optimal topology configuration and the convergence histories of the Z-direction displacement and volume, with values normalized to their initial states. The results demonstrate a steady increase in the ratio of displacement to volume, achieving a maximum value while satisfying the specified volume constraint of $\hat{M} = 15\% M_0$.

5 CONCLUSIONS

This paper proposed a topology optimization approach for designing an optimal columella to enhance hearing restoration in the sound conduction reconstruction of a damaged human middle ear. The design objective was to maximize the displacement of the stapes footplate by employing the concept of mutual mean compliance. Utilizing the proposed method, optimal topology configurations of the columella were determined based on topology sensitivity, which was theoretically derived in this study. A numerical example of the topology optimization of a columella, used in a surgical procedure, was provided to demonstrate the effectiveness and practical utility of the proposed approach. This methodology enabled the optimization of the columella prior to surgery, offering a novel medical treatment for the recovery of conductive or cochlear hearing loss.

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