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Using fibrincollagen composite hydrogel and silk for bio-inspired design of tympanic membrane grafts: A vibro-acoustic analysis

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ABSTRACT

Tympanic membrane (TM) is vulnerable to a variety of middle ear diseases. In some cases, reconstruction or repair of the TM is essential for recovering the hearing. Although there are many kinds of materials and therapeutics for TM reconstruction, tissue engineering of the TM is still in its initial steps of advancement. Treatment of damaged TM is usually carried out by otology-related techniques such as myringoplasty and tympanoplasty. Most of the novel tympanoplasty methods employ artificial grafts made of biomaterials and polymers for scaffolds. One biomaterial candidate for design and fabrication of synthetic grafts is spider silk, which has excellent mechanical and acoustic characteristics. On the other hand, the structural function of the spider web is also one of the potential inspirations for designing tissue-engineered grafts on micro-scale explorations. In this study, a bio-inspired design and analysis of silky TM grafts are carried out employing finite element modeling and vibro-acoustic investigation. A comparative and statistical analysis is also performed with experimentally validated data to check the suitability of the materials and design. The numerical study shows that the proposed bio-inspired models are appropriate for TM graft design and fabrication. The effects of inspired architecture and materials on obtaining an optimum design for TM grafts are put into evidence via a parametric study, and pertinent conclusions are outlined.

1. Introduction

Tympanic membrane (TM) is a thin and resilient membrane in the middle ear. TM captures acoustic energy from the environment to start the hearing process and transmits it to the ossicular chain as a vibration response. The TM is a vulnerable membrane to middle ear diseases such as otitis media or traumatic perforations [1], injuring externally applied stresses like blast-induced loads [2]. This may lead to hearing loss and recurrent infections in individuals, but the most prevalent problem is TM perforation. On the other hand, the most common causes of TM perforation are middle ear infections, postoperative complications, and traumatic rupture because of increased pressure [3,4]. However, TM can show auto-regenerative ability in most cases. Reconstruction of intensive perforations may be necessary by micro-surgical approaches using unique materials such as autologous tissue, temporalis fascia (the most commonly used material), cartilage, fat, or perichondrium [5]. The typical therapeutic methods are based on using grafts (produced with biodegradable polymeric materials) to repair the perforation of the TM to protect the middle ear from external causes and infectious agents [6]. However, the well-known methods with high success rates for restoring damaged TM are myringoplasty and tympanoplasty. Myringoplasty is a surgical technique performed by otolaryngologists to repair the TM, improve hearing, and reduce and control middle ear infections. Multiple autologous grafts, allografts, and synthetic grafts are essential materials for carrying out this therapeutic [7]. It is also worth mentioning that the most commonly used and proven to be effective graft material is the autologous temporalis fascia. But the other harvested materials, such as cartilage, perichondrium, fat, and some synthetic graft materials such as paper and alloderm, are a vital part of myringoplasty as well. In comparison, the elimination of disease and restoration of function requiring a healthy TM and a reliable connector to join the TM to the inner ear fluids are performed by tympanoplasty [8]. Although these methods are widely used, they have limitations that encourage researchers to find low-cost, non-surgical, and more reliable alternatives based on novel tissue engineering approaches such as growth factors, cells, and artificial scaffolds [9]. Using grafts in surgical methods has limitations, such as

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possible donor site morbidity, lack of transparency, vibration at lower amplitudes, acoustic implications, air-dried characteristics, re-perforation of TM, and other operating special assignments [7]. As a result, designing the optimum and robust model of the grafts considering all related bioengineering aspects is essential. Not only the geometrical characteristics, but also graft fabrication materials play an imperative role in achieving a better design. Thus, finding novel and more applicable methods and materials to produce artificial samples with inspiration TM structure and function is vital. This may fill significant gaps between defects in existing grafts and expected features of future exploration. On the other hand, because of having no support under the epithelial layer of the TM structure, the clinical repair and reconstruction procedures need different scaffolds or grafts that support cells and nutrients migration towards the perforation [10]. Mentioning stands are generally produced with decellularized tissue (obtained after cell removal of allografts or xenografts) and/or polymers [3]. Each graft materials has some advantages and unique features, but materials showing good acoustic properties often do not offer adequate mechanical support and vice versa. A common strategy used to design scaffolds in microscale is to employ the lattices engineering features. In addition, bio-inspired lattices have obtained a significant role in structural optimization and design. Dal Poggetto and colleagues [11] used optimization techniques to design the spider web-inspired single-phase phononic crystals to show the spider web geometrical specifics in wave propagation. A similar study was performed by Wang et al. [12] to demonstrate the ability of spider web-shaped photonic crystal fiber for long-distance and high-performance transmission of terahertz waves.

In summary, the development of superior graft materials remains controversial. But finding a material with high mechanical strength to resist negative pressures in addition to excellent acoustic properties would be an ideal solution. As normal human hearing is most sensitive in the range of 1 to 4 kHz, showing good vibration characteristics in this range of frequency is expected from using graft materials. The chosen material must balance both acoustic properties and mechanical stability [13]. An excellent solution could be obtaining a much stiffer membrane at a given thickness through selecting a material with a higher Young's modulus.

For this reason, researchers have studied different materials that have revealed promising results, but investigations into finding more suitable materials are continuing. Among these studies, research on silk materials has become more attractive because of its higher modulus and resistance to deflection [14,15], biocompatibility, biodegradability, and ability to support cell growth as a scaffold. Application of silk is not only performed by bio-inspiration of silk fibroin for advanced studies [16], biomedical engineering [17], and other biomaterial-based investigations, but could also be inspired because of its excellent acoustic properties [18]. However, more and more studies are needed to find the best application methods and optimum design for use in tympanoplasty. For example, the frequency response, strength, and acoustic properties of the silk membrane were investigated with the well-known grafts of cartilage and paper to show the ability of this material in TM repair [13]. The ability of the silk fibroin protein in the cell growth reconstruction method of TM was revealed when the interaction of this material with human TM keratinocytes was found. This was proven by a study performed in [19] to show the advantages of biocompatibility, biodegradability, and transparency of silk fibroin for potential use as a tissue engineering scaffold. They used a silk fibroin-made scaffold to support the growth and proliferation of human TM keratinocytes. The effectiveness of the silk fibroin in TM repair by proving its main advantages of optimal mechanical properties, transparency, and ease of handling is also investigated [3]. The study was supported by results from a comparative analysis of the silk fibroin scaffold in improving the structural function of repaired TM with a paper patch. A similar study to show silk patch potential use in functional restoration of TM was also performed in [20] comparing the designed thin silk patch and the commonly used paper patch. Some other researchers tried to show that silk has great potential to be an alternative to tissue-culture methods in TM repair. This is the issue that Ghassemifar and colleagues [6] studied with the higher number of cells growing on fibroin in their investigation. They used domesticated silkworm silk fibroin to grow tympanic cells. Their studies showed that silk fibroin could be a more suitable substratum for growing tympanic cells when compared to a commercial tissue-culture plastic. Besides, spider silk has significant biocompatibility because of its main component of silk protein. Also, spider silk is a nontoxic natural material that no immune rejection reaction has been reported for the human body yet [21]. The mentioned characteristics have made it a great alternative as a bionic material for bioengineering applications.

However, investigations into exploration, design, and fabrication of more suitable grafts for office-based techniques for treating humans TM with silk materials continue. This study presents the design and modeling of silk-based grafts with bio-inspired architectural geometry for potential use in artificial polymeric-based graft fabrication. Indeed, using lattice structure patterns with applying the topology optimization method is the initial step of designing grafts architecture. For this, the spider web and the other natural engineered structures are inspired to design unit cells of TM grafts. Firstly, a computational modeling of the cases is carried out by the COMSOL Multiphysics software package according to the inspired architectural and material properties. Then, simulation results are taken under comparative and statistical analysis. To this end, existing experimentally validated data prepared by digital optoelectronic holography (DOEH) and laser Doppler vibrometry (LDV) tests are taken from [22]. Finally, the optimal and suitable models are introduced by analytical demonstration according to the finite element method (FEM) simulation results and experimental test data. Due to the absence of similar results in the specialized literature, this paper is likely to fill a gap in the state of the art of this problem, and provide pertinent results that are instrumental in the design of TM grafts. The remaining of the paper is organized as below: Section 2 explains the general conception of the research and considering materials for designing the grafts. Analysis and research method are mentioned in Section 3 comprehensively. Section 4 discusses the obtained observations from the numerical analysis. And highlighted conclusions are drawn in Section 5.

2. Materials and conception

The modeling assumptions of the designed grafts are made based on the technical requirements of using one of the novel technologies such as 3D bioprinting in graft manufacturing. A comprehensive background and application of printing methods in biomedical engineering can be reviewed at [23]. As it can be seen in Fig. 1, the grafts are designed with a circular geometry including filaments modeled with silk materials and the infilling area that is filled with a fibrincollagen composite hydrogel matrix [22].

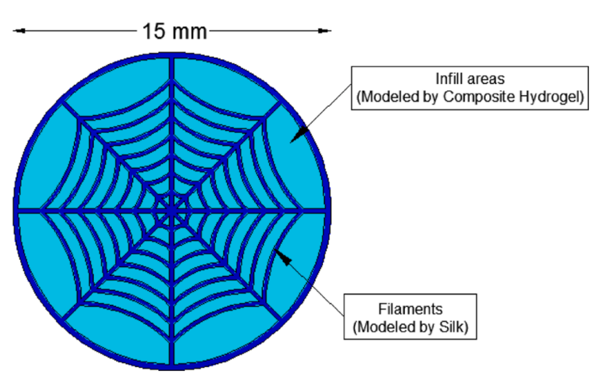


Fig. 1. A TM graft model components and simulation assumptions.

2.1. Fibrincollagen composite hydrogel

From a 3D bioprinting standpoint of TM composite grafts designing, creating an environment that closely mimic the native extracellular matrix of human TM should be performed by using a fibrin collagen composite hydrogel [24]. Hydrogels are three-dimensional polymeric networks, which are composed of cross-linked hydrophilic polymer chains. Flexibility to be cast into a desirable shape, size, and form with high water absorption up to thousands of times their dry weight are the significant properties of the hydrogels [25]. The novel applications of hydrogels have appeared in cell therapy, stem cell and cell culture research, cancer and in vitro diagnostics, tissue engineering, immunomodulation, implants, 3D bioprinting, and other biomedical engineering fields. In this study, to obtain a uniform infill between designed filaments, using the fibrincollagen composite hydrogel with material properties similar to experimentally validated samples [22] is assumed for simulation of the models (see Fig. 1).

2.2. Araneus major ampullate (MA) silk

Silk is one of the natural high-molecular-weight polypeptide composites that includes a group of fibrous proteins and also collagen, elastin, keratin, and myosin with excellent mechanical propeties such as high strength, Young's modulus, and flexibility [26]. Silk is obtained from the larvae of certain species in the order Lepidoptera and spiders (Araneae). Because of this, the material properties of silk are different from specimen to specimen. Table 1 shows selected Araneus major ampullate (MA) silk material properties to carry out numerical analyses and numerical tests [27,28]. Establishing a unique combination of strength and toughness characterized by a sigmoidal, balanced stress-strain relationship, and a significant level of shear rigidity with time-dependent mechanical properties makes the spider MA silk more attractive for use in engineering applications [29]. The anisotropic and non-linear viscoelastic behavior of spider silk fiber is another remarkable characteristic of polymeric materials [30].

2.3. Structural function and acoustic properties of Araneus major ampullate silk and web

The structural function and mechanical characteristics of two Araneus diadematus silks of MA and viscid are illustrated in Fig. 2 as stress-strain curves. The stiffness of the material and the energy required to break the material (quantify toughness) can be obtained from the slope and the area under the stress-strain curve respectively. These curves demonstrate that the spider MA silk is one of the stiffest and strongest polymeric biomaterials. Furthermore, the essential mechanical properties of web silk, such as a balance between strength and extensibility, and considerable toughness with a high level of hysteresis due to a significant level of internal molecular friction [28], introduce it as an attractive material for use in biomedical engineering applications. Despite superior mechanical properties, suitable acoustic characteristics are also needed for the multi-physical application and engineering of both employed inspired silk material and spider web in tympanoplasty. In fact, because they consist of different radiation silk and catching silk, spider webs can resonant at a specific frequency. This helps the spider web show the ability to reduce and absorb the vibration energy in a wide resonance frequency band [21]. To achieve an optimum bio-inspired design of the TM graft, both silk material properties (mechanical, acoustic, etc.) and geometrical web architecture play essential roles. Inspiration of the spider web architecture as a locally-resonant acoustic material for low-frequency elastic wave manipulation has uncovered many advantages [31]. These features can improve the reflective performance and also help to achieve tunability of wave manipulation characteristics of corresponding acoustic materials [32]. Besides these, the wave speed (CL) in silk material, which is another vital acoustic property for applying the models, can be calculated with Eq. (1) based on silk's modulus [33].

Table 1
Mechanical properties of spider silk [27, 35].

Mechanical Characteristics of Araneus MA Silk					
Density (kg/m3)	Stiffness (GPa)	Strength (GPa)	Extensibility (%)	Toughness (MJ/m^3)	Hysteresis (%)
1320	10	1.1	27	160	65

$$\mathrm{CL} = \sqrt{\frac{\mathrm{E}}{\rho}} \quad (1)$$

where E is the storage modulus (measured by purely elastic stiffness), and ρ is the density.

2.4. Architectural and geometrical inspiration

For the architectural and geometrical planning of the TM grafts, lattices general conception is considered by employing a periodical pattern of a unit cell. Specific characteristics such as high strength-to-mass ratio with the other high-impact properties of lattice structures have revealed novel generation of engineering products. Also, lattice engineered structures are capable to be optimized aiding novel optimization methods to obtain a more suitable model [36,37]. This conception is applied as bio-inspired architectural plans such as spider orb-web, honeycomb, and hexagonal-shaped pattern unit cells (see Table 2). Besides, structural function and material properties, architectural and geometrical specifications, and the other notable characteristics of spider webs and silk materials have attracted researchers to inspire these nature-based conceptions. The high strength, toughness, and possessing a high damping capacity of kinetic energy, extensionality, and torsional qualities of spider silk are the leading causes of different functions in house protection, trapping, and capturing high-velocity insects [34]. All of these features are highly dependent on the web structure and geometry. The web contains the web frame and dragline (stiffer elements) with MA gland and viscid silk (tougher elements) excretion, as shown in Fig. 2 [28]. On the other hand, geometry plays a vital role in the mechanical and wave-propagation properties of periodic materials. Hence, altering the geometric parameters can lead to significant differences in the dynamic behavior and responses [35].

Considering all this knowledge of silk and spider web, the spider-web hexagonal and snowflake triangular lattice structures geometrical properties are employed for designing the corresponding models. Table 2 shows five architectural models in radial threads, orb-web, and hierarchical conceptions in a circular shape with a 15mm diameter. In order to validate architecture, all models are selected as unit conceptions from research works.

3. Methodology

To study the acoustic performance of models, numerical investigations are carried out via FEM. The two main steps of the stationary and frequency domain are selected for carrying out the research. The COMSOL Multiphysics Software package is implemented to perform the simulation procedure. To have a wide range of data for obtaining an optimized geometry, five models are created as different cases for the investigation. Architectural conceptions of geometrical characteristics of the models are defined according to the details presented in Table 2. Different mesh types are used to simulate the FEM model. The mesh convergence is evaluated for these models, and the acceptable mesh type has a good fit in this FEM. However, for the generation of the meshes, after applying different meshing techniques to the models to find the more suitable method, the fine size is selected. The triangular element type is used for meshing the models. Each element has three nodes and

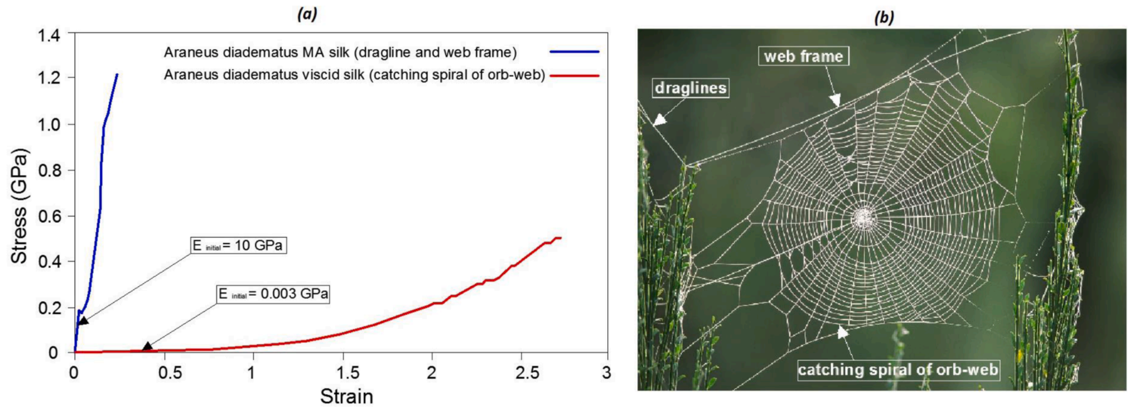


Fig. 2. The structural function and mechanical characteristics of two Araneus diadematus silks of MA and viscid: a) Stress–strain curves of MA and viscid silk [34], b) Araneus web and its architectural and structural components.

three sides with contributing two degrees of freedom. Mesh size and the overall number of elements computed based on physics-controlled mesh sequence type, the maximum element size should be smaller than $\left(\frac{\text{wave length}}{5}\right)$, then the maximum element size of 1.68mm is selected. The overall number of triangular elements composing the FE models at the macroscopic scale differs from designed models and is presented in Table 3. The frequency-domain study is carried out by using an acoustic module prepared by COMSOL to create the Pressure Acoustics Frequency Domain (ACPR) interface. Although ACPR can be used to analyze the pressure variations caused by the propagation of acoustic waves in the corresponding model into a fluid environment, it is also a suitable tool for modeling acoustics phenomena without considering fluid flow. In this method, the Helmholtz equation in the frequency domain for given frequencies is solved at the physics interface. After choosing the ACPR physics interface, acoustic loading referred to the future experimental test conditions is also applied to the models. Also, the sound hard boundary (SHB) or wall and initial values are added to the default nodes on models. The boundary conditions are also applied to the outer border region with an assumption close to the actual behavior of the TM following the ACPR requirements. In fact, because of the boundary area of the ear that acts as a wall boundary condition, the sound hard boundary condition is used in each case of TM graft models. Assignment of the acoustic environment to the model is performed by applying acoustic pressure to the understudying cases by creating a sound wall. The MUMPS Solver of the stationary solver is appropriate for pressure acoustic frequency domain analysis. Hence, a tool for carrying out the frequency-domain study in the human range of sound perception is applied. This method provides numerical vibro-acoustic analysis results for comparative and statistical analyses between human TM dynamic responses and results obtained from simulations. Also, the human TM behavior patterns at three different frequencies into the hearing range are taken from DOEH and LDV [22]. Two main demonstration factors of displacement measurements and velocity variations are considered for performing comparative analyses.

4. Results and discussion

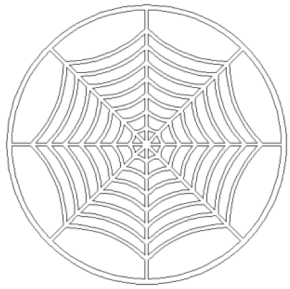
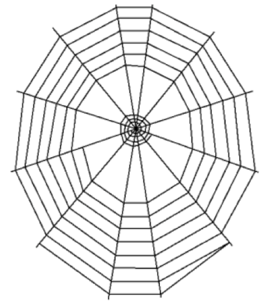
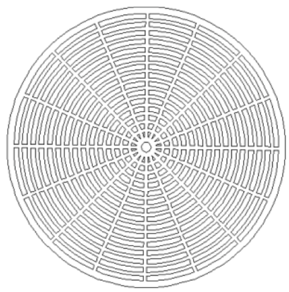
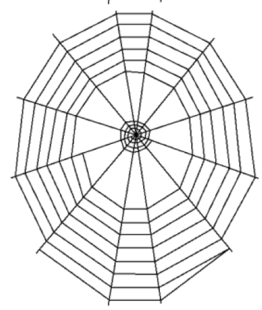
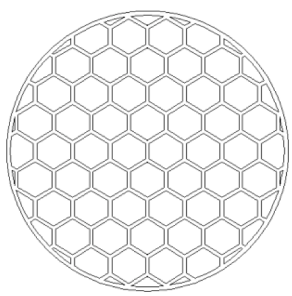
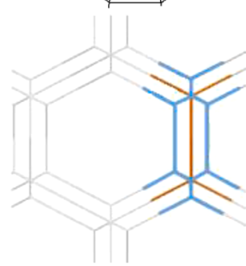
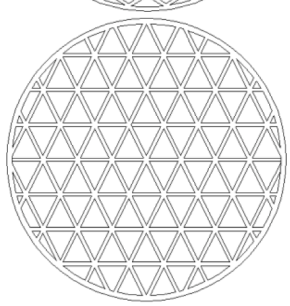
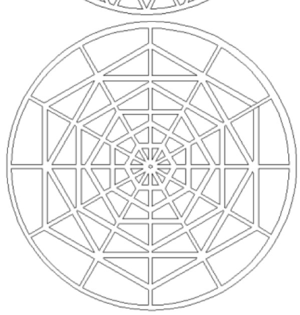
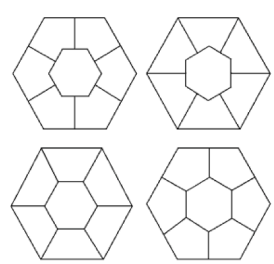
4.1. Surface motion and displacements

All designed TM graft scaffolds composed of silk material are simulated to evaluate their mechanical and acoustic behaviors at three frequencies of 400, 1000, and 3000Hz (human range of sound perception). The vibro-acoustic analysis results are provided as color bars mapping to explain the motion patterns in the data format of (frequency – dB) range. On the other hand, the motion patterns related to the human TM are taken from the experimental tests provided by [22]. The data for performing comparative and statistical analyses between computational modeling and DOEH results are adjusted for all five cases mentioned in Table 2. This information is presented as normalized displacement by sound pressure at (dB re μm/Pa) unit. Fig. 3 shows both the surface motion patterns of all five cases at three different frequencies obtained from vibro-acoustic FEM analysis and the human TM response demonstrated by experimental tests for the sake of comparative analysis. As mentioned before, the FEM analysis is performed based on the frequency domain presented in three columns at 0.4, 1, and 3kHz with standardized color bars at each frequency according to the output color bar ranges of the ODEH test mapping.

For the first case study, although a good general correlation can be seen, it is more observable at 1kHz frequency that the model (1) shows a good homogeneity in acoustic and dynamic response with human TM. In other words, between 100 dB and 120 dB, the motion patterns are similar in most segments with some differences in surface areas. But at frequencies more than 1000 Hz, the homogeneity of the displacement pattern is not very close to the experimentally validated motion pattern of the human TM. Although the orb- web conception of the first and second models are similar to each other (see Table 2), filaments with inverse centrist architecture (1) are altered into radial filaments with the centric arrangement. This architectural alternative to the model (2) could be effective for dynamic behavior. Motion patterns for model (2) show the effect of the filaments architecture on the dynamic response of the grafts. While the second case of study has notable dynamic behavior at ($<$ 1000 Hz) frequencies, it is undeniable that at lower frequencies, model (2) cannot show a good correlation on the dB scale. This means that the architectural design for the graft of this model is affected by both geometrical structure and the conceptual arrangement of filaments. Generally, both models have nearly equal performance at frequencies less than 1000 Hz. But model (2) tends to show a different behavior (a slight correlation with human TM behavior) at frequencies higher than 1 kHz. At 3000 Hz frequency, the radial architecture of filaments is in an excellent dynamic response mapping for normalized displacement between 80 dB and about 95 dB. Likewise, for displacement magnitudes at 400 Hz, the correlation of FEM output for case study (3) with the human TM behavioral range is meaningful. Furthermore, the dispersion of color bar patterns for the FEM model 400 Hz and 1000 Hz are satisfying homogeneity, especially for 80 to 100 dB sound pressure range. Again, the low range of correlation is recorded at the 3000 Hz frequency.

The same observation can be reported for case study (4) with an important difference in the displacement pattern of the model for frequencies less than 400 Hz. Also, the correlation between FEM color mapping and human TM is only reported at 100 dB to 120 dB for a few segments. In this case, the acoustic and dynamic response of the designed graft is in good homogeneity with DOEH color mapping for human TM at 1 kHz frequency. At higher frequencies, model (4) shows

Table 2
Geometrical conception and details of the designed models.

Case/Model	Geometry/Design	Conception (unit cells)	References
Case 1			[38,39]
Case 2			[22,39]
Case 3			[35]
Case 4			[35]
Case 5			[40]

considerable differences in displacement magnitudes.

The employed spider-web hexagonal structure for this model helps distribute dynamic response (here is surface motion) in a simple pattern with nearly uniform magnitudes. Noteworthy, the jointing locations of the hexagonal lattice connectivity (honeycombs) in the model (3) and snowflake triangular lattice in the model (4) play essential roles in response transition between unit cells with the aid of connecting beams. In contrast, this issue is not confirmed in case (5) ultimately. Because of the color bar patterns related to the acoustic behavior of FEM models that show a satisfying homogeneity at frequencies (< 1000 Hz), the designed graft model has good performance at the frequency of 400 Hz. In a sound pressure range of 100 db and about 110 dB, the correlation between the FEM output pattern for 0.4 kHz frequency and the human TM motion pattern helps to demonstrate that the architectural conceptions with a radial arrangement of filaments are qualified to show a good dynamic performance. This issue is also observable in case study (2)

Table 3
The overall number of elements composing the FE models.

Case No.	No. of elements	Max. element size	Min. element size	Max. growth rate
Case 1	16,758	1.68	0.0075	1.3
Case 2	17,264	1.68	0.0075	1.3
Case 3	13,548	1.68	0.0075	1.3
Case 4	12,459	1.68	0.0075	1.3
Case 5	14,950	1.68	0.0075	1.3

with circular filaments of its model. But the other common characteristic of radial filament architecture is the structural function of the filament junction points. Models (1) and (5) show maximum response magnitudes at these locations. This may be a cause to lead companion designs to perform a little better than the other models in frequencies (< 3000) with a complex motion pattern.

4.2. Surface velocity

The DOEH test results for presenting the motion patterns of local displacement on sample surfaces have limitations in their frequency resolution [22]. To tackle this, LDV was employed by [41] to measure the sound-induced velocity of the center of the human TM across more than 400 Hz frequencies, ranging from 100 Hz to 10 kHz. Fig. 4 shows the mean velocity measurements normalized by sound pressure for all case studies and human TMs. The sensitivity analysis of normalized velocity to the number of elements is performed for all cases. Also, the peak in the normalized velocity patterns for all models is collected in Table 4. Fig. 5 shows the sensitivity analysis for case 1 and case 5.

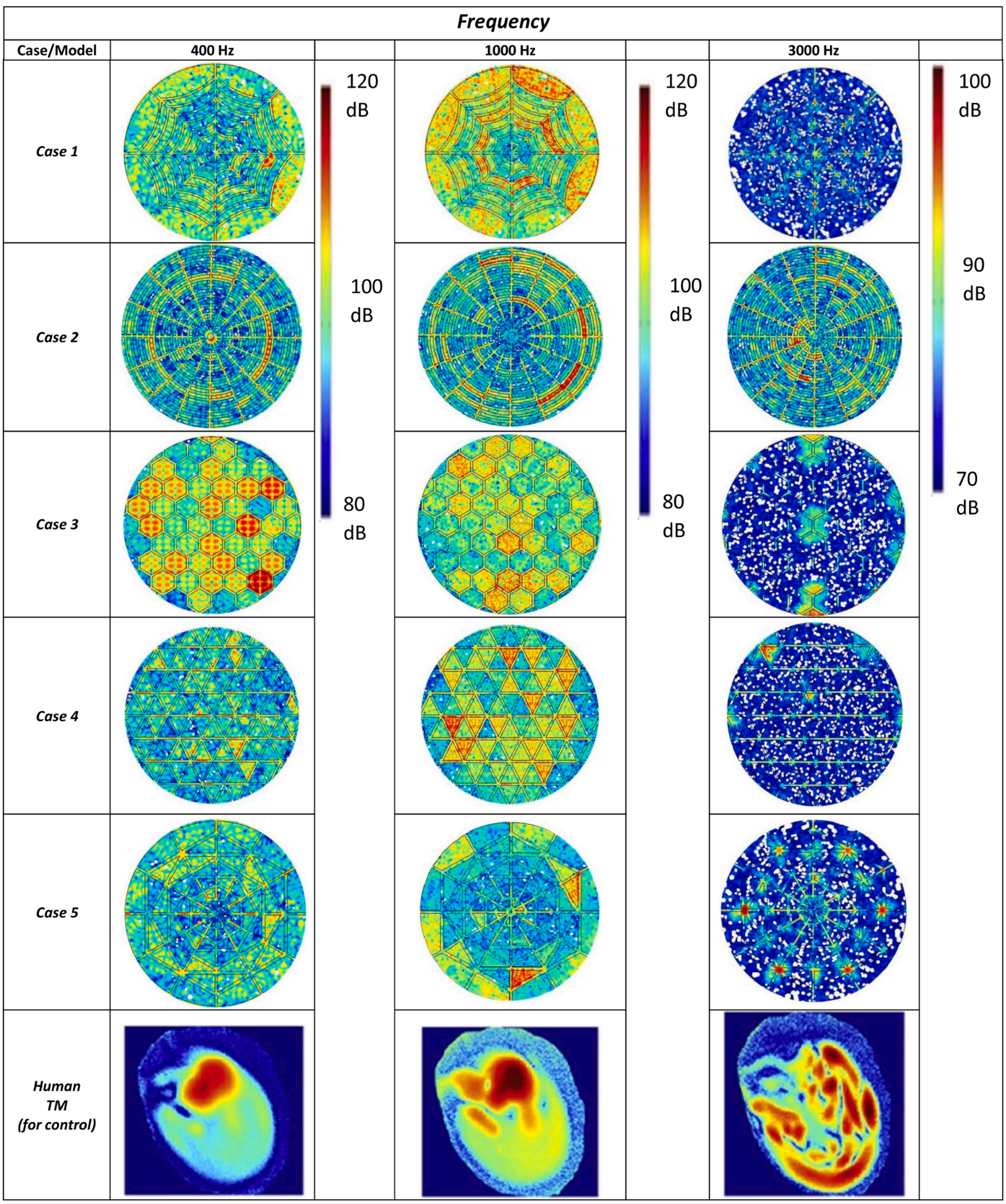


Fig. 3. Vibro-acoustic FEM analysis results for all study cases and the motion pattern of the human TM taken from DOEH at three different frequencies.

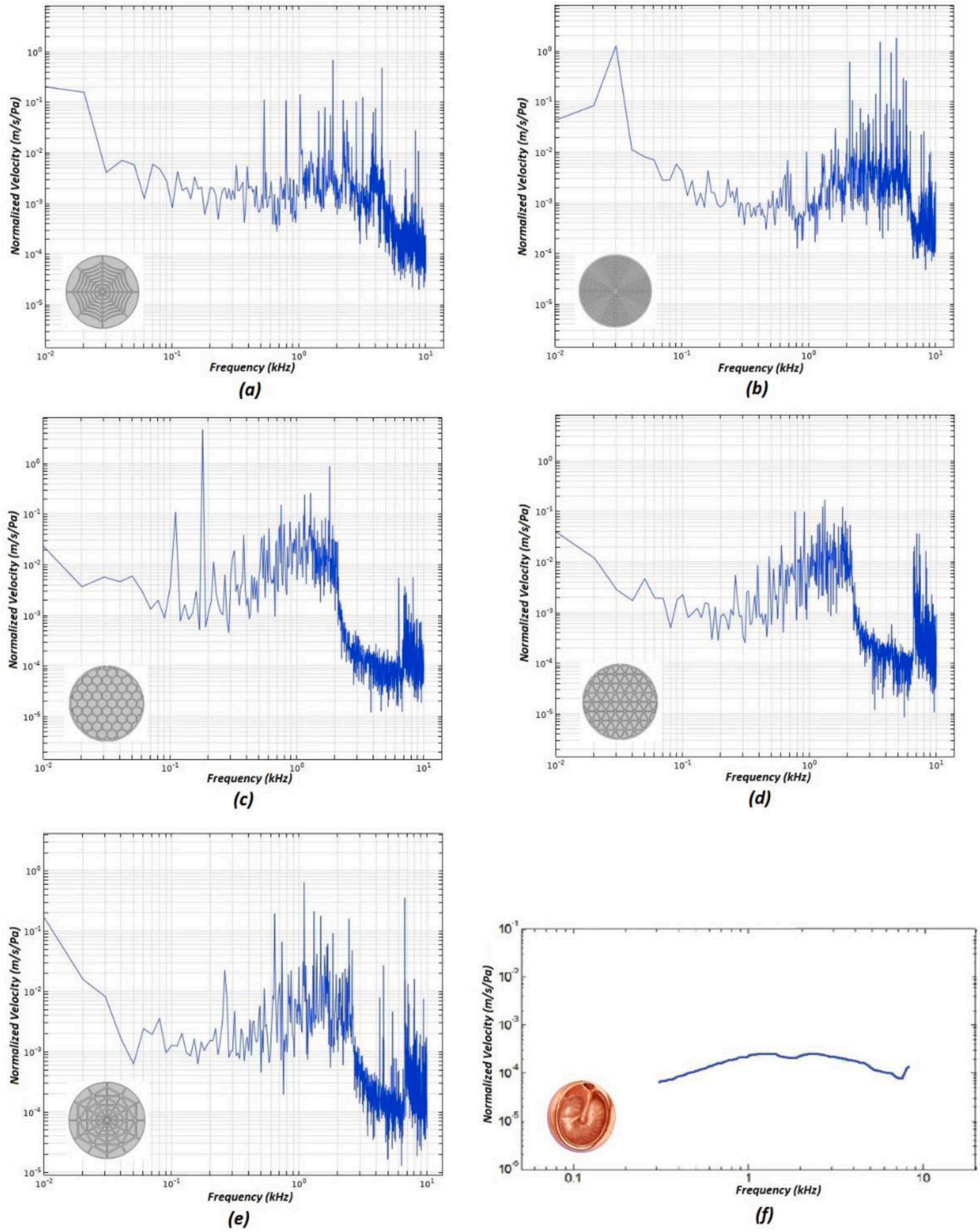


Fig. 4. Normalized velocity results by stimulus sound pressure of designed grafts: a) results for model (1), b) results for model (2), c) results for model (3), d) results for model (4), e) results for model (5), and f) human TM [41].

According to the results of these analyses and based on the mesh convergence results the normal mesh type with a maximum element size of 1.8 mm is considered.

Table 4
Summary of the normalized velocity max magnitudes for models and LDV.

Model	1	2	3	4	5	Human TM [41]
Velocity Max (m/s/Pa)	0.70	1.20	1.60	0.20	0.70	0.051
Frequency (Hz)	200	650	130	180	1000	180

However, the normalized velocity of a specific point in TM is selected for physical response in the models. The first interesting observation is that both model (4) and human TM show their max normalized velocity at 180 Hz. With a magnitude of about 200 Hz, model (1) is also has a peak in the normalized velocity graph close to the human TM. Also, model (1) and model (5) obtain the same max velocity (0.70 m/s / Pa) but at different frequencies of 200 Hz and 1 kHz, respectively. Again, the models with radial architecture and centrist arrangement of filaments (model (2) and model (5)) exhibit the highest velocity with a peak at frequencies of more than 600 Hz. In general, the designed grafts have a good performance in sound-induced velocity. Still, the obtained max

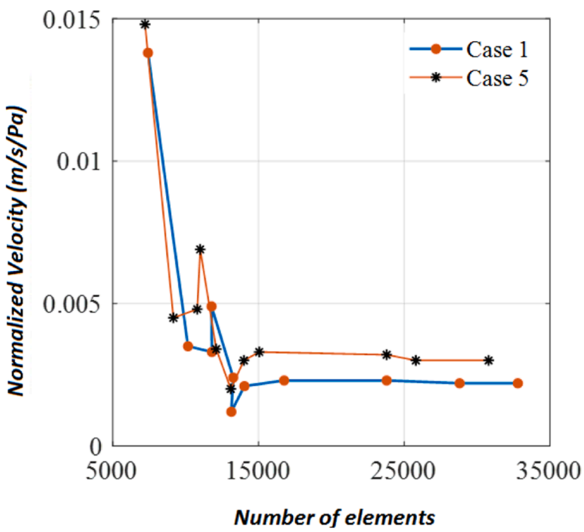


Fig. 5. The sensitivity analysis of the normalized velocity to the number of elements in two different cases.

value for grafts is in a considerable amount of difference compared to human TMs.

4.3. Summary

Two important factors of sound pressure-induced motion and normalized velocity have been employed to qualify the study of the proposed models for potential use in the design of tympanoplasty. In this section, a summary of highlighted results is presented according to the comparative and statistical analyses:

1 All models can show a satisfying performance at frequency lower than 3000 Hz, but more investigations are required for a higher range of hearing.
2 Models with spider orb web-inspired architecture are in good homogeneity with human TM behavioral patterns.
3 The models designed with a spider-web hexagonal structure show a qualified performance in the uniform distribution of the response through the surface.
4 The junction points of the hexagonal lattice connectivity in the snowflake triangular lattice-inspired models play an essential role in response transition between unit cells.
5 In general, the dynamic response patterns of the models with radial (centrist architecture) filaments are in a good correlation with human TM.
6 The model with snowflake architecture shows an excellent correlation in sound-induced normalized velocity maxima.
7 Spider orb-web-inspired geometries show the peak of normalized velocity at low frequencies near human TM behavior.

5. Conclusion

The paper concludes by arguing the potential use of spider web and silk materials in designing and fabricating suitable polymeric grafts and scaffolds for human tympanic membrane reconstruction. In this study, many bio-inspired models were proposed for designing silk-based polymeric scaffolds. All of the models were vibro acoustically analyzed by COMSOL Multiphysics Software according to the silk biomaterial characteristics. The numerical outputs were studied with comparative statistical analysis considering existing experimentally tested data taken from DOEH and LDV. Thus, the qualification of proposed models in both aspects of architectural inspiration and material function was investigated. Observations showed that the proposed TM graft models were biomechanically qualified for potential use in the TM grafts designing and fabrication procedure. Although more studies are essential for optimizing the model's performance at higher frequencies, the models with radial filaments arrangement showed a better structural function in both sound pressure-induced motion and normalized velocity control factors. These results follow from the fact that the merging architectural and mechanical features of the spider web and silk can provide a unique opportunity for studying the bio-inspired acoustic design of synthetic grafts.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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