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# NATURE AS INPUT: A FRAMEWORK FOR DEFINING BIOINSPIRED INPUT PARAMETERS IN TOPOLOGICAL OPTIMISATION

**Summary**

This paper presents a novel approach to the integration of biological inspiration into topological optimisation through the specification of input parameters derived from nature. The aim is to create biomimetic designs that may incorporate the multifunctionality inherent in natural systems. The presented methodology for modelling bioinspired structures using topological optimisation provides critical insights into translating natural forms and their load-bearing characteristics into topological optimisation design parameters (design space, boundary conditions, and loads). The proposed BioTop method is a structured framework that guides designers through a design-to-biology approach for conducting truly bioinspired topological optimisation by systematically defining the required inputs. An illustrative case study demonstrates the practical application of the BioTop method and its capacity to create bioinspired topologically optimised structures. While acknowledging current simplifications, this research lays a foundation for future research in bioinspired design by providing a systematic method for using nature as an informed input source for the standard topological optimisation software.

*Key words:* *bioinspired design; biomimetic; topological optimisation; design method*

## 1. Introduction

Lightweight structures are highly desired in mechanical design, as a reduction in product mass is associated with many benefits, such as easier handling, improved fuel efficiency, cost savings on raw materials, etc. [1]. One of the methods for designing lightweight structures is topological optimisation (TO), an iterative computational design method that determines the most efficient layout of the material for a set of loads, boundary conditions, and constraints within a given design space [2]. Topological optimisation can generate very complex structures, often hard to manufacture using traditional manufacturing methods. However, with the advent of additive manufacturing, which allows for the fabrication of intricate geometries, TO has become widely used for designing complex lightweight structures that use the minimal amount of material required to sustain the applied load [3], [4], [5]. Hence, more and more designers are using TO in their designs.

Another approach to lightweight design involves drawing inspiration from nature [6], [7], the so-called Bio Inspired Design (BID), as biodiversity found in nature represents a large source of inspiration for designers and engineers [8], [9]. Nature exhibits excellent capabilities in creating functional and complex structures with good mechanical performances optimised for the imposed load case under specific environmental conditions [10]. Natural structures, or biostructures, have evolved over a long period of time and countless iterations [11], achieving the optimal balance between the minimum use of energy and material while maximising their functionality, as the natural resources in a particular area are often limited [8]. McNulty et al. [12] showed in their research that natural cellular structures, while optimised for structural loads, can perform multiple functions. Their research suggests cellular structures can be used as an inspiration for creating additively-manufactured lattice structures. Similarly, Torreblanca-Díaz et al. [13] studied growing morphologies in nature to create an additively-manufactured stool, showcasing nature's optimisations in transferring mechanical loads.

Therefore, both biostructures and TO structures have a common objective of efficiently transferring mechanical loads using the minimal amount of material necessary. One could argue that TO exists in biostructures; for example, Darda et al. [14] reported that TO patterns are very similar to patterns biologically evolved in nature. Although the TO structures often have an "organic" appearance, as if inspired by nature, TO remains a purely numerical method. Because TO lacks any biological input, it cannot be considered a true BID [15]. Furthermore, the TO structures are iterated following only the goal of transferring mechanical forces using the least amount of material possible, whereas biostructures must often fulfil multiple functions. For example, the wing skeleton of cabbage white butterflies, besides transferring mechanical load, also provides a large surface area needed for reflecting sunlight into the butterfly's body to warm its muscles [16]. Importantly, the lack of a systematic approach for incorporating biological features into TO, such as geometric boundaries and load paths, prevents designers from creating true bioinspired designs using TO.

Because of the similarities between the TO structures and biostructures, we pose a question: "Can a structured framework be developed to translate biological features into the necessary design input parameters for standard TO?" A positive answer would mean moving beyond the mere functionality of transferring mechanical loads toward the design of truly bioinspired TO structures. Incorporating biological inspiration into the definition of the TO design space, load case, and boundary conditions could result in more holistic and multifunctional designs. Such designs would not only mimic the geometry of natural forms but could also integrate additional functionalities deriving from the geometry developed through evolution, thus achieving a true bioinspired design.

In this paper, the authors explore the integration of biological principles into the TO process by investigating how biostructures can form and modify the definition of TO design space and boundary conditions. The study begins with numerical experimental modelling of various biostructures using TO in order to examine the influence of biological input on TO outcomes. Based on the insights gained from these numerical experiments, a prescriptive method for incorporating biostructural features into TO is proposed, enabling the creation of true bioinspired TO models. To demonstrate and preliminarily verify the proposed approach, a case study in which flower petals serve as inspiration for the design of a lightweight car wheel is presented. The case study illustrates the application of the method and its potential benefits. The results are discussed, and the limitations of the method and potential directions for future research are given in the last two sections of the paper.

## 2. Methodology of the TO modelling of biostructures

To develop a method for applying bioinspired design within TO, a seven-step descriptive methodology [17] was used, as outlined by Rešetar [18]. This methodology falls under the category of biology-to-design approaches [8], [19]. The primary goal of this experimental phase was to analyse selected biostructures in terms of their load case scenarios and functions as well as to experimentally model those structures using the available TO software. The learning-bydoing approach provided the necessary insights for deriving a structured, prescriptive method [17] for translating the input from nature into TO design parameters and creating viable bioinspired TO models.

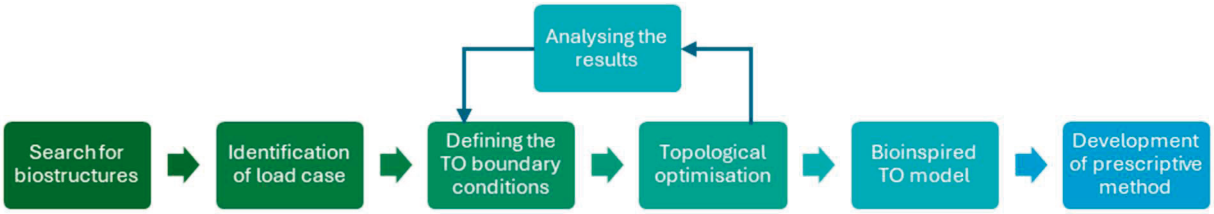



**Fig. 1** Methodology for the experimental TO modelling of biostructures

The first step in the applied methodology for the analysis of biostructures was the search for suitable candidates. In that step, priority was given to structures with clearly defined, macroscopic skeleton-like features, rather than cellular geometries, as those types of features are suitable for the TO modelling of bioinspired structures. The search was focused on identifying structures with known mechanical functions and well-understood load paths. It was conducted using asknature.org, an open-source database of deep biological knowledge as recommended by Goel et al. [20], but any literature describing natural structures can be used. Furthermore, in that step, the additional functions of those biostructures were observed.

Following the selection of biostructures, the next step was focused on the analysis and identification of loads applied to the selected biostructures. For each observed biostructure, primary loads were identified (forces, pressures, and torque), as they are the main input into TO. Also, a very important part in that step was the identification of the load type (compression, tension, bending, torsion, or shear) [12]. While this step seems trivial, it required detailed observation of the biological structures, as well as the environmental context in which those biostructures exist, to understand the loads they withstand. For the sake of simplicity and consistency, all loads were considered static because the topical optimisation was conducted on the assumption that boundary conditions were constant.

The gathered information served as the foundation model for the experimental TO simulations conducted using the Altair Inspire software [21]. The objective of the experimental TO was to replicate the base geometry of the biostructures. As TO requires the definition of several parameters, such as geometry, boundary conditions, and loads, to ensure the comparability of results across cases, most parameters were standardised to limit the total number of variables. A stainless steel, X5CrNi18-10 (AISI 304), was used as the material. The design space was limited to 100 x 100 x 20 mm to reduce the computational time, as numerous iterative simulations had to be completed. The loads were fixed at 100 N for forces and 1 MPa for pressure because these values reflect the load-to-size ratio found in many mechanical components. The optimisation objective for all simulation runs was to maximise stiffness, with the final structure retaining 30% of the initial design volume.

The design space in which TO is performed was modelled using the primitive geometric shapes to achieve the broad, abstract outlines of natural structures. This approach was adopted to simplify the process of shaping the design space because primitive geometric shape modelling is found in the majority of CAD and TO software; it also aims to reduce the time needed for modelling, since one of the research objectives is to help designers get complex optimised structures from a simple starting geometry rather than one requiring extensive CAD modelling. The boundary conditions were defined based on the knowledge gathered in the previous step. The experimental TO was highly iterative and was repeated multiple times, adjusting the design space and boundary conditions until the TO structure resembled the biostructure used as an inspiration.

To illustrate the experimental modelling process, the TO modelling of a spider web is shown in Fig. 2, clearly depicting the steps of the approach [18]. The spider web is a biostructure of octagonal shape attached to trees and other structures at its edges. It primarily withstands the forces caused by wind or the impact from a flying insect. It is a strong and elastic structure [22] that, besides withstanding mechanical loads, has many other functions. Some of the spider web functions include decoration to warn birds [23], continuous collection of water from air [24], impact absorption [25], and vibration transmission to signal the point where the prey is caught [26].

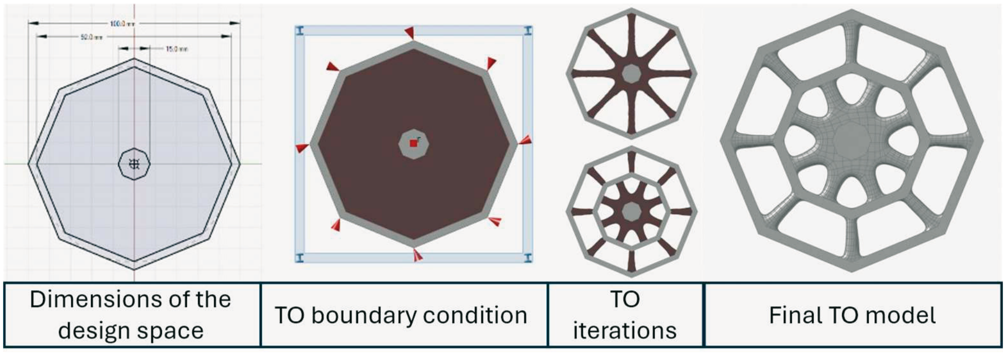
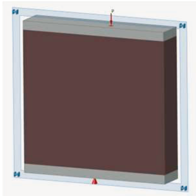
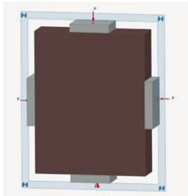
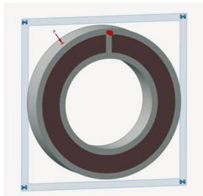
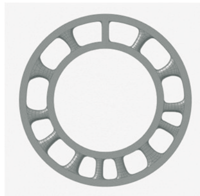
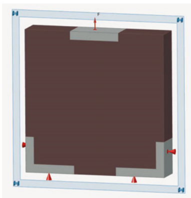
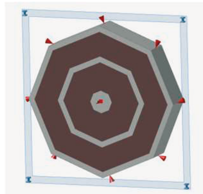
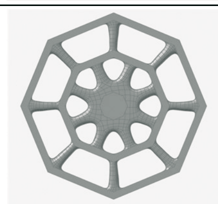
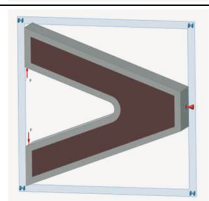
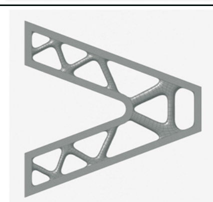
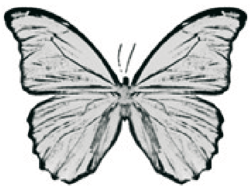
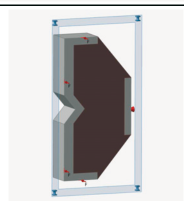
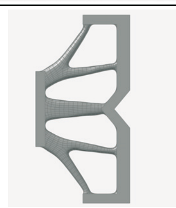
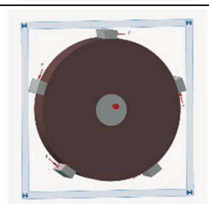
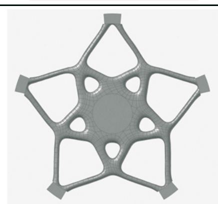



**Fig. 2** Overview of the spider web TO process

After analysing the spider web and its load case, as well as its functions, the experimental TO started with the definition of the design space. The design space was defined as an octagonal shape with maximum dimensions of 100 mm in accordance with previously defined limits. The centre and the outer edge of the design space were designated as preserved geometry during TO, to which the boundary conditions were applied. To present the loading conditions of the spider web, support boundary conditions were applied to the eight edges of the octagon, while a normal force was applied to the centre. Once all parameters for the TO were defined, the first simulation run was conducted, resulting in a simple TO structure with eight radial struts connecting the centre to the outer edge. While the TO structure resembled a basic spider web structure, it was less complex due to the absence of perpendicular struts. To improve the resemblance to the original structure, the design space was modified by adding additional preserved geometry in the shape of an octagonal ring in the middle of the design space, while keeping the boundary conditions unchanged. The second iteration of TO produced a structure with a greater resemblance to the spider web used as a biological input for conducting TO. This iteration results in a significant finding: when the results of TO do not align with the original biostructures, one can still achieve a required resemblance by incorporating the specific preserved geometry.

This example illustrates the process of experimental TO modelling using biostructures as both inspiration and input for the TO. The same process was applied to a total of eight biostructures listed in Table 1. The table shows each biostructure and the identified type of main load applied to it. It also depicts the final shape of the design space and boundary conditions needed for the TO, as well as the final model obtained from it. For brevity, intermediate iterations are omitted from the table. The conducted analysis demonstrated the potential of using nature as an input for the TO. Through careful shaping of the design space using primitive geometry and the definition of boundary conditions based on observing biostructures, it is possible to produce a TO model that closely resembles the biostructure used for inspiration. These insights form the empirical foundation upon which the prescriptive method (presented in Section 3) is built.

**Table 1** Overview of experimental TO modelling of various biostructures

| Biostructure | Biostructure picture | Type of load | TO design space & boundary conditions | TO model |
|---|---|---|---|---|
| Tree branches |  | Compression |  |  |
| Knee bones |  | Compression |  |  |
| Nautilus |  | Compression |  |  |
| Tree roots |  | Tension |  |  |
| Spider web |  | Bending |  |  |
| Hornbill beak |  | Bending |  |  |
| Butterfly wings |  | Bending |  |  |
| Flower petals |  | Torsion |  |  |

## 3. A prescriptive framework for bioinspired topological optimisation

Building on the empirical insights and the lessons learned from the experimental modelling, a prescriptive BioTop method [17] for conducting true bioinspired topical optimisation [20] has been developed. The BioTop method is an eight-step framework that systematically guides designers through the entire process of translating natural features into the required TO input parameters [18]. The method adopts a design-to-biology approach [8], [19], which means that this method should be applied to cases where the design problem is known and the inspiration for how to solve it is drawn from nature. The aim of the method is to facilitate the topological optimisation of load-bearing structures in products and assist designers in shaping these structures with inspiration from nature, while potentially incorporating additional functions, desired aesthetics, or other product requirements.

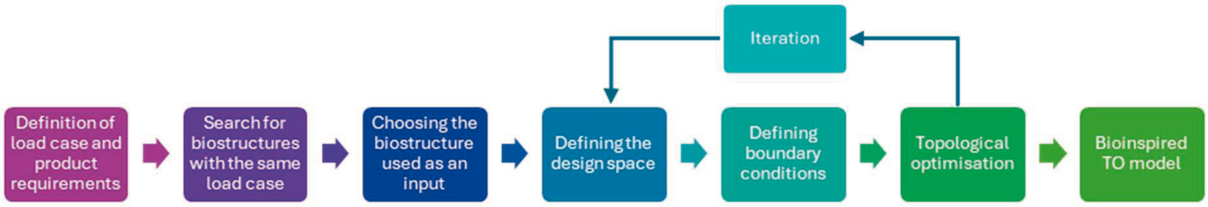



**Fig. 3** Workflow of the BioTop method

The method consists of two main stages: analysis and design. In the first stage, both the design problem and relevant biostructures are observed and analysed, while in the second stage, inspiration from nature is applied to the design process and TO modelling.

The first stage of the method starts with the definition of the load case, the understanding of product functions, the estimation of the design space, and the definition of other product requirements. This information is used as input in the search for comparable biological structures. The main criteria in searching for biological structures should be the similarities in load cases between the product being designed and the biostructures. Once biostructures with similar load cases are identified, their characteristics and functions should be examined. These observations are intended to act as a source of inspiration for enhancing the design beyond the structural performance of the load-bearing structures. When multiple biostructures meeting the basic load case criteria are found, the designer should use the one offering the greatest similarity and possibility for providing an additional design value to the problem at hand. Of course, here one could also use one of the available methods to facilitate the selection process, such as pros-and-cons lists, a selection matrix, and a ranking matrix [27], to achieve a more objective decision.

The second stage of the method starts with the definition of the design space and boundary conditions. The aim is to define the outline of the observed biostructure using primitive geometric shapes, as well as to define the parts of geometry that need to be preserved during the TO process. The preserved geometry must include the areas where forces are applied as well as areas of support. Additional geometric areas of importance for the design of the future product could also be preserved. Simultaneously, the loads and boundary conditions (supports) are applied to the design space according to the observed characteristics of the biostructure. Subsequently, the TO can be performed and the output model observed. Depending on the output of the TO process, that stage should be iterated by adjusting the design space and boundary conditions until a satisfactory level of resemblance between the biostructure and the TO structure is achieved. Afterwards, the model is further developed according to other design requirements or adjusted for manufacturing until it is ready for prototyping, production, or any other subsequent design and development activity.

## 4. Case study

To illustrate the use of the proposed method and to perform the initial verification of the method, a case study [28], [29] of designing a bioinspired car wheel is presented [18]. A car wheel is a rotating part that primarily transmits torque. It is a relatively simple element, but its shape and performance requirements will clearly depict how efficient the proposed method is.

In the first step of the method, the load case and product requirements are defined. For a car wheel, when torque is transferred from the axle, tangential forces occur on the outer rim. Due to the simplification of the case study, only the tangential force is considered, and the weight of the car acting on the wheel is omitted. Furthermore, assuming that the diameter of the wheel is 16” (406.4 mm) and that it transfers 1500 Nm of torque, we can calculate the tangential force on the outer rim.

$$F_t = \frac{T}{R} = \frac{1500}{0.2032} = 7382 \text{ N} \quad (1)$$

Additional design requirements for the wheel are that it must have a standard rim that holds the tyre and the centre bore that ensures the wheel is properly aligned on the axle. Here, these two elements will not be subjected to TO.

In the second step, a search for similar load cases in nature was conducted. A flower with its petals [30] and sycamore seedpods spirals [31] that exhibit similar loads were identified as potential candidates. The flower was selected as an input for TO due to its greater resemblance to the wheel, with its multiple petals similar to spokes, as well as its potential to provide a distinctive, aesthetically pleasing appearance, satisfying an additional design requirement beyond pure structural performance.

In the following steps, a design space and boundary conditions were defined. The design space was a circle (Ø 406.4x30 mm). Non-modified geometry included the central hub (Ø 114.5 mm) where support was applied and five equally spaced areas on the periphery where tangential forces were introduced (Fig. 4a). Subsequently, TO was performed, resulting in the structure shown in Fig. 4b. The TO structure forms only the central part of the wheel, so the model was modified to include the outer rim and the central hub. This represents the final wheel design (Fig. 4c), a TO structure inspired by flower petals. In addition to its load-bearing structure derived from the TO, the model has an aesthetically pleasing appearance inspired by nature.

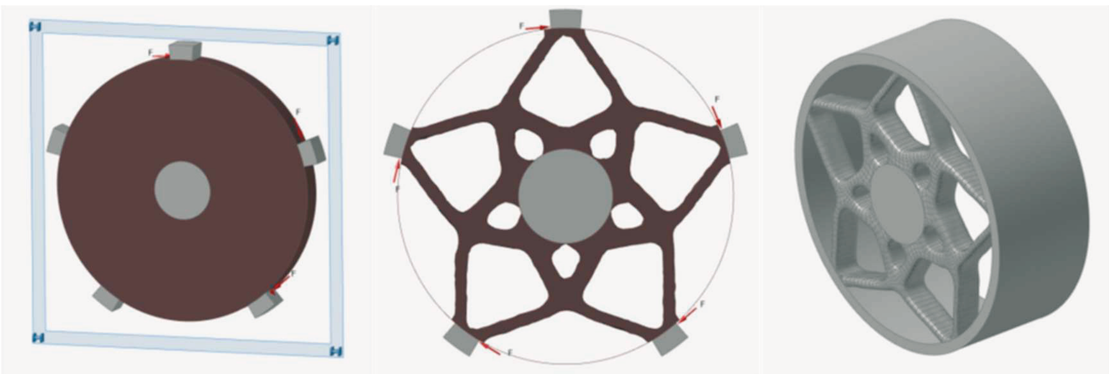


**Fig. 4** Steps in the case study: a) initial design space and boundary conditions; b) results of TO; c) final model

## 5. Discussion

This study investigates the use of biological features found in nature in the creation of input specifications for topological optimisation (TO) in the context of bioinspired design (BID). The research was focused on incorporating biological inspiration into the definition of the TO design space, load case, and boundary conditions, which would mimic the natural forms and could enable the creation of true BID structures. This approach supports the design of structurally efficient geometry that could simultaneously incorporate additional requirements and functions inspired by nature.

The investigation started with a biology-to-design approach focused on modelling various biostructures using TO, aiming to gain an insight into how biostructures can be used to facilitate the TO. The biology-to-design approach demonstrated the feasibility of using biological input to facilitate the specification of input parameters for TO, as the resulting TO models had significant resemblance to the biostructures used as an inspiration. These observations are in accordance with similar observations reported by Darda et al. [14]. The main challenge in the biology-to-design approach was the accurate identification of the load case scenario for each biostructure, requiring the comprehensive observation of the biostructures. The experimental modelling of various biostructures provided a valuable insight into the feasibility of replicating natural forms through TO. It highlighted the importance of careful observation of biological features and their translation into the design parameters for TO. Furthermore, the conducted experimental research yielded important contributions: a table summarising the investigated structures, a definition of the TO design space, and resulting models. Although the number of categorised structures is small, the table contributes to the growing body of knowledge on the bioinspired design which can be stored in a future repository of biostructures to be used for TO.

An additional contribution of the paper is the proposal of the BioTop method developed from lessons learned in the biology-to-design approach. The novelty of the method is the direct integration of inspiration from nature through the translation of natural features into input parameter specifications for the TO, specifically through shaping the design space and defining the boundary conditions. The method offers a structured framework providing systematic guidance for designers on how to apply the knowledge about biostructures through input specifications for the TO. Another advantage of the method is that it could assist designers in achieving a multifunctional design, as the TO structure is not only the output of numerical optimisation, but due to biological input, also resembles a multifunctional biostructure. Since biostructures evolved through numerous iterations over long periods of time, they serve multiple purposes beyond the simple bearing of the load. This is an opportunity for designers to seek inspiration in nature and to use this potential for multifunctional structures by integrating additional functions and requirements into the TO design, thus creating more efficient and resourceful designs. Importantly, the method facilitates a high degree of biomimicry in TO outputs and genuine biological resemblance, leading to true bioinspired design. Finally, by leveraging TO and multifunctional bioinspired design, this approach could enable the design of lightweight structures across various product domains.

The conducted research and the proposed method have limitations that must be addressed. The experimental modelling was primarily conducted on biostructures with clearly defined skeleton-like features. While this limitation provided a clear starting point and simplified the TO modelling, it inherently limited the number of biostructures that can be used as input. Additionally, it potentially restricted the applicability of the proposed method to more complex cellular biostructures. Another limitation of the experimental modelling is that the search for suitable biostructures was conducted using only one repository of biological knowledge, i.e., asknature.org. Although it is a comprehensive repository, relying on a single source of biological knowledge inherently limits the scope of the search [20]. Furthermore, the analysis of the structures was conducted by design engineers without the input from biologists. The lack of biologists involved in the design process is still one of the pressing issues in developing true bioinspired designs, as their expertise and in-depth knowledge would enable a broader understanding of the biostructures and enable proper mapping of functions between nature and engineering design [8], [32]. This also led to some simplifications regarding the boundary condition definition, for example, focusing only on the dominant observable load direction. Addressing this issue is crucial for future research.

The process of translating intricate features of biostructures into parameters for TO presents a significant challenge. Modelling the design space by using only primitive geometric shapes, assuming static loads, and fixing some design parameters facilitated that process, but at the same time it represented a considerable simplification of the dynamic nature of biological structures. However, simplification enables easier application of the method and requires fewer computational resources. The latter argument is significant because the iterative nature of the method can be computationally demanding, potentially limiting the practical application of the method for complex design problems and limited computational resources.

Furthermore, in the conducted research and the proposed method, the focus was on replicating natural forms through TO, thereby providing support and guidance in translating the input from nature into the definition of design space for TO. The research results demonstrate the suitability of the proposed method in this context. On the other hand, since the research was focused on specifying parameters for TO, the multifunctional aspect of bioinspired TO was not fully investigated, and dealing with it relies on the designer's ability to translate additional functions from nature into his designs. In addition, the TO was conducted with the optimisation objective of stiffness maximisation. However, in future research, additional objectives for TO could be investigated, such as minimum mass.

Additionally, since the research is in its early phase, validation is conducted through a case study. While the case study results support the hypothesis that inspiration from nature can be used for creating TO structures, the influence of the method on the designers and the design process should be thoroughly investigated in future research.

## 6. Conclusion

In conclusion, the conducted research established a novel framework for the integration of biological inspiration and the translation of natural features into parameters for topological optimisation (TO). The experimental modelling of biostructures provided valuable insights into the translation of natural forms into design parameters for TO. Building upon these findings, the proposed BioTop method offers designers a structured framework and a systematic pathway for conducting true bioinspired TO. The structures created using the proposed method are highly biomimetic designs with load-bearing capabilities achieved through a combination of the numerical TO approach and nature's evolutionary efficiency in designing lightweight structures. This is achieved using localised TO parameters that reflect crucial biological features and act as a systematic control to guide the optimisation toward the desired natural shape. Furthermore, the obtained structures have a potential for multifunctionality through secondary, non-structural functions, inherent in natural designs. This represents a significant step further from conventional TO, which typically focuses solely on structural performance. While acknowledging the necessary practical simplifications, such as the static load assumption, the load directions, the use of primitive geometries for the design space, and the exploratory nature of this study, its results provide a solid basis for further research in the field of bioinspired design.

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