Voronoi-based design for biomimetic lattice structures

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Abstract

This paper presents a Voronoi-based design concept for biomimetic lattice structures with a focus on bone implant applications. Based on specified boundary conditions, the study derives a parametric process for generating adaptive, reproducible lattices. Different seed point strategies, including stochastic and micro-computed tomography-based approaches, are implemented and compared with regard to specific cell metrics. The workflow is realized using the software demonstrator SliceIT developed at the Chair of Virtual Product Developement. The proposed approach provides a foundation for patient-specific, biomimetic implant design.

Keywords

Voronoi, design workflow, lattice structures, µCT, seed points

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1. Introduction

Biomimetic geometries are becoming increasingly important for the design of lattice structures in medicine, lightweight construction and materials research [1]. Due to their high complexity, the development of such geometrically adaptable structures poses a key challenge for product design. In particular, the replication of irregular, anisotropic lattice architectures, such as those found in natural structures, requires innovative, algorithmically controlled design methods that go beyond conventional, periodic approaches [2]. Voronoi tessellation serves as a generative, parametrically controllable tool that specifically tailors the design of lattice structures to application-specific requirements [3, 4].

Such a design process is required for the manufacture of biomimetic bone implants. Natural bone has an irregular, load-adapted structure that develops during growth in response to mechanical stress [5]. That is why mathematically describable, irregular lattice structures are being recently investigated [6, 7]. Therefore Voronoi-based approaches offer a promising way of generating a targeted biomimetic cell structure and thus novel lattice geometries, by creating seed points with specific characteristics. With targeted control, these can closely resemble the natural trabecular architecture of real bone [8].

Conventional lattice structure implants are currently unable to adequately replicate biomimetic geometries. In the literature, regular, periodic structures are usually employed for this purpose [1, 8, 9]. Whilst these can be mathematically described unambiguously on the basis of their unit cells, they are limited in their functional and structural adaptability. Voronoi seed points have so far mostly been generated randomly, thereby precluding a reproducible and parametrically describable process that takes previously defined boundary conditions into account [8, 9]. Furthermore, there is currently a lack of standardised and systematic methods for the algorithmically controlled arrangement of seed points for three-dimensional Voronoi structures [6, 7]. The central research question is therefore:

How can different seed point strategies be specifically employed in the Voronoi design algorithm to adapt structural lattice characteristics to specific product requirements?

The aim of this research is, first and foremost, to develop a parametric and reproducible design concept that takes into account the structure and function of the target design as early as the seed point generation stage, thereby enabling the design of a biomimetic bone implant for medical applications. Within this framework, the following sub-research question is defined: Which parametric seed point strategy is suitable as the basis for an adaptive, Voronoi-based overall process for the creation of bone implants?

2. Voronoi-based lattice design concept

Addressing the research questions first requires a design concept for analysing the control parameters and synthesising them into an innovative process. The methodological basis is provided by a literature review on lattice structures, cellular structures and the selected biomimetic application bone anatomy. The overall concept synthesised from this is based on a process which, starting from the analysis of real bone structures, utilises a targeted Voronoi algorithm to generate lattice structures. Figure 1 shows the schematic workflow, with the conceptual steps to which this paper relates highlighted (A, B).

In the first conceptual step (A), relevant bone parameters and trabecular characteristics are analysed in order to define geometric and functional target parameters for transfer to Voronoi-based mesh structures. In this process, a region of interest (ROI) is defined, within which the geometric parameters and stability properties of the target structure are determined. Within this region, characteristic bone parameters such as trabecular thickness (Tb.Th.), trabecular spacing (Tb.Sp), bone volume fraction (BV/TV), porosity and connectivity density can be determined in ImageJ (National Institutes of Health, USA) using the BoneJ plugin [10, 11]. In addition to anatomical bone characteristics, cell shape metrics such as cell size, shape,

number, aspect ratio and orientation are determined. These parameters are derived, for example, from the analysis of micro-computed tomography (µCT) datasets. For targeted planning of the lattice structure design, these geometric parameters must first be determined locally in the ROI.

The design process (B) is the conceptual stage of planning a bone-like target structure. The previously identified boundary conditions are translated into a parametric process that generates adaptive lattice structures. The resulting lattice structure contains information on the geometric arrangement of the nodes and struts, as well as the seed point positions. A bone-like structure suitable for manufacturing is then created in step D in combination with the lattice parameters (C).

The lattice parameters conceptual stage (C) examines possible forms of description for Voronoi structures and translates these into a generic design logic that encompasses both the geometric representation and the parametric control of global lattice properties. In the process, manufacturing-relevant parameters, such as strand radius, porosity, interconnectivity and curvature of the global lattice, are defined. Certain global bone structure characteristics of the target structure are derived from the gradation of the strand thickness.

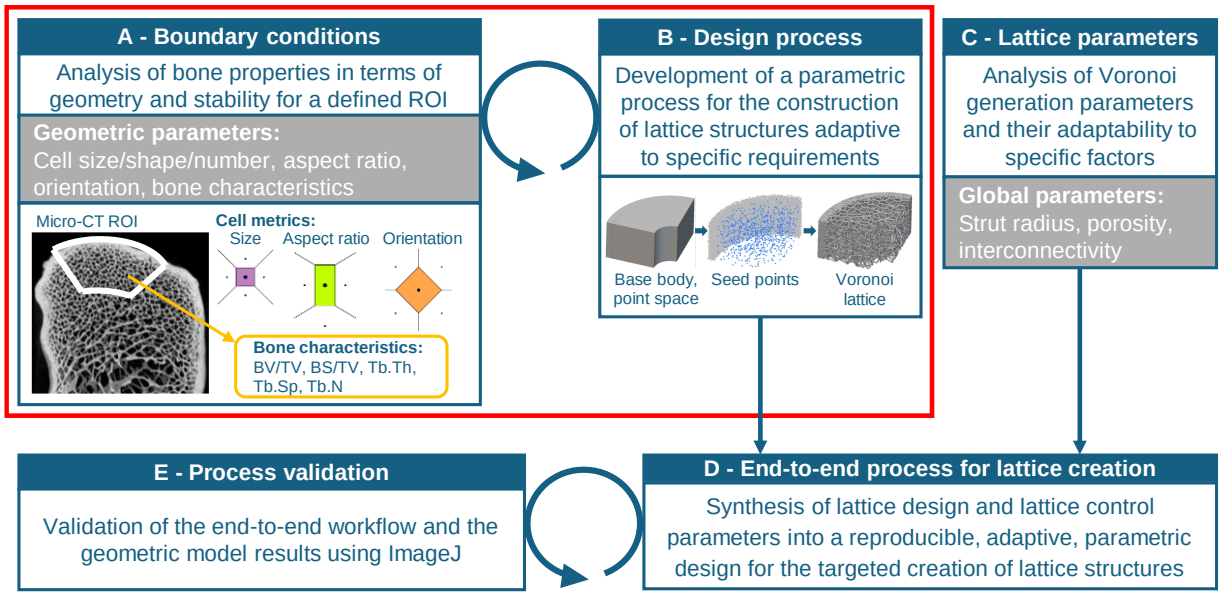

Figure 1: Concept for biomimetic lattice generation of bone structures based on Voronoi

The synthesis of the design concept phases described above takes place in the end-to-end process for lattice creation (D). This step delivers the target lattice structure and also allows for the adjustment of all input parameters. A reproducible, adaptive, parametric design approach is adopted, which carries out the design of manufacturable bone implants whilst taking all preliminary considerations into account.

To compare the generated lattice structures with the target geometry, the respective lattice models are evaluated during process validation (E) and analysed on the basis of defined geometric properties. For biomimetic bone implants, µCT reference data are used to calibrate the synthetically generated lattice structures. This enables the accuracy of the generated biomimetic Voronoi lattices to be directly compared with and evaluated against biological reference values.

3. Boundary conditions of the medical application

In this paper, Conceptual Step A is applied to the medical use case of a femur, which consists of an outer cortical region and a spongy trabecular structure [11]. For the medical use

case of the bone implant, the boundary conditions arise from the biological function of the target tissue and the resulting requirements for the implant structure. The focus is on approximating the natural pore architecture of the bone as closely as possible, as this both absorbs mechanical loads and supports mass transport as well as the ingrowth of bone tissue [5, 11]. Furthermore, defined microstructural properties are required for successful osseointegration. Relevant target parameters include sufficient porosity, high interconnectivity and suitable pore sizes to support cell migration, angiogenesis and mass exchange. Specific microstructural properties are required to achieve this. The optimal pore sizes that promote bone ingrowth are 300-700 µm with a porosity of 60-80 per cent and high pore interconnectedness [12]. The structure must therefore be designed in such a way that open pore spaces are created and interconnected channels are provided for biological ingrowth.

A key boundary condition is also to prevent stress shielding. Conventional, overly rigid implant structures can take over loads from the surrounding bone, thereby promoting bone resorption. This has a significant negative impact on the long-term stability of implants [13]. In terms of design, this means that the lattice structure must be adapted as closely as possible to the surrounding bone in terms of its stiffness and load distribution. This gives rise to the need for a porous, load-adapted and locally variable structure.

Specific geometric target values for femoral bone structures can be derived from medical imaging datasets. These include trabecular thickness, trabecular spacing, bone volume fraction, porosity and connectivity density, which serve as reference parameters for the subsequent evaluation of the generated lattice structure [11]. These parameters form the biological reference against which the parametric design of the Voronoi structures is aligned. These parameters are determined on the basis of µCT data and their analysis using ImageJ as concept stage A suggests.

4. Design process

The starting point of the design process (B) is the processing of the previously defined target structure and the generation of irregular, load-adapted lattice structures. The input is therefore a base body that limits the point cloud to the previously defined ROI. The qualitative workflow shown in Figure 2 describes three main steps, with the seed point generation broken down further.

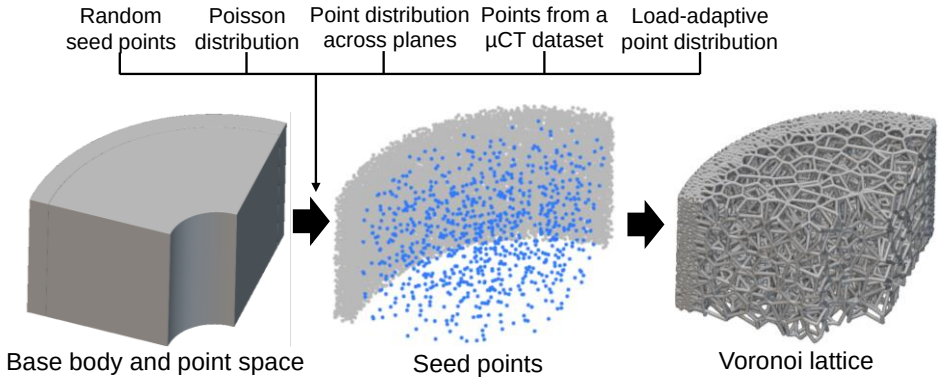

Figure 2: Process workflow of biomimetic lattice generation visualised in nTop (USA, New York)

In the first step, the analysis results are imported. This contains additional information about the desired bone characteristics in its individual regions and a base body which serves as point space. In the example shown in Figure 2, the boundary geometry represents dense cortical bone and the interior represents the trabecular region. This information forms the basis for the

parametric design of the seed point distribution and thus directly determines the subsequent Voronoi geometry.

Within the specified geometry, various seeding strategies are implemented and compared with one another in the next process step. These include both randomised and deliberately controlled point arrangements. The focus of this process step is on determining the extent to which the resulting lattice properties can be systematically influenced by controlling the seeding points. A detailed breakdown of the different seed point strategies can be found in the following paragraphs.

The software demonstrator SliceIT (Germany, Dresden), developed at the Chair of Virtual Product Development, is used to generate the lattice structure and create the stochastic point distributions in the last workflow step of the design process. The generated structures can be analysed geometrically within the software and further processed as exportable lattice files. This creates a seamless workflow from point generation through structure derivation to evaluation.

4.1. Seed point strategies

Seed point generation represents the central design parameter of the Voronoi-based design process, as it directly determines the local cell shape metrics. The choice of seed point strategy is therefore crucial for the translation of biomimetic boundary conditions into a geometrically describable mesh structure. Within the scope of the research presented, different strategies for point generation are examined and compared with one another. The various seed point strategies are evaluated on the basis of their effects on the resulting Voronoi lattice structure.

As a simple and generally applicable reference method, stochastic seed point distributions are investigated first. These serve to systematically analyse the influence of purely random point arrangements on the resulting structure. The focus here is on the question of the extent to which stochastic methods alone can be used to generate Voronoi lattices that are functionally suitable and geometrically comprehensible. To ensure comparability with examples from the literature, these point placements are implemented using the following stochastic generation algorithms:

- Random point distribution with a seed and number of points (a)
- Poisson distribution with point spacings (b)
- Poisson distribution in horizontal planes with point spacing and number of planes (c)

The structures described are illustrated in Figure 3 using an example geometry corresponding to a cube with an edge length of 10 mm and 159 seed points each.

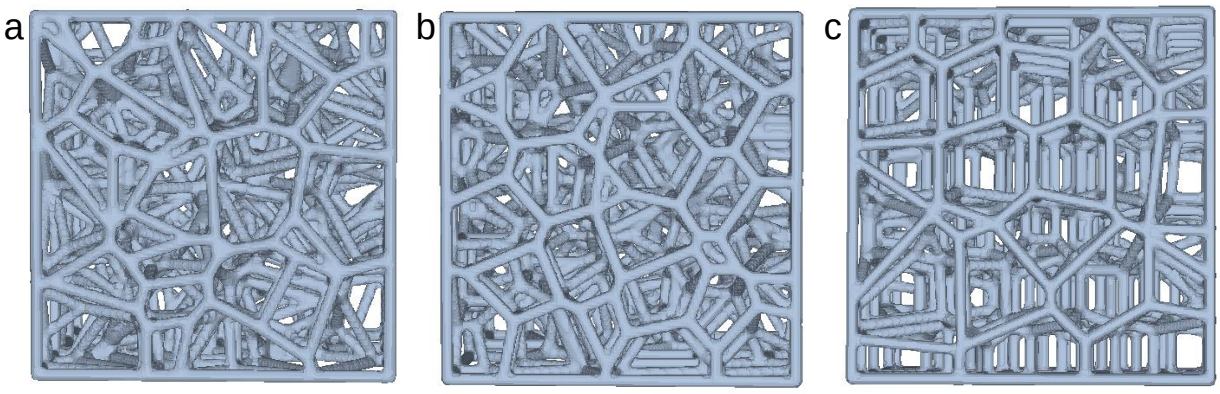

Figure 3: Voronoi lattice structures in SliceIT, each comprising 159 seed points from the stochastic distributions

The first variant generates a random, unweighted point distribution with a fixed seed (a). The number of points serves as an additional control parameter. Whilst this approach can be implemented quickly, the resulting structures vary significantly depending on the number of points and spatial distribution. Inappropriate random seed point locations lead to widely varying cell sizes, cell shapes and merging struts in subsequent steps. For biomimetic applications, this high variability and inhomogeneity are of limited suitability, as they make it difficult to adapt specifically to defined boundary conditions.

To counter this, the Poisson-based point distribution is considered (b). Here, seed point placement is determined by a point spacing radius within a specified space. The larger the point spacing, the fewer points lie within the given geometry. The Poisson algorithm produces a more uniform spatial distribution of points and reduces local clusters as well as excessively small point spacings [14]. his results in more homogeneously distributed cell structures, which are generally more stable and balanced compared to a purely random distribution. Nevertheless, this approach also remains stochastic and is therefore of limited suitability when an exact representation of local biological target parameters is required.

To additionally model anisotropic effects, Poisson-distributed points are also generated in horizontal planes (c). This layered arrangement allows the spatial cell distribution to be influenced in specific directions, which can result in elongated or compressed structures. Such variants are particularly relevant when load-directed or direction-dependent properties of bone tissue are to be modelled.

Overall, the stochastic distributions primarily serve as a reference. They demonstrate the extent to which the resulting lattice structure depends on the point arrangement and provide a basis for comparison with specifically controlled seeding strategies. For medical applications, whilst randomised methods do allow for simple generation and limited local controllability, they are only able to achieve the desired biomimetic adaptation to a limited extent.

A particularly targeted seeding strategy involves deriving the point distribution and a field description from µCT data of a biological reference structure. This approach uses the actual geometry of healthy bone as a template, so that the Voronoi structure is not merely generated abstractly, but is aligned with real microstructural properties. This makes it possible to incorporate local density differences, anisotropic transitions and structural heterogeneities directly into the design process. A possible qualitative workflow is shown in Figure 4.

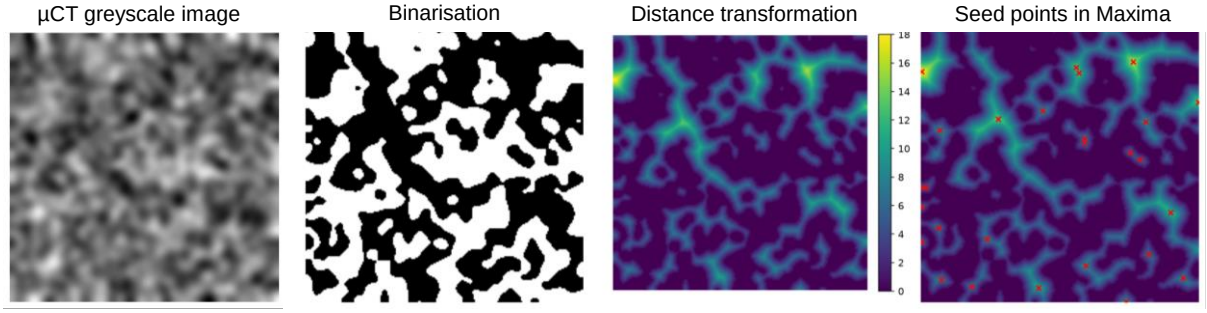

Figure 4: Pipeline from µCT images to distance fields and points via thresholding and binarisation

This method is based on µCT image data of healthy target bone tissue. First, the previously defined ROI and the relevant bone regions are projected onto the specific application. Subsequently, image processing involving thresholding and binarisation is carried out to separate bone and pore regions, thereby enabling analysis of the trabecular structure. The quality of this pre-processing is crucial, as the subsequent parameters and point positions depend directly on the segmentation.

Distance fields can be derived from the binarised data. Seed points for Voronoi generation can be placed at the maxima of these fields. This creates a direct correspondence between the biological reference structure and the resulting mesh geometry. In contrast to randomised

methods, this approach allows for a more targeted representation of the actual trabecular architecture and improves the traceability of the design process.

This approach is of particular relevance for medical applications, as the characteristic parameters of the bone are already contained within the boundary conditions. This enables the Voronoi lattice structures to be adapted independently of the anatomical position of the original µCT dataset. Point generation from CT images thus represents the most biomimetic of the strategies investigated. At the same time, the approach remains parameterisable, as the selection of ROIs, segmentation and point generation can be specifically controlled. This provides a methodological basis for patient- or region-specific bone implant designs.

4.2. Voronoi lattice generation process

The process for generating Voronoi lattice structures is carried out using the software demonstrator SliceIT and is shown schematically in Figure 5. The procedure comprises the following steps: geometry specification, seed point integration, Voronoi calculation, structure definition and export. Within the programme, these are divided into three functional blocks, each with configurable input and output parameters. The workflow described enables the reproducible and parameterisable generation of Voronoi structures. It is suitable both for investigating different seed point strategies and for the production-ready implementation of biomimetic lattice structures in medical applications.

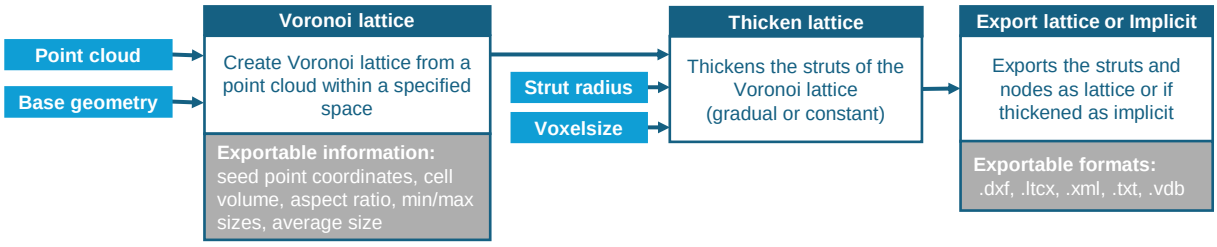

Figure 5: Workflow for creating lattice structures as lattices or implicit bodies in SliceIT (Germany, Dresden)

The starting point is a defined base geometry mesh, which is either generated as an analytical base body or imported as an STL file. This geometry defines the available space within which the lattice structure is generated. For implant-related applications, the STL file contains only the body of the ROI, in order to limit the design process to the functionally relevant area. The point cloud used can also be generated within the programme using the stochastic seed point algorithms. For field-driven approaches, the adapted seed point cloud must be imported.

The Voronoi lattice is then calculated on the basis of this set of points. The Voronoi tessellation divides the space into cells, the boundaries of which are defined by the distance to neighbouring seed points [4]. From this cell structure, SliceIT derives a strut system that uses the cell edges as its geometric basis. This results in lattice structures whose cell volume, aspect ratio, minimum and maximum cell sizes, and average cell dimensions can be evaluated. These parameters are relevant for the subsequent assessment of structural homogeneity and biomimetic suitability.

To generate an implicit, manufacturable geometry from the idealised structures, the struts are thickened in the next step. The thickness can be defined as either constant or locally graded, thereby allowing the mechanical and functional properties to be specifically influenced. In particular, the control parameter strut radius affects the porosity and interconnectivity of the global lattice structure.

In the final functional block, the lattice structure is exported as a mesh or as an implicit volume. Depending on the intended use, various formats are available, including STL, DXF, TXT or VDB. Whilst mesh formats are primarily suitable for additive manufacturing, implicit

formats offer advantages for downstream processing steps and smooth transitions. In addition, cell characteristics, node information and seed point coordinates can be exported to document the process in a traceable manner and to make it usable for numerical simulations.

5. Results and Discussion

The overall concept and the design process demonstrate that the targeted control of Voronoi-based mesh structures must begin not at the stage of the final geometry, but at the level of seed point generation. The position of the seed points can specifically influence the architecture of the cells in order to fulfil specified boundary conditions. This shifts the focus of the design from purely geometric post-processing towards a parametric, process-oriented design approach. Significant differences in cell size, cell shape, porosity and local homogeneity are already apparent at the level of point distribution. This is particularly relevant for biomimetic bone implants, as the target biological structure does not correspond to regular unit cells.

The purely random point distribution proves to be straightforward to implement and reproducible, provided a fixed seed is used. However, it becomes apparent that small changes in the number or position of points can lead to highly variable structures. For biomimetic applications, this approach is therefore only of limited suitability, as targeted adaptation to defined boundary conditions is only possible to a limited extent. By comparison, the Poisson-based distribution yields more uniform and stable structures. The defined minimum distance between the points prevents local clustering, resulting in more homogeneous cell geometries. Stochastic seed point generation algorithms generally are only of limited suitability for adaptive lattice designs due to their lack of reproducibility, local controllability and biomimetic target adaptation. They are therefore primarily suitable as reference structures and for lattice prototypes.

The point distribution derived from µCT data has greater biomimetic relevance. This field-based approach translates real bone microstructures into a parametrically usable seed point cloud, thereby enabling the targeted consideration of local density distributions and anisotropic structural gradients. The pipeline comprising binarisation, distance transformation and point extraction thus provides a methodological basis for patient- or region-specific implant designs. However, it should be noted that the image analysis must be implemented in a robust and reproducible manner. Even minor differences in pre-processing can significantly influence the resulting point cloud and, consequently, the subsequent mesh structure. Furthermore, implementation requires a µCT dataset of the ROI that depicts the desired healthy target structure.

From the perspective of the overall workflow, this paper should be understood as a methodological process development. The approach presented lays the foundation for the systematic generation of adaptive mesh structures, but does not yet replace full validation. In particular, the transition to a robust, quantitatively assessable development process requires further steps, such as the comparison of several point strategies using clearly defined parameters, the mechanical evaluation of the resulting structures, and the assessment of manufacturability in the additive manufacturing process.

A further important step involves linking the approach with numerical and experimental validation methods. The purely geometric similarity to bone tissue initially sought is not sufficient for a medical application. Additional boundary conditions are required, which can be determined via finite element analyses, permeability assessments and µCT-based measurements. Greater standardisation of the boundary conditions is also required for future research. This includes, for example, uniform rules for the selection of ROIs, for defining minimum distances between seeding points, and for deriving target values from µCT data. Without such standardisation, the process remains flexible but is only transferable to a limited extent. However, particularly for patient-specific applications, it is crucial that the procedure is reproducible and scalable to different anatomical situations.

6. Conclusion

This paper develops a design concept for Voronoi-based lattice structures and, thereby, an approach to the biomimetic replication of bone tissue. In particular, the distribution of seeding points proves to be a key control parameter for specifically influencing cell metrics. Whilst stochastic methods provide an initial reference, it is primarily the field-based point derivation that enables a significantly closer approximation to real bone architectures.
The process presented forms a methodological basis for the development of adaptive, parametrically controllable bone implants. At the same time, the approach should currently be regarded as a methodological concept, the full validation of which is still pending. The next stage of development will therefore require quantitative parameter analyses, mechanical testing and a closer integration with numerical simulation and experimental evaluation. Overall, this work provides a reproducible starting point for the targeted design of biomimetic Voronoi lattice structures and paves the way for a robust design and validation workflow for bone implants.

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