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Design of finger joint implants based on triply periodic minimal surfaces

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Abstract: Due to the high demands placed on finger joint implants, the most common therapy for joint diseases is still the use of silicone spacers or even joint stiffening. For this reason, the Fraunhofer PREPARE project FingerKIt has set itself the goal of developing a new form of therapy in which patient-specific implants are automatically generated that meet the high requirements placed on them. First steps toward achieving this goal are presented in this paper.

I. Introduction

In the Fraunhofer-internal project FingerKIt, individualized implants for finger joints of the human hand are currently being developed [1]. These implants are relatively small, but have high requirements regarding fit and mechanical load. In order to improve the ingrowth of bone into the implant and to avoid the so-called “stress shielding” effect – difference in stiffness between implant and bone that can lead to failure –, the use of mesostructures is investigated. In this context, a first joint implant design based on triply periodic minimal surfaces – a special lattice structure – has been created. This paper outlines the requirements and the corresponding design process of the implant.

II. Design requirements

Both medical and technical requirements are placed on the implant design. The medical requirements mainly include:

- high osseointegration,
- avoidance of “stress shielding,” and
- sufficient strength.

The technical requirements derived from this are shown in Fig. 1. These can be broken down to the following essential requirements for the mesostructure:

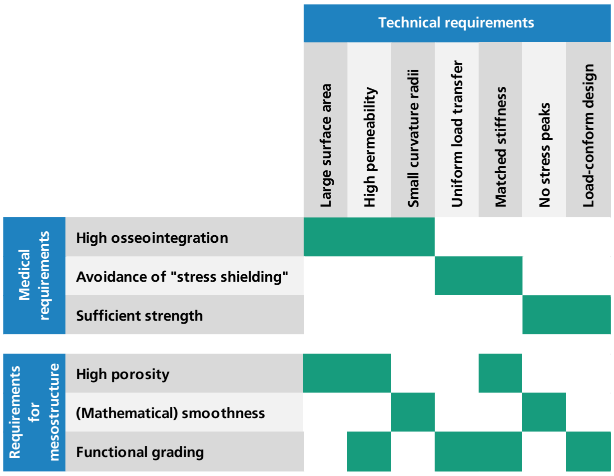
- high porosity,
- (mathematical) smoothness, and
- functional grading.

III. Design development

The technical requirements from Section II are fulfilled, for example, by structures based on triply periodic minimal surfaces (TPMS), cf., e.g., [2]. These will be applied in the area of the implant stem.

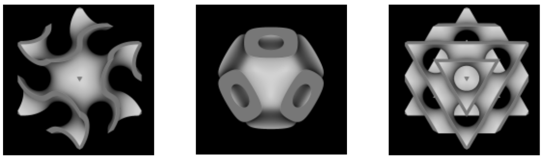
III.I. TPMS structures

Structures based on TPMS exhibit physical properties that are superior to other lattice types, such as strut-based lattice structures. Advantageous properties include high stiffness-to-weight and surface-to-volume ratios while maintaining low hydrodynamic resistance. Mathematically, TPMS are smooth, have no sharp edges or corners, and divide the space into two (or more) separate intertwined regions. The smoothness of TPMS theoretically leads to lower stress peaks and therefore to a better fatigue behavior compared to other porous geometries. Examples of TPMS-based structures are shown in Fig. 2.



		Technical requirements						
		Large surface area	High permeability	Small curvature radii	Uniform load transfer	Matched stiffness	No stress peaks	Load-conform design
Medical requirements	High osseointegration	🟩	🟩	🟩				
	Avoidance of "stress shielding"				🟩	🟩		
	Sufficient strength						🟩	🟩
Requirements for mesostructure	High porosity	🟩	🟩			🟩		
	(Mathematical) smoothness			🟩			🟩	
	Functional grading		🟩		🟩	🟩		🟩

Figure 1: Requirements matrix for the mesostructure; the green fields mark matching requirements.



Gyroid Primitive Diamond

Figure 2: Exemplary structures based on TPMS; shown are the respective (thickened) unit cells.

Advancements in manufacturing technologies, especially additive manufacturing, and software development enable the design and implementation of such structures in real

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products. In our case, the metal binder jetting process shall be applied for the fabrication of the implants.

III.II. Porosity

TPMS-based structures are created by either thickening the surface or by defining one of the separated regions as solid. They can then be uniquely defined by specifying the cell size and wall thickness. The ratio of enclosed void space to total volume is called porosity. It can be adjusted by the unit cell size of the TPMS. Here, a small cell size means a large surface area, but it hinders tissue cell permeability and thus oxygen and nutrient transport. In turn, a large cell size results in high permeability, but the related smaller surface area leads to poorer tissue cell adhesion [3]. Consequently, a tradeoff between a sufficiently large surface area and permeability must be found, see Fig. 3. In our case, the porosity can be narrowed down to the range between 30 and 90% [3]. Correspondingly, a wall thickness of 200–600 µm and a pore size of about 600 µm seem to be reasonable.

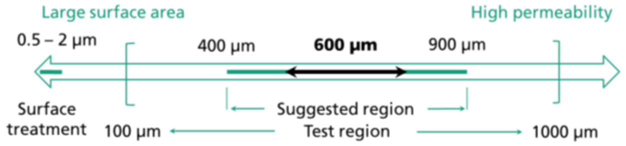
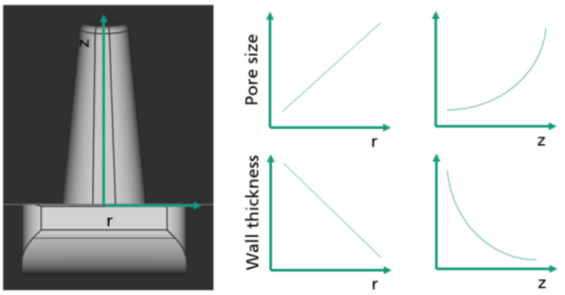


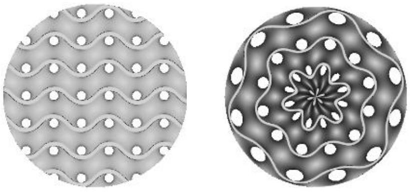
Figure 3: Pore sizes of TPMS and their influence on surface area and permeability (according to [3]).

III.III. Grading and transformation

In addition to setting the structural parameters cell size and wall thickness, grading TPMS offers further design options to influence the physical properties of the mesostructure. Furthermore, the structure can be transformed or distorted. By transforming the structure, the periodic arrangement of the TPMS can be transferred into another mathematical space (e.g., from Cartesian to polar coordinates). In this way, circular or spherical arrangements can be created, for instance. Example gradings and transformations of a TPMS structure are illustrated in Fig. 4.



Possible grading schemes of wall thickness and pore size as a function of radius and stem height



Possible Cartesian (left) and polar transformation (right)

Figure 4: Example gradings (top) and transformations (bottom) of the TPMS structure of the finger joint implant stem.

According to our application, the grading aims at adjusting the Young's modulus in the range of 0.5 to 4 GPa.

IV. Implant design

A first implant design with an integrated mesostructure is shown in Fig. 5. Here, only the stem, which is anchored in the bone, is provided with a TPMS structure. However, it is also possible to structure the planar base surface of the implant, which also comes into contact with bone.

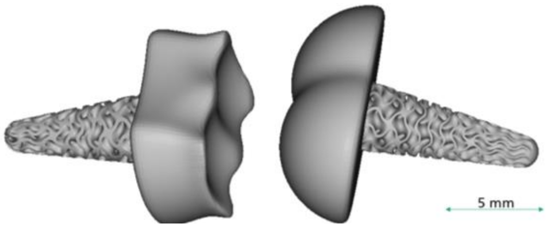


Figure 5: First design of a finger joint implant with integrated TPMS structure.

The TPMS structure used for the stem is of gyroid type. It is graded from coarse to fine along the z coordinate and in radial direction (cf. Fig. 4, top). The implant is designed for a proximal interphalangeal (PIP) finger joint. However, the principle can also be transferred to distal interphalangeal (DIP) and metacarpophalangeal (MCP) finger joints.

V. Conclusions

Finger joint implants pose great challenges for the designer. They must withstand biomechanical loads, their stiffness – at least in the contact area with the bone – must be adapted to it, and the implant must also fit the patient individually. All these requirements can be addressed, for example, by structures based on TPMS and have been realized in a first PIP joint implant, as described in this paper. A compromise must always be found between a sufficiently large surface area for the adhesion of bone cells and a sufficiently large porosity to ensure a proper bone cell and blood transport. Furthermore, the structure should be graded in order to realize a stiffness match between bone and implant and thus reduce the risk of a potential failure due to stress shielding.

In the next step, AI algorithms for the autogeneration of individualized implant designs will be used. With the help of deep neural networks, implant designs corresponding to the individual clinical case will be automatically generated from X-ray images of the patient's hand to enable rapid and individualized treatment.

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AUTHOR'S STATEMENT

Conflict of interest: Authors state no conflict of interest.

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