MULTI-FUNCTIONAL VARIATIONAL POROSITY IN BONE TISSUE SCAFFOLDS

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ABSTRACT: Commonly used homogeneous scaffolds do not capture the intricate spatial material concentration presented in bone internal architecture. On the other hand gradient in porosity along the internal scaffold architecture might contribute for performing diverse mechanical, biological and chemical functions of scaffold. Thus the need for reproducible and fabricatable scaffold design with interconnected and continuous pore and controllable gradient in porosity for tissue regeneration is obvious but is thwarted by design and fabrication limitations. In this work, a novel heterogeneous scaffold modeling approach has been proposed targeting the bio-mimetic porosity design. First, an optimum filament deposition angle has been determined in slices based on the contour geometry of targeted region. And the internal region has been discritized considering the homogeneity factor along the deposition angle. Finally, an area weight based approach has been used to generate the spatial porosity function that determines the filament deposition location for desired bio-mimetic porosity. The proposed methodology has been implemented an illustrative examples using computer simulation. A comparison result of effective porosity has been presented between proposed design model and conventional fixed filament distance scaffolds respectively. The result shows a significant error reduction towards the achieving bio-mimetic scaffold design concept and provides more control over the desired porosity level. Moreover, the resultant model can easily be fabricated with simple SFF processes.

KEYWORDS: Deposition angle, porosity function.

1 INTRODUCTION

Bone has a varied arrangement of material structures whose architecture differs at each level in concert to perform diverse mechanical, biological and chemical functions. And thus the bone material distribution may vary considerably making the bone architecture highly anisotropic in nature [1]. Researchers [2] have invested in bio-mimetic scaffold design concept via inversing the morphological structure to achieve the desired and choreographed multi-functionality from scaffold structure. Bone is a hierarchical material whose mechanical properties can vary considerably within the same specimen and does not depends upon its density alone [3]. Thus achieving the bio-mimetic scaffold design by only mimicking the bone morphology may not capture the regional heterogeneity in bone's spatial extrinsic and intrinsic properties. More over such complex design requires significant amount of computational resources and might become infeasible in terms of its fabricatability. On the other hand bone structures adapt its strength via remodeling [4] in response to the anisotropic load distribution along every direction. This physiological multi-axial load transfer through the inhomogeneous cross-section of bone along the length supports its spatial and regional heterogeneous structural properties [5]. But such imminent factors are completely ignored in current design of temporal bio-mimetic scaffolds. Thus the design of bio-mimetic scaffold with homogenization of property and/or material distribution might not be the proper functional representation.

In this work, a novel heterogeneous scaffold modeling approach has been proposed targeting the bio-mimetic porosity design. First, an optimum filament deposition direction has been determined in slices based on the contour geometry and their intervention along the homogeneous deposition path. And then the internal region has been discritized as strips considering its spatial homogeneity factor along the optimum deposition angle. Finally, an area weight based approach has been used to generate the spatial porosity function for each strip that determines the filament deposition location for desired bio-mimetic/heterogeneous porosity. The proposed method generates a heterogeneous scaffold by designing controllable porosity to capture the functional and regional heterogeneity along the structure that conforms the shape of the targeted contours and maintains the continuity with connectivity using simple 3D micro-nozzle deposition system.

The rest of the paper is organized as follows. We provide the description of our methodology and our approach of modelling and optimization of deposition-path planning

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in Section 1. Section 2 shows the methodology of the proposed technique. The proposed design has been implemented and results have been shown in section 3. And finally, we draw conclusions in section 4 followed by the references.

2 METHODOLOGY

2.1 SLICE GENERATION WITH INTERNAL ISO-FEATURE

The proposed design methodology has been targeted for layer manufacturing processes and thus has been implemented on a pair of planner slice for demonstration. And a 3D model with desired regional heterogeneous porosity can be obtained by orderly stacking the layers. Thus to achieve the planner slices, the medical image has been obtained and mapped into a CAD system by a methodology discussed in our previous paper [6]. The internal spatial structural or extrinsic properties that represent the regional heterogeneity can be obtained from literatures [3, 4]. As discussed earlier, such regional heterogeneity exists in bone and allows bone to perform its multi-objective functionality i.e. mechanical, biological and chemical functions simultaneously. The corresponding property for each iso-region can also be interpreted as uniform material concentration or iso-porosity regions. Thus the term iso-porosity and iso-property have been used alternatively in this paper.

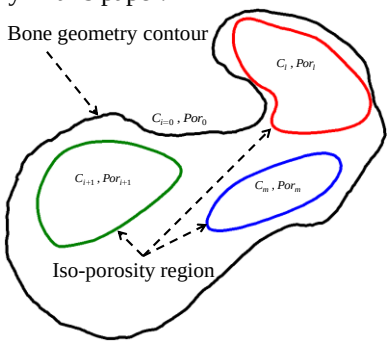

Figure 1: *A sample slice of bone outer contour and the corresponding arbitrary internal iso-porosity contours.*

A set of curves has been obtained for every single slice where the outer contour slice contain all the internal iso-porosity contours shown in the Figure 1 as sample. All contour curves are simple planner closed curve i.e. the planner curve does not intersect itself other than its start and end points and have the same (positive) orientation. And the general equation for these contour can be parametrically represent as-

$$C_i(u_i) = (x(u_i), y(u_i)) \quad \forall i = 0,..m$$
$$u_i \in [a_i, b_i]; \; C_i(a_i) = C_i(b_i) \qquad (1)$$

Here, $C_i(u_i)$ represent the parametric equation for i^{th} contour with respect to parameter u_i at a range between $[a_i, b_i]$.

2.2 CONTOUR DISCRETIZATION AND OPTIMIZING OF THE FILAMENT DEPOSITION DIRECTION

Current designs for homogeneous scaffold assume property homogenization that results equidistant filament deposition parameter throughout the internal region. Such property homogenization may address the desired property of a single uniform region, but completely ignore the presence of any regional heterogeneity which could have a cost function that may generate design error. And for multiple regional heterogeneity, this design error could accumulate and may follow exponential growth. To demonstrate, a simple example has been presented in the following Figure 2, where the outer boundary contour contains four sets of regional heterogeneity. By designing a homogeneous scaffold with equidistant filament location along an arbitrary direction may result severe intervention by internal heterogeneous region and generate design error for almost every segment between those filaments as shown in Figure 2(a). But by choosing the proper deposition direction or frame angle, this intervening segment area can be reduced significantly which may reduce the error of targeted region shown in Figure 2(b).

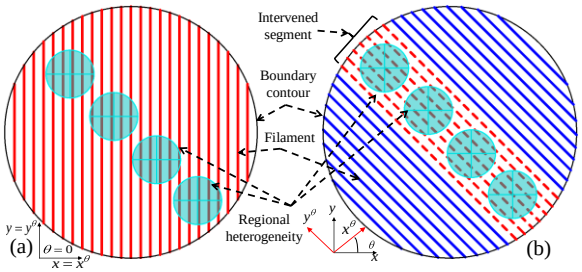

Figure 2: *(a) Filament deposition pattern at θ=0^0 (b) aligned filament deposition pattern at θ for the same regional heterogeneity in a boundary contour.*

Thus to increases the homogeneous deposition path via reducing the heterogeneous region intervention, an optimum filament deposition direction need to be determined in slices based on the contour geometry and location of the targeted region.

2.3 STRIP GENERATION AND WEIGHT DETERMINATION

To determine the cost function based on the heterogeneous region intervention, the targeted region first need to discretized based on the heterogeneity factor. The region can be discretized by introducing a set of parallel lines where the area generated between two parallel lines has been denoted as strips. Then each strip area needs to be analyzed for heterogeneity to determine its cost function. Now these parallel lines might be equidistant from each other or varying distant and could be a design variable. But to avoid virtually infinite combinations a novel technique of 'strips from contour's tangent' [7] approach has been considered that would eventually reduce the feasible solution space

significantly without compromising the optimality shown in Figure 3.

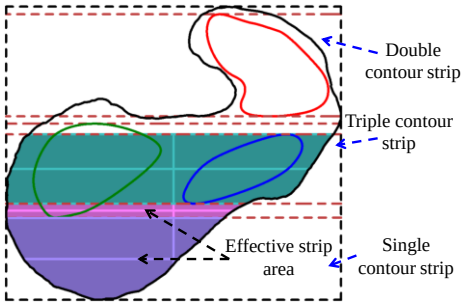

Figure 3: *Generating the strips and effective strip area with heterogeneity.*

After discritizing the region with strip, the area based heterogenity weight for each strips has been calculated by using the following equation.

$$Weight\_ST_j = \left(\left(A_j - \sum_{i=1}^{m} CA_{A_j}^i\right) + \sum_{i=1}^{m} (CA_{A_j}^i \times het_j^{Contour})\right) \times het_j^{Property} \ \forall j \quad (2)$$

Where, $Weight\_ST_j$ is the weight; A_j is the effective area, $CA_{A_j}^i$ is the area of i^{th} contour contributed to the effective area; $het_j^{Contour}$ and $het_j^{Property}$ are the heterogeneity factor due to contour and property of j^{th} strip. And thus by summing weight for all strips, the total weight of the slice at frame angle θ can be calculated.

$$Total\_Weight^{\theta} = \sum_{j=1}^{n} Weight\_ST_j \ \forall \theta \quad (3)$$

Here, $Total\_Weight^{\theta}$ is the accumulated total weight evaluated at frame angle θ. This accumulated weight is a non-linear function of contributed area and in ideal case i.e. for complete homogeneous region the weight would be minimum. And increasing the heterogeneity would increase the weight of the slice.

By using the same methodology described above, the weight can be determined for every frame angle $\theta \in [0, \pi]$ interval and the optimum deposition direction θ^* can be determined by the function, Min $\{Total\_Weight^{\theta}\}$.

2.4 FUNCTION BASED FILAMENT DEPOSITION LOCATION

After getting the optimum filament deposition directions θ^* a function based filament distance determination methodology has been implemented to determine the optimum filament location. The functional area for each contributing contours along the width of the strip have been plotted as shown in Figure 4.

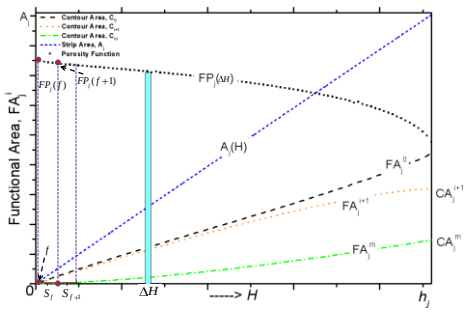

Figure 4: *Filament positional function determination for a heterogeneous triple contour strip* j^{th}.

The functional porosity, FP for any small segment, ΔH in the strip can be calculated by the following equation where, $\Delta H \to 0$ and is the function of strip width and its contour property.

$$FP_j(\Delta H) = \sum_{i=0}^{m} \frac{FA_j^i(\Delta H)}{A_j(\Delta H)} \times Por_i \ \forall \ j, FA_j^i > 0; \quad (4)$$

Where, $FA_j^i(\Delta H)$ is the functional area generated by i^{th} contour, $FP_j(\Delta H)$ is the functional porosity for j^{th} strip with equidistant width ΔH and is calculated by considering the weighted area contribution of corresponding contours and porosity. After plotting the porosity function for the strip, the distance between filaments for any spatial segment can be determined by using that function.

For evaluation purpose the porosity deviation from the designed one to the desired porosity has been calculated by Equation 5.

$$E = \sum_{j=0}^{n} \sum_{i=0}^{m} \left(\left|FP_j(f) - Por_i\right|\right) \times FA_j^i(f) \ \forall \ f \quad (5)$$

Where, E is the resultant porosity evaluation index.

3 IMPLEMENTATION AND DISCUSSION

The proposed techniques have been implemented on 2.3 GHz PCs using Rhino Script and Visual Basic programming languages. The same femur slice example has been discussed in this section with three iso-property internal region. The geometric shapes of such internal regions have been chosen arbitrarily to represent the heterogeneity and there designed property has been presented in Table 1.

Table 1: *Contour property for femur slice.*

Contour, C_i	Porosity, Por_i	Area, mm²
C_0	$Por_0 = 60\%$	199.95
C_1	$Por_1 = 88\%$	50.81
C_2	$Por_2 = 50\%$	27.85
C_3	$Por_3 = 75\%$	48.79

The optimum deposition direction or frame angle for k^{th} slice has been achieved as $\theta_k^* = 41^0$ which has the minimum total weight. And for the consecutive $(k+1)^{th}$ layer has been achieved as $\theta_{k+1}^* = 158^0$.

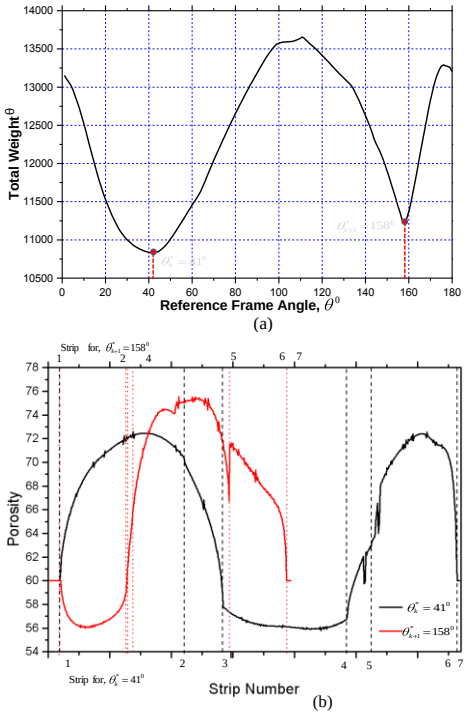

Figure 5: *(a) The total weight plot for femur at $\Delta\theta = 1^0$ (b) Porosity function for consecutive optimum layer of femur slice*

The porosity function clearly represents the heterogeneity within the strip, as higher heterogeneity introduce higher deviation in the porosity range to minimize the disparity. And the corresponding filaments have been drawn in Figure 6. By combining two consecutive optimized slices generate pore cell which are highly anisotropic in nature creating gradient in porosity and follow the heterogeneity of the internal regions as shown in Figure 6. As shown in the Figure 7, the porosity deviation is always lower than the traditional average equidistant filament location method. The deviation data has been calculated by using Equation 5 and compared and plotted with average 68% constant porosity.

4 CONCLUSION

In this research, a novel modeling approach for heterogeneous scaffold has been proposed. The design methodology generates spatial variational porosity following the heterogeneity of the internal regions. At the same time, the proposed methodology generates interconnected and controlled pore size with desired accuracy along the scaffold architecture resulting variational porosity. Attaining the exact porosity with a controllable, continuous and fabricatable design is highly unlikely, but the proposed method minimizes the deviation between the desired and design property and follow the spatial heterogeneity. Moreover, the resultant model can easily be fabricated with simple SFF processes.

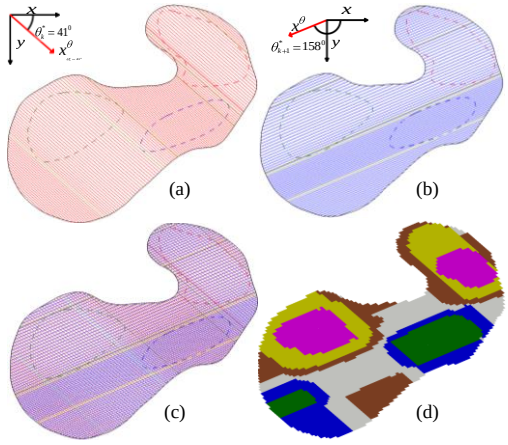

Figure 6: *Variational filament locations following the porosity function (a) for the 1st (b) consecutive 2nd and (c) combined layer (d) combined porosity gradient.*

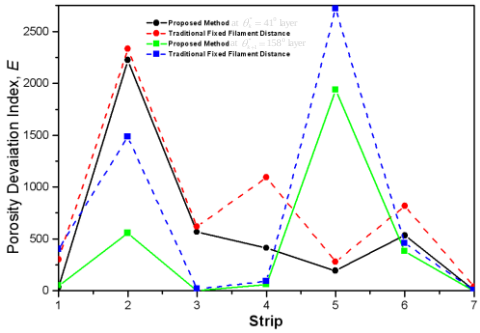

Figure 7: *Porosity deviation index for both layer compared with proposed method and average 68% porosity.*

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