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Design of braided fibrous scaffold for spinal cord injury applications: Using Rhinoceros 3D and Grasshopper plugin

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ABSTRACT

Spinal cord injuries (SCI) result from causes such as traffic accidents and falls. Scaffold construction strategies are limited in design and functionality due to fabrication methods. The objective of this work was to 3D model braided textile structures (scaffolds) suitable for assisting in the treatment of SCI. Using parametric modelling in Rhinoceros with Grasshopper, the study integrates design thinking and computational thinking to create and prototype structures. Selection criteria included the number of yarn layers (internal and external), angle, structural diameter, and porosity. The structures consist of an internal layer with eight yarns and an external layer with eight or 16 yarns. The main requirement for selection was porosity, and two primary structures with different topologies were simulated and subsequently characterized. A porosity of 84.77% indicates feasibility for implementation. The use of Rhinoceros 3D and the Grasshopper plugin facilitated the creation and assessment of the structures in terms of topology.

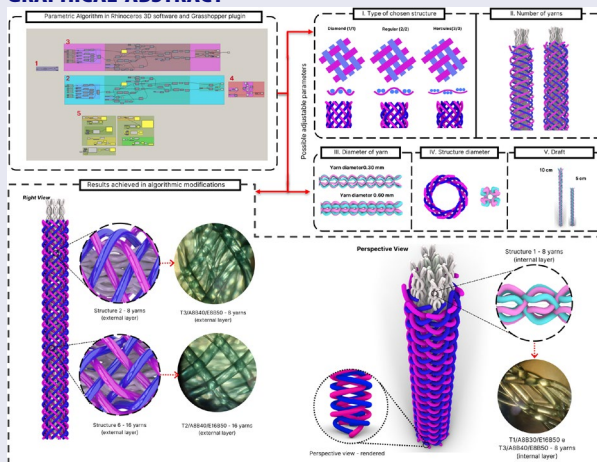
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KEYWORDS

Braided, textile, spinal cord injury, parametric design, scaffold, porosity

GRAPHICAL ABSTRACT



1. Introduction

Representation is a fundamental aspect of design work, playing a pivotal role in establishing communication, evaluation, conceptualization, and cognition within the field of design (Cash and Maier 2021; Oxman 1997). Traditional design representation methods, such as sketching, diagramming, and schematics, necessitate knowledge and human proficiency in manual drafting skills. Conversely, various forms of automated representations have emerged, evolving with the integration of artificial intelligence (AI) (Sarica, Han, and Luo 2023). Currently, parametric design functions as a valuable tool for modelling intricate shapes, standing out as a distinctive and unique design paradigm. Moreover, both exploratory research and the practical application of parametric design exert a substantial influence on the reformulation and alteration of the theoretical approach (epistemology) within the realm of design. In this context, contemporary Parametric Design platforms are adapting to incorporate new programming techniques, relational topological schemes, associative geometries, as well as computational models for digital design (Oxman 1997; Wang et al. 2020; Zhou et al. 2022). Considering this information, it is noteworthy to underscore the significance of utilizing parametric design in the development of textile structures. Nonetheless, the design project involving these structures serves as an added value for the advancement of implantable fibrous textile structures, owing to the necessity of simulating geometries, mechanical and physical properties, along with their associated variables (Silva 2022).

In the past decade, there has been a discernible increase in the incidence of injuries to the spine and spinal cord. Traffic accidents, falls, high-impact sports, and acts of violence predominantly account for spinal cord injuries (SCIs). Nevertheless, the ageing process and resultant bone degeneration also contribute to such injuries (World Health Organization, 2013). A spinal cord injury involves a fracture, dislocation, or trauma affecting the spinal cord, the entity responsible for overseeing essential bodily functions, including respiratory, circulatory, excretory, sexual, and homeostatic activities. Crucially, it serves as the conduit for nervous stimuli that directly influence sensory-motor capacity through afferent and efferent pathways (Liu et al. 2021; Murta and Guimarães 2007). Among contemporary strategies for addressing this issue, several noteworthy interventions have emerged. Firstly, spinal stabilization aims to enhance decompression of the spinal cord (Ahuja et al. 2017; Ying et al. 2023). Secondly, the administration of high doses of corticosteroids seeks to mitigate inflammatory processes and prevent lipid peroxidation, which instigates free radical production (Gaschler and Stockwell 2017). Thirdly, the injection of neurotrophic factors at the injury site aims to reduce or prevent apoptosis and facilitate axon regeneration (Kramer et al. 2013). Finally, the implantation of three-dimensional supports (scaffolds) is intended to alleviate spinal cord compression, act as structures stimulating neuron growth in

affected areas, and contribute to spinal cord regeneration, as evidenced by studies (Bedir et al. 2020; Eli, Lerner, and Ghogawala 2021; Karsy and Hawryluk 2019; Koffler et al. 2019; Zhang and Ma 2018).

In general, implantable structures for the treatment of SCIs are typically developed through various methodologies, including: (1) Electrospun membranes; the fabrication of these structures may encompass processes such as rolling, overlapping folding, creating hollow cylinders or cylinders filled with beams, or other hollow cylinders (Cheng, Zhang, and Wu 2021; Pawelec et al. 2018; Xue et al. 2021; You et al. 2020); (2) Utilizing 3D printing with a focus on crafting a precise structure tailored to the implantation area; additionally, the structure incorporates small channels to guide cells (Chen et al. 2024; Koffler et al. 2019; Liu et al. 2023); and (3) Hydrogels have emerged as a viable option, facilitating the filling of the injured site; however, this is only optimal for injectable hydrogel types. Moreover, the typical outcome with the utilization of hydrogels is the formation of a porous structure, highly effective in drug and stem cell transportation (Costăchescu et al. 2022; Ehsanipour et al. 2021; Qu et al. 2020). Nevertheless, the construction strategies for these structures remain restricted in terms of design and functionality due to their construction methods. In this regard, it is imperative to devise strategies that prioritize essential properties for tissue regeneration.

The implementation of parametric design and computational tools, such as Rhinoceros 3D software and the Grasshopper plugin, for simulating and optimizing braided textile structures represents a significant advancement in design research and textile material science, particularly in tissue engineering applications. This methodology offers substantial benefits across three key dimensions: (1) Enhanced Design Capabilities – Enables exploration of diverse structural configurations through precise parameter control (including yarn diameter, strand count, braiding angle, and porosity), facilitating the development of complex, application-specific geometries and innovative textile architectures; (2) Optimized Material Performance – Improves critical mechanical and functional characteristics such as axial strength and cellular permeability, which are vital for biomedical implementations; and (3) Process Efficiency – Replaces physical prototyping with digital simulation, reducing both development time and production costs while aligning with Industry 4.0 digital transformation initiatives (Aguiar Souza and Kohan 2024).

The use of a textile material scaffold represents a potential advancement in treatment collaboration, as it encapsulates critical characteristics such as three-dimensionality (3D), porosity, rigidity, elasticity, mechanical resistance, and biocompatibility. The integration of these features enables the scaffold to foster nerve cell growth and regeneration while facilitating the release of bio-active compounds. Furthermore, the scaffold exhibits potential in reducing cystic cavities and, consequently, diminishing glial scarring (Bedir et al. 2020; Cheng, Zhang, and Wu 2021; Hollister 2005; Hu et al. 2019).

Braided structures have been widely applied in the biomedical field due to their versatility in producing stable and mechanically resistant constructions. The braiding technique involves intertwining one or more threads to create diverse structures, with the possibility of incorporating molds or additional elements during the process. Braided scaffolds have gained prominence in rehabilitating soft musculoskeletal tissues, such as tendons and ligaments, which exhibit slow healing due to limited vascularization. Without surgical intervention, these tissues often fail to regenerate their extracellular matrix (ECM) efficiently (James and Laurencin 2014). Beyond scaffolds, braiding techniques are also employed in suture manufacturing, with variations like the two-layer model seen in Arthrex, Inc's FiberWire (Olliviere et al. 2014; Wissgott et al. 2015). Additionally, braided structures are used in stents to maintain luminal patency in blood vessels, the esophagus, and airways (Ding, Gu, and Lu 2024; Feng et al. 2022; Shanahan, Tofail, and Tiernan 2017; Tong et al. 2023). However, their direct application in SCI repair remains unexplored. This work thus proposes repurposing braided scaffolds – already established in other tissue engineering fields – for potential use in SCI cases.

Therefore, it is pertinent to underscore the pivotal role of porosity in scaffold structures; the latter necessitates meticulous design to facilitate the establishment of a 3D porous framework conducive to structural permeability (facilitating nutrient exchange), surface adhesion of cells to foster neurite elongation and neuronal growth. Moreover, pores serve as catalysts for cellular activity, amplifying vascularization and providing an optimal milieu for cell proliferation (Abbasi et al. 2020; Aguiar Souza 2023; Chen et al. 2020; Huang et al. 2019). In studies on the development of non-woven reinforced hydrogels for spinal cord repair, the fibre architectures were arranged unidirectionally, with 65–75% of the fibres aligned within $\pm 10^\circ$ of the preferred direction. The mechanical compression properties of the hydrogel at a concentration of 0.8 yielded results closely resembling those of animal spinal cord tissue (150–500 kPa maximum tension), with a recorded maximum tension of 128 ± 9 kPa and a maximum force of 1.0 ± 0.1 N (Golland et al. 2022). In contrast, braided structures produced for implantable applications exhibited different mechanical characteristics: a porosity of 50.7%, high elastic recovery (96.47%) after 10 cyclic compression tests, and a tensile strength of 1,674 N (Aguiar Souza et al. 2025).

The design project of fibrous scaffold structures facilitates the integration of aspects of design thinking and computational thinking through algorithmic programming. In this context, the parametric project enables modifications in fields focused on by design, yielding significant contributions, including: (1) Surface – within the representational domain, emphasizing Geometry and Graphic Representation; (2) Shape – the discernment of limits (shape) of the structure to adapt to the injured site; and (3) Structural properties (mechanical and physical) – compressive and tensile strength compatible with the installation site. It is noteworthy that, through design, one can

devise scaffold structures tailored to the intended tissue. This accomplishment results from a combination of factors such as porosity, pore geometry, tension in the area of scaffold application, biodegradability of the structure, and the manipulation of rigidity and flexibility, as adeptly outlined by Aguiar Souza (2023).

Hence, the aim of this study was to visually design braided textile structures capable of aiding in the treatment of SCIs and measure their morphological properties through characterization using Rhinoceros 3D software. These structures were selected based on criteria such as the number of yarns (internal and external), angle, structural diameter, and porosity. The modelling process was executed using Rhinoceros 3D software and the Grasshopper plugin.

2. Method and technique

2.1. Software

Rhinoceros CAD, commonly referred to as Rhino, operates through the utilization of Application Programming Interface (API), conventional textual scripting tools such as Python, or Rhinoceros Script—a language derived from Visual Basic for Applications (VBA). Various plugins enhancing the software's functionalities have been integrated into the system. The introduction of Grasshopper, a graphical scripting platform, facilitated the creation of a data flow model known as Algorithm-Aided Design. This algorithm plays a pivotal role in guiding the construction and modelling of structures, as illustrated in Figure 1.

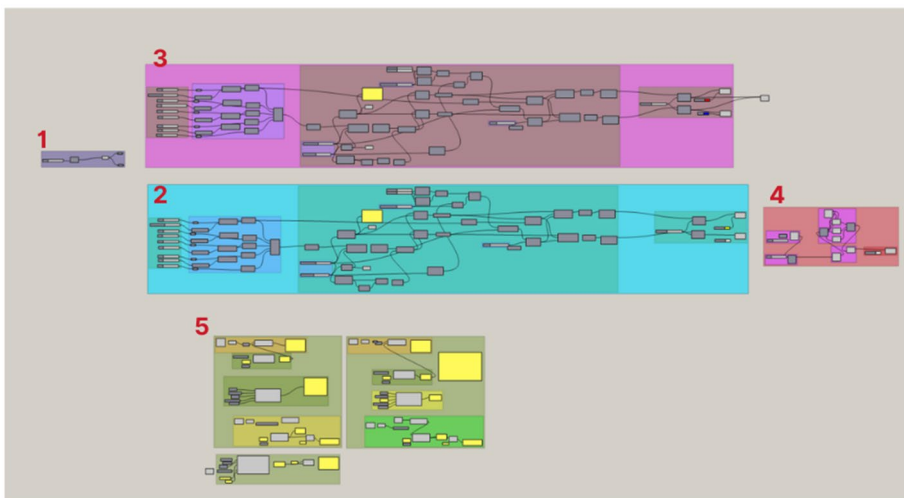


Figure 1. (1) Creation of the point for the development of the braided structure in the direction of the Z-axis; (2) Internal layer braid structure; (3) External braid structure; (4) Mechanism for duplicating the structure produced in two based on dividing a circle into points; and (5) Structure analysis model based on established criteria for selecting the best model. Source: The Authors.

2.2. Algorithmic structure in Grasshopper

The initial structure was conceived based on a central point that incorporates parameters from slider inputs. The sliders highlighted in red control the following parameters: (1) Circumference – Defines the radius of the circles at different heights; and (2) Height – Specifies the elevation of each level where a circle is generated. These values are essential for creating the sequence of circles along the Z-axis. In the blue section, the Unit Vectors (Unit Z) – Each height defined by the sliders is multiplied by a unit vector, generating a vertical displacement for each circle. In orange, the Move components receive a geometric object and displace it according to a motion vector. In this case, the displacement vectors come from Unit Z, meaning each circle is moved to its respective height. In green, the circles are positioned according to the slider inputs. Highlighted in white, the Merge component consolidates all elements, allowing the circles to be treated as a single collection of objects. This facilitates subsequent operations (such as lofting, extrusion, or mesh generation) (Figure 2).

In this section, the input parameters in the Sliders that control different aspects of the structure are highlighted in black. These parameters include: (1) Number of interlaces – Defines how many divisions or intersections occur in the structure; and (2) Number of wires – Controls how many curves or lines are generated; (3) Type of structure – A categorical slider that defines different geometric generation configurations. These parameters directly influence subsequent operations. Highlighted in green are the components of the Generation of Numerical Series (Series). These components generate numerical sequences, which are used to: (1) Define heights and spacings; (2) Create repeating patterns in the subdivisions of the surface; and (3) Organize the indexing of points and geometries. Each Series has the following inputs:

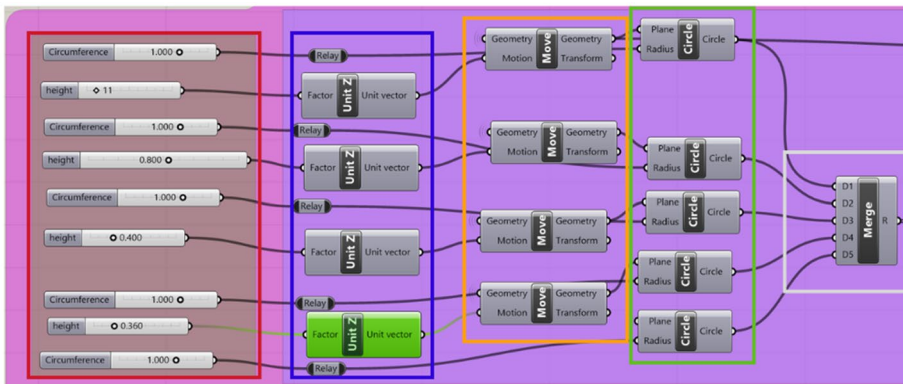


Figure 2. In red: Input parameter sliders. In blue: Unit vectors (Unit Z), multiplication, and vertical displacement. In orange: The Move components – receive a geometric object and displace it according to a vector. In green: The circles positioned based on slider parameters. Source: The Authors.

(1) Start – Initial value; (2) Step – Increment between values; and (3) Count – Total number of elements generated. Highlighted in red is the Subdivision of the Surface (Divide Surface) component. This component divides a surface generated by Loft, creating a matrix of points. The divided points serve as the basis for interlacing or patterns. Highlighted in blue are the list manipulation components (Cull Index, Cull Pattern, Shift List). These components organize the generated points and lines: (1) Cull Index – Removes specific elements from the list, adjusting the geometry according to desired patterns; (2) Cull Pattern – Follows a binary pattern (0 or 1) to activate or deactivate elements; (3) Shift List – Shifts the list indexes, allowing interlacing or shifting in the structure. These operations are essential for creating repetitive pattern effects and geometric connections.

In the data organization section, highlighted in white, matrix manipulation is performed using the Flip Matrix component. This component rearranges the data of two-dimensional lists, ensuring correct connectivity between elements, especially in structured meshes. Highlighted in orange is the construction of curved lines using the components Line, Curve Closest Point, and Nurbs Curve: (1) Line – Creates direct connections between points; (2) Curve Closest Point – Finds the closest points on a curve for correct alignment; (3) Nurbs Curve – Constructs smooth curves from generated points. These components ensure that the structure maintains continuity and geometric coherence. Highlighted in yellow are the components Move Away From and Trim Tree. The Move Away From component moves geometries away from an emitting point, which can be used to create variations in the weave or avoid intersections. The Trim Tree component then organizes the data to maintain consistency. Finally, highlighted in light blue is the Pick n Choose component. This component allows switching between different patterns of yarn arrangement or weave, generating different configuration variations. It is controlled by parameters defined in the Sliders (Figure 3).

The construction of the internal part was developed by creating a circle using the Circle component, highlighted in green. In light blue, the Sliders manipulate the circle's parameters and its subdivisions. The Divide Curve component, highlighted in dark blue, divides the circle into corresponding points and is controlled by the Sliders, which define the parameters. In yellow, the Vector Calculation includes: (1) The pDecon component, which decomposes points into X, Y, and Z coordinates; (2) The DeVec component, which calculates differential vectors between points; (3) Mathematical operations ($A+B$, $A-B$) that manipulate the vectors; and (4) The Vec2Pt component, which converts vectors into points. In red, the Move component shifts points based on the calculated vectors. Finally, the Custom Preview component displays the geometry with the color selected in the Color Swatch, highlighted in green (Figure 4).

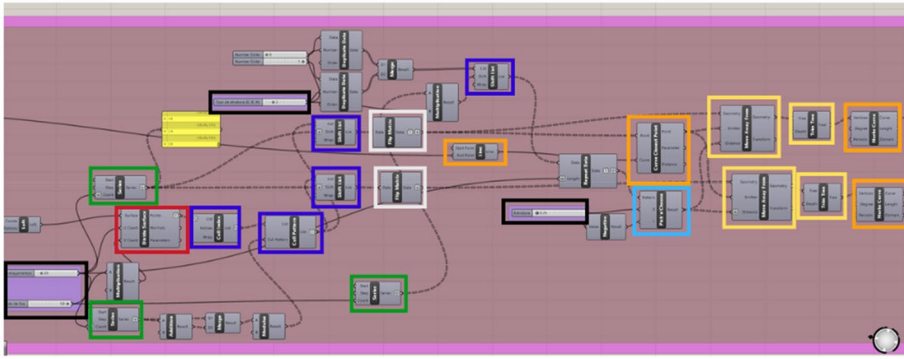


Figure 3. Black (Sliders): Control parameters such as the number of weaves, the number of threads, and the structure type. Green (Series): Generate numerical sequences for heights, spacings, and patterns. Red (Divide Surface): Subdivide the surface into points to create weaves. Blue (Cull Index, Cull Pattern, Shift List): Manipulate lists to adjust geometries and create patterns. White (Flip Matrix): Rearrange matrices to ensure correct connectivity. Orange (Line, Curve Closest Point, Nurbs Curve): Construct smooth lines and curves. Yellow (Move Away From, Trim Tree): Adjust geometries and organize data. Light Blue (Pick n Choose): Toggle between different pattern configurations. Source: The Authors.

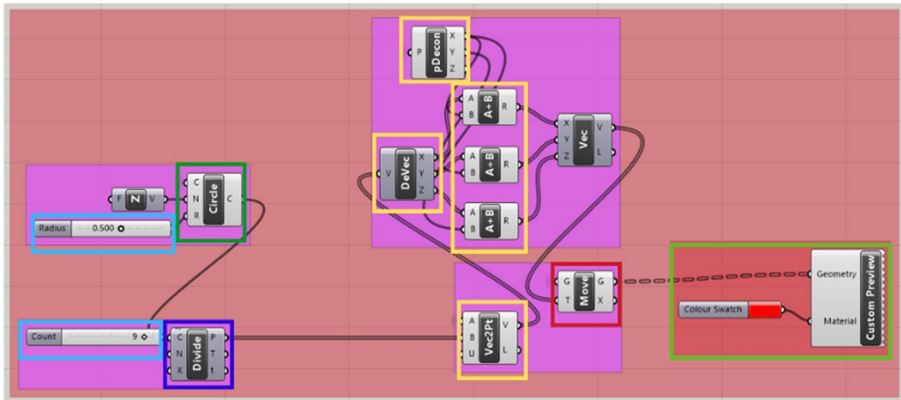


Figure 4. The internal structure is created using a Circle (green). Sliders (light blue) control its parameters and subdivisions. Divide Curve (dark blue) divides the circle, adjusted by the sliders. In yellow: vector calculations, including XYZ decomposition, differential vectors, mathematical operations, and conversion to points. Move (red) shifts points based on vectors. Custom Preview displays the geometry in the selected color (green). Source: The Authors.

2.3. Characterization method simulation

2.3.1. Morphological characterization

A correlation exists between the angles of the braids and the mass per unit surface (g/m^2). Consequently, the impact of the mass per unit of surface intensifies with a decrease in the angle size, while an increase in the angle corresponds to a reduction in the unit mass per unit of surface. The calculation of the mass per unit surface adhered to the following procedure:

I. Area Calculation Formula

The computation involves the principles governing the surface area of a cylinder. Initially, the area of the base of the lateral surface is determined by flattening one side of the cylindrical structure. Upon opening the cylinder, a rectangular structure is formed, and the perimeter of the circle is equivalent to $2\pi d/2$.

(Equation 1)

$$A = d / 2 \times 2 \times \pi \times h$$

Where:

d – Braid diameter (mm);

H – Braid height (mm).

II. Mass formula per unit surface:

(Equation 2)

$$M(g/m^2) = (P \times 10^6) / A$$

Where:

M – Mass of surface unit in g/m^2 .

P – Braid weight in grams;

A – Braid area in mm^2 .

2.3.2. Crossover density

The density in the braids was measured using a thread counter device and in 5cm. After the ligament counting process, the value was divided by five, and the crossing density per cm was obtained.

(Equation 3)

$$DC(cm) = (NCru5cm) / 5$$

where:

DC (cm) – Crossing quantity per centimetre;

NCru – Number of crossings in centimetres.

2.3.3. Braiding angle

Concerning the angle, it is formed through the interlacing procedure and governs the mechanical performance of braided structures. The angle is determined by factors such as the number of interlaced strands and the stretching and braiding speed. In this context, the interlacing angle is denoted as alpha (α), and the formula for calculating the interlacing angle can be found in the work by Rebelo (2017).

I. Next is the definition of the average diameter of the braided structure. (Equation 4)

$$D_m = (D_i + D_e) / 2$$

where:

D_m – Average diameter (mm);
D_i – Internal diameter (mm);
D_e – External diameter (mm).

II. Setting the frame angle
 (Equation 5)

$$\tan_{(\theta)} = (\pi \times D_m) / h$$

2.3.4. Coverage factor and porosity assessments

Porosity stands as a pivotal consideration in the development of scaffold structures. To assess porosity, one must scrutinize the quantity of fibrous materials deposited on the mandrel surface. The coverage factor precisely represents the proportion of the mandrel area covered by individual filaments. Additionally, the coverage factor serves as an indicator of the uniformity of the braid. It is defined by the following equations, as outlined in the works by Rebelo et al. (2015) and Rebelo (2017):

I. Definition of cover factor
 (Equation 6)

$$\text{Cover factor} = 1 - \sqrt{1 - \left(\frac{W_y \times N_c}{4\pi R \cos \alpha} \right)^2}$$

where:

W_y – Monofilament diameter (mm);
N_c – Number of coils;
R – Mandrel radius (mm);
α – Braid angle (rad).

II. Porosity Definition
 (Equation 7)

$$\text{Porosity} = 1 - \text{Cover factor}$$

3. Results and discussion

3.1. Parameters for structural changes in software

The software enables the insertion of various information, including: (1) Type of chosen structure – selecting a model from the three most common struc-

tures of braided yarns: Diamond (1/1), Regular (2/2), and Hercules (3/3); (2) Number of yarns – specifying the quantity of yarns, recognizing that a greater number of yarns contributes to increased geometric complexity. Additionally, control over the number of ligaments per centimetre is achievable (Aguiar Souza and Kohan 2024); (3) Diameter of yarn – the yarn diameter stands as a crucial parameter in braid production, as it alters the architecture of the structure, the formed angles in the braid, and may enhance structural rigidity and mechanical resistance. The selection of yarn diameters is informed by pertinent literature reviews (Aguiar Souza and Kohan 2024; Rebelo 2017; Rebelo et al. 2015); (4) Structure diameter – the overall diameter of the structure also influences its geometry and, consequently, the angles formed; (5) Draft – the algorithm's draft can be manipulated through parameters such as braid height, the number of braids per centimetre, as shown in Figure 5 (Aguiar Souza and Kohan 2024).

Modifications to structural parameters enable the adjustment of critical mechanical and physical properties in braided structures, including porosity, tensile strength, cyclic compression resistance, flexibility, coverage, and stiffness. In this context, simulation tools such as Rhinoceros 3D and Grasshopper

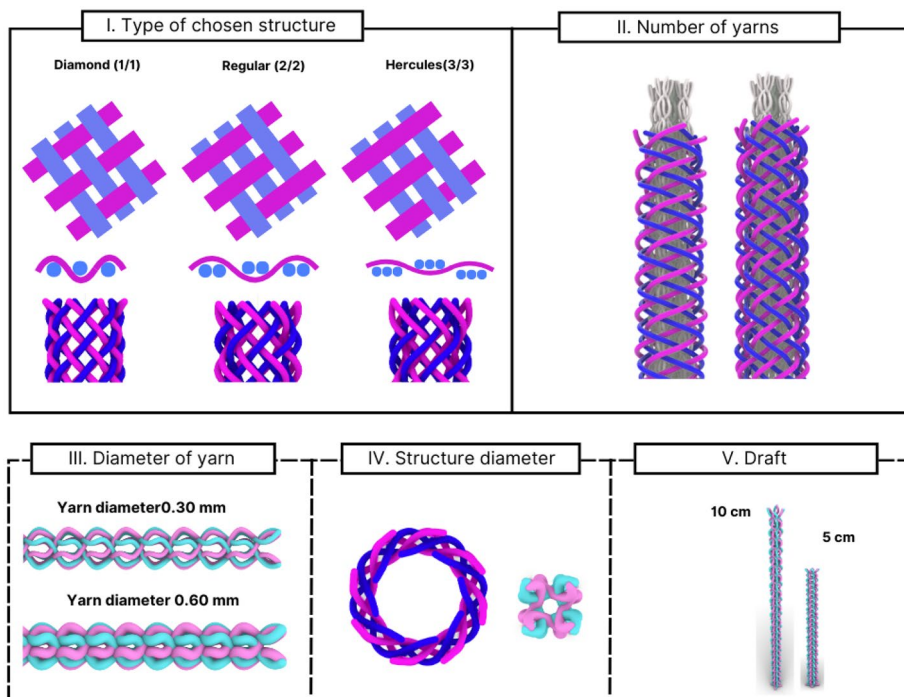


Figure 5. (1) Types of structures (variations in interlacing patterns) – Diamond (1/1), Regular (2/2), Hercules (3/3); (2) Selection of the number of yarns in the structure; (3) Control of yarn diameter within the structure; (4) Structure diameter – allows for the selection of dimensions/size of the braided circumferences; and (5) Draft represents the adjustability of braid height, number of interlacing points per centimetre, and diameter. Source: The Authors.

are essential for predicting and optimizing geometric parameters. Structural simulations ensure the accurate reproduction of complex geometries and yarn trajectory patterns.

3.2. Trajectory and topology of structures

Braided structures consist of filaments that follow a helical trajectory with a constant helix angle, corresponding to the so-called braiding angle (α) relative to the horizontal axis (Z). The geometry of filament paths in Regular (2/2) tubular braided structures combines straight segments (crossover regions) and sinusoidal segments (undulation regions), resulting in a repeating pattern throughout the structure, as illustrated in Figure 6.

It is worth noting that the braiding process consists of continuous turns in concentric circles, alternating between clockwise and counterclockwise directions, while simultaneously intersecting and interlacing with other filaments. As shown in Figure 7, the addition of filaments modifies the braid's geometry and trajectory.

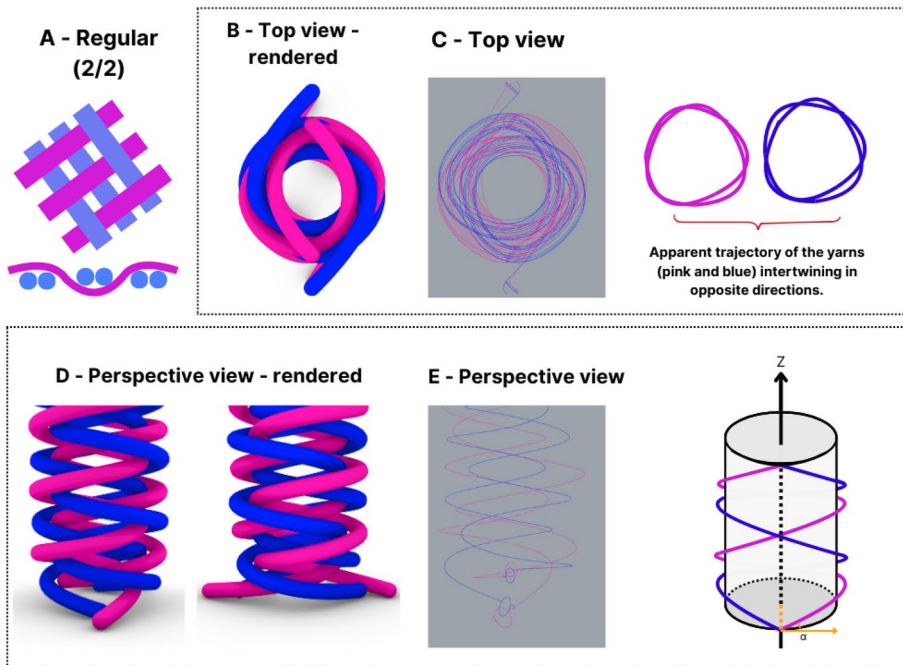
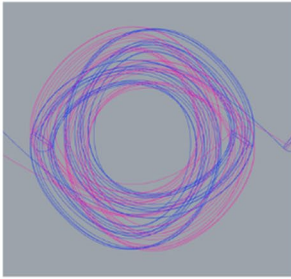
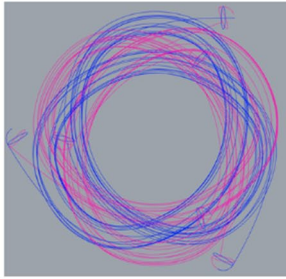


Figure 6. A – Schematic illustration of the Regular (2/2) braided structure used in the investigation. B – Rendered top view of a braid with 4 filaments. C – Top view of the braiding pattern (note the formation of two distinct trajectories with a certain symmetry in the resulting paths of the blue and pink filaments. The filaments exhibit a particularly similar trajectory shape due to simultaneous braiding in opposing positions – one group of filaments is braided clockwise while the other is braided counterclockwise). D – Rendered perspective view showing the braid bases and their crossovers. E – Perspective view of the braided structure along the Z-axis, highlighting the interlacing and a helical system. Source: The Authors.

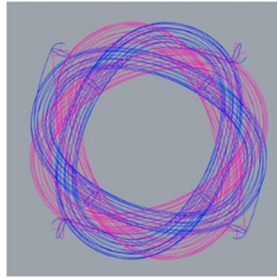
Struc 1 - 4 yarns



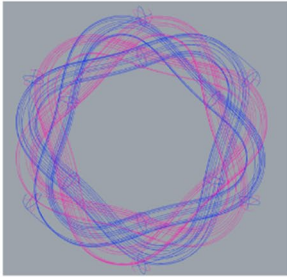
Struc 2 - 6 yarns



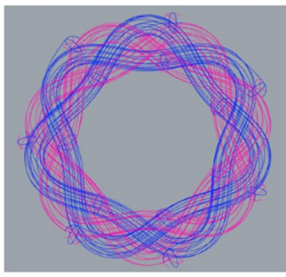
Struc 3 - 8 yarns



Struc 4 - 12 yarns



Struc 5 - 14 yarns



Struc 6 - 16 yarns

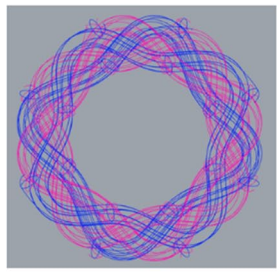


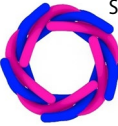
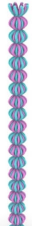
Figure 7. Struc 1: four yarns (the trajectories of the yarns describe a shape resembling a circle). Struc 2: six yarns (the trajectories of the yarns resemble the shape of a triquetra). Struc 3: eight yarns (the trajectories of the yarns exhibit similarity to an ellipse). Struc 4: 12 yarns (the trajectories of the yarns approximate a shape similar to an equilateral triangle with rounded corners). Struc 5: 14 yarns (the trajectories of the yarns also display a shape similar to a Lissajous curve). Struc 6: 16 yarns (the trajectories of the yarns also exhibit a shape resembling a super ellipse). Source: The Authors.

In [Figure 7](#), the simulations reveal, from a top view, the emergence of a geometric shape. This shape varies across the structures due to the addition or reduction of yarns. In this sense, it is possible to observe a periodic geometric or topological structure. Additionally, it is evident in the braids that periodicity is displayed in two representative sets of yarns (as demonstrated by the blue and pink colors). The trajectories of yarns of the same color (pink or blue) also exhibit high similarity and repeatability in the braided structures, which can be explained by the fact that, in these braided architectures, the yarn carriers follow an ordered and periodic arrangement ([Ren et al. 2025](#)).

3.3. Results of designed structures

The process of sample selection prioritized porosity as a central requirement, driven by the necessity for cell adhesion and the pore's capacity to create a conducive environment for the regeneration of the ECM. Moreover, it facilitates the development of homogeneous tissue at the implanted site ([Chen, Ushida, and Tateishi 2002](#); [Echeverria Molina, Malollari, and Komvopoulos 2021](#)). Regarding porosity, it was calculated based on the cover factor, which

Table 1. Tables with structures modified by different parameters to be selected for the external and internal layers.

Selection of structural samples for the external layer				Selection of structural samples for the internal layer			
Structures	View1 – Perspective	View 2 – Front	View 3 – Top	Structures	View1 –Perspective	View 2 – Front	View 3 – Top
Struc 1				Struc 1			
Struc 2				Struc 2			
Struc 3				Struc 3			
Struc 4				Struc 4			
Struc 5							

(Continued)

Table 1. Continued.

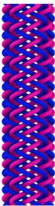
Selection of structural samples for the external layer			Selection of structural samples for the internal layer		
Struc 6					

Table 2. Comparison of information collected to select the external structure.

Structures	Struc 1	Struc 2	Struc 3	Struc 4	Struc 5	Struc 6
Diameter	5 mm	5 mm	5 mm	5 mm	5 mm	5 mm
N. of Interlacing (10cm)	40	50	50	50	50	50
Quantity of yarn	6	8	10	12	14	16
Diameter of yarn (mm)	0.50 mm	0.50 mm	0.50 mm	0.50 mm	0.50 mm	0.50 mm
Medium angle (°)	31.415	31.415	31.415	31.415	31.415	31.415
Cover factor (%)	13.55%	17.85%	22%	26.13%	30.10%	33.96%
Porosity (%)	86.44%	82.14%	77.95%	73.86%	69.89%	66.03%
Layer	External	External	External	External	External	External
Type of structure	Regular (2/2)	Regular (2/2)	Regular (2/2)	Regular (2/2)	Regular (2/2)	Regular (2/2)

Source: (the authors).

Table 3. Comparison of the information collected to select the internal structure.

Structures	Structure 1	Structure 2	Structure 3	Structure 4
Diameter	1.8 mm	1.8 mm	1.8 mm	1.8 mm
N. of Interlacing (10 cm)	50	50	50	50
Quantity of yarn	8	12	14	16
Diameter of yarn (mm)	0,40 mm	0,40 mm	0,40 mm	0,40 mm
Medium angle (°)	21.36	21.36	21.36	21.36
Cover factor (%)	15.22%	22.36%	25.81%	29.18%
Porosity (%)	84.77%	77.63%	74.18%	70.81%
Layer	Internal	Internal	Internal	Internal
Type of structure	Regular (2/2)	Regular (2/2)	Regular (2/2)	Regular (2/2)

Source: (the authors).

represents the proportion of the area covered by the yarns. Porosity is defined as a value inversely proportional to the cover factor.

A group of braided structures with different structural characteristics was developed, as shown in Table 1. Additionally, a set of equations was incorporated to bolster the morphological characterization and selection of structures. Notably, among the various equations employed, the following are highlighted: angle calculation and porosity calculation (Tables 2 and 3).

Upon analysing Tables 1–3, it is observed that the angle of the structures remains constant when their diameter is maintained. However, discernible variations exist between the internal layer structure, exhibiting an average angle of (31.41°), and the external layer, characterized by an average angle of (21.36°). Additionally, the introduction of more yarns into the structure leads

to a reduction in porosity, aligning with findings documented in the existing scientific literature (Aguiar Souza et al. 2024; Rebelo et al. 2015). The diameters of both internal and external structures were held constant, unaffected by alterations in the number of yarns.

In contrast, the study by Aguiar Souza et al. (2025) produced a group of T3/A8B40/E8B50 structures, consisting of eight braided yarns with a diameter of 0.40 mm in the internal layer and another eight yarns with a diameter of 0.50 mm in the external layer. The T2/A8B40/E16B50 configuration features eight yarns of 0.40 mm diameter in the internal layer, while the external layer of both structures contains 16 yarns of 0.50 mm diameter. The mean braiding angle for the T2/A8B40/E16B50 structure was $\pm 31.59^\circ$ in the external layer, compared to $\pm 31.90^\circ$ for T3/A8B40/E8B50, while the internal layer of both structures exhibited a similar angle ($\pm 24.46^\circ$). The external and internal layers modelled in Rhinoceros and Grasshopper closely matched the experimental results, with minor discrepancies likely attributable to manual sample production. This finding validates the use of the software as a key tool in the design process of braided structures.

3.4. Proposed structure model

The structures chosen to compose the external layer were presented in structure 2 and structure 6 (Tables 1 and 2). These structures have different morphologies; structure 2 has eight yarns, and structure 6 has 16 yarns. As for the internal part, structure 1 was chosen, which presents a configuration built with eight yarns and greater porosity (Table 3). The model was designed in Rhinoceros and Grasshopper (Figure 8).

The selection of the structure (Figure 8) was informed by the data presented in Tables 1 and 2. The guiding criterion in the structure selection process was porosity, as the presence of pores establishes a connection with permeability and the potential for nutrient exchange. Additionally, pores play a vital role in cellular activity by promoting vascularization and providing a conducive space for cell proliferation (Chen et al. 2020; Huang et al. 2019). Consequently, structures with higher structural porosity were prioritized from among those designed in the software. Thus, the internal layer's selected structure, which exhibited the highest porosity at 84.77%, was the braid composed of eight yarns with a diameter of 0.40 mm. For the external layers, two structures were chosen: one with eight yarns displaying 82.14% porosity, and the other with 16 yarns demonstrating 66.03% porosity. Both structures were crafted using the Rhinoceros program, utilizing yarns with a diameter of 0.50 mm.

The T2/A8B40/E16B50 structure exhibited an external layer with porosity (50.7%) and coverage (49.3%), while the T3/A8B40/E8B50 structure had an external layer porosity of 64.4% and coverage of 35.56%. Both internal layers

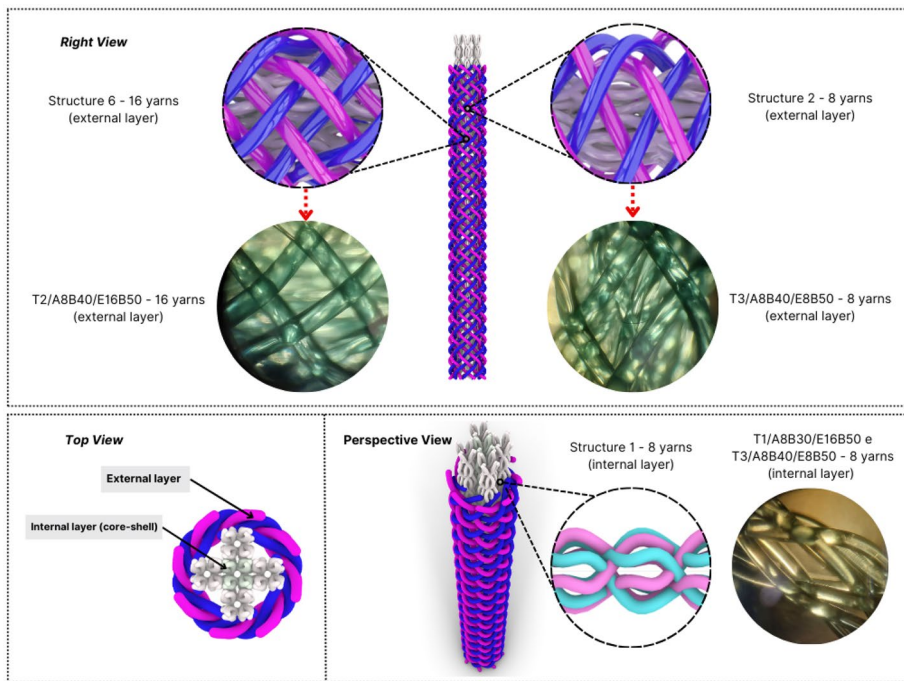


Figure 8. Final design of the structure designed using Grasshopper and Rhinoceros algorithms. The image shows the construction model of the structure in two layers, internal layer (core-shell) and external layer. It is also possible to compare Structure 6 – 16 yarns (external layer) with T2/A8B40/E16B50, 16 yarns (external layer), Structure 2 – eight yarns (external layer) with T3/A8B40/E8B50, eight yarns (external layer), and Structure 1, eight yarns (internal layer) with the core structure of T3/A8B40/E8B50 and T2/A8B40/E16B50. Source: The Authors.

showed porosity (34.5%) and coverage (65%). Comparing Structure 2 and T2/A8B40/E16B50, the braided structure design algorithm estimates a porosity of 15.33% in the external layer. In the comparison between Structure 1 and T3/A8B40/E8B50, the difference presented by the algorithm was 22.04%. For the internal structure, the difference was 50.27%. It is worth noting that in T2/A8B40/E16B50 and T3/A8B40/E8B50, the internal structure has a smaller diameter. The braiding process of the external layer may cause flattening of the internal part. However, in Figure 6, the preservation of structural characteristics is observed, with pores maintaining their shape in both the 16-yarn and eight-yarn external layers. In the internal layer, the structures exhibit small pores (Aguiar Souza et al. 2025).

4. Conclusion

Presently, braided structures are not utilized in spinal scaffolds; however, they are already employed in various other domains such as tendons, ligaments, and others. This investigation is rendered feasible owing to the fact that

braided structures fulfil pivotal requirements in tissue engineering, notably: a 3D framework, porous architecture facilitating cell infiltration and adhesion, and subsequent cellular differentiation. Upon comparison with the references outlined in the literature, it is discernible that such structures offer potential enhancements in terms of both tensile and compressive strength. This is attributable to the inherent properties of braided structures, in conjunction with the porous architecture and the ease of fabrication thereof.

The development of the programming and project afforded significant insights into the structures. Consequently, external layers (comprising eight and 16 yarns, respectively) and an internal layer (comprising eight yarns) were designated. Remarkably, despite the constancy of angles with the addition of yarns, such augmentation diminishes critical factors like porosity, while simultaneously augmenting geometric complexity. Notably, alterations in angles are accentuated by variations in structure diameters.

Two distinct structures were formulated: one featuring eight yarns of 0.40mm calibre for the internal layer, and eight yarns of 0.50mm calibre for the external layer; the other incorporating eight yarns of 0.40mm calibre for the internal layer and 16 yarns of 0.50mm calibre for the external layer. The selection of the internal layer (referred to as Structure 1) is predicated upon structural porosity (84.77%). Conversely, within the respective external layers, the structure comprising 16 yarns (referred to as Struc 6) demonstrated a porosity of 66.03%, while the structure with eight yarns (referred to as Struc 2) exhibited a porosity of 82.14%. These divergent selections underscored distinct attributes – the ultimate structure crafted with eight yarns in both internal and external layers showcased heightened porosity across both strata, albeit potentially compromising the mechanical robustness of the construct. Conversely, the structure featuring an internal layer of eight yarns and an external layer of 16 yarns may embody superior mechanical properties; notably, the augmentation of thread count within the external layer does not jeopardize structural porosity, underscoring its suitability for application.

The utilization of Rhinoceros 3D and the Grasshopper plugin facilitated the creation and assessment of the structure in terms of morphology, enabling the observation of critical characteristics before actual production. It is noteworthy that the porosity criterion guided the observation and selection of structures, allowing for a morphological characterization based on the software-designed model. The scaffold project devised in Grasshopper streamlined the process in terms of cost and time, leveraging the multitude of structures already generated using the braiding technique as a starting point.

Future perspectives include refining the project's algorithms. Furthermore, it is essential to conduct Finite Element Analysis (FEA) to optimize the structures. Additionally, cell growth (*in vitro*) assessments are necessary to verify the material's efficacy and *in vivo* application.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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