Construction and simulation of braided textile structures: considerations for teaching textile design[1]

Construção e simulação de estruturas têxteis entrançadas: considerações para o ensino de design têxtil

Construcción y simulación de estructuras textiles trenzadas: consideraciones para la enseñanza del diseño textil.

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Abstract

The aim of this study was to develop braided fibrous structures for scaffold implant applications, utilizing graphical simulation with Rhinoceros 3D® software (version 6) and the Grasshopper plugin. The research aimed to emphasize key aspects of woven textile structures and support textile design education. To achieve these goals, the study proceeded through two stages. Stage 1 involved an exploratory-descriptive phase with a brief literature review, while Stage 2 comprised applied qualitative and descriptive research. Morphological analyses of the braided structures indicated that the average interlacing angle was consistently influenced by yarn diameter, number of yarns, orientation, applied tension, material, and structure diameter. These findings align with existing literature and underscore the significance of graphic simulation and advanced software in advancing both the development and pedagogy of textile design.

Keywords: *Braid, Education, Textile Design, Rhinoceros 3D®, Grasshopper.*

Resumen

El objetivo del trabajo fue desarrollar estructuras fibrosas entrelazadas para su aplicación en implantes de andamios, utilizando simulación gráfica mediante el software Rhinoceros 3D® (versión 6) con el plugin Grasshopper. La investigación buscó destacar y seleccionar los aspectos más importantes de las estructuras textiles entrelazadas, además de brindar apoyo para la enseñanza en el campo del diseño textil. Para alcanzar los objetivos definidos, se

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llevó a cabo una investigación en dos etapas. Etapa 1: exploratoria-descriptiva con una breve revisión del tema. Etapa 2: investigación aplicada de naturaleza cualitativa y descriptiva. Los resultados de los análisis morfológicos de las estructuras entrelazadas revelaron que el ángulo promedio de entrelazado fue consistentemente influenciado por el diámetro del hilo, número de hilos, orientación, tensión aplicada, material y diámetro de la estructura. Los hallazgos corroboran la literatura existente y destacan la importancia de la simulación gráfica y el uso de software avanzado en el desarrollo y la enseñanza del diseño textil.

Palabras clave: *Entrelazados textil, Enseñanza, Diseño Textil, Rhinoceros 3D®, Grasshopper.*

1. Introduction

Braids are possibly one of the most well-known types of textile structures across various cultures throughout history (Araújo, Fangueiro, & Hong, 2001). For instance, in Brazilian indigenous cultures, there is extensive production of household utensils utilizing braided structures, particularly for processing and refining cassava/ manioc by-products. These structures consist of hollow conical cylinders, braided with notable elasticity and tensile strength, which are typical characteristics of braided textiles (Falco *et al.,* 1987).

The use of CAD (Computer-Aided Design) systems offers solutions to challenges ranging from clothing design to knitting and other applications in the development of design projects. Advances in this technology have facilitated the simulation of geometric, mechanical, and physical properties and their variables (Silva, 2022). Recently, parametric design, which employs algorithms and mathematical calculations to create complex geometries based on predefined criteria, has gained prominence. Simulation has become increasingly significant due to its ability to provide immersion in structures, enabling the construction and representation of data, performance visualization, structural analysis, and interactive and immersive construction simulation (Malkawi, 2004). Furthermore, the simulation process serves as a foundation for optimization and automation, allowing designers to work from a perspective of continuous improvement and practical application in the design process (Humppi, 2015).

Fashion design education can benefit from the application of CAD tools, particularly in the teaching of textile structures. In the information age, the integration of Information and Communication Technologies (ICT) in textile education and construction has received limited attention, despite the growing relevance of textile structures in fields beyond textiles and fashion, such as Tissue Engineering (Aguiar Souza, 2023; Aibibu *et al.,* 2016).

Textile structures are constructed using complex geometries. Braids, as one of these structures, can be shaped by introducing solid molds into their interior. These structures are further categorized into two main classes of textile braids: (I) two-dimensional (2D) — composed of two or more braided yarns within a Cartesian XY plane; and (II) three-dimensional (3D) — structures where the yarns progress in three directions defined within a Cartesian XYZ plane (Liu et al., 2022; Araújo, Fangueiro, & Hong, 2000).

2D textile braids are produced using a braiding device (braiding machine), which can create structures that are predominantly cylindrical/tubular but can also produce flat, asymmetric geometries (axial geometries). These 2D structures consist of yarns arranged in a biaxial configuration relative to the longitudinal direction of the braids, with angles of ±θ°. 3D structures are manufactured using either Cartesian or rotary braiding machines. Cartesian machines are designed with a column-track (or column-row) configuration. In this system, the yarn carriers move along a continuous path, systematically advancing columns and rows forward and backward; the resulting structures can be biaxial, triaxial, or fully 3D (Li et al., 2022; Melenka & Ayranci, 2020).

Figure 1 illustrates a top view of the braiding mechanism in a circular braiding machine. Group A represents the hexagonal circular braiding machine, which produces a Cartesian (or track and column) braided structure. This process involves the selective movement of the bobbins along a network of tracks and columns, utilizing alternating movements. Also in Figure 1, Group B depicts the braiding mechanism of circular 2D braided structures, produced through continuous turns in concentric circles (clockwise), where yarns simultaneously converge and intertwine with each other (Schreiber, 2016; Aguiar Souza, 2023).

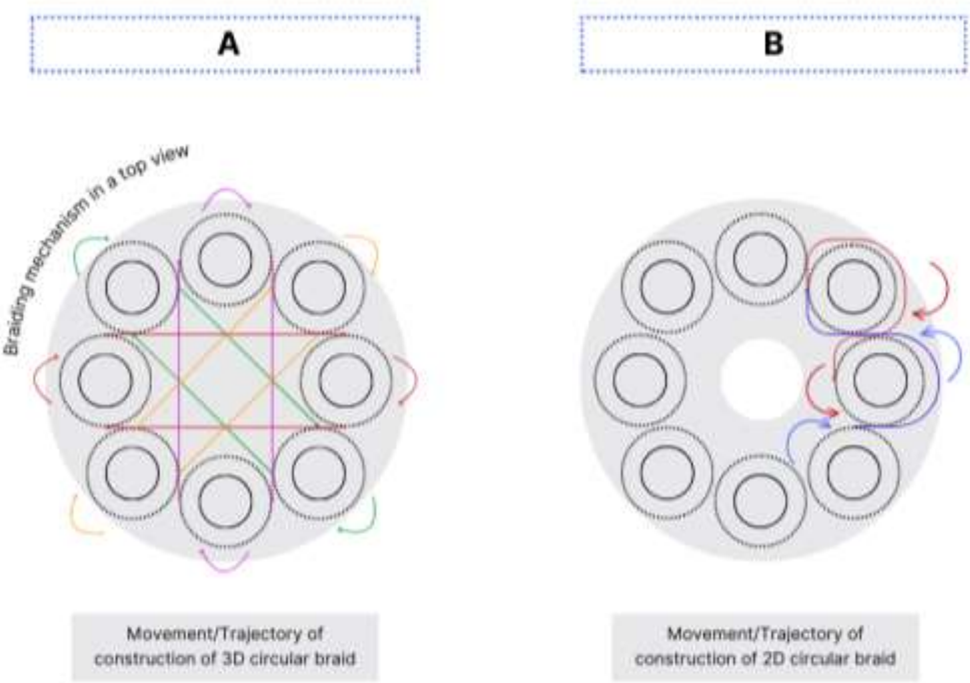

Figure 1. Machine movement/trajectory for the construction of interlaced geometries. ***Group - A:*** *3D circular hexagonal interlacing.* ***Group - B:*** *2D circular interlacing.*

Fonte: Elaborado pelo Autor

In the current context, braided structures have seen increased application in the biomedical field, particularly circular 2D structures and hexagonal 3D braids.

Simulations of the structural geometry of hexagonal braids, such as horngears[2] (Figure 2 - Group A), facilitate the creation of bifurcated structures for medical applications, including bifurcated arterial prostheses or stents[3]. 2D structures also offer advantages in the biomedical field, particularly in the production of stents and scaffolds[4], as shown in Figure 2 - Group B (Schreiber, 2016; Aguiar Souza, 2023; Rebelo et al., 2015; Vila, 2009).

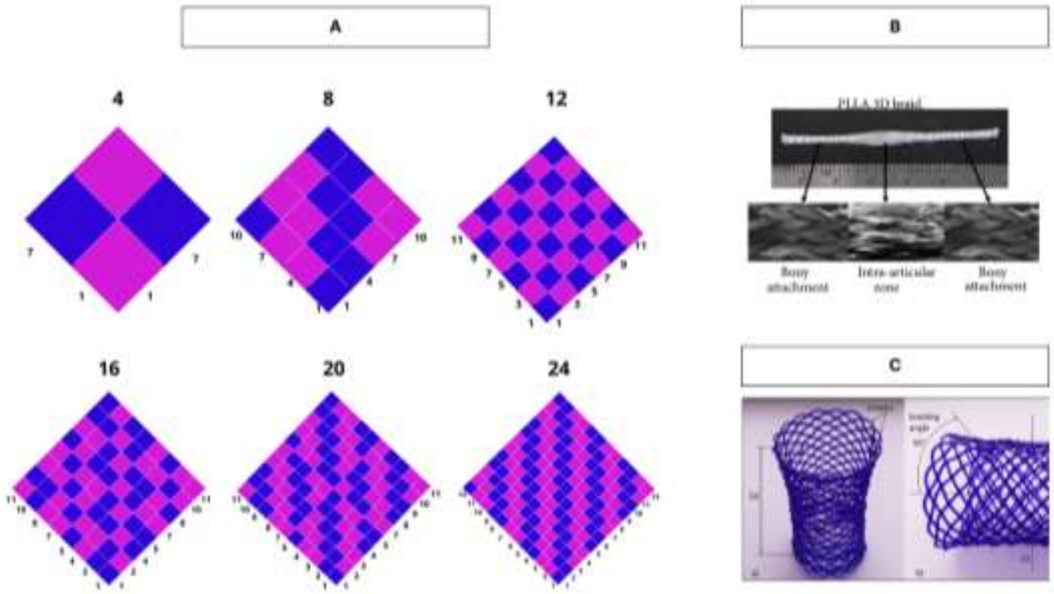

Figure 2. Group - A: Braided structures using varying numbers of yarns on a 12-gear Horngear braiding machine. Group - B: Braided scaffold structure for ACL ligament repair (Source: adapted from James & Laurencin, 2014). Group - C: Stent-type braided structure (Source: adapted from Shanahan et al., 2017).

Source: Prepared by the Author

The geometries of braids are noteworthy and exhibit distinct properties. For instance, the 2/2 (regular) braid type demonstrates higher strength and modulus of

[2] Horngear Braiding Machine: A structure produced by a Horngear 12-gear circular braiding machine, which offers 24 potential spindle positions (12 clockwise and 12 counterclockwise). As the spindles complete their rotations, they weave the yarn by passing over and under spindles moving in the opposite direction. By removing one or more spindles, braids with significantly different structures and geometries can be created. These geometries can be analysed and compared, resulting in braids that are not only aesthetically distinct but also possess varying mechanical properties. When fully loaded with spindles, the Horngear braiding machine produces a regular braid (Nawaz et al., 2013).

[3] Stent: A stent is a medical device in the form of a small tube or mesh, typically made of metal or polymer, used to keep narrowed or obstructed blood vessels or ducts open.

[4] Scaffolds: Scaffolds are structures composed of polymeric biomaterials that exhibit micro- and nanostructural characteristics, morphology, and surface properties suitable for providing structural support for cell attachment and the subsequent development of living cells and tissues (Ashammakhi *et al.,* 2022; Chan & Leong, 2008).

elasticity, along with greater stiffness and shear strength compared to 1/1 structures. Additionally, it exhibits a lower crimp angle of the yarn (yarn crimping), which correlates with increased stiffness and strength (Chai et al., 2020). Melenka and Carey (2017) developed parametric braided structures using a custom Python script and Computer-aided design software (Rhinoceros 3D® 5.0, Robert McNeel & Associates, Seattle, WA, USA) to visualize the geometries of three-dimensional braids.

In terms of structural geometry construction, a simplistic analogy can be drawn between textile braids and flat textiles. Just as flat textiles are classified based on their construction — taffeta (plain weave), twill, and satin—braided fabrics are differentiated by the pattern of yarn crossing, known as the "ligament" or "crossing". Braided structures are categorized into the following types: Diamond (1/1), Regular (2/2), and Hercules (3/3). In the Diamond structure, for example, the yarns intertwine one by one, with one yarn floating while the other passes underneath, alternating in the next turn. In the Regular structure, two yarns float and two pass underneath, while in the Hercules structure, the yarns alternate three by three, as illustrated in Figure 3 (Aguiar Souza, 2023; Kim et al., 2019; Melnka & Ayranci, 2020).

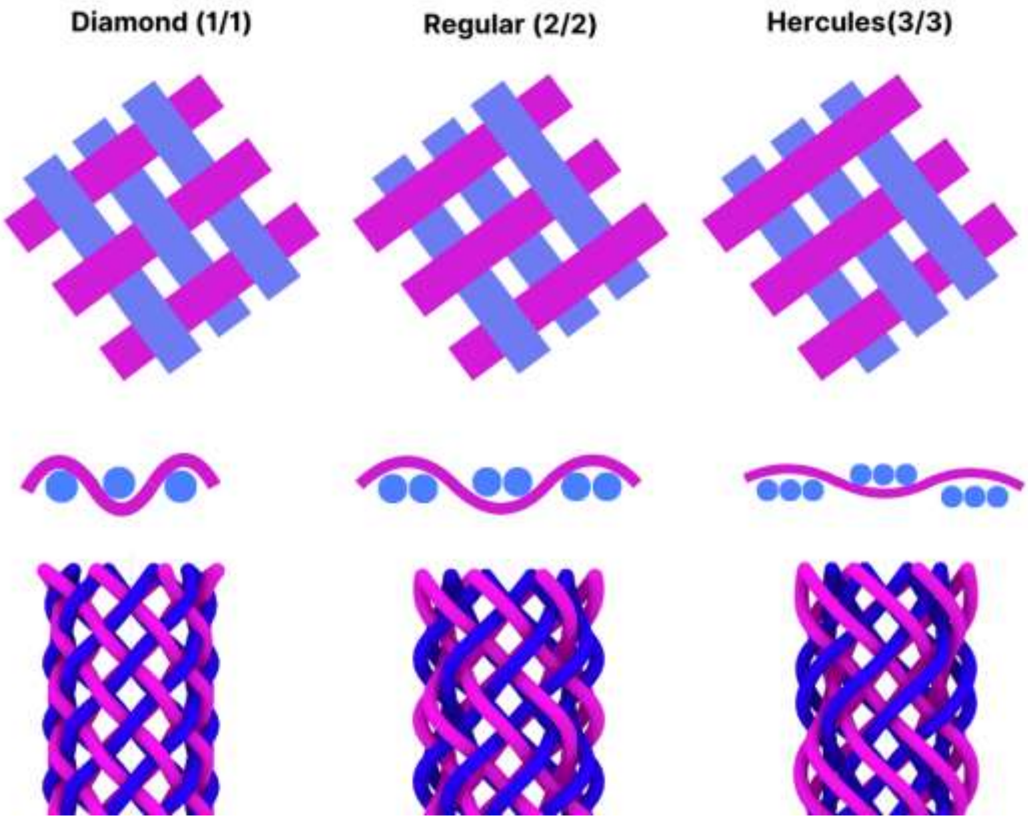

Figure 3. Braided structures with a model representing the ligaments. The three most common types of braided structures—Diamond (1/1), Regular (2/2), and Hercules (3/3)—are also illustrated. These structures were designed using algorithmic programming with Rhinoceros 3D® software and Grasshopper plugins.

Source: Prepared by the Author

The use of Computer-Aided Design (CAD) systems represents a significant departure from traditional methods of designing, planning, and implementing various artifacts or objects. Previously, these processes relied on the expertise of a technician who manually drafted designs on paper. Now, this activity has evolved into a structured design process that includes*: **(1) Design Process*** (i. Problem identification; ii. Product application; iii. Development of a potential solution; iv. Selection of applicable materials); ***(2) Analysis Process*** (i. Identification of product analysis methods; ii. Tools for analysing product properties; iii. Consideration of circularity or end-of-life); and ***(3) Data Analysis Process*** (i. Collection of results throughout the solution development process; ii. Verification of results; iii. Redesign/improvement of the product) (Vargas-Rojas, 2022).

In the field of medical structure production, CAD/CAM technology has been successfully applied in the modification of titanium scaffolds (implantable structures) (Fischer et al., 2022), including the construction of scaffolds based on image-derived designs. The surface design capabilities inherent in CAD-generated models, coupled with imaging techniques in the medical field, have led to the creation of high-quality structures with minimal labour. These structures efficiently meet criteria such as porosity and surface topography, with methodologies applied in bone tissue engineering (Top et al., 2021).

Given that society increasingly values the mastery and construction of visual intelligence—where visual codes structure the acquisition of information and guide the teaching-learning process—these tools can be effectively integrated into educational settings (Cadena et al., 2013). It is crucial to emphasize that visual language, within this communication and teaching context, is established through the interaction between students and teachers, both visually and auditorily, but primarily through graphic modes (Twyman, 1981).

In this context, the aim of this work was to develop woven fibrous structures for application in scaffold implants, using graphic simulation with Rhinoceros 3D® software (version 6) (McNeel, 2019) and the Grasshopper plugin. The goal was to highlight and select the most critical aspects of woven textile structures, while also supporting education in the field of textile design.

2. Methodological Procedures

Stage 1 — the research is characterized as exploratory-descriptive based on the review of the development of textile structures and the in-depth bibliographical analysis carried out in books, articles, theses and dissertations.

Stage 2 — in order to meet the defined aim, applied research was carried out with a qualitative approach and, as for the aim, descriptive. The focus of the applied research is to generate knowledge for practical application and problem-solving. The descriptive nature is established in the detailed description of the development procedures of the braided structures (Merino et al., 2020). As part of the applied research, braided structures were developed using Rhinoceros 3D® software and the Grasshopper plugin.

The choice of the software is justified by its ability to manipulate Non-Uniform Rational Basis Spline (NURBS) objects, a type of surface and curve widely used in graphics programs (Hsu *et al.,* 2015). The use of NURBS has been widely used in visual programming, especially with the addition of the Grasshopper plugin, used for parametric geometry projects. This plugin allows the visualization and isogeometric creation of finite elements in several ways, offering: I. Improvement in the modelling of complex geometries; II. Guarantee of accuracy in geometries, eliminating geometric errors; III. Providing systematic refinement approaches (Bazilevs *et al.,* 2006). The Grasshopper plugin has stood out in the fields of medicine, architecture, fashion and design, due to its ability to handle multiple parameters and render complex models (Eltaweel & Su, 2017).

2.1. Creative method

The methodological model used to develop the framework involved parametric modelling in Rhinoceros® software with the Grasshopper plugin. A group of design methodologies was also analysed, specifically those proposed by Löbach (2001), Munari (1981), and Simlinger (2007). Following this analysis, the common steps across all methodologies were identified, and the computational thinking framework of Shute et al. (2017) was incorporated through the parametric algorithm.

Figure 4 illustrates the creative method and its steps. Step 1 involves the detailed identification of the problem, followed by Step 2, which consists of a comprehensive analysis of the context and existing knowledge on the topic. Based on this analysis, it is crucial to define clear aim, establishing a specific perspective of action.

Next, in Step 3, possible solutions are proposed, fostering creativity and employing various techniques to explore different applications of the ideas. During this process, it is important to observe and identify patterns in the established knowledge. Step 4 involves analysing the proposed solutions, selecting the models that best fit, and determining the most effective implementation strategy.

Step 5 focuses on developing a well-structured algorithm, which includes the organized design of the steps, parallelism for simultaneous task execution, efficiency in minimizing steps, and the generation of interactive visual representations. Step 6 requires careful selection of materials, evaluating their properties and suitability for the solution. Step 7, the prototyping phase, allows verification that all designed attributes are present, while Step 8, model validation, ensures the reliability of the design through rigorous testing. If the model fails validation, it necessitates returning to Step 4. Finally, Step 9 consolidates the final solution, providing a robust and efficient response to the initial problem.

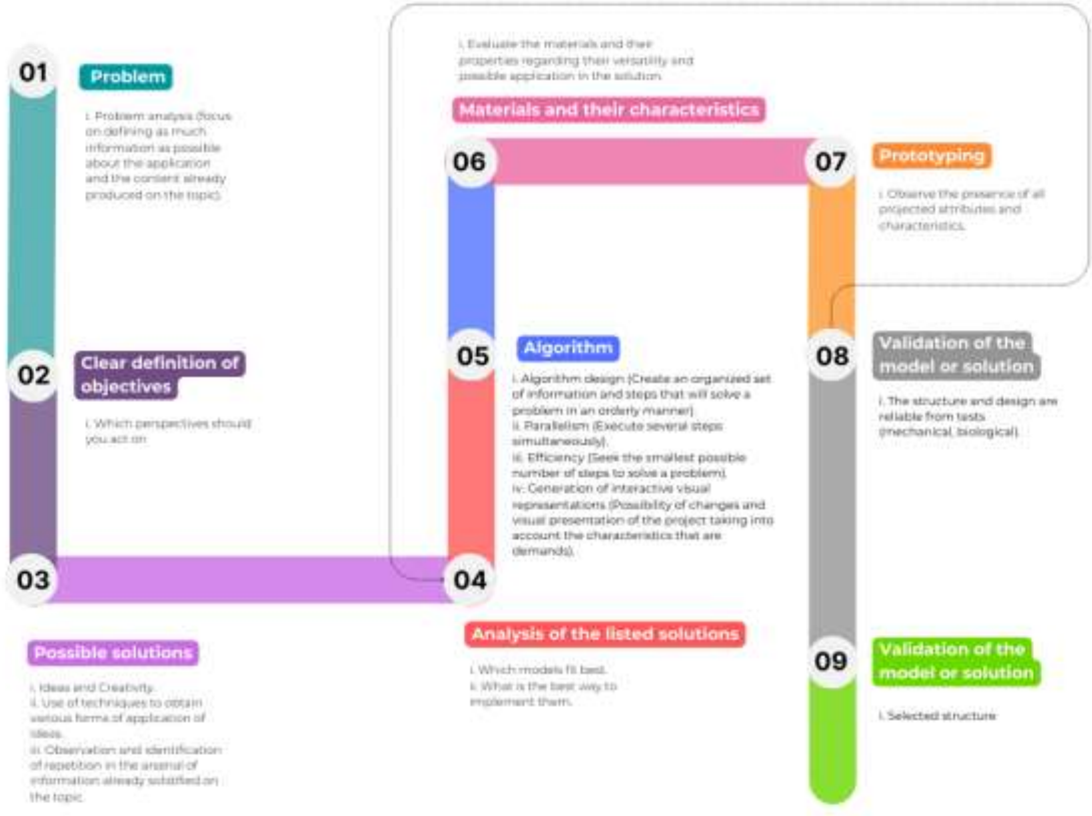

Figure 4. Graphical model illustrating the creative method in structural design.

Source: Prepared by the Author

The model applied to the textile structure project (Figure 4) delineates design thinking through the specification and expansion of the problem, the definition of aim, the exploration of potential solutions, the analysis of these solutions, and the validation of the model. Additionally, computational thinking is incorporated into the project via an algorithm that enables the design and simulation of various structures, aiming to develop a prototype of a textile structure in accordance with key design criteria. Moreover, the algorithmic model is formulated to predict the morphological characteristics of the woven structures.

3. Visual Programming and Software Interface

One of the most significant contributions to the popularization of the term 'parametric design' is the use of visual programming packages. Visual programming can be defined as a representation modality that eliminates the need for direct coding by encapsulating code within modules, each possessing its own 'inputs' and 'outputs' which are interconnected in a logical arrangement that processes information at each connection. Compared to conventional programming, visual programming offers a more intuitive approach, making it relatively more accessible to beginners. This facilitates its direct application in design, architecture, engineering, and construction, thereby promoting the use of visual programming packages (Ajouz, 2021).

Currently, the most prominent packages are Grasshopper, which integrates with Rhinoceros 3D® and is geometry-oriented, enabling rapid calculations, and Dynamo, which operates with Revit software and is primarily used in architecture for the design of buildings and metal structures. The interfaces of these packages differ: Grasshopper employs bright colours and logos, whereas Dynamo features an interface with fewer icons, as illustrated in Figure 5 (Ajouz, 2021).

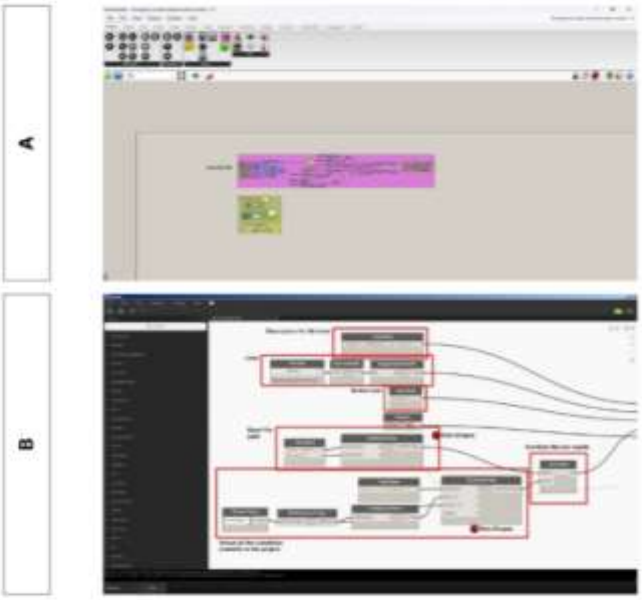

Figure 5. Grasshopper visual programming interface (**A**); Dynamo visual programming interface (**B**).

Source: Prepared by the Author

Regarding the Rhinoceros 3D® (or Rhino) system, once the Grasshopper plugin is added, the program supports two distinct programming methods. The use of scripting languages enables programming that transcends the limitations of the user interface; however, this approach requires knowledge of programming languages to manage the code. Alternatively, graphical programming (visual language) involves the interconnection of stacks or nodes. Table 1 outlines the differences and specific characteristics of these methods, as well as their respective functions and distinctions (Voltolini et al., 2020).

Table 1. Functions of each programming method.

TEXTUAL PROGRAMMING	VISUAL PROGRAMMING
Script	Bypass-code
Text Line	Connection between stacks
Compilation	Real-time results
Specialist	Intuitive
Allows for more refined programming	Based on editable components within stacks

Fonte: extraído de Voltolini *et al.,* (2020).

The software in question supports the integration of a range of plugins that enhance its functionalities. A notable example is Ladybug, which, through the incorporation of these plugins, enables the evaluation of energy consumption in buildings and the analysis of climatic factors, among other capabilities. Conversely, Karamba facilitates structural analysis by allowing the simulation of material behaviour under various types of stresses, such as tension and compression, based on the definitions provided in the visual programming environment.

4. Results

An algorithm was employed, defined as a procedure used to solve a specific problem or perform particular tasks. It consists of a finite set of basic and well-defined instructions. In the context of Grasshopper modelling, the creation of an algorithm involves: I. Defining a specific set of inputs; II. Developing a consistent algorithm with a clear and defined set of instructions; III. Generating a clear and well-defined output, as illustrated in Figure 6 (Tedeschi, 2014).

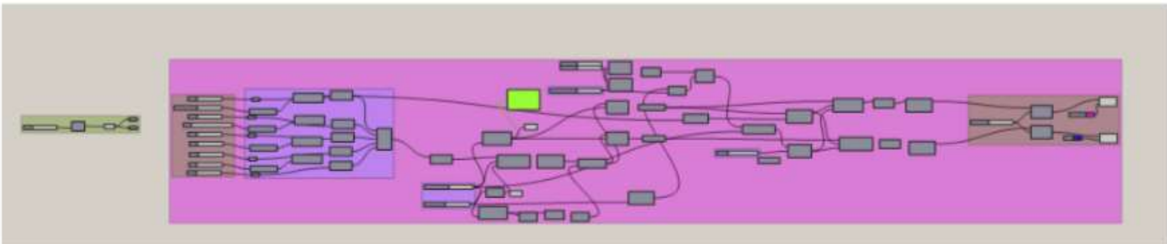

Figure 6. Representation of the Algorithm Developed in Grasshopper.

Source: Prepared by the Author

The initial construction in the Grasshopper software begins with a point, which is initially connected and duplicated. These duplicated points are then moved to a set of predefined positions along the Z axis, organizing them around a cylindrical structure that simulates a mold. Additionally, several horizontal subdivisions are generated along the Z axis to facilitate the formation of ligaments and intersections in the braided structures. A point positioning system was also implemented to enable modifications to the types of braided structures produced. The points were connected to form yarn structures using NURBS curves, and a command was added to control the yarn diameter (Aguiar Souza, 2023).

4.1. Parameters Utilized in the Construction of a Braided Structure within the Algorithm

Type of Structure Selected – The model designed by the algorithm permits the selection among three common structures (ligaments): Diamond, Regular, and Hercules (Figure 7). Additionally, it facilitates the experimentation with structures incorporating various ligaments.

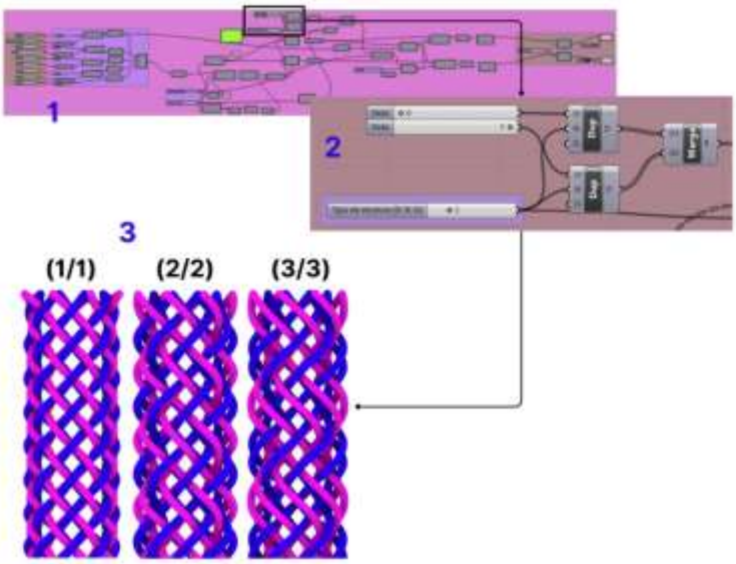

*Figure 7. **1**. In pink, the complete structure of the algorithm. **2**. Part of the algorithm responsible for defining the parameter/type of structure regarding the ligament. **3**. The types of structures resulting from the definition of the ligament, Diamond (1/1); Regular (2/2) and Hercules (3/3).*

Source: Prepared by the Author.

Number of yarns – The number of strands is a crucial element in the construction of braided structures, as a higher number of strands results in more complex geometry. Additionally, it is possible to control the number of strands per centimeter (Figure 8), which indicates how frequently the strands intersect.

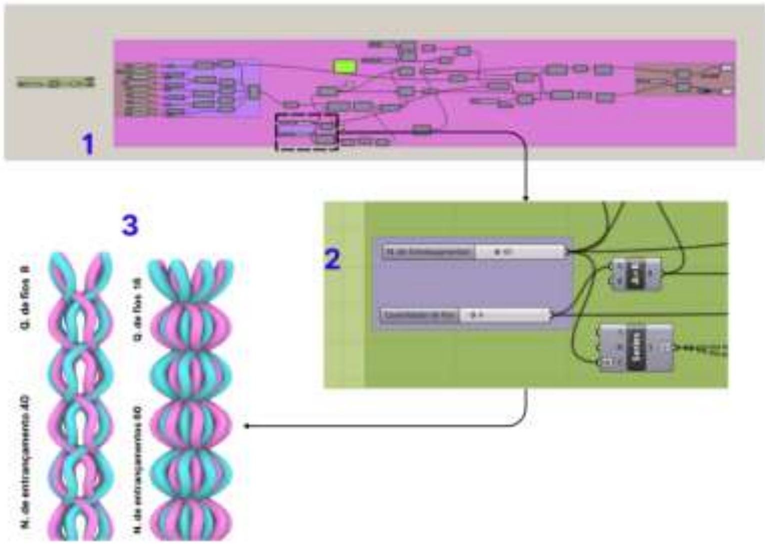

*Figure 8. **1**. The complete structure of the algorithm is shown in pink. **2**. A section of the structure responsible for defining the number of braids and the number of strands. **3**. The types of structures resulting from modifications in the parameters for the number of strands and number of braids.*

Source: Prepared by the Author

Yarn Diameter – The diameter of the strand is crucial in the manufacturing of braided structures as it directly affects the structure's architecture, and the angles formed in the braid. An increase in the yarn diameter can enhance the rigidity and mechanical resistance of the braided structure by impacting the distribution of forces and overall stability of the system (Figure 9).

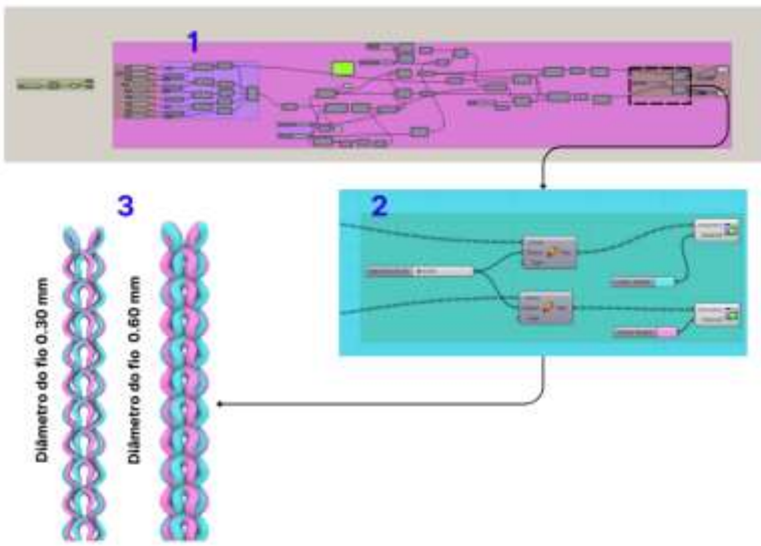

Figure 9. **1.** In pink color, the complete structure of the algorithm**. 2.** Part of the structure responsible for “extrusion” and regulation of the yarns diameter. **3.** The types of yarns with different dimensions, respectively 0.30mm and 0.60mm.

Source: Prepared by the Author

Structure Diameter – Variation in the structure's diameter also affects its geometry and consequently the angle (Figure 10). Specifically, a larger diameter results in a smaller angle.

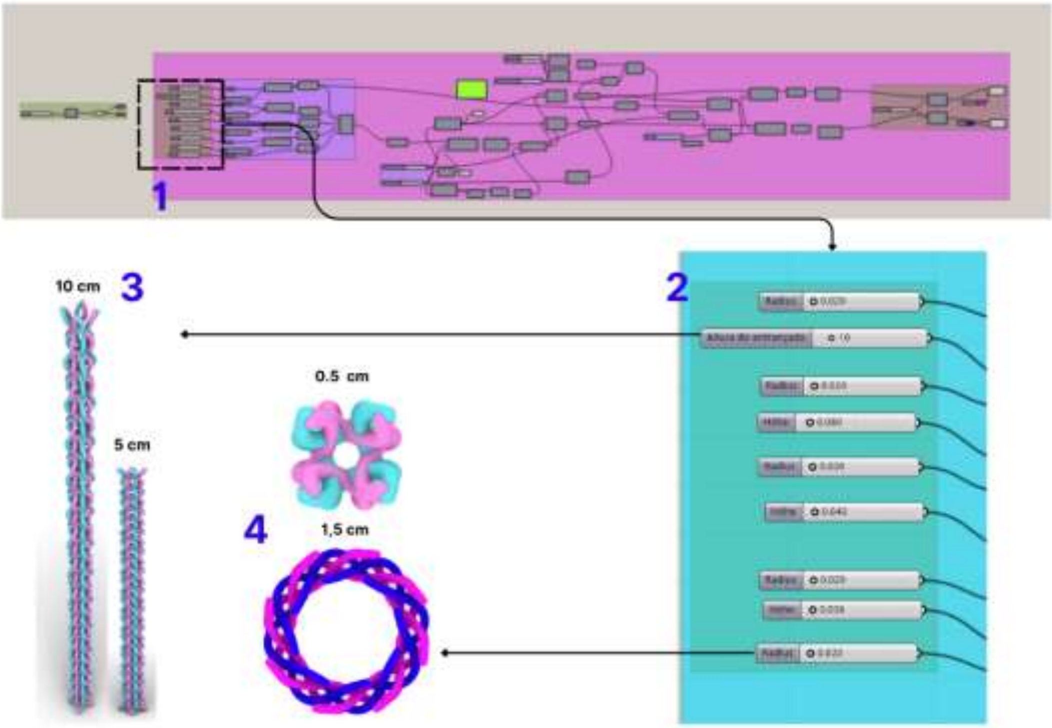

*Figure 10. **1.** In pink color, the complete structure of the algorithm. **2.** Part of the structure responsible for "extrusion" and regulation of the yarn diameter. **3**. The types of yarns with different dimensions, respectively 0.30mm and 0.60mm.*

Source: Prepared by the Author

Drawing – Drawing, defined as the process of removing and stretching the braided structure from the braiding machine, is influenced by parameters such as traction speed. In the algorithm, drawing can be controlled through parameters like braid height, number of braids per centimeter, and yarn diameter (Figures 8, 9, and 10).

4.2. Physical characterization methods

The physical characterization process is essential in the production of woven structures, relevant not only for biomedical applications but also for other fields such as civil construction. In the biomedical domain, porosity is a critical parameter, as it influences permeability, adhesion, and cell growth. Specifically, porosity, permeability, and topography are key characteristics. Researchers emphasize that these properties enhance fluid and nutrient exchange (permeability), promote surface adhesion, and increase the contact surface area within the structure's cavities (porosity), as well as guide neuron growth (topographic guidance) (Pawelec et al., 2018; Aguiar Souza, 2023).

4.2.1. Coverage factor and porosity assessments

Porosity is a critical parameter in the analysis of braided structures. To evaluate it, one must consider the amount of fibrous material deposited on the mandrel's surface. The coverage factor is calculated based on the proportion of the mandrel's surface covered by the yarns and also serves as an indicator of the uniformity of the braid. The coverage factor can be defined by the following equations (Aguiar Souza, 2023):

I. Definition of coverage factor
(Eq.6)

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

Where:

W_y – Diameter of the monofilament (mm);

N_c – Number of bobbins.

R – Radius of the mandrel (mm);

α – Braiding angle (rad).

II. Definition of Porosity
(Eq.7)

$$Porosity = \quad 1 - Coverage\ Factor$$

In this context, porosity is defined as the area of the surface that is not covered. Thus, higher porosity indicates lower uniformity of the braid, making it an inversely proportional measure to the coverage factor.

4.2.2. Variations in Structural Cell Geometry and Modifications of the Angle

The structural cell of a braided structure is a crucial factor in assessing quality both during and after the production process (Hunt & Carey, 2019). There is a correlation between the coverage provided by the yarn’s width and the braiding angle, which allows for the analysis of braid distribution (Aguiar Souza, 2023; Vila, 2009). Furthermore, the angle is determined by the longitudinal positioning of the yarns. Variations in the structural cell result in changes in the angle, with a reduced braiding angle generally leading to increased mechanical properties, particularly radial strength; conversely, the opposite effect is also true (Omeroglu, 2006).

The coverage and angle can be determined using the following equations:

(Eq. 1)

$$WL + (WB/cos\theta)/2N = P$$

Where:

WL – Width of the longitudinal yarn.

WB – Width of the diagonal yarn.

N – Number of active bobbins.

Θ – Angle between the braided yarn.

P – Perimeter of the core.

(Eq. 2)

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

Where:

Dm – Mean diameter (mm).

Di – Internal diameter (mm).

De – External diameter (mm).

I. Definition of structural angle

(Eq.5)

$$tan_\theta \frac{\pi \quad \times \quad D_m}{h}$$

Morphological analysis of the samples (Tables 2 and 3) reveals important characteristics related to aspects such as the average angle of the structures. It appears that factors impacting the angle include the diameter of the yarn, the number of yarns, their orientation, tension, material, and the core's gauge and diameter (Aguiar Souza, 2023).

Table 2. Characterization of structures produced in software with 0.50 mm yarn (external layer)

IMAGENS	ESTRU.1	ESTRU. 2	ESTRU. 3	ESTRU. 4	ESTRU. 5	ESTRU.6
Diameter	5 mm	5 mm	5 mm	5 mm	5 mm	5 mm
Number of Interlacements (10 cm)	40	50	50	50	50	50
Number of yarns	6	8	10	12	14	16
Yarns diameter (mm)	0,50 mm	0,50 mm	0,50 mm	0,50 mm	0,50 mm	0,50 mm
Average angle (°)	±31,415	±31,415	±31,415	±31,415	±31,415	±31,415
Coverage factor (%)	±13,55%	±17,85%	±22,0%	±26,13%	±30,10%	±33,96%
Porosity (%)	±86,44%	±82,14%	±77,95%	±73,86%	±69,89%	±66,03%
External structure	Regular (2/2)	Regular (2/2)	Regular (2/2)	Regular (2/2)	Regular (2/2)	Regular (2/2)

Source: Prepared by the Author

The results in Table 2 indicate that the average braiding angle remained consistent. This can be attributed to the constant diameter of the structure, the maintenance of the number of interlacements, and the yarn diameter. Excluding Structure 1, which has a different number of interlacements compared to the others, Table 2 also reveals that adding two yarns to the braid results in an average increase of 4.03% in the coverage factor and a corresponding average decrease of 4.03% in porosity. Consequently, between Structures 2 and 6, there was an average increase of 16.11% in the coverage factor and a corresponding decrease in structural porosity.

Table 3. Characterization of structures produced in software with 0.40 mm yarn (Internal Layer)

IMAGENS	ESTRU. 1	ESTRU. 2	ESTRU. 3	ESTRU. 4
Diameter	1,8 mm	1,8 mm	1,8 mm	1,8 mm
Number of Interlacements (10 cm)	50	50	50	50
Number of yarns	8	12	14	16
Yarns Diameter (mm)	0,40 mm	0,40 mm	0,40 mm	0,40 mm
Average angle (°)	±21,36	±21,36	±21,36	±21,36
Coverage factor (%)	±15,22%	±22,36%	±25,81%	±29,18%
Porosity (%)	±84,77%	±77,63%	±74,18%	±70,81%
Internal structure	Regular (2/2)	Regular (2/2)	Regular (2/2)	Regular (2/2)

Source: Prepared by the Author

Table 3 also shows a similar angle across the four analyzed structures, due to the similarity in parameters. The braided structure with 6 yarns was excluded from consideration for the inner layer, as it did not present an appropriate braiding geometry. Therefore, the braided structures with the best structural geometry are those designed with 8 yarns, as they exhibit better porosity. Structures 2, 3, and 4 demonstrate greater density compared to Structure 1; thus, Structure 1 can be assessed in terms of meeting the primary requirement of porosity.

The algorithm and its incorporated parameters enhance the possibilities and opportunities in the design of structures, allowing manipulation of the relationships that define geometries. In this context, yarn diameter plays a crucial role in the angle. Structures with a 5 mm diameter exhibited an average angle of 31.415°, while structures with a 1.8 mm diameter had an average angle of 21.36°; the yarns showed minimal difference (Figure 11). It is noteworthy that a smaller angle (closer to the longitudinal axis of the textile braid) tends to increase the axial strength and rigidity of the structure. This occurs because the yarns are more aligned with the direction of the applied load. Additionally, a smaller angle corresponds to a higher yarn's density per unit area, meaning a greater coverage factor and lower porosity.

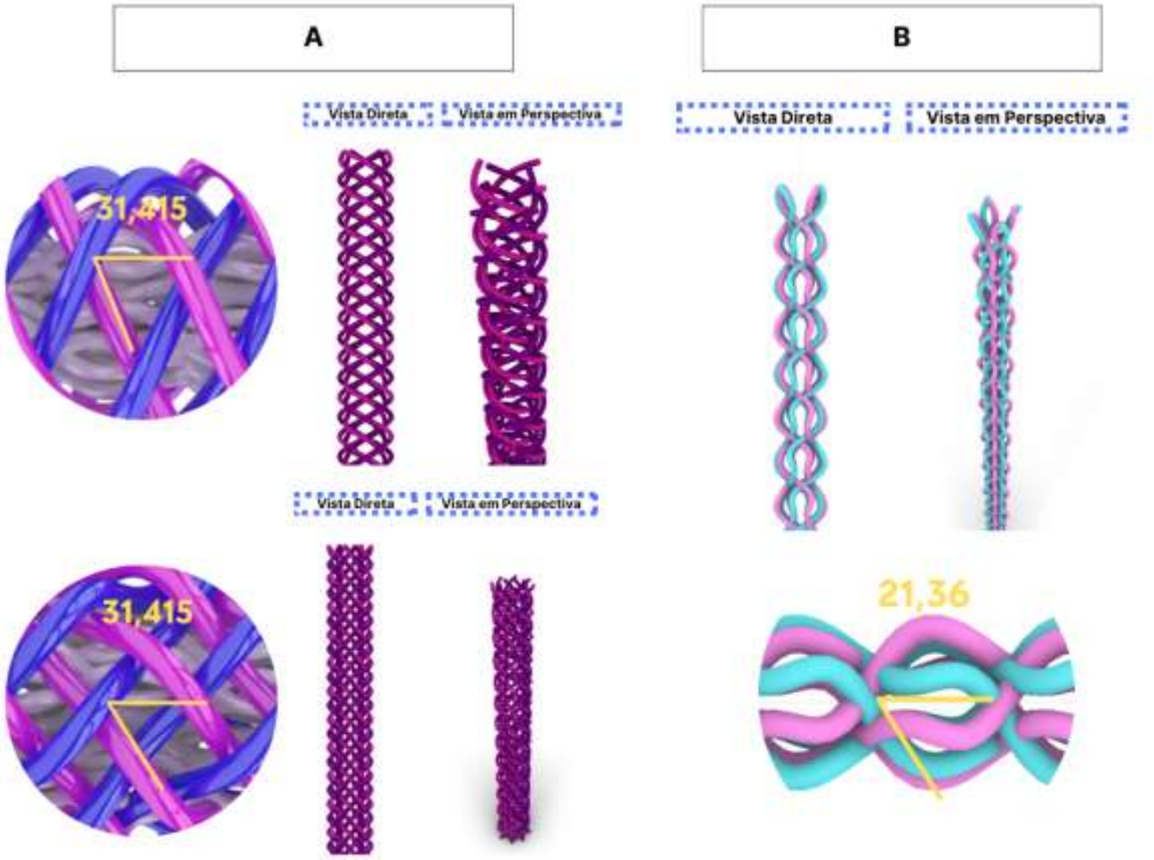

*Figure 11. **A.** Graphical representation of the textile structure of the outer layer, produced using the software. Structures with 8 yarns and 16 yarns, with an average angle of ±31.415°. **B.** Graphical representation of the textile structure of the outer layer, produced using the software. Structure with 8 yarns and an average angle of ±21.36°.*

Source: Prepared by the Author

As previously mentioned, Tables 2 and 3 confirm the literature findings that indicate a higher number of yarns and larger yarn diameters result in increased coverage and decreased porosity. In this regard, Structures 1 and 6 from Table 1 are highlighted: Structure 1 has 13.55% coverage and 86.44% porosity, while Structure 6 has 33.96% coverage and 66.03% porosity. These findings are crucial for the morphological analysis of the structure. Emonts *et al.* (2022) demonstrate that porosity, pore size, and three-dimensionality are critical variables for the suitability of scaffolds. Pore distribution and connectivity directly influence cellular adhesion, permeability, and tissue growth.

The geometry of braided structures exhibits differences in braiding form. Circular and flat textile braided structures show minimal differences in scaffold porosity. However, multilayer braids (multiple layers) connected at the centre exhibit increased porosity compared to those without inter-layer connections. Porosity can be adjusted according to the physiological needs of the tissues (Emonts *et al.,* 2022).

4. Considerations

The aim of this study was to develop braided fibrous structures for use in scaffold implants through graphical simulations using Rhinoceros 3D® software (version 6) (McNeel, 2019) with the Grasshopper plugin. This approach aimed to highlight and select the most critical aspects of braided textile structures while also supporting educational initiatives in the field of textile design.

The results presented in Tables 2 and 3 provide significant insights into how the number of yarns and their diameter influence the geometry of braided structures. The constancy of the average braiding angle, coupled with the maintenance of both the structure's and yarn's diameter, ensures substantial structural stability. An increase in the number of yarns is associated with a higher coverage factor and a corresponding decrease in porosity.

Structures with 8 yarns exhibited the optimal structural geometry due to enhanced porosity, whereas Structure 1, despite its lower density, satisfies the primary requirement of adequate porosity. Additionally, the analysis of the diameter of the structures shows that smaller braiding angles lead to greater strength and axial stiffness, attributed to the closer alignment of the fibers with the direction of load application.

These findings are consistent with existing literature, which indicates that a higher number of yarns and larger diameters provide increased coverage and reduced porosity—key factors for the functionality of textile scaffolds. In summary, manipulating these parameters offers valuable opportunities for optimizing the morphological and mechanical properties of braided structures, thereby enhancing their suitability for specific applications in tissue engineering[5].

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