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Electrospinning Structural Parameter Design in Achilles Tendon Heals

Yixuan Li*

Beijing 101 Middle School, Beijing, 100000, China
lyr20050418@outlook.com
**Corresponding author*

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Abstract: Traditional achilles tendon heals methods often use traditional biomaterials, but these materials have certain limitations. According to the different conditions of achilles tendon heals injury and physical condition of each patient, traditional methods can not provide a satisfactory solution. Traditional healing methods cannot effectively simulate the biomechanical properties of the natural achilles tendon heals. This paper uses electrospinning technology to solve these problems. The fiber diameter is designed and controlled to meet the patient's achilles tendon heals requirements. By adjusting electrospinning process parameters, nozzle diameter and voltage, fibers with excellent performance can be obtained. The structure parameters of electrospinning were used to design and adjust the fiber arrangement to simulate the structure of natural achilles tendon heals. Optimizing the connection between the different fiber layers in electrospinning can improve the biocompatibility of the film. On this basis, this paper combined with electrospinning structural parameter design, designed a personalized three-dimensional model. The findings highlight the importance of electrospinning technology in the design of personalized achilles tendon heals devices, which enables fine control of fiber diameter to meet individual patient needs. After testing, the connection strength reached 985 n after applying a force of 1000 N, and after 10,000 load cycles, the model fraction was calculated to be 88. The research in this paper is helpful to improve the biocompatibility and durability of the healing device, and provides a solid foundation for clinical application. These results demonstrate the great potential of electrospinning technology in the design of personalized achilles tendon heals devices and provide a valuable reference for future research.

1. Introduction

Achilles tendon heals injury is one of the most common sports injuries. Traditional therapeutic approaches rely mainly on traditional biomaterials, which have poor performance in terms of strength [1], biocompatibility [2-3] and simulated biomechanical properties, and are unable to meet the individual needs of different patients [4]. Traditional treatments have not yet provided satisfactory results.

For achilles tendon heals injury, traditional methods are flawed, so it is necessary to seek new methods to meet the individual healing needs. Some researchers have explored bioengineering approaches: Biomaterials play a key role in maintaining the regenerative potential of stem cells, while also improving the survival rate of transplanted cells and promoting tissue regeneration. Madl C M's team also successfully cultivated patient-specific organoids using the three-dimensional hydrogel culture platform, discovered some drugs that can stimulate endogenous tissue-specific stem cells, and carried out drug screening for treating diseases [5]. Stem cell therapy is considered a promising therapeutic approach, but its clinical effectiveness is limited. To improve the survival and paracrine activity of stem cells, the researchers developed polymer biomaterial systems as a niche for stem cells, as well as different modification strategies to improve stem cell survival and differentiation. Polymer scaffolds have been used to deliver stem cells and their efficiency has been tested in animal models of preclinical wounds [6]. 3D printing technology is combined with the diversity of multidisciplinary fields such as tissue engineering, digital medicine and materials science to prepare 3D printed products with good biocompatibility, excellent bone induction ability and stable mechanical properties [7], including the improvement of biomaterials and the application of 3D printing technology to improve the healing effect of injuries. Despite some advances in these methods, modeling the biomechanical properties of the natural achilles tendon heals remains challenging [8].

This paper combines electrospinning technology and structural parameter design to provide a new method to improve achilles tendon heals. Electrospinning technology can adjust the degree of refinement of the fibers [9] and the arrangement of the fibers [10] to meet the individual healing needs of different patients. At the same time, the structural parameter design can be used to optimize the connection of electrospinning [11] to improve mechanical properties [12] and biocompatibility [13].

In this paper, computer aided design software is used to establish the models of different fiber arrangement, and finite element analysis software is used to simulate the mechanical properties of the models, and evaluate the performance of the models in practical application has met the needs of the human body. Through computational fluid dynamics simulation and cell distribution and cell movement analysis, it was found that the influence of different fiber arrangement on biocompatibility was very obvious. The model is tested for connection strength and durability, and its performance and stability are good. The electrospinning technology and fiber arrangement are linked to the design of the achilles tendon heals device by the above method. These methodological steps turn the design of a personalized achilles tendon heals device into a reality and improve the biocompatibility and durability of the healing device.

2. Personalize Achilles Tendon Heals Approach

2.1 Electrospinning Structure Parameter Design

2.1.1 Fiber Diameter Control

In order to meet the personalized requirements of patients with achilles tendon heals, this study focuses on the design and adjustment of the fiber refinement in electrospinning technology. This is done by fine-tuning electrospinning process parameters, including nozzle diameter and voltage, to ensure that the prepared fibers meet specific individual requirements.

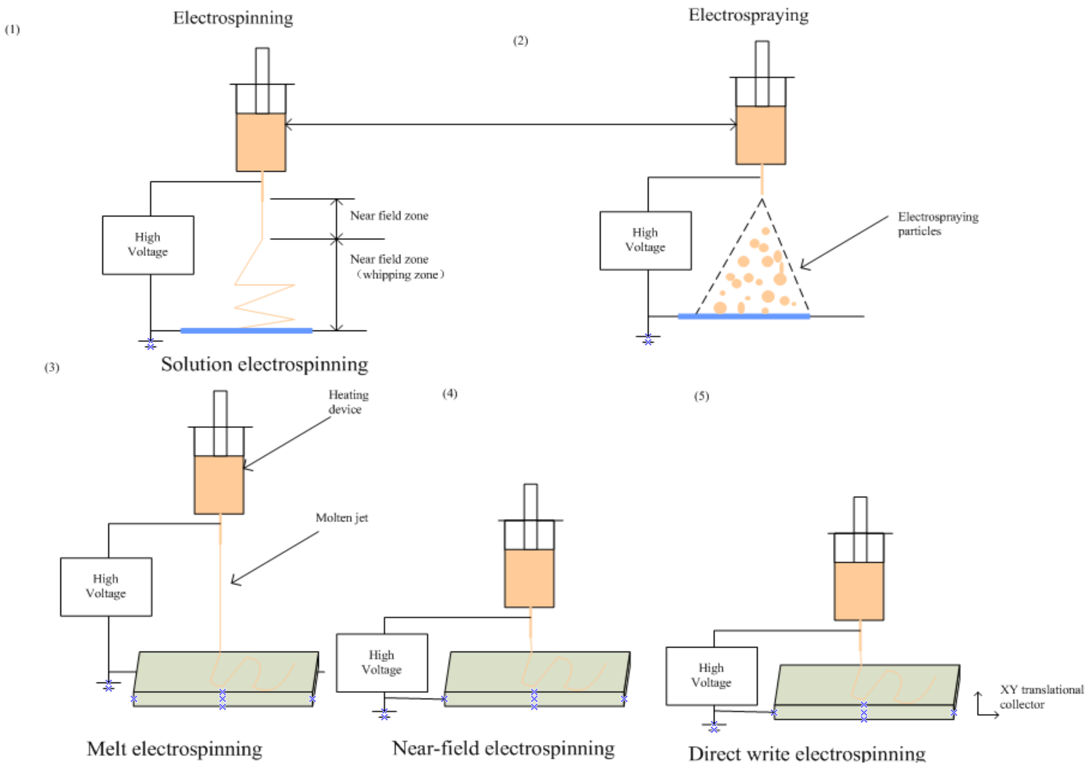


Figure 1: Diversity and application of electrospinning technology

Figure 1 refers to the research of Liu Z et al. [14] and describes three different electrospinning technologies, namely conventional electrospinning, molten electrospinning and near-field electrospinning. And a direct-write electrospinning technology that combines Additive Manufacturing (AM) concepts with electrospinning.

Figure (1) depicts the process of conventional electrospinning. In this process, the charged jet stream remains in a continuous state and generates fibers under the action of an electric field. The jet stream follows a straight line in the near field region and then undergoes wobbling and thinning in the far field region.

The process of molten electrospinning is depicted in figure (3). The process differs from conventional solution electrospinning, which uses a heating device to keep the jet stream in a molten state. In this case, the jets travel in a straight line and create micrometer-scale fibers.

The process of electrospinning in the near field is depicted in Figure (4). In this process, the jet stream is deposited on the collector, and this deposition area is within the straight section, showing greater spatial control, but also producing a larger fiber diameter.

Figure (5) depicts the direct-write electrospinning technique that combines the AM concept with electrospinning. This process uses a translation collector to build predefined patterns.

The electrospinning technology is a method of preparing nanoscale to micron scale fibers that use electrostatic action to stretch and solidify the fibers in a polymer solution, creating filaments that can be used in the medical field. Controlling the fiber diameter is important because the fibers needed for achilles tendon heals should be strong enough while remaining flexible enough to fit biological tissue.

Adjusting the nozzle diameter is one of the key processes in electrospinning. By changing the diameter of the nozzle, the speed and diameter of the fiber are affected. Smaller diameter nozzles produce finer fibers, while larger diameter nozzles produce coarser fibers. In fact, the precise control of the fiber diameter scale is now available. The nozzle diameter adjustment also directly affects the fiber arrangement density and the connection mode between fiber layers.

In addition to the adjustment of the nozzle diameter, the control of voltage is also an important factor affecting the fiber diameter. In the electrospinning process, the change of voltage would directly affect the formation speed and stretching degree of the fiber. Higher voltages would speed up the elongation of the fibers to produce finer fibers, while lower voltages would cause coarser fibers to form. Therefore, the regulation of voltage is indispensable to meet individual healing needs.

According to the above results, the control formula of fiber diameter (D) can be obtained:

$$D = (K_1 * V) / (K_2 * Dn) \tag{1}$$

D represents the diameter of the fibres produced, K_1 and K_2 are the regulating factors, depending on the polymer and electrospinning equipment used, V represents the voltage, and Dn represents the nozzle diameter.

Precise control of fiber diameter is achieved through fine adjustment of electrospinning process parameters, which is of great significance for simulating the biomechanical properties of natural tissues. Therefore, in the process of personalizing achilles tendon heals, the fiber diameter control of electrospinning is a crucial link.

2.1.2 Fiber Arrangement Design

How the fibers are arranged affects achilles tendon heals, and different patients require different structures to suit their specific needs. In this study, the following methods were used to design and control the arrangement of fibers:

CAD Modeling: This paper first uses Computer Aided Design (CAD) software to create a 3D model that takes into account the actual shape and length of the patient's achilles tendon heals. This model is personalized and adjusted according to the specific anatomical characteristics of the patient.

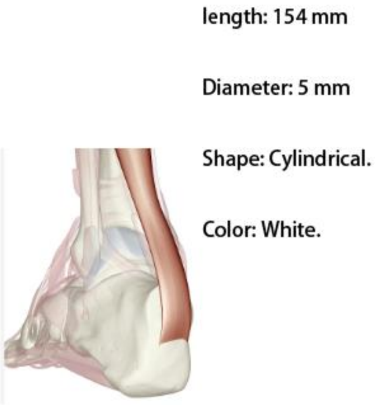


Figure 2: Schematic diagram of the patient's achilles tendon heals

Figure 2 shows a three-dimensional diagram of a typical patient's achilles tendon heals, 154 mm long, 5 mm in diameter, cylindrical in shape and white in color.

Electrospinning techniques use professional modeling software ANSYS to simulate the impact of different fiber arrangements on the mechanical properties of the Achilles tendon. ANSYS created a 3D finite element model to simulate the Achilles tendon region, setting different simulated loading conditions such as tension and shear to observe the actual stress situation of the Achilles tendon.

Researchers can evaluate stress distribution and deformation under different arrangement modes through finite element analysis, as shown in Figure 3.

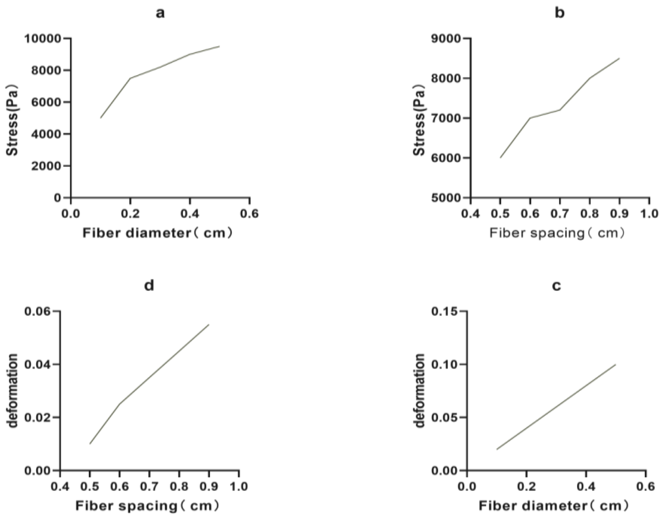


Figure a: Effect of fiber diameter on achilles tendon heals stress
Figure b: Effect of fiber spacing on achilles tendon heals stress
Figure c: Effect of fiber diameter on achilles tendon heals deformation
Figure d: Effect of fiber spacing on achilles tendon heals deformation

Figure 3: Schematic diagram of stress and deformation

In Figure 3a, the X-axis is the fiber diameter in cm, and the Y-axis is the stress in Pa. The decrease in fiber diameter results in a significant decrease in stress. This means that smaller fiber diameters have higher strength.

In Figure 3b, the X-axis is the fiber spacing in cm, and the Y-axis is the stress in Pa. The decrease in fiber spacing significantly reduces the stress on the Achilles tendon. This indicates that reducing fiber spacing improves stress distribution.

In Figure 3c, the X-axis is the fiber diameter unit cm, and the Y-axis is the deformation. The deformation represents the relative change of length and is the ratio of shape variable to the original length size. As shown by simulation, when the fiber diameter is small, the deformed film has little difference from the original film. It shows that smaller fiber diameter can better maintain the shape and integrity of the achilles tendon heals and reduce the degree of deformation.

In Figure 3d, the X-axis is fiber spacing in cm, and the Y-axis is deformation. Smaller fiber spacing helps to provide better support and stability, reducing the deformation of the achilles tendon heals under stress.

In general, fiber diameter and fiber spacing, their mechanisms of action are similar, so they lead to almost the same result, that is, reduced deformation, conducive to the healing and stability of the achilles tendon heals. This result reinforces the importance of these two factors in the design of achilles tendon heals devices. It also shows that in personalized achilles tendon heals, by adjusting the fiber diameter and fiber spacing, the mechanical properties of the achilles tendon heals can be significantly improved to reduce stress and deformation, so as to better meet the personalized healing needs.

Computational Fluid Dynamics (CFD) simulation: In order to better understand the impact of how fibers are arranged on biocompatibility, CFD simulation is used to simulate the flow of fluid between fibers. This helps determine the effect of the fiber arrangement on cell planting and maintenance to ensure that the patient's achilles tendon heals is compatible with the implanted fibers.

Its simulation of fluid flow and assessment of biocompatibility are crucial steps. The following is a more detailed approach, including simulation experiments and using ANSYS Fluent software:

2.1.3. CFD Model Establishment

In this paper, a 3D CFD model is created to simulate the achilles tendon heals region with a fibrous membrane. In order to better understand the fiber arrangement of the achilles tendon heals, a variety of arrangement methods are used to ensure that the model has a variety of fiber films. This provides a better understanding of the patient's achilles tendon heals structure and personalized treatment recommendations, as shown in Table 1:

Table 1: Various arrangements of fibers

Fiber arrangement	Fiber spacing	Fiber diameter	Fiber layer thickness
Parallel arrangement	0.1 cm	0.02 cm	0.05 cm
Grid arrangement	0.2 cm	0.03 cm	0.08 cm
Oblique arrangement	0.15 cm	0.025 cm	0.06 cm
Random arrangement	0.1 cm - 0.3 cm	0.02 cm - 0.04 cm	0.05 cm - 0.1 cm
Sparse arrangement	0.05 cm	0.015 cm	0.04 cm
Compact arrangement	0.3 cm	0.04 cm	0.1 cm
Circular arrangement	0.1 cm	0.02 cm	0.05 cm
Spiral arrangement	0.15 cm	0.025 cm	0.06 cm
Diagonal arrangement	0.2 cm	0.03 cm	0.08 cm
Orthogonal arrangement	0.2 cm	0.03 cm	0.08 cm

2.1.4. Setting Model Parameters

Set fluid properties: The density and viscosity of the fluid used in the simulation took into account the values of the density and viscosity of different fluids in the achilles tendon heals region under various fluid conditions, as shown in Table 2.

Table 2: Density and viscosity of various fluids

Simulated fluid	Density	Viscosity
Physiological fluids that simulate human tissue	1.025 g/cm ^{3}	0.0075 Pa s
Physiological saline (physiological saline is commonly used in biomedicine simulations)	1.004 g/cm ^{3}	0.001 Pa s
Mixing physiological saline and plasma (considering more complex simulations)	1.030 g/cm ^{3}	0.003 Pa s
Blood	1.060 g/cm ^{3}	0.004 Pa s
Fibrin glue (considering wound healing process)	1.100 g/cm ^{3}	0.005 Pa s
Drug delivery carriers	1.020 g/cm ^{3}	0.0025 Pa s
Cell culture medium (used in the cell culture process)	1.015 g/cm ^{3}	0.002 Pa s
Extracorporeal abrasion solution (considering the wear of implant materials)	1.040 g/cm ^{3}	0.006 Pa s
Extracorporeal lubricants (considering joint simulation)	1.045 g/cm ^{3}	0.007 Pa s
Joint synovial fluid (considering joint health)	1.070 g/cm ^{3}	0.008 Pa s

2.1.5 Setting up CFD Simulation:

In ANSYS Fluent software, the geometric model simulated before is imported and the corresponding calculation domain is created.

This article uses ANSYS Fluent's simulation Setup wizard to configure the fluid flow simulation.

The following is part of the simulation data. In this paper, parallel arrangement (model A) and staggered arrangement (model B) are used to outline the specific process of simulation, as shown in Table 3.

Table 3: Flow rate analysis and pressure analysis

		Model A	Model B
Flow rate analysis	Average pressure	84mmHg	86mmHg
	pressure distribution	Evenly distributed, without obvious high or low pressure areas.	The distribution also shows a uniform trend, with no pressure concentration areas.
Stress analysis	Average flow rate	16 cm/s	13 m/s
	Flow velocity distribution	Evenly distributed, without significant eddy currents or velocity gradient anomalies.	Displayed relatively uniform characteristics, with a smooth flow velocity gradient.

Pressure comparison: The average pressure of the two models is basically similar, indicating that the different arrangement has no obvious effect on the pressure distribution.

Summary: In this particular study, the parallel arrangement of model A may be more suitable for applications requiring high flow rates, while the staggered arrangement of model B may be suitable for some cases where flow rates are not emphasized. However, the specific application situation needs further consideration.

Table 4: Biocompatibility assessment and analysis report

		Model A	Model B
Cell distribution analysis	cell density	6,436 (one/cm^3)	6,144 (one/cm^3)
	Distribution	Presents a uniform distribution without any clustering or sparsity.	It also exhibits uniform distribution without obvious cell aggregation.
Cell motion simulation	Exercise situation	The movement speed of cells is relatively fast, showing an active trend.	The movement speed of cells is relatively slow, showing a relatively stable trend.
	Cell interaction	Moderate interaction between cells helps with cell growth and healing.	It also shows moderate interaction, which helps with cell growth

In the biocompatibility assessment in Table 4, the cell distribution under both models showed uniform distribution without significant difference.

The cells of model A showed more active movement, while the cells of model B were more stable. Two different fiber arrangements (Model A and Model B) showed similar results in terms of cell distribution and movement. This indicates that they have good biocompatibility in the cultivation and maintenance of cells.

By comprehensively applying these methods and accurately designing the arrangement of fibers, it can meet the personalized healing needs of different patients, ensure the success of achilles tendon healing, and reduce the risk of postoperative complications.

2.2 Optimization of Fiber Interlayer Connection

Firstly, a unique cross woven structure is adopted, which can disperse stress and prevent delamination between layers, thereby significantly improving the overall strength of the film.

Secondly, surface treatment and impregnation of the film are carried out using biocompatible agents, which can ensure that the film does not cause immune or rejection reactions, thereby ensuring the safety of the patient.

Then, a biocompatible interlayer adhesive was introduced, which can firmly bond fibers from different layers together, enhancing the overall stability and strength of the film, while avoiding potential defects or incomplete connections.

Next, hot pressing molding technology was adopted. At a certain temperature and pressure, fibers from different layers are tightly bonded together through hot pressing technology. This method ensures a strong connection between fibers and maintains the overall shape and stability of the film.

Finally, it can use an electron microscope to carefully observe the connecting part. This helps to identify potential defects and ensure the high quality of the film.

These improvement measures can significantly improve the mechanical properties and biocompatibility of the film, ensuring its compatibility with the patient's Achilles tendon structure, providing new possibilities for future medical applications.

2.3 Three-dimensional Model Design

Data acquisition and processing:

Through CT scanning, the patient's Achilles tendon image data, including length, diameter, shape and other information, were obtained successfully. This data is used to create a personalized healing device for the patient.

In order to design the healing device of Achilles tendon muscle, the polygonal mesh modeling method was adopted on the basis of the existing Achilles tendon model.

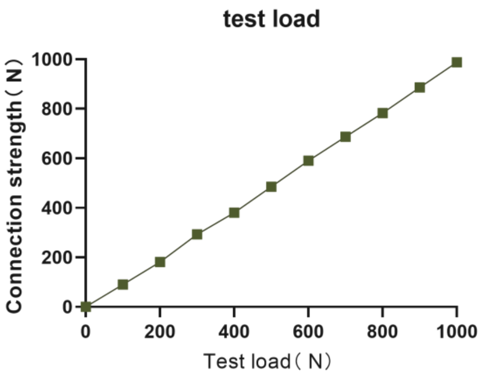
Using the obtained Achilles tendon data, the current 3D model is edited and optimized. By adjusting the parameters, the model is perfectly matched to the specific requirements of the patient's Achilles tendon.

In order to attach the 3D model to the existing Achilles tendon model, the biological glue connection method was adopted. This connection ensures adequate support and protection while maintaining comfort.

The paper chose materials with excellent biocompatibility to ensure that the 3D model can coexist harmoniously with the patient's physical environment.

3. Model Verification and Testing

In this paper, the 3D model is verified and tested to ensure that it meets the design requirements. The durability test and connection strength test were performed in Figure 4.



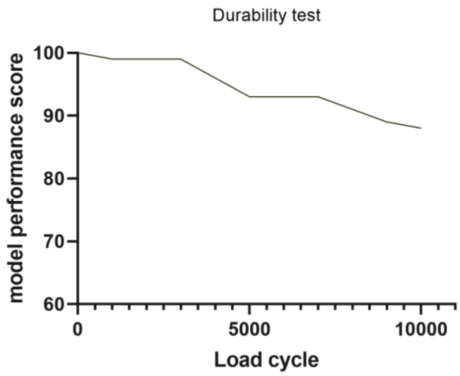


Figure a: Connection strength test results Figure b: durability test results

Figure 4: Model testing

The X-axis of Figure 4a is the test load (N, Newton) and the Y-axis is the connection strength (N, Newton). In the connection strength test, after applying a force of 1000 n, the connection strength was measured as 985 N, indicating that the two materials connected in the model still maintained a high degree of strength under a load of 1000 N. This connection can withstand considerable forces without breaking or separating. It shows that the connection method has high strength and stability, which is very suitable for use in the human body, especially in the case of high loads.

In Figure 4b, X axis is the load period, which is calculated as a normal person running for 20 minutes, and Y axis is the performance score of the achilles tendon heals model. In the endurance test, after 10,000 load cycles, the model state is 88 points, indicating that the state of the model remains very good relative to the initial state. This shows that the model can still maintain most of its performance after certain fatigue tests under continuous load cycles. This is a positive result, indicating that the model shows good durability and stability under long-term use or multiple loads, and is suitable for use in the human body.

4. Conclusions

This paper successfully combined electrospinning technology and structural parameter design to provide a solid ground for innovative design of achilles tendon heals devices. Through electrospinning technology, the fiber refinement degree and arrangement mode are adjusted to meet the needs of different patients. By optimizing the design of structural parameters, the mechanical properties and biocompatibility of the device are improved, which is essential for successful clinical application. However, there are also some potential shortcomings in this paper, which does not mention specific clinical trials or practical applications, and only relies on simulation and calculation results to evaluate performance. The next step is expected to be clinical trials to fully evaluate the feasibility and practicability of the design.

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