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Role of Textiles in Tissue Engineering – A Biological and Engineering Perspective

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Abstract
Tissue engineering (TE) offers solutions for repairing or replacing damaged tissues where traditional autologous and homologous transplants face limitations such as donor shortages and morbidity. Textiles have emerged as promising scaffolds due to their tunable mechanical properties, structural versatility, and similarity to the fibrous extracellular matrix. This review provides an overview of the major fiber formation methods and textile technologies—including weaving, knitting, braiding, spacer fabrics, and electrospinning—and highlights how each can be tailored for specific TE applications. The suitability of textile scaffolds for different tissues is discussed based on mechanical requirements, porosity, and biological performance. Although textile-based scaffolds show strong potential in preclinical studies, challenges remain in achieving clinically scalable, biologically relevant designs. Advances in 3D bioprinting, melt electrowriting, and smart textiles may further enhance their applicability. Overall, this review guides researchers in selecting and optimizing textile structures for regenerative medicine and tissue engineering applications.

Keywords: Textile Scaffolds, Tissue Engineering, Fiber Formation, Knitting ,Weaving, Braiding, Electrospinning ,Spacer Fabrics, Biotextiles & Regenerative Medicine.

Introduction

Tissue engineering (TE) aims to provide personalized solutions for tissue loss caused by trauma, tumors, or congenital defects. While traditional methods like autologous and homologous tissue transplants face challenges such as donor shortages and risk of donor site morbidity, TE provides a viable alternative using scaffolds, cells, and biologically active molecules. Textiles represent a promising scaffold option for both in-vitro and in-situ TE applications.

Textile engineering is a broad field and can be divided into fiber-based textiles and yarn-based textiles. In fiber-based textiles the textile fabric is produced in the same step as the fibers (e.g. non-wovens, electrospun mats and 3D-printed). For yarn-based textiles, yarns are produced from fibers or filaments first and then, a textile fabric is produced (e.g. woven, weft-knitted, warp-knitted and braided fabrics).

The selection of textile scaffold technology depends on the target tissue, mechanical requirements, and fabrication methods, with each approach offering distinct advantages. Braided scaffolds, with their high tensile strength, are ideal for load-bearing tissues like tendons and ligaments, while their ability to form stable hollow lumens makes them suitable for vascular applications. Weaving, weft-, and warp-knitting provide tunable structural properties, with warp-knitting offering the greatest design flexibility. Spacer fabrics enable complex 3D architecture, benefiting applications such as skin grafts and multilayered tissues. Electrospinning, though highly effective in mimicking the ECM, is structurally limited. The complex interactions between materials, fiber properties, and textile technologies allows for scaffolds with a wide range of morphological and mechanical characteristics (e.g., tensile strength of woven textiles ranging from 0.64 to 180.4 N/mm2). With in-depth knowledge, textiles can be tailored to obtain specific mechanical properties as accurately as possible and aid the formation of functional tissue. However, as textile structures inherently differ from biological tissues, careful optimization is required to enhance cell behavior, mechanical performance, and clinical applicability.

This review is intended for TE experts interested in using textiles as scaffolds and provides a detailed analysis of the available options, their characteristics and known applications. For this, first the major fiber formation methods are introduced, then subsequent used automated textile technologies are presented, highlighting their strengths and limitations. Finally, we analyze how these textile and fiber structures are utilized in TE, organized by the use of textiles in TE across major organ systems, including the nervous, skin, cardiovascular, respiratory, urinary, digestive, and musculoskeletal systems.

Trauma, tumor-related complications, or congenital influences can lead to the loss of functional body tissue such as muscles, tendons, and skin. The gold standard for treatment is autologous or homologous tissue transplantations [1, 2]. Autologous transplants use the patient's own tissue [3], with the risk of donor site morbidity [4, 5], while homologous transplants, using genetically different donors of the same species [6, 7], are limited by donor availability, especially for complex organs [8, 9].

Tissue engineering (TE), addresses these problems by aiming to restore or replace damaged tissue and organs [10-12]. Although tissue engineering has already shown initial success, particularly in bone [13-15] and vascular implants [16-18], the production of flexible, large tissues such as the heart remains a major challenge.

Given the fibrous nature of the extracellular matrix (ECM) in biological tissue, the use of fibrous textiles that provide cell alignment through contact guidance and sufficient stability for implantation (e.g. suture retention) is a logical approach for the development of scaffold-based tissue constructs. In recent years, textile structures have been increasingly used in biomedical implants to support or replace both soft and hard tissues. Thanks to their adaptable structures and strong mechanical and biological properties, fibrous scaffolds are particularly suitable for mimicking the architecture and mechanical properties of natural tissues [19-21].

Although the biological and medical perspective is often highlighted in TE reviews, the inherent mechanical and morphological properties of the different fibers and textiles is seldomly shown. Textiles can be engineered to fit certain properties, but the selection of material, fiber formation technique and textile production technique is often challenging. In addition, each textile technology offers a variety of design freedoms. In the jungle of textile options, the question of which textile to use for one specific application stands out. This review aims to provide insight into this question from a textile technology point of view.

In this review, the role of textiles in tissue engineering is studied, starting with an overview of key methods, techniques, and requirements in the field of tissue engineering. In the second part of this review, the common fiber formation methods as well as the main yarn-based and fiber-based textile structures are introduced, including main options for textile design choices. Finally, approaches for textile scaffolds are analyzed for different target tissues. The textile and it's fit for demonstrated application are discussed. This review is intended for TE experts interested in using textiles as scaffolds, providing a detailed analysis of the available options, their characteristics and known applications.

The combination of textile engineering and cell culture methods provides wide possibilities for tissue engineering applications. Most textile-based scaffolds aim to mimic the mechanical properties of the native tissue. However, the extremes of soft and hard tissues such as muscle or bone remain challenging (Fig. 4). This is due to the highly complex interaction between material, fiber properties, textile technology and textile design, which leads to this wide range of possible properties, making the selection process when designing a scaffold a challenge.

Fiber formation technologies are selected based on the polymer material and desired properties. Melt spinning is ideal for thermoplastics like polyamide and polylactide, offering a cost-effective and solvent-free process. Solution spinning suits polymers such as collagen and silk fibroin but may leave solvent residues. It enables the creation of highly porous fibers. Electro- and microfluidic spinning are specialized methods for producing nanofibers. Independent of the technology chosen, the raw material, fiber and textile should be tested for biocompatibility in in-vitro cytotoxicity tests.

Each textile technology offers distinct advantages for tissue engineering and can be tailored to meet specific mechanical and biological requirements. Weaving may provide high mechanical strength and controlled porosity, making it suitable for creating durable and precisely structured scaffolds. Braiding offers flexibility and a high strength-to-weight ratio. All yarns used in a braid are orientated mainly in the longitudinal direction, which leads to high tensile strength. Knitting has high structural elasticity, which can be beneficial for dynamic tissues that undergo frequent deformation. In general, porosity, pore size and mechanical properties of warp-knits are more customizable than those of weft-knits and can be designed in larger ranges. However, the pore size of weft-knits and elastic warp-knits largely depends on the applied stretch of the textile.

While textile scaffolds can be optimized for various applications, the selection of a specific technology depends on the target tissue, required mechanical properties, and available fabrication methods. Hereby, some technologies may be more suitable for some applications than others. Braided scaffolds, with their longitudinal orientation of fibers, may be best suited for axially loaded tissues such as tendons and ligaments. In addition, braiding enables the production of stable hollow lumens that can be used in venous scaffolds as well as circular weft-knitted textiles. Flat textiles produced by weaving, weft- or warp-knitting can be chosen depending on the availability of the technology, with warp-knitting being recommended for the greatest flexibility in structure and design. Spacer fabrics extend the potential of 2D textiles to 3D scaffolds [22-24] and are particularly promising for applications such as skin grafts or multilayer structures. For researchers without direct access to textile manufacturing, electrospinning remains the most accessible method, as it requires fewer pre-processing steps such as yarn fabrication. It can produce nanofibers with a high surface area, closely mimicking the extracellular matrix to enhance cell attachment and growth. However, its structural limitations must be considered.

Regardless of the technology used, textile structures (e.g. stitches) do not naturally exist in biological tissues, and their impact on cell behavior, particularly for alignment-dependent applications, require careful evaluation. Achieving nonlinear mechanical behavior and radial compliance, such as in vascular grafts, necessitates fine-tuning. Despite numerous in-vitro and preclinical successes, human trials remain rare, raising concerns about whether textile-based scaffolds are advancing toward clinical application or merely undergoing incremental refinements without real-world translation. In-vivo studies, such as those by Politikou et al. [25], are critical to bridging this gap.

Future research needs to focus on scalable and clinically feasible solutions rather than isolated material optimizations to ensure that textile-based scaffolds move beyond laboratory development into viable medical applications. While textile production is not the limiting factor here, the manual processing of most textile scaffolds in TE is. For this reason, the use of large textile machines for small-scale production can often be excessive and labor intensive. Looking ahead, advances in tissue engineering could benefit from techniques such as 3D screen printing [26, 27], which could enable upscaled applications with textile scaffolds. For personalized applications and as long as these techniques are not yet established, 3D printing and melt electro-writing offer promising solutions as they enable the production of intricate, customized textile scaffolds [28, 29]. Besides technical scalability, if the size of the engineered tissue exceeds the diffusion limit for nutrients, some form of vascularization is required, which poses further challenges.

Furthermore, advancements in textile technology open possibilities for multifunctional bioreactors, wearable devices, and biosensors. Inspired by the concept of self-pumping spacer fabrics, textiles could be engineered as microfluidic bioreactors, enabling dynamic cell culture environments [30]. Additionally, conductive fibers have the potential to facilitate electrostimulation, which could be harnessed for regeneration of nerves and muscles [31]. By adapting fiber shapes and improving conductivity, textiles could enable health monitoring systems powered by energy generated by the human body, such as motion, pressure, and heat, serving as platforms for advanced biosensors.

The future of tissue engineering is promising and is driven by the interdisciplinary collaboration of textile technology, materials science and biomedical research. Both research into implantable textiles, whose patterning and properties are tailored to body tissue, and research into novel solutions for tissue regeneration have the potential to advance the field of TE. By innovative technologies such as 3D bioprinting and advanced biosensors, the integration of textiles into tissue engineering is leading to a new era of personalized and regenerative medicine, offering the prospect of better medical outcomes and a higher quality of life[32].

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