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Applications of 3D bioprinting in neurogenic bladder following spinal cord injury: Research and clinical translation to artificial intelligence-empowered prospects

Yuxin Zhang and Lei Pang*

The Urology Department of Shanxi Provincial People's Hospital, Taiyuan, 030012, China

Abstract

Neurogenic bladder (NB) after spinal cord injury (SCI) remains a major clinical challenge. Three-dimensional (3D) bioprinting technology offers a systematic solution in this field. This review summarizes its multidimensional applications in post-SCI NB. In basic research, the technology can be used to construct *in vitro* biomimetic "nerve-bladder" models for mechanism elucidation and high-throughput drug screening. In therapeutic strategies, it enables the fabrication of bioactive scaffolds that guide nerve regeneration and structurally biomimetic bladder tissues, synchronously promoting neural repair and tissue reconstruction. In clinical translation, image-based personalized 3D-printed models have been utilized for surgical planning and simulation. The integration of artificial intelligence further advances personalized design, printing process optimization, and multimodal collaborative research paradigms. Although major challenges remain in mechanistic understanding, manufacturing workflows, ethics, and regulation, 3D bioprinting may help shift NB management from "symptom management" to "functional reconstruction," presenting tremendous and optimistic possibilities for transferring to the clinical end.

Keywords: Three-dimensional bioprinting; Spinal cord injury; Neurogenic bladder; Tissue engineering; Neural regeneration; Artificial intelligence

***Corresponding author:**
Lei Pang
(pauldoctor@sxmu.edu.cn)

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1. Introduction

Spinal cord injury (SCI) is a major global public health concern.[1] The annual incidence of SCI in China is about 1/100,000.[2] Neurogenic bladder (NB) is a common problem after SCI, with an estimated incidence as high as 70–80%.[3] Persistent NB may result in urinary retention, incontinence, urinary tract infections, and even renal failure. Such complications can severely impair patients' lives and quality of life, and they also increase the burden on the wider population.[4] Current NB treatments include clean intermittent catheterization, medications, surgery, and electrical stimulation. However, these methods often rely heavily on caregivers, have limited efficacy, frequent side effects, and potential complications, resulting in overall limited clinical outcomes.[5,6] Therefore, improving post-SCI NB management and patients' quality of life remains a problem to be solved in medical treatment.

The emergence of tissue engineering and regenerative medicine provides a new theoretical framework and technical pathway for radical treatment of post-SCI NB. Among them, three-dimensional (3D) bioprinting is one of the most efficient methods to reconstruct complex tissue structures and functions. It requires cells, biomaterials, and bioactive factors as "bioinks" to precisely arrange them in a 3D space, thereby fabricating bionic living tissue or organ prototypes.[7,8] Post-SCI NB is a complicated condition; it involves interruption of central neural control, damage to peripheral nerve innervation, and degeneration of the end-target organ in structure and function. 3D bioprinting offers an integrated research platform. Not only can it fabricate *in vitro* disease models to interpret disease, but it can also directly produce biologically active nerve repair scaffolds and bladder tissue transplants, which provide a technical platform to enable the ultimate goal of "dual regeneration of structure and function."

At the same time, the rapid development of artificial intelligence (AI) technology has advanced 3D bioprinting.[9] From the formulation optimization of bioinks to the intelligent control of printing parameters to the bionic design of stent structures, AI is empowering the entire bioprinting process and enabling personalized and precise treatment in practice. In the field of NB, multi-scale modeling and an AI-augmented intelligent decision-making system are expected to realize personalized reconstruction of the "nerve–muscle composite unit" from the spinal cord to the bladder in the future.

However, at present, most related research focuses on a single aspect, such as SCI repair or bladder tissue engineering, and there is a lack of an integrated review of the overall pathogenesis of post-SCI NB. Based on this, this paper systematically summarizes the application status and frontier progress of 3D bioprinting in the field of post-SCI NB from three dimensions: basic research, clinical transformation, and AI empowerment, focusing on its clinical problems, current transformation paths, and core challenges, and analyzing the future development direction of this field driven by AI, with a view to providing forward-looking reference for researchers and clinicians in this field.

2. Application of three-dimensional bioprinting in basic research for post-spinal cord injury neurogenic bladder

Basic research is crucial for elucidating pathogenesis and screening novel therapies. Traditional research has largely relied on two-dimensional (2D) cell culture and animal models. Although each one might be good in its own way, it is not perfect. 2D cultures fail to replicate the 3D tissue architecture, cell–cell interactions, and dynamic mechanical and biochemical microenvironments.[10,11] Animal models have the problem of variation between species, ethical limitations, long cycle times, low throughput, and large individual variation.[12] In addition, different segments of the SCI (thoracic, lumbar, and sacral) result in distinct types of bladder dysfunction, which also makes it difficult to standardize animal-model experiments and compare results.[13]

2.1. Constructing biomimetic "nerve-bladder" models

The core advantage of 3D bioprinting lies in its spatial controllability, allowing precise regulation of the distribution and structure of cells, biomaterials, and bioactive factors in 3D space.[14] Researchers can print bladder urothelial cells, smooth muscle cells, fibroblasts, and vascular endothelial cells layer by layer to form a multilayered 3D bladder wall structure comprising the mucosa, lamina propria, and muscular layer, thereby optimizing scaffold porosity and mechanical strength while simulating bladder contraction and relaxation.[15]

The choice of bioink directly determines the functional performance of building a bionic "nerve-bladder" model using 3D bioprinting. Extracellular matrix (ECM) hydrogels can effectively promote the adhesion, migration, and differentiation of neurons and bladder urothelial cells because they retain natural biological signaling molecules, such as collagen and laminin, and exhibit excellent biocompatibility.[16] However, their mechanical strength is low, and their photo-crosslinking efficiency is easily affected, limiting printing accuracy and structural fidelity.[17] Gelatin methacryloyl (GelMA) has both the cell-recognition site (such as the RGD sequence) of gelatin and the controllable photocrosslinking ability from methacryloyl groups.[18] This characteristic makes its compression modulus adjustable over the range of 5–15 kPa, supports high-resolution extrusion printing, and maintains cell viability above 85%.[19] However, when used alone, there are problems with rapid *in vivo* degradation and insufficient creep resistance.[20] Alginate has excellent ionic crosslinking responsiveness (instant gelation triggered via calcium ions), high shear-thinning behavior, and good shape fidelity.[21] This makes it especially suitable for high-precision printing of complex hollow structures, such as a bladder cavity.[21] However, alginate lacks cell-adhesion ligands, and its biodegradability is uncertain, which limits its application as bioink.[22] GelMA and alginate composite ink overcome the limitations of a single material through synergy and complementarity. GelMA provides biological activity and mechanical adjustability, while alginate enhances printing stability and structural support.[23] This

composite ink maintains more than 90% of the initial cell viability while achieving a multi-objective balance among compression modulus, elongation at break, and printing resolution.[24] Therefore, when building a bionic "nerve-bladder" model with both innervation and urine storage functions, it is necessary to weigh the biocompatibility, mechanical strength, and printing accuracy of materials according to specific functional requirements, or adopt a multi-material composite strategy to achieve complementary performance.

In the future, motor neurons and sensory neurons of the spinal cord, as well as bladder smooth muscle cells, can be further incorporated into the model to establish a more simplified "spinal cord-bladder reflex arc."[25] Such models are particularly suitable for simulating bladder dysfunction following injuries at different spinal segments. By applying mechanical compression, chemical damage, and ischemia-reperfusion to the "neural" component of the model, changes in bladder smooth muscle contraction patterns can be dynamically observed. Several studies have incorporated periodic mechanical stimulation (simulating bladder contractions) alongside microfluidics to maintain constant medium perfusion, thereby creating an *in vivo*-like nutrient-metabolism environment that closely resembles *in vivo* bladder function. This approach allows for a more accurate investigation of bladder dysfunction at the cellular and molecular levels when neural signaling is disrupted.[23,26]

2.2. Controllable pathological microenvironments and high-throughput screening platforms

3D bioprinted models can precisely simulate NB-related pathological microenvironments through various strategies. For instance, introducing specific inflammatory factors (such as tumor necrosis factor-α, interleukin-6) or adjusting the ECM elastic modulus can simulate chronic inflammation and fibrosis associated with NB, replicating post-SCI bladder tissue pathology.[27,28] By regulating the gradient of oxygen concentration, local hypoxic microenvironments can be established at the injury site, which is conducive to the research on the mechanism of hypoxia-induced bladder dysfunction.[29]

More importantly, such standardized, miniaturized models serve as ideal high-throughput drug-screening platforms. Standardized printing processes enable batch fabrication of uniform, stable "post-injury nerve-bladder units" in multi-well plates for rapid evaluation of the effects of neurotrophic factors (e.g., brain-derived neurotrophic factor [BDNF], neurotrophin-3 [NT-3]), small-molecule drugs, or stem cell-derived exosomes on functional recovery.[15] This platform can effectively preserve patient heterogeneity. Patient-derived printed models can accurately replicate individual drug response patterns, providing a basis for personalized treatment plans.[30] Simultaneously, the high-throughput nature significantly improves drug screening efficiency and shortens preclinical development cycles (Figure 1).

3. Therapeutic strategies and clinical translation of three-dimensional bioprinting for post-spinal cord injury neurogenic bladder

3.1. Restoration of neural innervation

Restoring central or peripheral physiological control of the bladder is key to curing NB.[31] 3D bioprinting shows great potential for repairing the central nervous system and precisely repairing peripheral nerve injuries that cause NB dysfunction. Post-SCI NB dysfunction primarily stems from the interruption of descending pathways and the formation of an inhibitory local microenvironment at the injury site. The pelvic nerve, as a key peripheral hub for bladder voiding control, is often directly damaged, leading to voiding dysfunction and NB. 3D bioprinting offers new approaches to repairing complex nerve injuries by constructing biomimetic scaffolds and precisely delivering bioactive substances.

3.1.1. Central repair: Three-dimensional bioprinted spinal cord scaffolds

For central nervous system repair, 3D bioprinted spinal cord scaffolds effectively address challenges associated with axonal regeneration after SCI.[32] Sensory and motor deficits after SCI result from limited neural regenerative capacity and glial scarring. The glial scar constitutes a physical and chemical barrier that is rich in inhibitory factors, such as chondroitin sulfate proteoglycans, and strongly inhibits axonal growth.[33] Using 3D printing, we can create a biomimetic spinal cord scaffold with longitudinally aligned microchannels.[34,35] The microchannels simulate spinal white matter tracts to provide physical guidance for axonal directional growth. Scaffold materials are often made of poly(lactic-co-glycolic acid) (PLGA) with ECM composite ink to balance mechanical support and bioactivity, providing an appropriate environment for cells to grow and regenerate neural tissue.[36] For example, researchers have developed 3D bioprinted scaffolds incorporating neurotrophic factors (e.g., BDNF, NT-3) to promote neuronal survival and axonal growth.[37,38] Loading neural stem cells (NSCs) or Schwann cells into the scaffold further enhances neural regeneration effects.[36,39] NSCs can differentiate into neurons and glial cells.[40] Schwann

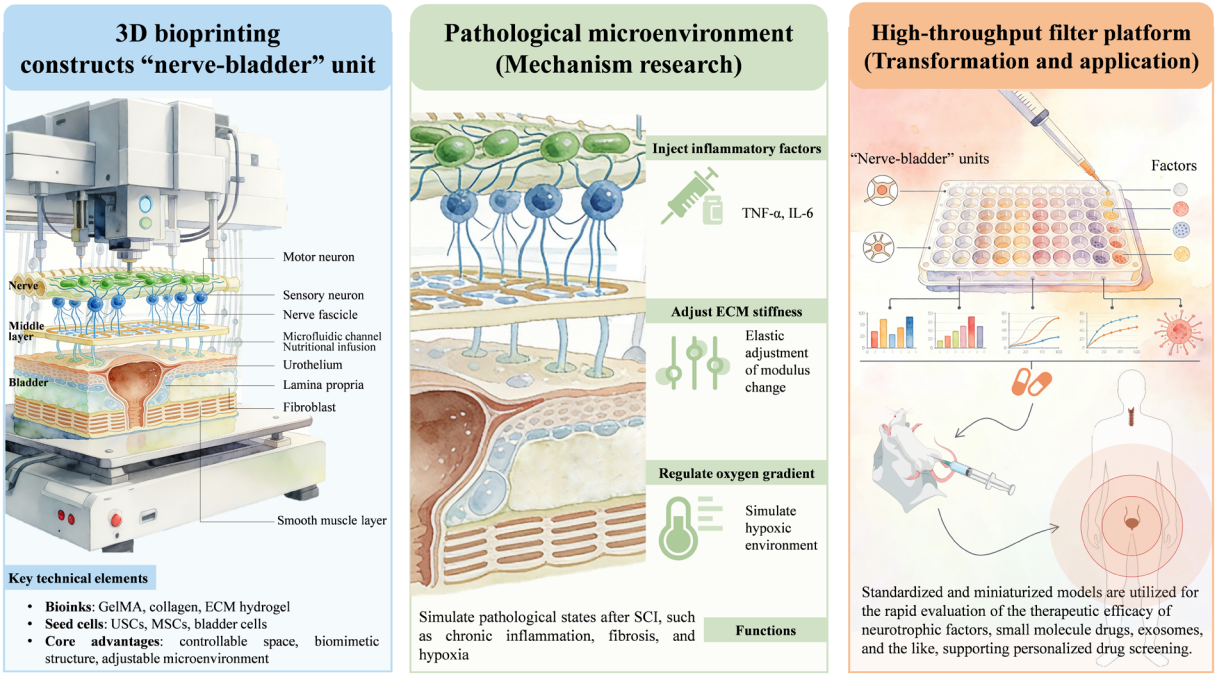

Figure 1. Applications of 3D bioprinting in basic research for post-SCI NB
Abbreviations: 3D: Three-dimensional; ECM: Extracellular matrix; GelMA: Gelatin methacryloyl; IL: Interleukin; NB: Neurogenic bladder; SCI: Spinal cord injury; TNF: Tumor necrosis factor.

cells play a crucial role in peripheral nerve regeneration by clearing debris and forming a regeneration-promoting environment.[41] Several studies have also embedded conductive microstructures in scaffolds to promote nerve regeneration, as electrical signals positively influence neuronal growth and differentiation.[42] Implanted at the injury site, such scaffolds not only resist glial scar invasion and provide physical support for regenerating axons but also create a pro-regenerative microenvironment through the sustained release of active components, thereby substantially improving axonal regeneration rates.[43]

3.1.2. Precise peripheral nerve repair: The pelvic nerve

The pelvic plexus, a key peripheral hub for bladder voiding control, is often directly damaged, leading to voiding dysfunction and NB.[44] Recent pioneering research provides strong evidence for the potential of 3D bioprinting to precisely repair bladder-innervating peripheral nerves.[45,46] Researchers used printing technology to fabricate a bilayered flexible "cellular band-aid," with its inner layer loaded with human umbilical vein endothelial cells. Wrapping this around injured rat pelvic ganglia effectively protected neurons and promoted neural structural repair and functional recovery through sustained vascular endothelial growth factor (VEGF) secretion. It provides a potential and precise repair option for NB as a result of localized peripheral nerve damage from pelvic operation or injury.

3.2. Bladder tissue reconstruction and replacement

If neural repair is not possible in the short term, or if there has been an irreversible organic alteration of the bladder (severe fibrosis and contracture), we will need bladder tissue reconstruction and implantation.

3.2.1. Structural biomimicry: Printing multilayered bladder patches

Bladder augmentation with intestinal segments in the past was associated with mucus secretion, electrolyte imbalances, stone formation, and malignancy after a long time.[47] This drives exploration of 3D bioprinting as an alternative for bladder repair, aiming to provide anatomically and functionally compatible bladder patches.

Biomechanical characteristics of the normal bladder wall are key benchmarks for the design of bladder tissue-engineering scaffolds, and the core lies in its unique nonlinear stress-strain behavior and viscoelastic characteristics. In the low-pressure filling stage, the bladder shows high compliance, but as volume approaches the physiological limit, its stiffness increases rapidly, thereby effectively performing urine storage and protecting the

upper urinary tract.[48] This mechanical response is mainly attributed to the directional rearrangement of collagen fibers in the bladder wall and to the passive response of smooth muscle.[49] During continuous filling, the bladder wall will exhibit stress relaxation and creep; that is, stress will decay over time under constant strain, or strain will increase over time under constant stress. This viscoelastic behavior enables the bladder to adapt to the slow filling of urine, avoid excessive wall pressure, and respond immediately to rapid pressure changes, such as during coughing and jumping, thereby protecting the upper urinary tract from back-pressure injury.[50]

However, one of the main reasons for the failure of transplanting plants/grafts in bladder tissue engineering is the mismatch in compliance between scaffold materials and the soft, dynamic host tissue.[51] The rigid synthetic scaffold cannot deform with the host tissue during filling, leading to local stress concentrations and a foreign body reaction, ultimately resulting in fibrotic wrapping and graft contracture. Therefore, given the viscoelastic characteristics of the normal bladder, it is of great practical significance to re-examine the mechanical properties of existing scaffold materials for guiding the accurate design of a 3D bioprinted bladder patch.

At present, the scaffold materials used in the preparation of bladder patches are mainly divided into three categories: natural acellular, synthetic polymer, and composite scaffolds, each with its own advantages and disadvantages in mechanical properties, biocompatibility, and clinical transformation effect.

Natural decellularized scaffolds, such as bladder ECM and small intestinal submucosa (SIS), offer excellent biocompatibility and can partially support cell migration.[52,53] From the mechanical characteristics, the biggest advantage of this kind of scaffold is that it retains the viscoelastic characteristics and biological activity signals of natural ECM, and can show compliance similar to that of the host bladder in low stress areas. However, its limitation is that the mechanical strength is generally insufficient, and the Young's modulus of a single acellular scaffold is mostly in the order of kPa, which is far lower than the mechanical requirements of MPa in the state of bladder filling. This leads to complications such as contraction, calcification, and even heterotopic ossification when applied to large-scale bladder repair.[54] This means that although the natural acellular scaffold has achieved a certain degree of compliance matching, it lacks sufficient strength to withstand physiological loads and is difficult to meet the bladder's dynamic mechanical needs.

Synthetic polymer scaffolds include PLGA and polycaprolactone (PCL). The advantage of this kind of material is that its mechanical strength can be precisely controlled, facilitating standardized preparation. Among them, PCL is widely used as a scaffold material for 3D bioprinting because of its low melting point and good printability, and its Young's modulus is as high as 200–400 MPa, providing excellent deformation resistance for implants.[55] The Young's modulus of PLGA can be flexibly adjusted in the range of 1–50 MPa to meet different mechanical design requirements.[56] However, its core defect is the lack of viscoelasticity. The stiffness of this scaffold material is far beyond the physiological range of natural bladder tissue, and it cannot simulate the bladder's stress relaxation behavior after implantation. It is easy to produce a stress-shielding effect at the material-host interface, which can induce a strong foreign-body reaction and fibrosis wrapping. In addition, degradation products of synthetic polymers can readily create a local acidic microenvironment, and the material itself lacks natural biological signaling, which will further affect the survival of seed cells and the regeneration and integration of host tissues.[33]

To address both mechanical strength and compliance, composite stents were developed. Its core design idea is to combine the advantages of natural acellular and synthetic polymer scaffolds to achieve a "combination of rigidity and flexibility" in scaffold mechanical properties. At present, commonly used composite systems include collagen-PLGA composites, PCL grids, and GelMA-alginate gel co-printing scaffolds. The core design idea of this kind of scaffold is that synthetic polymers (such as PCL) are used as a "skeleton" to provide structural support and anti-deformation ability, and natural hydrogels (such as GelMA, collagen, and ECM hydrogels) are used as "soft tissues" to load cells and mediate host integration. By adjusting the proportions, spatial distribution, and crosslinking density of the two-phase materials, the overall modulus of the composite scaffold can approach the physiological range of the natural bladder while also partially reproducing the viscoelastic response of the natural tissue. Studies have shown that this kind of scaffold exhibits better tissue-integration potential in animal experiments, with less severe fibrous encapsulation (Table 1).[55]

However, static Young's modulus matching and basic viscoelastic reappearance are only the first step of mechanical bionic design. The bladder, as a typical dynamic mechanical organ, undergoes numerous cyclic mechanical loads from filling and emptying daily, which imposes higher requirements on 3D bioprinted stent fatigue resistance under cyclic loading.[57] If the stent has only static mechanical strength and lacks fatigue resistance, even if the initial modulus and viscoelasticity are good, it

Table 1. Comparison of Young's modulus of common bioinks and native bladder tissue

Material category	Specific material	Young's modulus range
Native bladder tissue	Normal bladder wall	0.1–10 MPa (estimated range)[111]
Natural decellularized scaffolds	ECM, SIS	0.1-50 kPa [112]
Synthetic polymers	PCL	200–400 MPa[113]
Synthetic polymers	PLGA	1–50 MPa[114]
Hydrogels	GelMA	5–15 kPa (compression modulus)[115]
Composite materials	GelMA-alginate composite, etc.	Designable to 0.1–10 MPa[116] (approaching native tissue)

Notes: The data in the table are typical reference values and are not fixed constants. The modulus of native tissues varies with species, age, and testing methods. Synthetic and composite materials, on the other hand, are highly dependent on factors such as molecular weight, component ratios, and processing conditions, and are therefore tunable. Therefore, the values in the table are intended primarily to reflect the relative relationships and orders of magnitude among materials. In actual experimental design, it is recommended to rely on experimentally measured values obtained under specific formulations and testing conditions.

Abbreviations: ECM: Extracellular matrix; GelMA: Gelatin methacryloyl; PCL: Polycaprolactone; PLGA: Poly(lactic-co-glycolic acid); SIS: Small intestinal submucosa.

is easy to cause microcrack initiation and propagation, and even structural collapse within weeks to months after operation due to repeated periodic stress. Therefore, the ideal bladder bioink not only needs to have a mechanical modulus suitable for the host in the initial state, but also needs to maintain sufficient fatigue life during the dynamic balance between degradation and tissue regeneration in vivo until the new tissue fully replaces the scaffold's mechanical function.

In response to this challenge, 3D bioprinting can enhance stent fatigue resistance through the following strategies. Firstly, applying physiological periodic mechanical stimulation to the printed construct in the *in vitro* dynamic culture system can not only achieve efficient screening of fatigue-resistant materials, but also upregulate the expression of contraction phenotypic markers of smooth muscle cells through mechanical signal transduction, and promote the active functional integration between the graft and the host tissue.[58] Secondly, the energy-dissipation mechanism (such as nanocomposites and double-network hydrogels) is incorporated into the scaffold design, so that the energy generated by periodic loading can be dissipated and crack propagation can be delayed.[59] Thirdly, the fatigue life of the bracket under long-term cyclic load is predicted by multi-scale simulation, and the printing parameters and material ratio are optimized.[60] Finite element analysis can predict the mechanical behavior of 3D bioprinted tissue-engineering scaffolds, thereby guiding scaffold design to achieve the desired mechanical characteristics.[60]

To sum up, based on the viscoelastic characteristics of normal bladder, three types of scaffold materials have their own mechanical characteristics and applicable scenarios: natural acellular scaffold has excellent viscoelastic properties but insufficient strength, synthetic polymer scaffold has high strength but lacks viscoelastic properties, and composite scaffold is expected to achieve a balance between viscoelastic properties and strength through collaborative design of multiple materials. In the future, the research and development of 3D bioprinted bladder patches must leap from static modulus matching to dynamic mechanical bionic, and systematically consider the initial compliance, viscoelasticity, and cyclic fatigue resistance of the scaffold, to fundamentally overcome the failure of graft fibrosis caused by mechanical mismatch and provide a tissue engineering substitute with real physiological functions for bladder reconstruction.

Although the bionic design of dynamic mechanics based on multi-material composites points to the core optimization direction for the research and development of bladder patches, the clinical translation of prefabricated bladder patches has yet to achieve a breakthrough. Using SIS for bladder augmentation can improve capacity and compliance in the short term, but long-term follow-up shows limited functional improvement.[61] The study shows that this limitation is mainly due to the mismatch between the material degradation rate and the tissue regeneration rate. The degradation of SIS was delayed during the early stage of implantation, triggering a significant

inflammatory reaction and physically hindering the formation of functional smooth muscle. It was not until 24 weeks after the material had fully degraded that the function of the regenerated tissue gradually returned to near-normal levels. This discovery suggests that the degradation kinetics, biological stability, and dynamic balance of the host inflammatory response in natural scaffold materials are key to determining the long-term function of the tissue-engineered bladder. Furthermore, several problems, such as graft contraction and fibrosis, recurrent infections, and urinary leakage, are common. Therefore, these *in vitro* patches cannot currently replace traditional enterocystoplasty, the gold standard. This highlights significant challenges remaining in mechanical property matching, long-term volume maintenance, and effective functional integration.

To address these problems, *in situ* bioprinting, as an innovative solution, has attracted wide attention. This method can achieve precise deposition of cells mixed into the bioink onto the bladder defect during operation, enabling minimally invasive, integral repair of the bladder.[62] For instance, research teams have created miniaturized bioprinters that can be delivered via endoscopes for *in situ* repair of the gastric wall.[63] In the future, a transurethral insertion of a miniaturized printhead might enable printing of the patients' own autologous cell-laden bioink directly onto post-augmentation cystotomies. This strategy not only achieves a morphological match between the subcutaneous adipose tissue patch and the wound skin, but also enables the use of subcutaneous adipose tissue or the bladder wall itself as a natural bio-reactor, providing a functional physiological microenvironment for each cell. Moreover, it can play a more efficient role in promoting angiogenesis, inhibiting fibrosis, promoting tissue integration, and facilitating functional recovery. This approach represents a shift from the traditional process of "*in vitro* fabrication followed by implantation" to an *in vitro* fabrication within an *in vivo* environment, offering a novel concept for bladder repair.

3.2.2. Functional integration: the synergistic challenges of vascularization, anti-fibrosis, and graft innervation

Survival and functional integration of clinical-scale tissue-engineered bladders more than 1 cm thick depend on rapid vascularization.[64] Insufficient blood perfusion leads to central necrosis and blocks host-cell infiltration and functional integration.[65] In particular, for larger constructs, the diffusion limit for oxygen and nutrients is approximately 150–200 μm, and the region beyond this limit will suffer from hypoxic necrosis.[66] Therefore, we must create vascularizable perfusable vascular networks *in vitro* to enable long-term survival and incorporation of clinical-scale tissue-engineered bladders.[67] Conventional tactics involve relying on the host vessel's slow ingrowth or auxiliary vascularization from omental wrapping. However, this cannot ensure a continuous supply of blood and nutrients to the large graft and has shown obvious shortcomings in reliability and effect.[68] Advanced 3D bioprinting strategies aim to simultaneously build biomimetic vascular networks within the patch by pre-seeding vascular endothelial cells on their inner surfaces. Postoperative microsurgical anastomosis to host vessels can achieve immediate blood perfusion, thereby greatly improving graft survival rates.[69,70]

Additionally, graft fibrosis is an important cause of clinical failure. Urine exposure, chronic inflammation, and foreign body reaction can all lead to excessive fibrous tissue hyperplasia, resulting in graft contraction, loss of elasticity, and other serious complications such as abdominal adhesion.[71] In urology, 3D bioprinting of a kidney tissue-engineering scaffold was applied to simulate the kidney's complex microvascular architecture and functional units, which are necessary for renal regeneration and repair.[72] This demonstrates 3D bioprinting's significant advantage in constructing tissues with complex internal structures, including the potential to incorporate anti-fibrotic strategies.

Functional reconstruction of innervation is the key interface between upstream nerve repair and downstream bladder tissue reconstruction, and it is also the core premise to realize synchronous contraction of bladder smooth muscle. If only the upstream repair of the peripheral or central nervous system is completed and the bladder graft lacks functional innervation, the smooth muscle will inevitably atrophy and undergo fibrosis, ultimately leading to loss of the graft's physiological contractile function.[73] Therefore, the integrated design of nerve repair strategies and bladder construction, especially the targeted regeneration of functional neuromuscular junctions (NMJs) guided and accelerated by biological manufacturing technology, has become the frontier direction in this field. Its core scientific logic is that it is necessary to provide regenerative nerve with a physical channel for directional growth, a suitable biochemical microenvironment and an effective electrical signal conduction interface, to accurately match multiple biological processes, such as nerve axon extension, targeted dominance and smooth muscle maturation in time and space, which is the core to break through the current isolated research dilemma of nerve repair and bladder repair, and also the key to realize synchronous and coordinated contraction of bladder smooth muscle.

Introducing nerve guidance conduits (NGCs) into the bladder wall design is a core strategy. Micro-scale NGCs connected to a peripheral nerve repair scaffold can be directionally embedded in the muscularis of a 3D-printed bladder patch, providing a physical channel for pelvic nerve or regenerated spinal nerve fibers to grow and be guided to accurately infiltrate the bladder smooth muscle. Schwann cells and neurotrophic factors can be co-loaded into the catheter, thereby further promoting the growth, maturation, and myelination of nerve fibers and providing a structural framework for NMJ formation.[74] At the same time, by using the precisely controlled release characteristics of 3D bioprinting, neurotrophic factors can be released sequentially in time and space in the patch, and nerve growth-promoting factors, such as BDNF and NT-3, can be released in high concentration in the area connected with the nerve to guide nerve growth.[75] Neuroregulatory factors and acetylcholinesterase inhibitors are released in the smooth muscle layer, promoting nerve ending formation and synaptic maturation, and activating the expression of nerve receptors in smooth muscle cells, thereby achieving temporal and spatial coordination among factor release, nerve fiber growth, and smooth muscle maturation. However, the current research remains in the early stage of exploration, and there is still a significant gap to clinical transformation. Limited studies have systematically optimized physical guidance, biochemical induction, and electrical signal integration. Whether regenerated NMJs are completely equivalent to natural NMJs in terms of molecular structure, transmitter release efficiency, and fatigue resistance remains to be verified via in-depth functional electrophysiological studies.

It is noteworthy that the coordinated regulation of vascularization, anti-fibrosis, and innervation reconstruction is key to realizing the graft's function. Stable vascularization provides continuous nutritional support for innervation reconstruction, and an effective anti-fibrosis strategy removes the physical barrier for nerve fiber growth, while functional innervation can activate the physiological activity of smooth muscle cells, further inhibit the transformation of smooth muscle into fibroblasts, and reverse the fibrosis process. At the same time, this coordinated approach promotes functional integration between the graft and host tissue, and the collaborative design of the three is also the core guarantee for 3D bioprinting bladder reconstruction from "structural repair" to "functional regeneration".

3.3. Three-dimensionally printed custom-made precision planning for complex surgery

Although 3D bioprinting of living tissues for direct repair is still in development and translation, its non-living counterpart—using patient imaging data to fabricate precise, individualized anatomical models—has already found clinical application.[76,77] These models, primarily developed from biocompatible inert materials, including polylactic acid or resin based on 1:1 full-color printing of computed tomography (CT) or magnetic resonance imaging (MRI) data, can accurately reproduce anatomical structures of bones, nerves, and vessels, remarkably enhancing planning accuracy and operative safety for NB-related surgeries.[78,79]

Sacral neuromodulation is an effective therapy for NB[80,81], and its success depends heavily on precise electrode placement.[82] Traditional fluoroscopy-guided placement faces challenges, including non-intuitive localization and radiation exposure. Custom-made pelvic models generated from patients' imaging data can accurately depict the sacral foramen, nerve pathways, and surrounding blood vessels. These models also allow surgeons to practice the preoperative puncture path repeatedly to improve electrode positioning.[83,84] From the clinical trials, these models shorten operation time, reduce the incidence of puncture, increase electrode positioning accuracy, and decrease the dose that is accidentally given off during intraoperative radiation.[85] They have become an increasingly established application of 3D printing in urological neuromodulation.

Furthermore, for patients requiring complex reconstructive surgeries, such as bladder augmentation or urinary diversion, due to NB complications, 3D-printed pathological bladder models can visually depict atrophic, diverticular, or fibrotic morphology. This assists surgical teams in developing individualized plans, such as determining patch size, selecting anastomosis sites, and anticipating surgical difficulties (e.g., bladder neck repair), and facilitates more effective preoperative communication with patients via visual models, enhancing treatment adherence (Figure 2).[86,87]

4. Artificial intelligence empowerment

The deep integration of 3D bioprinting with AI is driving post-SCI NB research and treatment toward precision, automation, and intelligence.[88] In the previous sections, the multidimensional applications of 3D bioprinting in

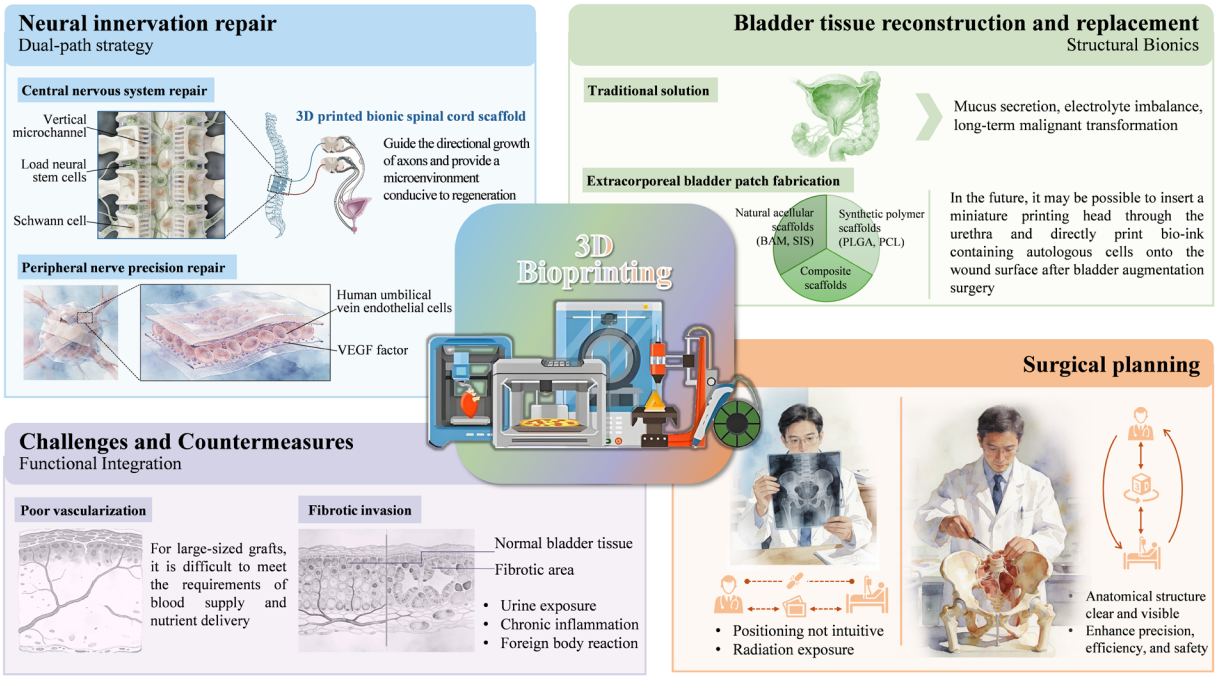

Figure 2. 3D bioprinting-driven comprehensive therapeutic strategies and clinical translation pathways for post-SCI NB
Abbreviations: 3D: Three-dimensional; BAM: Bladder acellular matrix; NB: Neurogenic bladder; PCL: Polycaprolactone; PLGA: Poly(lactic-co-glycolic acid); SCI: Spinal cord injury; SIS: Small intestinal submucosa; VEGF: Vascular endothelial growth factor.

constructing a bionic "nerve-bladder" model, preparing nerve repair scaffold, reconstructing bladder tissue, and assisting clinical surgery planning are systematically expounded. The successful implementation of these applications is highly dependent on the precise control of complex biological structures and dynamic physiological processes, a field in which AI can play a core role.

4.1. Artificial intelligence-driven personalized design and printing optimization

The algorithms of AI study numerous patients' medical diagrams (CT, MRI) and urodynamics, as well as genomics information, to design an optimal treatment plan tailored to each individual.[89]

Convolutional neural networks (CNNs) play a key role in image analysis and structure segmentation due to their remarkable advantages in medical image feature extraction.[90] It can automatically learn discriminative multi-level features and achieve accurate 3D segmentation of spinal cord lesions, identification of bladder morphological abnormalities (such as trabeculation and diverticulum formation), and localization of innervated areas.[91] Detailed anatomical information can provide an important foundation for the design of microchannel structures in neural scaffolds, ensuring geometric matching with patient physiology and improving the environment for neural regeneration. However, its practical utility in the NB field is limited by the scale and representativeness of training data. If the CNN model is mainly based on the patient data of a specific injury segment (such as the thoracic segment), its segmentation accuracy of bladder morphological changes in patients with lumbar or sacral segment injury may be substantially reduced, and this sensitivity to the distribution of training data limits the clinical universality of the model.

Generative adversarial networks (GANs) are superior at generating and imitating real data distributions through adversarial training.[92] They can simulate the physiological structure of the normal spinal cord-bladder reflex arc to create a biomimetic scaffold topology at the patient's injury level, guiding neural cell growth and neural connection recovery while providing structural support for NB treatment. However, in the case of a limited sample size, the "bionic" structure generated by GAN may only be a simple reorganization of limited samples in the training set, rather than a real innovative design, and may even amplify the anatomical variation noise existing in the training data and generate a guiding structure that deviates from the physiological reality. This problem is particularly prominent with a limited sample size.[93]

To address the limitations of a single data source, researchers can use multimodal fusion models based on architectures such as the Transformer.[94] Through the use of a sophisticated weight assignment mechanism to achieve a highly successful combination of unstructured picture information and organized physiologic and genetic information. Deep learning of such multimodal data yields more precise and robust forecasts of optimal printing parameter pairs, facilitating "tailor-made" fabrication with customized dimensions and cell ratios for a bladder patch or neural scaffold. However, under the condition of scarce data, it is difficult for the model to learn the real correlation between different modal data, and its prediction results may be mainly dominated by a single modality (such as images) with a large amount of data, which fails to achieve real multimodal synergy gain, thus limiting its application value in complex clinical situations (Table S1).

In real-time printing control, machine learning algorithms play a central role in parameter optimization and quality monitoring. The random forest algorithm established a mapping relationship between the historical printing data (extrusion pressure, nozzle temperature, motion speed) and the results (cell deposition uniformity, viability), and predicted printing defects.[95] The support vector machine is a classification model that rapidly identifies anomalies (cell aggregation, pore clogging) in the vision system's images, triggering dynamic parameter adjustments. These vision systems generally combine the high resolution of microscopy with computer vision technology to detect key parameters, such as cell deposition density and ink solidification status, in real time, and achieve structural consistency of the construct and functional stability.[96]

This AI-enabled real-time feedback closed-loop system significantly improves the success rate and product quality in 3D bioprinting, providing reliable technical support for tissue engineering treatment of post-SCI NB. It promotes the field's evolution from empirical operation toward high intelligence, automation, and precision, ultimately aiming for more effective clinical translation and patient functional recovery.

Although AI shows the technical potential outlined above, in the specific field of post-SCI NB, its application faces a fundamental challenge: data scarcity. The incidence of SCI is relatively low, and the number of patients who can provide high-quality images, complete clinical follow-up data, and biological samples simultaneously is limited.[97] This problem with a limited sample size poses a severe challenge for the data-driven AI model. Complex deep learning models usually require large amounts of data to avoid overfitting, but with a limited sample size, the model may memorize noise and specific examples in the training set, resulting in poor generalization. When the training data cannot fully represent the real-world patient population, the AI model will internalize and amplify this deviation, potentially producing misleading outputs for "atypical" patients.[98] This fundamental challenge suggests that in the AI application in this field, it is necessary to develop learning strategies that adapt to small sample scenarios, such as transfer learning[99], data enhancement[100], and federated learning[101], to achieve reliable model performance under the condition of limited data.

4.2. Multimodal fusion research paradigm: Establishing a synergistic validation system integrating animal models, three-dimensional bioprinting, and artificial intelligence

The 3D bioprinted model can achieve a good simulation of the human microenvironment and enable high-throughput studies, but the animal model is unable to fully reproduce the overall physiological response, systemic immune regulation, and long-term functional integration.[102] Therefore, it is inevitable that a synergistic "animal model-3D bioprinting" research system be established to systematically advance this field towards clinical application.

Within such a synergistic framework, the animal model is used to verify whether the potential mechanism or drug target identified in the 3D bioprinted model holds.[103] Simultaneously, 3D bioprinted neural scaffolds or bladder patches may be implanted in animals for a systematic study of long-term survival, vascularization, innervation, and functional integration.[56] Moreover, the urodynamic parameters of animals (such as bladder capacity, pressure, and compliance) can also be used to optimize the physiological state of the printed model, improving its clinical predictive value.

The integration of AI will further amplify this paradigm's efficacy. By integrating large-scale macrophysiological data from animal experiments and small-scale microresponse data from printed models, AI can help build precise pathophysiological models and enable intelligent, iterative optimization of printing parameters. This *in vitro–in vivo* approach establishes a closed-loop, mutually validating research pathway, which is expected to advance neurogenic bladder research and enhance its translational potential for clinical applications.

5. Challenges and limitations

The clinical translation of 3D bioprinting in post-SCI NB patients is currently constrained by several challenges, the resolution of which will facilitate its clinical translation.

Survival and functional integration of thick, functionally viable tissue-engineered bladders made from clinical tissue depend mainly on the rapid and effective formation of a vascular network, which poses a major challenge. Although it is currently possible to pre-design vascular channels using printing strategies, it is difficult to rapidly anastomose them to the host vasculature after implantation, and the maturity and long-term stability of the newly formed vessels are far from meeting clinical requirements, thereby frequently resulting in ischemic-hypoxic necrosis at the center of the graft.[66] Aiming to address this core problem, the current research explores a multi-path cooperation strategy.

At the bioink design level, integrating angiogenic factors enables active guidance of vascular network extension and docking with host blood vessels. VEGF is one of the main factors that induce angiogenesis, stimulating the proliferation and migration of endothelial cells. Platelet-derived growth factor (PDGF) mainly mediates the recruitment of pericytes and promotes the maturation and stability of new blood vessels. Studies have shown that bioengineered patches capable of sequentially releasing VEGF and PDGF can effectively promote vascularization in bladder reconstruction.[104] In addition, vascular progenitor cells (such as endothelial progenitor cells) can be printed alongside structural cells, thereby enhancing the vascularization of tissue-engineered constructs. These cells can self-assemble into a capillary-like network after implantation, thereby accelerating integration with the host vascular system. The combined application of autologous endothelial progenitor cells and bioactive factors (such as VEGF and PDGF) has been shown to improve smooth muscle regeneration and vascularization in the tissue engineering of the bladder.[105]

At the level of surgical strategy, the omentum is used for pre-vascularization *in vivo* because of its rich vascularization and healing potential. Incubation of bioprinted bladder stent with omentum can promote vascularization of the stent and provide a good blood supply basis for subsequent bladder reconstruction.[106] For example, in one study, a bladder patch constructed of bladder acellular matrix and adipose-derived stem cells was wrapped by omentum and pre-vascularized *in vivo*, successfully promoting bladder tissue regeneration.[107] In addition, *in vivo* pre-vascularization techniques, such as arteriovenous loop construction, create a vascular-rich microenvironment for the graft and aim to align with the functional window for vascular network remodeling.[108] The coordinated application of these complementary strategies is expected to significantly shorten revascularization time and lay the foundation for long-term graft survival.

Post-implantation of the host vascularization also triggers a strong immune response, which is an important factor leading to the graft becoming fibrous and adhered, degrading performance and impacting biocompatibility and treatment efficacy. Developing bioinks with immunomodulatory functions is one of the key strategies to address graft immune rejection. By adding specific anti-inflammatory cytokines to the bio-ink or using exosomes from mesenchymal stem cells, the immune microenvironment after implantation can be effectively regulated, macrophages can be induced to polarize toward a reparative phenotype, and inflammatory reactions can be inhibited, thereby promoting graft integration and functional maintenance.[109]

Another important strategy to reduce the risk of immune rejection at the source is to prioritize the use of patients' autologous cells or low-immunogenic cells to induce the differentiation of pluripotent stem cells (PSCs) as seed cells. Using patients' own cells for tissue engineering can fundamentally avoid immune rejection, because these cells have the same genetic background as the host.[110] Induced PSCs have the potential for self-renewal and multi-directional differentiation, and their immunogenicity can be reduced using gene-editing technologies, thereby providing potential cell sources for allogeneic transplantation. For example, reducing the expression of major histocompatibility complex molecules on the surface of induced PSCs and their differentiated cells through genetic modification can decrease T-cell recognition and activation of T cells, thereby reducing immune rejection.[109]

In addition to vascularization and immune compatibility, the bladder, as a typical dynamic mechanical organ *in vivo*, undergoes periodic pressure changes during filling and emptying, imposing extremely high requirements for the long-term mechanical stability and functional maintenance of the graft. However, at present, the research on the evolution of mechanical properties of 3D bioprinted bladder graft during its long-term service *in vivo* remains absent, especially the lack of empirical data on key issues, such as whether its contractile function can be maintained and whether there is plastic deformation or loss of compliance after one year of implantation. The existing research mostly focuses on short-term histocompatibility and vascularization but pays little attention to the fatigue life of the graft under repeated urinary pressure load, the dynamic matching between material degradation and tissue regeneration, and the durability of functional reconstruction of the smooth muscle layer. In the future, it is necessary to introduce a culture system loaded with dynamic mechanics to simulate the *in vivo* environment,

develop intelligent biomaterials with self-reinforcing or mechanical response characteristics, and evaluate the mechanical properties and time window of functional maintenance of grafts through a long-term animal model system to consolidate the reliability foundation of clinical application.

In addition, the transition of this technology from laboratory samples to repeatable, stable clinical products faces severe challenges in large-scale production and quality standardization. At present, the bioprinting process lacks batch-to-batch consistency, has a low degree of automation, and lacks a full-process quality control system. Therefore, they are unable to meet the strict requirements of product stability and safety in clinical applications. For this purpose, it is necessary to develop closed-loop, automated bioprinting systems to minimize human interference with product quality. At the same time, an evaluation system for critical quality attributes, including cell viability, material mechanical properties, sterility, and biosafety, should be established to achieve full-chain quality control across cell preparation, bioink formulation, and printing and fabrication. In addition, there should be collaborative efforts among regulatory authorities, industry, and academia to jointly establish classification criteria, production standards, and regulatory review guidelines for living bioprinted products, thereby providing institutional guarantees for large-scale translational applications.

To address a fundamental scientific question, we still do not fully understand what constitutes normal bladder function from a biological perspective. For example, accurate neural circuitry for normal voiding, a mechanical feedback mechanism of smooth muscle cells, and complex communication between the urothelium and nerve endings are knowledge gaps that limit the degree of biomimetic design. Therefore, 3D bioprinting is not only a manufacturing tool; the precise model it produces can advance basic science, deepen our knowledge of organ function, and support organ regeneration.

6. Future perspectives

Looking ahead, the development of 3D bioprinting technology in the field of NB treatment after SCI will continue to advance along the path of "two-track parallel and gradual integration," with the deep integration of AI becoming the core driving force, reshaping this pattern.

In vitro bioprinting is currently relatively mature, easier to standardize and control, suitable for constructing structurally regular nerve conduits or bladder patches, and allows thorough pre-implantation quality testing. Its limitations include the need for surgical implantation (potential secondary trauma) and the requirement for post-implantation vascularization and integration of *in vitro* constructs. To overcome these, future research should focus on developing bioinks with enhanced biocompatibility and pro-angiogenic properties, combined with stem cell technology to further improve tissue integration. In the next 5–8 years, personalized neural scaffolds or composite bladder patches based on *in vitro* printing are expected to enter clinical trials, offering more effective treatment options for NB patients.

In situ 3D bioprinting is known as a disruptive strategy. Its core advantage is the ability to directly deposit bioink at the injury site during surgery, enabling minimally invasive, shape-adaptable integrated repair. Furthermore, the *in vivo* microenvironment can be leveraged to promote cell survival and tissue remodeling, thereby avoiding secondary trauma and facilitating rapid integration of the implant with the surrounding tissue. Although it has a broad prospect, the current technical difficulties are more complex. These problems are mainly reflected in the high technical difficulty of obtaining high-strength, highly elastic 3D-printed tissues and organs, which demands high-performance, highly miniaturized printing equipment, real-time imaging navigation, and printing stability in the wet, *in vivo* environment. For example, accurately controlling the deposition and solidification of bioink in the urodynamically unstable bladder environment remains a critical challenge. At the same time, it is necessary to combine high-precision, real-time biosensing technology (such as local pH, temperature, or biomolecular concentration) with robot-assisted systems to achieve an automated, intelligent printing process. In addition, the development of bioinks that can rapidly solidify, maintain structural integrity, and exhibit good biocompatibility in the complex *in vivo* environment is also a key factor affecting the success of *in situ* bioprinting. It is expected that within the next 10–15 years, with breakthroughs in robot-assisted technology, real-time biosensing, and advanced bioink materials, the development of transurethral or laparoscopic-assisted *in situ* bladder bioprinting will advance to the stage of early clinical exploration, supported by large-animal experiments.

In the long term, these two approaches are not mutually exclusive and can be selected based on injury type, location, and patient condition. In the evolution of the two technical paths outlined above, AI will play an irreplaceable role, pushing the field towards intelligence, precision, and automation. AI-driven multimodal learning will become the core engine to realize "tailor-made" treatment. By integrating the patient's medical images, urodynamic parameters, and genomic information, an AI

model can automatically perform lesion segmentation, 3D reconstruction, and generate an ideal scaffold topology, ensuring that the graft is highly matched to the patient's physiological state in both geometric configuration and biological function. Furthermore, AI will reshape the collaborative research paradigm of "animal model-3D bioprinting-AI." By fusing macro-physiological data from animal experiments and micro-response information from printed models, AI can build accurate pathophysiological models, enable two-way closed-loop optimization between *in vitro* models and *in vivo* verification, and greatly enhance the translational value of preclinical research. Finally, with the deep integration of AI predictive models and multimodal surgical navigation systems, 3D bioprinting is expected to gradually undergo a paradigm shift from "offline design and *in vitro* manufacturing" to "real-time imaging and intraoperative printing," ultimately ushering in a new era of functional regeneration and accurate reconstruction of post-SCI NB.

7. Conclusion

Three-dimensional bioprinting offers a new possibility for treating post-SCI NB beyond traditional tissue engineering. Its fundamental value is not to simply reproduce the anatomical structure of an organ but to realize the systematic reconstruction of the complete functional unit of "center-periphery-target organ" for the first time. From the spinal cord stent to guide axon regeneration, to the "cell band-aid" to accurately repair the pelvic nerve, and then to the mechanical bionic bladder patch, the evolution of the technical path is pushing the therapeutic logic from substitution to regeneration. However, the real bottleneck is no longer the construction of a single tissue, but rather achieving real-time matching and coordinated regulation of innervation and target organ function in a dynamic physiological environment. When the speed of nerve growth, the rhythm of smooth muscle remodeling, and the duration of mechanical loading cannot be synchronized, the fine structure will eventually degenerate into a nonfunctional scar. This deep dilemma suggests that the future breakthrough lies not only in improving printing accuracy but also in a profound understanding and precise intervention in the emergence law of "living functional units."

Finally, whether this technology works depends on materials scientists, bioengineers, clinicians, ethicists, and regulatory bodies all pulling together. From the scientific basis to clinical application, it is anticipated that 3D bioprinting can evolve from a cutting-edge technology into a clinically accessible treatment within a decade, offering new prospects for true structural and functional dual regeneration to post-SCI NB patients.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Lei Pang
Formal analysis: Yuxin Zhang
Investigation: Yuxin Zhang
Methodology: Lei Pang
Writing – original draft: Yuxin Zhang
Writing – review & editing: Lei Pang

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Further disclosure

Artificial intelligence tools were used solely for auxiliary support in figure preparation for this review. All figures were independently designed and drawn by the authors, with original source files properly preserved. AI tools were not used to generate, analyze, or interpret any scientific data, nor to write, revise, or synthesize the scholarly content.

References

1. Anjum A, Yazid MD, Fauzi Daud M, *et al.* Spinal Cord Injury: Pathophysiology, Multimolecular Interactions, and Underlying Recovery Mechanisms. *Int J Mol Sci*. 2020;21(20):7533.

   doi: 10.3390/ijms21207533

2. Yang M, Du X, Tian T. Multivariate Logistic Regression Analysis of Risk Factors and Clinical Countermeasures of

Neurogenic Bladder After Spinal Cord Injury. *Br J Hosp Med*. 2025;86(12):1-17.

doi: 10.12968/hmed.2025.0227

3. Doelman AW, Streijger F, Majerus SJA, Damaser MS, Kwon BK. Assessing Neurogenic Lower Urinary Tract Dysfunction after Spinal Cord Injury: Animal Models in Preclinical Neuro-Urology Research. *Biomedicines*. 2023;11(6):1539.

doi: 10.3390/biomedicines11061539

4. Tate DG, Wheeler T, Lane GI, *et al.* Recommendations for evaluation of neurogenic bladder and bowel dysfunction after spinal cord injury and/or disease. *J Spinal Cord Med*. 2020;43(2):141-164.

doi: 10.1080/10790268.2019.1706033

5. Sabetkish S, Gashti RN, Jobani BM, *et al.* Management of urinary and bowel dysfunction in rabbit model of spinal cord injury using Schwann cells and muscle progenitors: functional study and evidence for novel mechanism of action. *Int Urol Nephrol*. 2021;53(5):893-906.

doi: 10.1007/s11255-020-02722-5

6. Lefaucheur JP, Aleman A, Baeken C, *et al.* Evidence-based guidelines on the therapeutic use of repetitive transcranial magnetic stimulation (rTMS): An update (2014-2018). *Clin Neurophysiol*. 2020;131(2):474-528.

doi: 10.1016/j.clinph.2019.11.002

7. Song Y, Jo H, Jeong S, Kim I, Lee SS. Vascularised Brain Organoids: Engineering Strategies and Neurobiological Applications. *Cell Prolif*. 2026;59(3):e70161.

doi: 10.1111/cpr.70161

8. Wiewiórska-Krata N, Foroncewicz B, Zagożdżon R, Mucha K. 3D Bioprinting Strategies in Autoimmune Disease Models. *Int J Mol Sci*. 2025;27(1):343.

doi: 10.3390/ijms27010343

9. Ramesh S, Deep A, Tamayol A, Kamaraj A, Mahajan C, Madihally S. Advancing 3D bioprinting through machine learning and artificial intelligence. *Bioprinting.* 2024;38:e00331.

doi: 10.1016/j.bprint.2024.e00331

10. Kapałczyńska M, Kolenda T, Przybyła W, *et al.* 2D and 3D cell cultures – a comparison of different types of cancer cell cultures. *Archives of Medical Science.* 2018;14(4):910–919.

doi: 10.5114/aoms.2016.63743

11. Ahammed B, Kalangi SK. A Decade of Organoid Research: Progress and Challenges in the Field of Organoid Technology. *ACS Omega*. 2024;9(28):30087-30096.

doi: 10.1021/acsomega.4c03683

12. Wang S, Cai S, Zhu Z, Zeng W, Hu S, Shi B. Spinal cord injury modeling: from modeling to evaluation using rats as examples. *Front Neurol.* 2025;16:1573779.

doi: 10.3389/fneur.2025.1573779

13. Perez NE, Godbole NP, Amin K, Syan R, Gater DR Jr. Neurogenic Bladder Physiology, Pathogenesis, and Management after Spinal Cord Injury. *J Pers Med*. 2022;12(6):968.

doi: 10.3390/jpm12060968

14. Maharjan S, Ma C, Singh B, *et al.* Advanced 3D imaging and organoid bioprinting for biomedical research and therapeutic applications. *Adv Drug Deliv Rev*. 2024;208:115237.

doi: 10.1016/j.addr.2024.115237

15. Carvalho D, Pinto S, Sarmento B. Modeling the human bladder tissue using three dimensional in vitro approaches as a tool for drug screening platforms. *Acta Biomater*. 2026;210:296-313.

doi: 10.1016/j.actbio.2025.12.018

16. Wang H, Yu H, Zhou X, *et al.* An Overview of Extracellular Matrix-Based Bioinks for 3D Bioprinting. *Front Bioeng Biotechnol*. 2022;10:905438.

doi: 10.3389/fbioe.2022.905438

17. Ashammakhi N, Ahadian S, Xu C, *et al.* Bioinks and bioprinting technologies to make heterogeneous and biomimetic tissue constructs. *Mater Today Bio*. 2019;1:100008.

doi: 10.1016/j.mtbio.2019.100008

18. Cruz EM, Machado LS, Zamproni LN, *et al.* A Gelatin Methacrylate-Based Hydrogel as a Potential Bioink for 3D Bioprinting and Neuronal Differentiation. *Pharmaceutics*. 2023;15(2):627.

doi: 10.3390/pharmaceutics15020627

19. Bova L, Maggiotto F, Micheli S, *et al.* A Porous Gelatin Methacrylate-Based Material for 3D Cell-Laden Constructs. *Macromol Biosci*. 2023;23(2):e2200357.

doi: 10.1002/mabi.202200357

20. Ling Z, Zhao J, Song S, *et al.* Chitin nanocrystal-assisted 3D bioprinting of gelatin methacrylate scaffolds. *Regen Biomater*. 2023;10:rbad058.

doi: 10.1093/rb/rbad058

21. Wei Q, Zhou J, An Y, Li M, Zhang J, Yang S. Modification, 3D printing process and application of sodium alginate based hydrogels in soft tissue engineering: A review. *Int J Biol Macromol*. 2023;232:123450.

doi: 10.1016/j.ijbiomac.2023.123450

22. Gao Q, Kim BS, Gao G. Advanced Strategies for 3D Bioprinting of Tissue and Organ Analogs Using Alginate Hydrogel Bioinks. *Mar Drugs*. 2021;19(12):708.

doi: 10.3390/md19120708

23. Chae S, Kim J, Yi HG, Cho DW. 3D Bioprinting of an In Vitro Model of a Biomimetic Urinary Bladder with a

Contract-Release System. *Micromachines*. 2022;13(2):277.

doi: 10.3390/mi13020277

24. Xuan Z, Peng Q, Larsen T, *et al.* Tailoring Hydrogel Composition and Stiffness to Control Smooth Muscle Cell Differentiation in Bioprinted Constructs. *Tissue Eng Regen Med*. 2023;20(2):199-212.

doi: 10.1007/s13770-022-00500-1

25. Li S, Meng X, Zhong Z, Li C. Advances in 3D bioprinting of functional biomaterials for neural tissue engineering. *Tissue Cell*. 2025;96:103024.

doi: 10.1016/j.tice.2025.103024

26. Lee S, Kim JH, Kang SJ, Chang IH, Park JY. Customized Multilayered Tissue-on-a-Chip (MToC) to Simulate Bacillus Calmette–Guérin (BCG) Immunotherapy for Bladder Cancer Treatment. *BioChip J.* 2022;16(1):67-81.

doi: 10.1007/s13206-022-00047-2

27. Zhao F, Yang T, Zhou L, *et al.* Construction of tissue-engineered bladders using an artificial acellular nanocomposite scaffold loaded with stromal vascular fraction secretome. *Acta Biomater.* 2023;167:260-277.

doi: 10.1016/j.actbio.2023.05.041

28. Adamowicz J, Pokrywczynska M, Van Breda SV, Kloskowski T, Drewa T. Concise Review: Tissue Engineering of Urinary Bladder; We Still Have a Long Way to Go?. *Stem Cells Transl Med*. 2017;6(11):2033-2043.

doi: 10.1002/sctm.17-0101

29. Yoshida T, Sopko NA, Kates M, *et al.* Impact of spheroid culture on molecular and functional characteristics of bladder cancer cell lines. *Oncol Lett*. 2019;18(5):4923-4929.

doi: 10.3892/ol.2019.10786

30. Wang Y, Shi J, Wang Y, *et al.* Advances in three-dimensional bioprinted tumor organoids: From model construction to clinical translation. *Int J Bioprint.* 2025;0(0):025390393.

doi: 10.36922/ijb025390393

31. Topoliova K, Harsanyi S, Danisovic L, Ziaran S. Tissue Engineering and Stem Cell Therapy in Neurogenic Bladder Dysfunction: Current and Future Perspectives. *Medicina*. 2023;59(8):1416.

doi: 10.3390/medicina59081416

32. Pokharel R, Leipzig ND. 3D Bioprinting for Spinal Cord Injury: Engineering Scaffolds for Functional Recovery. *ACS Biomater Sci Eng*. 2026;12(2):757-772.

doi: 10.1021/acsbiomaterials.5c01474

33. Huebner EA, Strittmatter SM. Axon regeneration in the peripheral and central nervous systems. *Results Probl Cell Differ*. 2009;48:339-351.

doi: 10.1007/400_2009_19

34. Jiu J, Liu H, Li D, *et al.* 3D bioprinting approaches for spinal cord injury repair. *Biofabrication*. 2024;16(3):10.1088/1758-5090/ad3a13.

doi: 10.1088/1758-5090/ad3a13

35. Koffler J, Zhu W, Qu X, *et al.* Biomimetic 3D-printed scaffolds for spinal cord injury repair. *Nat Med*. 2019;25(2):263-269.

doi: 10.1038/s41591-018-0296-z

36. Liu X, Song S, Chen Z, *et al.* Release of O-GlcNAc transferase inhibitor promotes neuronal differentiation of neural stem cells in 3D bioprinted supramolecular hydrogel scaffold for spinal cord injury repair. *Acta Biomater*. 2022;151:148-162.

doi: 10.1016/j.actbio.2022.08.031

37. Cao X, Li X, Shi W, *et al.* 3D-Bioprinted Scaffolds with Precise Factor Delivery for Spinal Cord Injury Repair. *ACS Appl Mater Interfaces*. 2025;17(30):42586-42601.

doi: 10.1021/acsami.5c03076

38. Kanai AJ, Andersson KE, Fry CH, Yoshimura N. Targeting neurotrophin and nitric oxide signaling to promote recovery and ameliorate neurogenic bladder dysfunction following spinal cord injury - Mechanistic concepts and clinical implications. *Continence*. 2023;6:100703.

doi: 10.1016/j.cont.2023.100703

39. Liu S, Yang H, Chen D, *et al.* Three-dimensional bioprinting sodium alginate/gelatin scaffold combined with neural stem cells and oligodendrocytes markedly promoting nerve regeneration after spinal cord injury. *Regen Biomater*. 2022;9:rbac038.

doi: 10.1093/rb/rbac038

40. Yu M, Sun P, Sun C, Jin WL. Bioelectronic medicine potentiates endogenous NSCs for neurodegenerative diseases. *Trends Mol Med*. 2023;29(11):886-896.

doi: 10.1016/j.molmed.2023.08.005

41. Stassart RM, Gomez-Sanchez JA, Lloyd AC. Schwann Cells as Orchestrators of Nerve Repair: Implications for Tissue Regeneration and Pathologies. *Cold Spring Harb Perspect Biol*. 2024;16(6):a041363.

doi: 10.1101/cshperspect.a041363

42. Gao C, Li Y, Liu X, Huang J, Zhang Z. 3D bioprinted conductive spinal cord biomimetic scaffolds for promoting neuronal differentiation of neural stem cells and repairing of spinal cord injury. *Chem Eng J.* 2023;451:138788.

doi: 10.1016/j.cej.2022.138788

43. Szymoniuk M, Mazurek M, Dryla A, Kamieniak P. The application of 3D-bioprinted scaffolds for neuronal regeneration after traumatic spinal cord injury - A systematic review of preclinical in vivo studies. *Exp Neurol*. 2023;363:114366.

doi: 10.1016/j.expneurol.2023.114366

44. Chen J, Wang L, Liu M, *et al.* Implantation of adipose-derived mesenchymal stem cell sheets promotes axonal regeneration and restores bladder function after spinal cord injury. *Stem Cell Res Ther*. 2022;13(1):503.

doi: 10.1186/s13287-022-03188-1

45. Zhang J, Chen Y, Huang Y, *et al.* A 3D-Printed Self-Adhesive Bandage with Drug Release for Peripheral Nerve Repair. *Adv Sci*. 2020;7(23):2002601.

doi: 10.1002/advs.202002601

46. He J, Qian L, Li Z, *et al.* A tissue bandage for pelvic ganglia injury. *Nat Commun*. 2024;15(1):8972.

doi: 10.1038/s41467-024-53302-5

47. Elia E, Brownell D, Chabaud S, Bolduc S. Tissue Engineering for Gastrointestinal and Genitourinary Tracts. *Int J Mol Sci*. 2022;24(1):9.

doi: 10.3390/ijms24010009

48. Azari F, Robertson AM, Tobe Y, *et al.* Elucidating the high compliance mechanism by which the urinary bladder fills under low pressures. *Sci Rep*. 2025;15(1):25356.

doi: 10.1038/s41598-025-07479-4

49. Habteyes FG, Komari SO, Nagle AS, *et al.* Modeling the influence of acute changes in bladder elasticity on pressure and wall tension during filling. *J Mech Behav Biomed Mater*. 2017;71:192-200.

doi: 10.1016/j.jmbbm.2017.02.020

50. Hu JC, Osborn SL, Sanchez PC, Xu W, Christiansen BA, Kurzrock EA. Using uniaxial tensile testing to evaluate the biomechanical properties of bladder tissue after spinal cord injury in rat model. *J Biomech*. 2023;152:111571.

doi: 10.1016/j.jbiomech.2023.111571

51. Hanczar M, Moazen M, Day R. The Significance of Biomechanics and Scaffold Structure for Bladder Tissue Engineering. *Int J Mol Sci*. 2021;22(23):12657.

doi: 10.3390/ijms222312657

52. Zhao Y, Peng H, Sun L, *et al.* The application of small intestinal submucosa in tissue regeneration. *Mater Today Bio*. 2024;26:101032.

doi: 10.1016/j.mtbio.2024.101032

53. Brown M, Li J, Moraes C, Tabrizian M, Li-Jessen NYK. Decellularized extracellular matrix: New promising and challenging biomaterials for regenerative medicine. *Biomaterials*. 2022;289:121786.

doi: 10.1016/j.biomaterials.2022.121786

54. Zhang XZ, Jiang YL, Hu JG, *et al.* Procyanidins-crosslinked small intestine submucosa: A bladder patch promotes smooth muscle regeneration and bladder function restoration in a rabbit model. *Bioact Mater*. 2020;6(6):1827-1838.

doi: 10.1016/j.bioactmat.2020.11.023

55. Zhao W, Yang Y, Liu Y, *et al.* Biomimetic multilayer scaffolds with prolonged retention of stem cells-recruiting and angiogenic peptides for promoting bladder regeneration. *Compos Part B Eng*. 2024;277:111409.

doi: 10.1016/j.compositesb.2024.111409

56. Forooghi M, Askari A, Haghdel M, *et al.* Engineering the Future of Bladder Repair: Can Biocompatible 3D-Printed Scaffolds Serve as a Novel Alternative to Intestinal Segments for the Treatment of Bladder Exstrophy? *Adv Urol*. 2025;2025:9437696.

doi: 10.1155/aiu/9437696

57. Ajalloueian F, Lemon G, Hilborn J, Chronakis IS, Fossum M. Bladder biomechanics and the use of scaffolds for regenerative medicine in the urinary bladder. *Nat Rev Urol*. 2018;15(3):155-174.

doi: 10.1038/nrurol.2018.5

58. Xuan Z, Gurevich L, Christiansen JC, Zachar V, Pennisi CP. Stable hydrogel adhesion to polydimethylsiloxane enables cyclic mechanical stimulation of 3D-bioprinted smooth muscle constructs. *Biotechnol Bioeng*. 2023;120(11):3396-3408.

doi: 10.1002/bit.28516

59. Ding W, Ge Y, Zhang T, Zhang C, Yin X. Advanced construction strategies to obtain nanocomposite hydrogels for bone repair and regeneration. *NPG Asia Mater.* 2024;16(1):14.

doi: 10.1038/s41427-024-00533-z

60. Soufivand AA, Abolfathi N, Hashemi SA, Lee SJ. Prediction of mechanical behavior of 3D bioprinted tissue-engineered scaffolds using finite element method (FEM) analysis. *Addit Manuf.* 2020;33:101181.

doi: 10.1016/j.addma.2020.101181

61. Wang Y, Liao L. Histologic and functional outcomes of small intestine submucosa-regenerated bladder tissue. *BMC Urol*. 2014;14:69.

doi: 10.1186/1471-2490-14-69

62. Zhang YS, Dolatshahi-Pirouz A, Orive G. Regenerative cell therapy with 3D bioprinting. *Science*. 2024;385(6709):604-606.

doi: 10.1126/science.add8593

63. Zhao W, Xu T. Preliminary engineering for in situ in vivo bioprinting: a novel micro bioprinting platform for in situ in vivo bioprinting at a gastric wound site. *Biofabrication*. 2020;12(4):045020.

doi: 10.1088/1758-5090/aba4ff

64. Masson-Meyers DS, Tayebi L. Vascularization strategies in tissue engineering approaches for soft tissue repair. *J Tissue*

Eng Regen Med. 2021;15(9):747-762.

doi: 10.1002/term.3225

65. Wang N, Wang H, Weng D, *et al.* Nanomaterials for small diameter vascular grafts: overview and outlook. *Nanoscale Adv*. 2023;5(24):6751-6767.

doi: 10.1039/d3na00666b

66. Yeo M, Sarkar A, Singh YP, Derman ID, Datta P, Ozbolat IT. Synergistic coupling between 3D bioprinting and vascularization strategies. *Biofabrication*. 2023;16(1):012003.

doi: 10.1088/1758-5090/ad0b3f

67. Guo HL, Peng XF, Bao XQ, *et al.* Bladder reconstruction using autologous smooth muscle cell sheets grafted on a pre-vascularized capsule. *Theranostics*. 2020;10(23):10378-10393.

doi: 10.7150/thno.47006

68. Keene JBD, Jackson R, Batra G, *et al.* Pre-vascularisation of the acellular bladder matrix using the omentum in a porcine model prior for bladder reconstruction-a step towards clinical application?. *Pediatr Surg Int*. 2024;40(1):308.

doi: 10.1007/s00383-024-05855-1

69. Ahmad A, Kim SJ, Jeong YJ, *et al.* Coaxial bioprinting of a stentable and endothelialized human coronary artery-sized *in vitro* model. *J Mater Chem B*. 2024;12(35):8633-8646.

doi: 10.1039/d4tb00601a

70. Zuo X, Han P, Yuan D, *et al.* Implantation of Adipose-Derived Mesenchymal Stromal Cells (ADSCs)-Lining Prosthetic Graft Promotes Vascular Regeneration in Monkeys and Pigs. *Tissue Eng Regen Med*. 2024;21(4):641-651.

doi: 10.1007/s13770-023-00615-z

71. Huang G, Zhao Y, Chen D, *et al.* Applications, advancements, and challenges of 3D bioprinting in organ transplantation. *Biomater Sci*. 2024;12(6):1425-1448.

doi: 10.1039/d3bm01934a

72. Christou CD, Vasileiadou S, Sotiroudis G, Tsoulfas G. Three-Dimensional Printing and Bioprinting in Renal Transplantation and Regenerative Medicine: Current Perspectives. *J Clin Med*. 2023;12(20):6520.

doi: 10.3390/jcm12206520

73. Booth D, Afshari R, Ghovvati M, Shariati K, Sturm R, Annabi N. Advances in 3D bioprinting for urethral tissue reconstruction. *Trends Biotechnol*. 2024;42(5):544-559.

doi: 10.1016/j.tibtech.2023.10.009

74. Zhu H, Kuang H, Huang X, *et al.* 3D printing of drug delivery systems enhanced with micro/nano-technology. *Adv Drug Deliv Rev*. 2025;216:115479.

doi: 10.1016/j.addr.2024.115479

75. Chowdhury SR, Mondal G, Ratnayake P, Basu B. Three-Dimensional Extrusion Printed Urinary Specific Grafts: Mechanistic Insights into Buildability and Biophysical Properties. *ACS Biomater Sci Eng*. 2024;10(2):1040-1061.

doi: 10.1021/acsbiomaterials.3c01422

76. Przedlacka A, Pellino G, Fletcher J, Bello F, Tekkis PP, Kontovounisios C. Current and future role of three-dimensional modelling technology in rectal cancer surgery: A systematic review. *World J Gastrointest Surg*. 2021;13(12):1754-1769.

doi: 10.4240/wjgs.v13.i12.1754

77. Pietrabissa A, Marconi S, Peri A, *et al.* From CT scanning to 3-D printing technology for the preoperative planning in laparoscopic splenectomy. *Surg Endosc*. 2016;30(1):366-371.

doi: 10.1007/s00464-015-4185-y

78. Segaran N, Saini G, Mayer JL, *et al.* Application of 3D Printing in Preoperative Planning. *J Clin Med*. 2021;10(5):917.

doi: 10.3390/jcm10050917

79. Kalidindi S. The role of three-dimensional (3D) printing in plastic and reconstructive surgery: innovations and applications. *Eur J Plast Surg.* 2024;47(1):96.

doi: 10.1007/s00238-024-02242-w

80. Vogel K, Nakib N. Off-Label but On-Target: Sacral Neuromodulation for Neurogenic Bladder Dysfunction. *Curr Urol Rep*. 2025;26(1):52.

doi: 10.1007/s11934-025-01280-6

81. Wei Z, Zhang Y, Hou J. Effectiveness and safety of sacral neuromodulation for neurogenic bladder. *Neurol Res*. 2023;45(6):520-529.

doi: 10.1080/01616412.2022.2162223

82. Yuan H, Xiao Y, Lin X, *et al.* Application of Augmented Reality for Accurate Punctures During Stage 1 Sacral Neuromodulation. *Int Neurourol J*. 2024;28(4):302-311.

doi: 10.5213/inj.2448330.165

83. Huri E, Tunç O, Küçük B. 240 - Evaluation of the Effectiveness of Patient-Specific 3D Modeling for Surgical Planning in Sacral Neuromodulation Surgery: Initial Case Results. *Continence*. 2025;15:102164.

doi: 10.1016/j.cont.2025.102164

84. Aydogan TB, Patel M, Digesu A, *et al.* Innovative training modality for sacral neuromodulation (SNM): Patient-specific computerized tomography (CT) reconstructed 3D-printed training system: ICS School of Modern Technology novel training modality. *Neurourol Urodyn*. 2023;42(1):297-302.

doi: 10.1002/nau.25083

85. Zhao J, Tang H, Xu R, Chen G. Intraoperative application of different imaging techniques in sacral neuromodulation: a systematic review and meta-analysis. *BMC Urol*.

2025;25(1):201.

doi: 10.1186/s12894-025-01903-7

86. Jacobson NM, Brusilovsky J, Ducey R, *et al.* The Inner Complexities of Multimodal Medical Data: Bitmap-Based 3D Printing for Surgical Planning Using Dynamic Physiology. *3D Print Addit Manuf*. 2023;10(5):855-868.

doi: 10.1089/3dp.2022.0265

87. Wang X, Zhang F, Liao L. Current Applications and Future Directions of Bioengineering Approaches for Bladder Augmentation and Reconstruction. *Front Surg*. 2021;8:664404.

doi: 10.3389/fsurg.2021.664404

88. Chen H, Zhang B, Huang J. Recent advances and applications of artificial intelligence in 3D bioprinting. *Biophys Rev*. 2024;5(3):031301.

doi: 10.1063/5.0190208

89. Bhardwaj N, Sood M, Gill SS. 3D-Bioprinting and AI-empowered Anatomical Structure Designing: A Review. *Curr Med Imaging*. 2024;20:e15734056259274.

doi: 10.2174/0115734056259274231019061329

90. Kourounis G, Elmahmudi AA, Thomson B, Hunter J, Ugail H, Wilson C. Computer image analysis with artificial intelligence: a practical introduction to convolutional neural networks for medical professionals. *Postgrad Med J*. 2023;99(1178):1287-1294.

doi: 10.1093/postmj/qgad095

91. Fasse A, Newton T, Liang L, *et al.* A novel CNN-based image segmentation pipeline for individualized feline spinal cord stimulation modeling. *J Neural Eng*. 2024;21(3):ad4e6b.

doi: 10.1088/1741-2552/ad4e6b

92. Hazra D, Byun YC, Kim WJ, Kang CU. Synthesis of Microscopic Cell Images Obtained from Bone Marrow Aspirate Smears through Generative Adversarial Networks. *Biology*. 2022;11(2):276.

doi: 10.3390/biology11020276

93. Ahmad Z, Jaffri ZuA, Chen M, Bao S. Understanding GANs: fundamentals, variants, training challenges, applications, and open problems. *Multimed Tools Appl.* 2025;84(12):10347-10423.

doi: 10.1007/s11042-024-19361-y

94. Wang T, Lan J, Han Z, *et al.* O-Net: A Novel Framework With Deep Fusion of CNN and Transformer for Simultaneous Segmentation and Classification. *Front Neurosci*. 2022;16:876065.

doi: 10.3389/fnins.2022.876065

95. Bediaga-Bañeres H, Moreno-Benítez I, Arrasate S, *et al.* Artificial Intelligence-Driven Modeling for Hydrogel Three-Dimensional Printing: Computational and Experimental Cases of Study. *Polymers*. 2025;17(1):121.

doi: 10.3390/polym17010121

96. Zhu Z, Ng DWH, Park HS, McAlpine MC. 3D-printed multifunctional materials enabled by artificial-intelligence-assisted fabrication technologies. *Nat Rev Mater.* 2020;6(1):27-47.

doi: 10.1038/s41578-020-00235-2

97. Chou A, Torres-Espin A, Kyritsis N, *et al.* Expert-augmented automated machine learning optimizes hemodynamic predictors of spinal cord injury outcome. *PLoS ONE*. 2022;17(4):e0265254.

doi: 10.1371/journal.pone.0265254

98. Ramchandani R, Guo E, Biglou SG, *et al.* Representation and Bias in Artificial Intelligence Models for Thyroid Cancer: A Systematic Review. *Thyroid*. 2025;35(12):1391-1402.

doi: 10.1177/10507256251372175

99. Jadhav S, Bharne S, Narawade V. Advancements in brain tumor classification: a survey of transfer learning techniques. *Int J Inform Commun Technol (IJ-ICT).* 2025;14(3):1002-1014.

doi: 10.11591/ijict.v14i3.pp1002-1014

100. Liu D, Kababji SE, Mitsakakis N, *et al.* Augmenting small tabular health data for training prognostic ensemble machine learning models using generative models. *BMC Med Inform Decis Mak*. 2025;25(1):435.

doi: 10.1186/s12911-025-03266-3

101. Bian X, Lin H, Wang Y, *et al.* Federated cross-source learning for lung nodule segmentation with data characteristic-aware weight optimization. *Pattern Recognit*. 2026;172:112396.

doi: 10.1016/j.patcog.2025.112396

102. Shen JD, Chen SJ, Chen HY, Chiu KY, Chen YH, Chen WC. Review of Animal Models to Study Urinary Bladder Function. *Biology*. 2021;10(12):1316.

doi: 10.3390/biology10121316

103. Hockney S, Parker J, Turner JE, *et al.* Next generation organoid engineering to replace animals in cancer drug testing. *Biochem Pharmacol*. 2023;213:115586.

doi: 10.1016/j.bcp.2023.115586

104. Zhao J, Zhang H, Ling Z, *et al.* A bilayer bioengineered patch with sequential dual-growth factor release to promote vascularization in bladder reconstruction. *Regen Biomater*. 2024;11:rbae083.

doi: 10.1093/rb/rbae083

105. Wang H, Zhang P, Lu P, *et al.* Neural tissue-engineered prevascularization *in vivo* enhances peripheral neuroregeneration via rapid vascular inosculation. *Mater*

Today Bio. 2023;21:100718.

doi: 10.1016/j.mtbio.2023.100718

106. Yu M, Chen J, Wang L, *et al.* Engineering pedicled vascularized bladder tissue for functional bladder defect repair. *Bioeng Transl Med*. 2022;8(5):e10440.

doi: 10.1002/btm2.10440

107. Xiao S, Wang P, Zhao J, *et al.* Bladder Acellular Matrix Prepared by a Self-Designed Perfusion System and Adipose-Derived Stem Cells to Promote Bladder Tissue Regeneration. *Front Bioeng Biotechnol*. 2022;10:794603.

doi: 10.3389/fbioe.2022.794603

108. Ren B, Jiang Z, Murfee WL, Katz AJ, Siemann D, Huang Y. Realizations of vascularized tissues: From *in vitro* platforms to *in vivo* grafts. *Biophys Rev*. 2023;4(1):011308.

doi: 10.1063/5.0131972

109. Wang J, Yang X, Xu M, Liu H, Liu L, Tan Z. Distinct cellular microenvironment with cytotypic effects regulates orderly regeneration of vascular tissues. *Materials Today Bio*. 2024;26:101033.

doi: 10.1016/j.mtbio.2024.101033

110. Shukla AK, Lee D, Yoon S, Ahn M, Kim BS. Vascularization strategies for human skin tissue engineering via 3D bioprinting. *Int J Bioprint*. 2024;10(3).

doi: 10.36922/ijb.1727

111. Guimarães CF, Gasperini L, Marques AP, Reis RL. The stiffness of living tissues and its implications for tissue engineering. *Nat Rev Mater*. 2020;5(5):351-370.

doi: 10.1038/s41578-019-0169-1

112. Garriboli M, Deguchi K, Totonelli G, *et al.* Development of a porcine acellular bladder matrix for tissue-engineered bladder reconstruction. *Pediatr Surg Int*. 2022;38(5):665-677.

doi: 10.1007/s00383-022-05094-2

113. Eshraghi S, Das S. Mechanical and microstructural properties of polycaprolactone scaffolds with one-dimensional, two-dimensional, and three-dimensional orthogonally oriented porous architectures produced by selective laser sintering. *Acta Biomater*. 2010;6(7):2467-2476.

doi: 10.1016/j.actbio.2010.02.002

114. Ghosh Dastidar A, Clarke SA, Larrañeta E, Buchanan F, Manda K. In Vitro Degradation of 3D-Printed Poly(L-lactide-Co-Glycolic Acid) Scaffolds for Tissue Engineering Applications. *Polymers*. 2023;15(18):3714.

doi: 10.3390/polym15183714

115. Ma C, Zhu H, Liu C, Wang W. Advanced biomaterials for radiation-induced dermatitis: from pathophysiological mechanisms to translational interfaces. *Mini Rev*. 2025;12.

doi: 10.3389/fmats.2025.1631141

116. Afewerki S, Sheikhi A, Kannan S, Ahadian S, Khademhosseini A. Gelatin-polysaccharide composite scaffolds for 3D cell culture and tissue engineering: Towards natural therapeutics. *Bioeng Transl Med*. 2018;4(1):96-115.

doi: 10.1002/btm2.10124