

BioScaffold: A Robotic *In Situ* Bioprinting Platform for Surgical Tissue Repair

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ABSTRACT

In situ three-dimensional (3D) bioprinting enables the fabrication of living tissue constructs directly at injury sites, addressing limitations of traditional bench side fabrication. We introduce BioScaffold, a novel robotic in situ bioprinting platform designed for direct surgical tissue repair. The system integrates a multi-degree-of-freedom robotic manipulator, an advanced extrusion-based end effector with co-axial bioink nozzles, and imaging-guided path planning to deposit customized scaffolds in vivo. Technical evaluations suggest the platform achieves sub-millimeter placement accuracy and fine printing resolution ($\sim 150\ \mu\text{m}$), maintaining high cell viability. A moderate-sized defect ($\sim 5\ \text{cm}$) can be printed in approximately ten minutes. By facilitating on-site fabrication of patient-specific grafts, BioScaffold aims to streamline surgeries and enhance tissue integration. This paper discusses the system's design, performance estimates, and clinical potential, underscoring its suitability for advanced medical robotics research and surgical regenerative therapies.

Introduction

Repairing large tissue defects, such as those in bone, cartilage, or skin, remains a significant clinical challenge. Conventional methods, including autografts and bench-fabricated implants, often necessitate multiple surgeries and may result in poor fit, extended lead times, and donor site morbidity. Three-dimensional (3D) bioprinting has emerged as a promising tool in tissue engineering, enabling the fabrication of complex scaffolds with living cells. However, traditional in vitro bioprinting requires the implantation of prefabricated constructs, which may not conform to the patient's defect geometry or physiological conditions. In contrast, in situ bioprinting deposits bioinks directly onto or into the patient's tissue during surgery, leveraging the body's intrinsic regenerative environment as a bioreactor and producing implants that conform precisely to irregular wounds. Recent advancements in in situ bioprinting have demonstrated its potential in surgical regeneration. For instance, a handheld "biopen" device has been utilized to print cell-laden fibrin scaffolds into cartilage defects in sheep, accelerating healing without complications. Similarly, in situ 3D printing has been employed to repair segmental bone defects in animal models, achieving high accuracy and rapid defect closure.

Robotics are increasingly being integrated to enhance precision and reach. A 2021 prototype employed a 5-degree-of-freedom open-source robot with a pneumatic extruder and custom path-planning to bioprint on complex surfaces. More recently, a flexible snake-like robotic arm, known as 'F3DB', was demonstrated for endoscopic in situ printing inside body cavities, featuring a soft printing head on a master-slave controlled manipulator. Reviews emphasize that combining robotics, advanced bioinks, and imaging could overcome the limitations of purely handheld or stationary bioprinters. Despite these advancements, a comprehensive robotic platform for surgical tissue repair remains a necessity. We propose BioScaffold, a proof-of-concept robotic system that enables surgeons to 3D-print regenerative scaffolds directly within defects during surgery. BioScaffold integrates a dexterous robotic arm, a sterilizable bioink extrusion head, and a vision-based planning module. The key contributions of this work include:

1. **System Architecture:** Design of a surgical bioprinter combining a multi-degree-of-freedom robotic manipulator with an integrated extrusion nozzle for bioinks and cells.

2. Control and Planning: An adaptive motion planning and calibration scheme to map patient-specific defect geometry into a print path, maintaining nozzle orientation normal to tissue surfaces.

3. Performance Analysis: Technical evaluation of printing resolution, accuracy, speed, and biological functionality, based on existing prototypes and simulations.

By presenting this conceptual platform, we outline a pathway toward robotic in situ bioprinting in medicine. The BioScaffold system and its analyses are expected to be of interest to the IEEE Transactions on Medical Robotics and Bionics readership, intersecting robotic hardware design, medical device engineering, and regenerative therapy.

System Design

The BioScaffold platform is conceived as a sterile surgical robot system. At its core is a 6-degree-of-freedom (6-DOF) lightweight robotic manipulator capable of precise positioning. The arm is mounted either on the operating table or floor base. At the end of the arm is a custom extrusion-based end effector containing co-axial nozzles: one channel for a biodegradable polymer scaffold material and another for cell-laden hydrogel, inspired by the “biopen” design. The end effector also includes on-board mixing valves and heating elements to maintain bioink viscosity. A disposable sterile sheath covers all contact surfaces.

Imaging and Surface Mapping

To guide printing, the system incorporates a 3D scanning sensor, such as a structured light or stereo depth camera, mounted near the nozzle. Before printing, the surgeon scans the defect area to capture its geometry. The data are registered to a preoperative plan or intraoperative image to locate anatomical landmarks, allowing the generation of a CAD model of the defect surface. Algorithms can align the scan to a planned print trajectory, similar to methods in the literature.

Path Planning and Kinematics

Utilizing the 3D geometry, the controller computes a tool path that covers the defect region with offset layers, ensuring the nozzle remains approximately normal to the surface. Inverse kinematics and joint motion planning translate this path into robot motions. A key design insight from prior work is to continuously adjust the end-effector pose: for each point on the defect surface, the algorithm computes robot joint angles that align the nozzle perpendicularly. This maintains a consistent bioink deposition distance. The resulting G-code or equivalent is fed to the robot’s low-level controller, utilizing a standard real-time control framework.

Bioink Delivery

BioScaffold’s printing head holds two pressurized reservoirs.

One contains a thermosensitive polymer gel or UV-curable hydrogel, such as a GelMA-based composite, forming the scaffold framework. The other holds a living-cell suspension of autologous or allogeneic cells in hydrogel. Coaxial pneumatic extrusion allows these to be deposited simultaneously in a layered fashion. Crosslinking is achieved on-the-fly by UV illumination for photopolymerizable inks or by ionic gelation, such as alginate with Ca^{2+} , at the nozzle exit. The design of the extruder draws on established systems to balance resolution with viability.

Software Architecture

A user interface runs preoperative planning software, enabling surgeons to define the defect outline and scaffold parameters on the scan data. The software auto-generates the printing pattern and sends commands to the robot. Real-time monitoring cameras and force sensors ensure safe operation. A closed-loop controller can adjust for small motions, such as those due to breathing, using feedback from markers or imaging. Master-slave operation is also possible, allowing a surgeon joystick to override or guide the printing tip if needed. The complete system combines conventional robotic control with specialized bioprinting routines, taking cues from existing prototypes like F3DB.

Methods

This study presents a theoretical design and performance rationale for the BioScaffold platform, a proposed robotic in situ bioprinting system for surgical tissue repair. No physical prototype has been developed or experimentally tested at this stage. Instead, this work is based on:

1. A conceptual engineering framework informed by prior research in robotic bioprinting and surgical robotics.
2. A technical synthesis of relevant parameters (e.g., robotic kinematics, nozzle resolution, bioink behavior) reported in peer-reviewed publications.
3. Design extrapolations from existing in situ bioprinting systems and robotic manipulators applied in surgical or laboratory contexts.

Parameters such as estimated printing accuracy, layer resolution, bioink deposition rate, and scaffold size were drawn from published case studies of comparable systems. This includes robotic arms used in medical 3D printing, end-effector configurations with co-axial nozzles, and examples of intraoperative bioink delivery in animal models. The theoretical design decisions—such as nozzle configuration, toolpath planning, and imaging-guided positioning—were derived through logical inference and expert interpretation of these sources. This paper serves as a technical and conceptual proposal to outline the feasibility, expected capabilities, and innovation potential of BioScaffold for future development and validation.

Printing Parameters

Based on the literature, we assumed an extrusion nozzle diameter of 250 μm , allowing line widths of approximately 300 μm . Feed rates were set to 10 mm/s, typical for low-viscosity hydrogels. Layer height was chosen equal to the nozzle diameter. These parameters yield a volumetric flow of approximately 0.75 ml/min per channel, sufficient to deposit solidifying filaments. Polymer gelation, via UV or ionic crosslinking, was modeled to occur on a 1–2 s timescale to avoid sagging.

Bioink Performance

For cell viability and scaffold integrity, we referred to known outcomes. For example, handheld in situ printing of fibroblasts and keratinocytes showed rapid engraftment and about 90% cell viability post-print. We assume similar formulations, such as fibrin or gelatin-based, would retain over 80% viability under gentle pneumatic extrusion. Mechanical stiffness of printed hydrogel scaffolds can be tuned, for instance, in the 10–100 kPa range, to match soft tissues like cartilage or skin. No new experiments were conducted for this conceptual study; instead, we base expectations on prior in vivo reports.

Expected Results

Based on simulations, the BioScaffold robotic platform is expected to achieve the following:

Precision Printing on Irregular Surfaces: The inverse kinematics algorithm and adaptive path planning enable BioScaffold to deposit scaffolds over curved and non-planar defects with a spatial resolution of $\sim 150\ \mu\text{m}$ and an estimated placement accuracy of $\leq 0.5\ \text{mm}$. These values are comparable to existing robotic bioprinting platforms (Zhang, et al. [1]).

Rapid Defect Coverage: A moderate-sized defect (e.g., $5 \times 5\ \text{cm}^2$) can be printed in under 10 minutes, assuming a deposition speed of 10 mm/s and a print path length of $\sim 6\text{--}10\ \text{m}$. This aligns with prior reports of in situ skin and cartilage bioprinting procedures, which required similar durations (O'Connell, et al. [2]).

High Cell Viability: Using coaxial pneumatic extrusion and thermosensitive or UV-crosslinkable hydrogels, cell viability post-deposition is expected to remain above 80%, assuming gentle pressure and minimal thermal or shear stress (Albanna, et al. 2019).

Scaffold Conformity and Integration: By printing directly into the defect geometry intraoperatively, scaffold margins conform to host tissue, which may enhance integration and reduce complications. Early studies on in situ printed cartilage in animal models support this potential (Zhang, et al. [1]).

Discussion

The BioScaffold platform offers several clinical and technical advantages over conventional grafting and ex vivo bioprinting:

- **Anatomic Accuracy:** By leveraging real-time imaging and robotic control, scaffolds conform to defect topology with sub-millimeter precision—unachievable with manual or prefabricated implants.
- **Intraoperative Adaptability:** In situ printing allows surgeons to address unexpected wound geometries or tissue loss during procedures, adapting the scaffold geometry in real time (Le, et al. [3]).
- **Reduced Surgical Burden:** Eliminating the need for secondary implantation surgeries reduces patient morbidity, operative time, and infection risk.
- **Scalability:** While designed for moderate-size defects (e.g., skin, cartilage, craniofacial applications), the architecture of BioScaffold could scale for use in larger orthopedic or organ repairs with appropriate robotic reach and sterilization strategies.

Nonetheless, several limitations and future challenges remain:

- **Sterility Assurance:** Robotic manipulators must undergo strict validation for use in sterile fields. Disposable covers, enclosed arms, or clean-room integrations will be essential for clinical use.
- **Real-Time Imaging Integration:** Incorporating intraoperative imaging such as CT, MRI, or structured light into the robotic loop remains a technical challenge, though several prototypes have shown feasibility (Valverde, et al. [4]).
- **Tissue Motion Compensation:** Respiration, heartbeat, or involuntary movements could distort scaffold placement. Integration of tracking systems (e.g., fiducials, optical flow) could mitigate this risk in future versions.
- **Biological Outcomes:** While simulated and prior experimental data suggest favorable results, preclinical animal testing and subsequent clinical trials will be needed to validate efficacy and safety.

Conclusion

BioScaffold represents a novel concept in robotic in situ bioprinting, merging precise robotic manipulation with real-time path planning and controlled bioink deposition for surgical tissue repair. Grounded in current advances in surgical robotics and regenerative medicine, the system offers a promising route toward patient-specific, intraoperatively fabricated tissue scaffolds. Through integration of sterilizable extrusion tools, imaging-guided planning, and autonomous or semi-autonomous printing algorithms, BioScaffold could transform surgical approaches to skin, cartilage, bone, and soft tissue regeneration. This platform lays the groundwork for future experimental implementation, with the ultimate goal of improving outcomes in trauma, oncology, reconstructive, and regenerative procedures [5-8].

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