REVIEW

3D Printing for Personalized Solutions in Cervical Spondylosis

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Abstract: In the context of the digital revolution, 3D printing technology brings innovation to the personalized treatment of cervical spondylosis, a clinically common degenerative disease that severely impacts the quality of life and increases the economic burden of patients. Although traditional surgeries, medications, and physical therapies are somewhat effective, they often fail` to meet individual needs, thus affecting treatment adherence and outcomes. 3D printing, with its customizability, precision, material diversity, and short production cycles, shows tremendous potential in the treatment of cervical spondylosis. This review discusses the multiple applications of 3D printing in the treatment of cervical spondylosis, including the design, manufacture, and advantages of 3D-printed cervical collars, the role of 3D models in clinical teaching and surgical simulation, and the application of 3D-printed scaffolds and implants in cervical surgery. It also discusses the current challenges and future directions.

Keywords: 3D printing, cervical spondylosis, cervical collar, orthopedic implants, biomaterials

Introduction

Cervical spondylosis is a common global spinal disease, primarily caused by degenerative changes in the cervical intervertebral discs, osteophyte growth, and joint degeneration. Not only does it manifest symptoms such as neck pain, upper limb numbness, nausea, and dizziness,[1] but it also leads to radiculopathy and myelopathy,[2] severely affecting patients' quality of life and functional abilities. Long-term pain may lead to psychological issues such as anxiety and depression, profoundly affecting patients and their families. With aging populations and changes in modern lifestyles, the incidence of cervical spondylosis is on the rise and showing trends of affecting younger populations.[2]

The causes of cervical spondylosis are diverse and complex, including age-related structural changes to the cervical spine and disc degeneration. Additionally, long-term poor posture, repetitive occupational injuries, congenital spinal stenosis, and participation in strenuous activities may accelerate the progression of the disease.[3] Diagnosis depends on clinical symptoms and radiological aids. Patients may exhibit symptoms such as discomfort behind the eye sockets and reduced neck mobility. When the spinal cord and nerve roots are affected, pain and numbness may radiate to the shoulders and arms.[4] Although magnetic resonance imaging is highly sensitive in detecting spinal pathologies, many asymptomatic individuals also show degenerative anomalies on it scans, so it should not be the primary diagnostic tool.[5] X-ray films are usually sufficient for initial examinations, while computed tomography combined with intrathecal contrast injection can more accurately assess the sites and extent of nerve compression.[6]

The treatment of cervical spondylosis includes both surgical and conservative methods, which aim to relieve pain, improve symptoms, and restore cervical function. Surgical treatments are generally indicated for patients who do not respond to conservative management or who present with neurological deficits or spinal cord compression. The natural progression of myelopathic cervical spondylosis tends to worsen over time,[7] so early surgery is recommended. However, surgical procedures, such as foraminotomy, anterior cervical discectomy and fusion, laminectomy, or laminoplasty, can be invasive and carry inherent risks. Moreover, these procedures are not universally suitable for all types of cervical

251

spondylosis and may not meet the specific needs of every patient.[6] Pharmacological treatments, including the use of steroids to reduce inflammation, NSAIDs for pain relief, and anticonvulsants or antidepressants for neuropathic pain,[8] are effective but often result in significant side effects. Consequently, long-term use of these medications is not advisable. Physical therapies such as traction help alleviate nerve compression, while acupuncture, massage, and electrotherapy can relieve pain and activate muscles. Sling exercise training, proprioceptive neuromuscular facilitation, and muscle energy techniques can increase muscle strength, improve flexibility, and enhance mobility.[9] However, the lengthy treatment duration and high costs limit many patients' accesses to treatment and long-term benefits. The complexity and heterogeneity of cervical spondylosis further complicate treatment effectiveness, underscoring the need for more personalized approaches. In this context, 3D printing technology offers substantial promise due to its customizability, precision, material diversity, and rapid production capabilities.[10] These features allow for more tailored treatment solutions that can potentially address the limitations of existing methods and improve patient outcomes.

This review aims to systematically expound on the applications of 3D printing technology in the treatment of cervical spondylosis, including the customization of cervical supports, surgical applications of bone implants, clinical teaching and surgery simulation through 3D models, analysis of material selection, and future prospects, providing references for clinicians to understand and apply this new technology, promoting the application and development of 3D printing technology in the treatment of cervical spondylosis, and ultimately enhancing treatment outcomes and quality of life for patients.

Introduction to 3D Printing Technology and Its Application in the Medical Field

Development of 3D Printing Technology

3D printing, also known as additive manufacturing, is a process that creates three-dimensional solid objects from a digital model by adding material layer by layer.[11] The primary steps include 3D modeling, slicing, printing, and post-processing. Based on the materials and techniques used, 3D printing can be divided into Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Direct Ink Writing (DIW).[10] FDM is known for its cost-effectiveness, using heated polymers to construct objects. However, its use of thermosetting materials limits sterilization processes, making it unsuitable for surgical applications and more commonly used for patient-specific drug delivery.[12] SLA and SLS utilize lasers to solidify or sinter materials, providing higher precision,[13] and making them suitable for creating sterilizable implant materials.[14] DIW is highly versatile, employing a syringe-like device to extrude gel materials, making it adaptable for various medical applications.[15] For a comprehensive overview of these 3D printing methods, their development, and medical applications, please refer to Figure 1.[10]

Since its inception in the 1980s with stereolithography, 3D printing's application in the medical field has expanded to include the creation of surgical models, personalized implants, and tissue engineering scaffolds.[10] The rise of 3D printing technology is attributed to its capability in complex and precise manufacturing; the diversity of materials has broadened its application scope, and the decreasing cost of 3D printing has made it more prevalent.

Applications of 3D Printing Technology in the Medical Field

3D printing has become a leading manufacturing technology in the medical field, revolutionizing tissue engineering, regenerative medicine, the pharmaceutical industry, and rehabilitation sectors.[16] Specific applications include: (1) Bioprinting of tissues and organs.[17] Bioprinting technology holds the potential for future breakthroughs in organ transplants, currently applied to skin, bone implants, and soft tissues.[18,19] (2) Surgical planning and simulation. 3D printed anatomical bio-similar models assist surgeons in understanding lesion sites, formulating detailed surgical plans, and conducting preoperative simulations to shorten surgery time and optimize outcomes, especially in vascular diseases, cardiac conditions, and oncological surgeries.[20,21] (3) Medical education and training. Color-printed models enable more intuitive and realistic learning and training for students and medical staff, enhancing educational effectiveness and training quality.[22,23] (4) Drug development and customization. 3D printing is used for tissue models in drug discovery, allowing precise control over drug dosage and release rates.[24,25] (5) Customized medical devices. Personalized medical
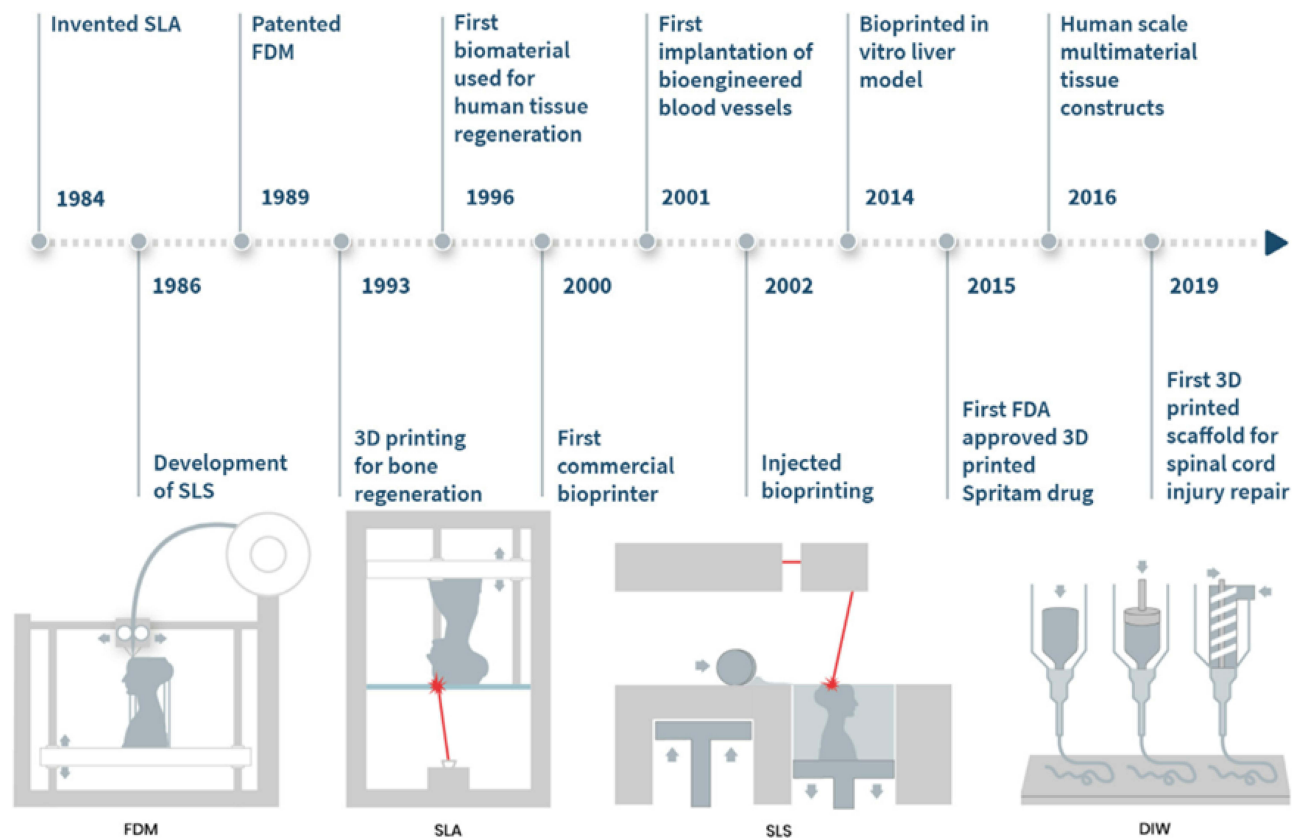
Figure 1 Methods of 3D Printing, Development History, and Medical Applications.
Abbreviations: FDM, Fused deposition modeling; SLA, Stereolithography; SLS, Selective laser sintering; DIW, Direct ink writing.

devices, prosthetics, and rehabilitation braces are fabricated based on specific patient needs and anatomical structures.[26–29]

Application of 3D Printing in the Treatment of Cervical Spondylosis
Personalized 3D Printed Cervical Collars

The human cervical spine is the most flexible but least stable joint. Repetitive movements beyond the normal range can lead to mechanical compression, increasing the risk of secondary injuries.[11] Wearing a cervical collar effectively provides support, alleviates pain and discomfort, improves the biomechanical load distribution between intervertebral discs, and promotes proper posture and functional recovery.[30–32] However, common cervical collars often fail to fully meet patient needs. 3D printed cervical collars are designed and manufactured based on the morphological and pathological characteristics of the patient's cervical spine through 3D scanning, modeling, and printing technologies. 3D scanning technologies like structured light capture the patient's neck shape in a natural standing or sitting position. This method offers more accurate cervical spine representations compared to CT scans, which are taken in a supine position. Combining with CT data enhances the precision of 3D-printed models and devices.[33] Cervical collars are beneficial in perioperative periods, acute trauma, and the management of chronic degenerative diseases.[34,35] Compared to common cervical collars, 3D printed personalized cervical collars offer numerous advantages, including precise fit to the patient's cervical spine morphology, enhanced comfort, precise control of the mechanical properties for personalized stable support, lightweight design to reduce the burden on the wearer, breathable material choices to avoid overheating and skin discomfort, and the ability to rapidly modify and produce based on changes in the patient's condition.[36] Figure 2 indicates that 3D printed cervical collars can improve patient compliance, ensuring continuity of treatment and enhancing overall satisfaction.

Figure 2 Common Types of Cervical Collars and a 3D-Printed Cervical Collar. (**a**) Soft collars, made of felt-like material, have a lower front and higher back to prevent hyperextension. (**b**) Rigid collars, made of hard plastic, offer strong fixation for severe neck injuries and post-operative care. (**c**) Inflatable collars, made of soft plastic, adjust by inflation for a better fit. (**d**) 3D-printed collars are customized from patient data, providing precise control over design, improving comfort and aesthetics.

The design and manufacturing of personalized 3D-printed cervical collars require multidisciplinary collaboration, tailored to the individual anatomical and pathological features of a patient's cervical spine to create comfortable, effective, and safe personalized brace. The process begins with data collection and processing. Data can be gathered using 3D scanning technology, which captures the shape of the patient's neck non-invasively to generate a high-precision 3D model. Common 3D scanning technologies include structured light scanning and laser scanning, known for their speed, high precision, and non-invasiveness.[37] Imaging data is then registered with 3D scanning data to create a comprehensive 3D model that includes both the internal and external morphology of the cervical spine. Based on this, virtual design and simulation are carried out to assess the fit, support effectiveness, and range of motion restriction of the collar. During the design, cervical spine biomechanical analysis is conducted. Professional CAD software and finite element analysis algorithms help in designing supports that conform to ergonomics and biomechanical principles, optimizing the collar design scheme.[38,39]

3D Printing Models, Devices, and Implants for Cervical Spine Surgery

Accurate 3D printed models of the cervical spine can assist in pre-surgical visualization and planning, providing surgeons with accurate simulation models that offer tactile feedback on varying bone densities.[40] These models aid in understanding disc herniation, nerve root or spinal cord compression, and joint fusion. They help determine the surgical approach and enable simulations to ensure optimal screw trajectories and precise implant placement,[41] reducing intraoperative risks and enhancing surgical success rates.[42,43]

3D-printed pedicle screw guides improve the accuracy and number of screw placements,[44] define safe screw trajectories, reduce vascular or nerve damage, shorten surgery time, and lessen radiation exposure,[45] and are suitable for upper, middle, and lower cervical spine surgeries.[46–48] In cases of cervical spine disease with cancer, preoperative use of 3D models to assess the extent of the tumor and its proximity to critical structures is highly valuable.[49]

Customized 3D printed implants enhance biological deficiencies for patients with abnormal anatomical structures or spinal deformities, avoiding damage to specific anatomical features, thus limiting trauma and complications.[50] The porosity and mechanical properties of 3D printed implants are comparable to cancellous bone, maximizing the reduction of stress shielding, and the microporous ultrastructure is conducive to bone induction, thus effectively preventing displacement or settlement.[51] 3D printing has improved the current manufacturing processes of implants and orthopedic surgeries, making significant advancements in printing bone graft substitutes and cartilage materials,[52] especially suitable for complex oncological pathologies and atypical bone defects.[50] Figure 3 shows the 3D printed models and implants used for cervical spine surgery.

In summary, 3D printing technology improves the treatment of cervical spondylosis in many aspects, including prevention, surgery, and protection. Figure 4 summarizes the applications of 3D printing in the prevention and treatment of cervical spondylosis.

Challenges and Future Prospects of 3D Printing

While 3D printing offers promising avenues for personalized treatment in cervical spondylosis, it also presents several challenges. Table 1 below outlines the main advantages and limitations observed in the use of this technology. 3D
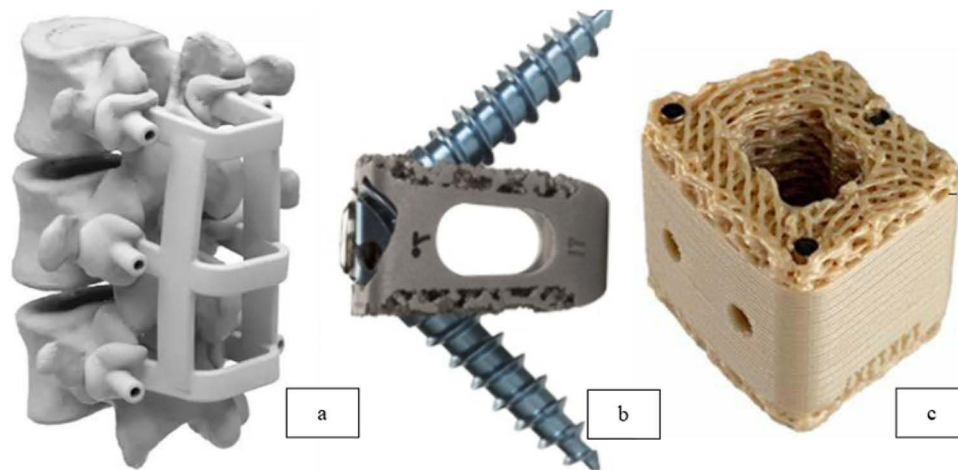
Figure 3 3D-Printed Spinal Models and Different Material Implants. (**a**) 3D printed spinal surgery guide plate includes vertebral models and pedicle screw guides. (**b**) 3D printed porous titanium cervical intervertebral fusion system. (**c**) Extruded 3D printed PEEK cervical implants.
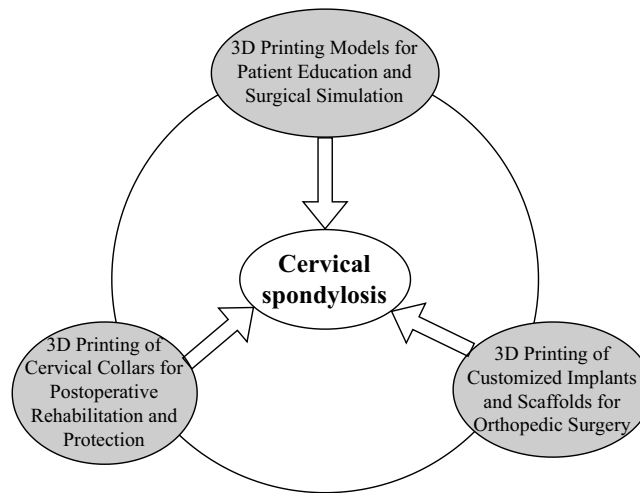

Figure 4 The Role of 3D Printing Technology in the Prevention and Treatment of Cervical Spondylosis.

printing technology presents challenges in terms of material selection and process optimization. While the variety of available 3D printing biomaterials is extensive, they still cannot fully replicate the complex structures and functions of human tissues. To address this, researchers are developing multi-material printing technologies and more advanced bio-ink formulations to better mimic the heterogeneity of human tissues.[10] The development of high-performance biomaterials requires not only appropriate chemical and mechanical properties but also biocompatibility and bioactivity. This

Table 1 Advantages and Limitations of 3D Printing in Cervical Spondylosis Treatment

Aspect	Benefits	Limitations
Customization	High customization based on individual patient data, tailored to specific clinical needs	Limited by the accuracy and resolution of scanning and printing
Design Flexibility	Enables the creation of complex shapes and structures	Requires specialized software and design skills
Production Speed	Faster production compared to traditional methods	Initial setup and design phases can be time-consuming

(*Continued*)

Table 1 (Continued).

Aspect	Benefits	Limitations
Cost Efficiency	Reduces material waste and potentially lowers production and development costs	High initial investment in equipment and materials
Functionality	Enhances device functionality through precise control and combination of materials	Material properties may not always meet the demands of complex clinical applications; performance can vary with usage environment and time
Accessibility	Increases patient access to personalized medical devices	Accessibility to the technology is still limited in certain regions
Comfort	Provides improved comfort and wearability through customized fit according to patient anatomy	May require several iterations and adjustments to achieve ideal comfort
Surgical Planning	Assists surgeons in preoperative preparation by providing detailed anatomical models, improving precision and effectiveness	Quality and detail of printed models are limited by imaging resolution and printer accuracy
Training and Simulation	Offers patient-specific anatomical models as training tools, enhancing pre-surgical simulation and practice for surgeons	Limited material feedback may not fully replicate the tactile sensation and operational experience of real tissue
Surgical Accuracy	Improves surgical precision with customized guides and implants, reducing intraoperative complications and errors	Size and shape deviations may occur due to material properties and printing processes
Patient Education	Provides tangible models to help patients better understand their condition and surgical procedures, enhancing the informed consent process	Creating accurate models for complex conditions or anatomical structures can be technically challenging and may not always be feasible
Material Versatility	Offers a range of biomaterials to simulate various tissue types, supporting a broad spectrum of medical applications	Limited variety and performance of current materials make it challenging to fully replicate the complex biomechanical properties of human tissues
Regulatory and Safety	Drives innovation in customized implants and devices with evolving materials and designs, potentially improving clinical outcomes	The regulatory approval process for custom 3D-printed implants can be complex and time-consuming, with ongoing safety concerns regarding long-term performance.

necessitates a comprehensive consideration of various parameters to find the most suitable printable materials for biomedical applications.[53,54]

Polylactic Acid exhibits good mechanical properties,[55,56] and compressive strength similar to bone,[57] often used for manufacturing rigid orthotics and support braces. However, the release of lactic acid byproducts during degradation may cause tissue inflammation, leading to poor long-term biocompatibility.[58] One solution is to combine polylactic acid with calcium phosphate to neutralize the acidity and buffer within physiological pH ranges.[59] Although acrylonitrile butadiene styrene has high strength and toughness, its biocompatibility is poor and it is non-degradable.[60] Improvements can be made by surface treatment or coating with biocompatible materials such as polyvinyl alcohol or polylactic acid.[61] Polycaprolactone is low-cost, with good rheological and viscoelastic properties, providing support for tissue regeneration or healing.[62] It is an appropriate material for producing scaffolds, though its biodegradation time is lengthy. Its degradation rate can be adjusted by adding enzymes.[63] Ceramic materials are widely used in orthopedic surgery due to their mineral-like compatibility with bone.[64] However, current 3D printing methods are mainly limited to direct ceramic printing. A potential solution is to use ceramic materials as powder additives in other materials.[65] Hydrogels, capable of absorbing and retaining significant amounts of water, exhibit good biocompatibility and minimal immune response elicitation.[66] However, hydrogels exhibit poor stability, which can be enhanced through chemical and photo-crosslinking.[67] Bio-inks containing cells or biochemical molecules can affect cell growth, proliferation, and differentiation,[64] but cells in bio-inks may face reduced survival rates during the printing and crosslinking process.[68] Cell viability can be improved using extrusion-based bioprinting technologies.[69]

Future research needs to delve deeper into the interactions between 3D-printed implants and human organs and tissues to better serve clinical needs. Multi-material printing technologies will enable 3D-printed cervical collars and orthopedic implants to have

more complex functions and superior performance.[70] The application of shape-memory alloys is expected to enable adaptive adjustment and precise control of support intensity in cervical collars, aiding tissue repair in implants.[71] Integrated sensors in cervical collars can monitor cervical activity, muscle status, and physiological parameters in real-time, providing crucial data support for personalized treatment plans.[71] Combined with artificial intelligence and big data technologies, a comprehensive evaluation system can be established, customizing optimal brace design and rehabilitation plans based on patient data, thereby enhancing treatment outcomes and quality of life for patients.[72] Furthermore, the personalized customization inherent in 3D printing technology requires stringent quality control standards. Machine learning methods can be effectively employed to model and predict surface roughness in additive manufacturing processes, significantly enhancing quality control and ensuring greater accuracy and improved outcomes in the production of these customized medical models.[73] Integrating response surface methodology with machine learning techniques has also shown promise in optimizing manufacturing and surface coating processes. This approach can improve the biocompatibility and mechanical properties of 3D-printed bone plates, contributing to the development of safer and more effective orthopedic implants.[74] Aspect of benefits and limitations are listed in Table 1.

Conclusion

3D printing technology, with its personalization and precision, offers new hope for the prevention and treatment of cervical spondylosis. Personalized cervical collars better meet patient needs, providing effective support and correction functions, while 3D-printed implants and surgical models increase the success rate and safety of surgeries. However, the application of 3D printing technology in the treatment of cervical spondylosis still faces challenges due to the insufficient diversity of biomaterials. Future research will focus on developing higher-performance biomaterials, multi-material printing technologies, integrating artificial intelligence and big data technologies to promote the widespread application of 3D printing technology in the treatment of cervical spondylosis, improving patient treatment outcomes and quality of life.

Funding

Disclosure

The authors report no conflicts of interest in this work.

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