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Application of a biomimetic continuum robot based on phase change materials for ligament delivery in orthopedic ligament reconstruction surgery

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Abstract. With the development of minimally invasive surgery and intelligent medical technologies, traditional rigid surgical robots have gradually revealed limitations in complex orthopedic ligament reconstruction procedures, particularly in terms of insufficient dexterity and difficulty adapting to narrow anatomical spaces. During the processes of bone tunnel creation and ligament graft delivery, surgical instruments must possess both high flexibility to maneuver around soft tissues and sufficient stiffness to ensure precise and stable operation. Therefore, achieving dynamic switching between flexible and rigid mechanical properties has become an important research direction in the field of orthopedic surgical robotics. Based on this background, this paper explores the application potential of a biomimetic continuum robot utilizing Phase Change Materials (PCMs) in orthopedic ligament reconstruction surgery. Through a literature review, the paper examines the current development of continuum robots and phase change materials, analyzes the dexterous operational advantages of continuum robots in minimally invasive medical procedures, and investigates the stiffness-regulation characteristics of phase change materials. Building upon these findings, a novel biomimetic continuum robot structure integrating a tensegrity framework with phase change materials is proposed. This design enables dynamic switching between a "flexible navigation" mode and a "rigid fixation" mode, thereby offering a promising solution for enhancing surgical adaptability and precision in orthopedic ligament reconstruction.

Keywords: biomimetic continuum robot, Phase Change Materials (PCMs), orthopedic surgical robot, variable stiffness control

1. Introduction

Biomimetic continuum robots are robotic systems inspired by the locomotion mechanisms of continuous biological organisms in nature, such as elephant trunks, octopus tentacles, and worm bodies. Unlike conventional rigid-link robots, they employ continuous flexible structures without discrete joints, enabling motion and manipulation through smooth and continuous deformation. As a result, they possess high dexterity and strong adaptability to complex environments.

Based on their structural characteristics, robots can generally be classified into traditional articulated robots and continuum robots. Traditional robots are composed of rigid links connected by discrete joints and are characterized by mature kinematic models and high positioning accuracy. In contrast, continuum robots do not contain discrete joints; instead, their flexible bodies can undergo continuous bending and deformation. This unique characteristic allows them to operate effectively in confined, complex, and unstructured environments. In addition to their inherent compliance, safety, and environmental adaptability, continuum robots can perform sophisticated tasks through body deformation or by carrying specialized end-effectors [1].

In recent years, with the rapid advancement of robotics and intelligent medical technologies, surgical robots have become an essential component of modern precision medicine. In addition to the widely adopted da Vinci Surgical System, specialized robotic platforms such as the MAKO orthopedic joint replacement robot, vascular interventional robots, and robotic bronchoscopy systems have emerged. Overall, surgical robotics is evolving toward greater specialization, intelligence, and minimally invasive capability.

In orthopedic ligament reconstruction surgery, critical procedures such as bone tunnel creation and graft fixation require surgical instruments with high stiffness and stability to ensure precision and accuracy. At the same time, minimizing tissue damage and navigating complex anatomical structures demand exceptional flexibility and dexterity. Therefore, the development of intelligent surgical instruments capable of dynamically adjusting their mechanical properties and achieving an integrated balance between rigidity and flexibility has become an important research direction for advancing ligament reconstruction procedures toward single-port, minimally invasive, and highly precise interventions.

To date, continuum robots have demonstrated considerable potential in minimally invasive intra-articular surgery. Previous studies have successfully conducted navigation and ablation experiments in ex vivo porcine knee joints and in vivo rat models, validating the feasibility of continuum robots in complex joint environments [2]. However, their application in orthopedic ligament reconstruction—a representative scenario that simultaneously requires both dexterous access and rigid manipulation—remains largely unexplored.

Against this background, this paper focuses on the integration of Phase Change Materials (PCMs) with biomimetic continuum robots. Through a comprehensive review of the current development of continuum robotics and PCMs, the stiffness-regulation mechanisms provided by PCMs are analyzed, and their potential value in key stages of ligament reconstruction surgery is discussed. Based on these findings, a conceptual design of a biomimetic continuum robot integrating a tensegrity-inspired framework and PCMs is proposed. The proposed design aims to achieve dynamic switching between flexible navigation and rigid fixation, thereby combining maneuverability and structural stability within a single robotic platform. Furthermore, the potential advantages of this technological approach and the key challenges that must be addressed for future clinical implementation are examined.

2. Review of continuum robot technologies

2.1. Applications and development of phase change materials in robotics: from general-purpose dexterity to precision orthopedic surgery

Phase Change Materials (PCMs) have emerged as a promising class of intelligent materials capable of overcoming limitations in conventional robotic design. By responding to external stimuli such as temperature, light, electricity, or magnetic fields, PCMs can undergo rapid, reversible, and significant transitions between solid and liquid states (or between different solid phases), resulting in dramatic changes in their physical properties [3]. The application of PCMs in robotics has evolved along a pathway from enhancing general environmental adaptability to enabling highly specialized medical operations, opening new possibilities for orthopedic surgical robotics.

2.1.1. Core mechanisms of application: three main technological approaches

The primary value of PCMs in robotics lies in the significant changes in mechanical properties induced by phase transitions. At present, three major technological approaches have emerged.

(1) Variable Stiffness Control and Structural Locking

The most direct application of PCMs is stiffness regulation. Materials such as low-melting-point alloys and phase change waxes exhibit high stiffness in the solid state and extremely low modulus in the liquid state, enabling programmable transitions between flexible and rigid configurations. This capability is particularly valuable in situations where a robot must navigate through narrow passages and subsequently provide stable structural support.

(2) Actuation and Motion Generation

PCMs can also serve as driving elements by exploiting the volumetric expansion and contraction associated with phase transitions. A representative example is vapor–liquid phase-change actuation using working fluids such as acetone. Localized heating generates expanding bubbles, which drive the motion of soft robotic systems. This actuation method is quiet, compact, and free of conventional motors, making it suitable for operation in sensitive imaging environments such as Magnetic Resonance Imaging (MRI) systems [4].

(3) Functional Integration and Energy Management

The latent heat associated with phase transitions can be utilized for passive thermal management and energy storage. PCMs can protect sensitive electronic components from overheating and facilitate thermal energy recovery and storage. These capabilities may be particularly valuable for surgical instruments that operate continuously for extended periods or under extreme thermal conditions [5].

2.1.2. Development trends: from general robotics to medical applications

During the early stages of development, research primarily focused on proof-of-concept demonstrations, including variable-stiffness joints and reconfigurable skeletal structures based on low-melting-point alloys or paraffin wax. These systems were mainly applied in general-purpose grasping tasks, such as handling fragile or irregularly shaped objects, and in search-and-rescue robots designed to navigate confined spaces.

In recent years, research has increasingly shifted toward high-end medical applications. PCMs have been integrated with continuum robots and miniature robotic systems for minimally invasive procedures. For example, vascular intervention catheters utilize PCM-based stiffness modulation at the distal tip to improve pushability and procedural stability. Similarly, neurosurgical probes employ phase transitions to enable compliant insertion into brain tissue, followed by rigid fixation at the target site.

2.2. Technical requirements for robots in surgical applications

Surgical robots have evolved from advanced assistive tools into intelligent platforms capable of transforming surgical practice. Their technical requirements are fundamentally centered on overcoming the physiological and cognitive limitations of human surgeons in order to achieve predictable, repeatable, and highly precise surgical outcomes. These requirements extend from basic performance capabilities to advanced intelligent functionalities.

2.2.1. Core requirements: precision, stability, and operability

One of the primary objectives of surgical robots is the elimination of physiological hand tremor while enabling highly stable manipulation in confined anatomical spaces such as the cranial cavity, spinal canal, and joint spaces. This capability is essential in neurosurgery, ophthalmology, and microsurgical vascular anastomosis.

Compared with other robotic systems, surgical robots place greater emphasis on dexterity and kinematic redundancy. Instruments equipped with wrist-like mechanisms, such as the EndoWrist system of the da Vinci Surgical System, or multi-degree-of-freedom continuum structures, can compensate for the limitations of conventional straight instruments in narrow surgical fields, enabling complex tasks such as suturing and tissue dissection from challenging angles.

Another critical requirement is the provision of magnified, high-definition three-dimensional visualization. Modern surgical robots should be capable of integrating preoperative imaging data such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), annotations of critical anatomical structures including nerves and blood vessels, and real-time navigation information directly into the surgeon's field of view, thereby creating a digital navigation environment that enhances surgical accuracy.

2.2.2. Functional requirements: sensing, feedback, and execution

Beyond basic manipulation, enhanced perception and interaction have become increasingly important. Most current surgical robots, including the da Vinci system, lack effective force feedback, leading many surgeons to describe the experience as "operating on cotton." The restoration of realistic haptic feedback is widely recognized as one of the most important and challenging technological goals, as it is essential for preventing tissue damage and assessing tissue properties.

Furthermore, robotic instruments should be capable of dynamically modifying their physical characteristics according to procedural requirements. Technologies such as PCM-based variable stiffness control and the integration of multiple energy modalities—including ultrasonic cutting, electrocautery, and laser ablation—can reduce the need for intraoperative instrument exchanges and improve procedural efficiency.

2.2.3. System-level and intelligent requirements

The future development of surgical robotics is directed toward greater intelligence, specialization, and ecosystem integration. Artificial intelligence can be employed to automatically segment multimodal medical images, reconstruct three-dimensional anatomical models, and generate patient-specific surgical plans. During surgery, AI systems may provide real-time warnings when instruments approach critical anatomical structures or deviate from predefined safety boundaries.

Under surgeon supervision, robotic systems may autonomously perform standardized and repetitive tasks, such as precise bone cutting in orthopedic surgery or implant placement along predetermined trajectories. This capability allows surgeons to focus on higher-level clinical decision-making rather than repetitive manual operations.

In addition, specialized robotic platforms should be developed for different medical disciplines—including orthopedics, neurosurgery, and vascular intervention—rather than relying on universal robotic systems. Modular design strategies can further reduce manufacturing and maintenance costs, facilitating broader clinical adoption.

3. Robot design principles and structure

3.1. Overall architecture and actuation concept

Based on a combinational innovation approach, the proposed design abandons conventional single-material solutions and introduces a novel concept of functional–structural integration. By combining phase change materials responsible for actuation and stiffness modulation with a tensegrity-inspired framework responsible for load-bearing and shape maintenance, the design achieves a high degree of functional integration at the physical level, resulting in a new composite robotic architecture.

The robot employs a lightweight and highly reconfigurable framework composed of carbon-fiber structural elements and Ultra-High-Molecular-Weight Polyethylene (UHMWPE) fibers as its fundamental morphological structure. Phase change materials are encapsulated around bundles of UHMWPE fibers, creating a robotic body that combines high dexterity and maneuverability with controllable structural stiffness. This integrated design enables both flexible deformation during navigation and enhanced rigidity when stable manipulation or fixation is required, making it particularly suitable for minimally invasive orthopedic surgical applications.

3.2. Design of core components

Table 1 presents common materials used for compression members and their characteristics. At present, the materials most frequently employed in continuum robots include metallic materials, polymers, composite materials, and smart materials. In recent years, the development of smart materials has attracted increasing attention. Examples include Shape Memory Alloys (SMAs), low-melting-point alloys, and Phase Change Materials (PCMs), all of which are capable of altering their mechanical properties in response to external stimuli. These materials provide new technological pathways for achieving variable stiffness in robotic systems.

Table 1. Common materials for compression members and their characteristics

Common materials	Core Characters
Titanium Alloy	Advantages: Extremely high specific strength, excellent biocompatibility, superior corrosion resistance, and non-magnetic properties. Disadvantages: Difficult to machine, expensive, and possesses relatively low thermal conductivity.
Carbon Fiber Reinforced Polymer (CFRP)	Advantages: Extremely high specific modulus and specific strength, excellent design flexibility, outstanding fatigue resistance, and high X-ray transparency. Disadvantages: Anisotropic mechanical properties, low interlaminar strength, high cost, and damage is often difficult to detect through visual inspection.
3D-Printed Photopolymer Resin	Advantages: Capable of producing highly complex geometries, enables rapid prototyping, and offers high surface accuracy. Disadvantages: Most materials exhibit limited mechanical strength, heat resistance, and long-term stability, making them primarily suitable for prototype validation or non-load-bearing components.

When selecting materials for continuum robots, several general criteria must be considered. First, lightweight construction is essential to reduce the overall mass of the robot, thereby improving motion efficiency and dynamic response. Second, materials should possess high specific stiffness and high specific strength to maintain structural stability while preserving flexibility. Third, they must withstand continuous bending and long-term cyclic loading while exhibiting both compliance and fatigue resistance. Finally, particularly in medical robotic applications, materials must satisfy stringent safety requirements, including biocompatibility and safe interaction with human tissues.

The aerospace industry places significant emphasis on lightweight design, high strength, structural stability, and fatigue resistance. These requirements closely align with those of continuum robots operating in minimally invasive surgical environments, making carbon fiber-reinforced composites highly suitable for technology transfer into medical robotic applications.

First, carbon fiber-reinforced composites possess exceptionally high specific strength and specific stiffness. Compared with traditional metallic materials such as steel and aluminum alloys, carbon fiber composites provide comparable or superior structural performance at a substantially lower weight. This characteristic is particularly important for continuum robots, which must frequently bend and maneuver within confined spaces. Excessive structural mass would increase actuation loads, reduce motion responsiveness, and compromise overall compliance.

Second, carbon fiber-reinforced composites exhibit excellent fatigue resistance and corrosion resistance. During surgical procedures, continuum robots are subjected to repeated cycles of bending, extension, and shape reconfiguration. Consequently, the structural material must be capable of withstanding long-term cyclic loading without significant degradation of its mechanical properties.

Furthermore, carbon fiber-reinforced composites offer a high degree of structural design flexibility. The orientation and stacking sequence of fiber layers can be optimized according to specific loading requirements, enabling tailored stiffness characteristics in different directions. This anisotropic design capability provides additional opportunities for enhancing the performance and adaptability of continuum robotic structures.

3.3. The use of PCMs

However, the selection of skeletal materials only addresses the issues of "baseline stiffness" and "lightweighting" of the robot, without touching upon the most critical contradiction in ligament reconstruction surgery—the same instrument requires extremely low bending stiffness during the navigation phase, yet extremely high axial stiffness during the fixation phase. This contradiction cannot be resolved by optimizing the skeletal material alone, as the elastic moduli of carbon fiber or titanium alloy remain essentially constant within conventional operating temperature ranges.

The introduction of Phase Change Materials (PCMs) is precisely intended to complement this "variable stiffness" functional module. In the present design, PCMs are not employed as structural skeletons but rather as "stiffness-regulating actuators" filled within the multi-lumen channels formed by braided fiber bundles or encapsulated around the skeleton's periphery. Specifically, low-melting-point alloys—such as Field's alloy (melting point ~62°C) or Wood's alloy (melting point ~70°C)—are selected as the core phase-change medium. In their solid state, these alloys exhibit an elastic modulus on the order of 10 GPa, comparable to that of cortical bone, enabling the robotic end-effector to provide sufficient push delivery and pull-out resistance. Upon heating above the phase-transition temperature, however, the modulus plummets to < 10 MPa, reducing bending stiffness by more than two orders of magnitude and restoring the robot body to a highly compliant state, allowing it to navigate around intra-articular soft tissues without causing damage.

More importantly, the phase transition of PCMs is reversible and actively triggerable—by means of integrated micro-heating electrodes (Joule heating) or externally temperature-controlled irrigation fluids, the switching between "solid→liquid" or "liquid→solid" states can be accomplished within seconds to tens of seconds, which closely aligns with the phased operational rhythm of ligament reconstruction surgery (i.e., navigation phase → placement phase → fixation phase). Furthermore, certain low-melting-point alloys have documented records of good biocompatibility (e.g., Field's alloy is free of lead and cadmium), and their solid-state density exhibits a relatively small mismatch with that of soft tissues, which facilitates radiographic localization under intraoperative imaging modalities such as X-ray or CT.

In summary, the carbon-fiber skeleton and the PCM functional core together constitute the "rigid–flexible dual-mode material system" of the proposed robot: the carbon fiber undertakes the fundamental functions of shape maintenance and tensile load-bearing, while the PCMs assume the core control function of dynamic stiffness switching. The two are physically coupled in structure and functionally complementary to each other, jointly achieving the design objective of "flexible navigation—rigid fixation" (Figure 1).

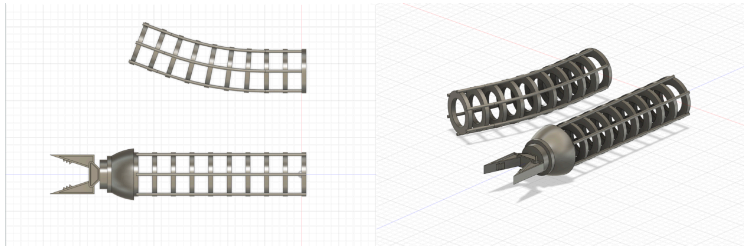

Figure 1. Schematic diagram of the proposed robot structure

4. Application scenario analysis: surgical operation

In patellar ligament reconstruction surgery, the delivery and precise placement of ligament grafts are well aligned with the advantages of non-rigid continuum robots. Due to the complex anatomical structure of the knee joint, it is necessary to avoid critical structures such as nerves, blood vessels, and cartilage tissue. Continuum robots, through their flexible and continuous structure, can navigate through a single minimally invasive incision and gently maneuver around important anatomical features within complex soft tissue environments, reaching target tunnel entry points that are difficult to access using conventional rigid instruments.

Since continuum robots theoretically possess infinite degrees of freedom, they can mimic wrist-like motions and perform delicate tasks such as graft grasping, threading, and knot tying within confined spaces. Moreover, due to their inherent compliance, they can reduce the risk of damage to the surrounding joint and soft tissues. Continuum robots can also integrate various end-effector modules to extend their functionality; for example, a grasping device can be mounted at the distal end to facilitate ligament transport and manipulation.

In addition, phase change materials enable reversible stiffness transformation. Therefore, after reaching the target site, the robot can transition from a compliant state to a rigid state, allowing for highly precise positioning and stable placement of ligament grafts.

5. Conclusion

This study aims to investigate the application potential of biomimetic continuum robots based on Phase Change Materials (PCMs) in orthopedic ligament reconstruction surgery, with a particular focus on their advantages in ligament graft delivery and precise placement. The results indicate that the high dexterity, compliance, and environmental adaptability of continuum robots enable flexible navigation within the complex and confined environment of the knee joint, where conventional rigid instruments are limited. Meanwhile, the reversible "soft-to-rigid" transition enabled by PCMs significantly enhances the structural stability and operational precision of the robot at the target site.

This work provides a systematic theoretical analysis of the integration between continuum robotics and smart materials and attempts to introduce the concept of "variable stiffness" into the context of orthopedic ligament reconstruction, a specialized minimally invasive surgical scenario. Compared with existing studies, this paper further expands the application boundaries of biomimetic continuum robots in orthopedic precision surgery and offers a reference value for the future design of "rigidity–flexibility coupled" medical robotic systems. From a practical perspective, the proposed robotic architecture and operational concept may improve the minimally invasive and precision-oriented nature of ligament reconstruction procedures, which is of significant importance for the future development of single-port, intelligent, and high-precision orthopedic surgery.

However, this study still has certain limitations. The discussion is primarily based on theoretical analysis and structural design, and a fully implemented robotic prototype with large-scale experimental validation has not yet been developed. Therefore, the conclusions remain insufficiently supported by experimental data. In future work, the author will further explore integration strategies for multifunctional end-effectors in continuum robots, such as combining bone drills, grasping tools, and real-time sensing modules within a unified system to enhance overall surgical capability.

Overall, this study provides a new theoretical perspective on the integration of phase change materials and biomimetic continuum robots in minimally invasive orthopedic surgery, and highlights the important role of variable stiffness technology in complex medical scenarios.

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