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Low-Melting-Point-Alloy-Based Variable-Stiffness Continuum Robots for Surgical Applications

Zhirou Li

School of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen, China
13715062595@163.com

Abstract. Minimally invasive surgery demands instruments that reconcile two conflicting requirements: sufficient compliance to traverse tortuous and fragile anatomical pathways and sufficient stiffness to transmit therapeutic forces at the target. Continuum robots with variable stiffness have emerged as a direct response to this conflict, and low-melting-point alloys (LMPAs) have become one of the most effective enabling materials, because a reversible solid-liquid phase transition within a narrow temperature band delivers stiffness gains of several orders of magnitude without bulky peripheral hardware. This review surveys the material basis, the structural designs, the actuation schemes, and the modeling, thermal management, and control strategies of LMPA-based variable-stiffness continuum robots, and examines reported implementations in endovascular and cardiac intervention, ophthalmic microsurgery, gastrointestinal endoscopy, and percutaneous tumour ablation. Representative prototypes are compared in terms of scale, stiffness ratio, transition time, and clinical task. Persistent obstacles are identified in thermal safety, transition speed, cyclic durability, and sensing integration, and the corresponding research directions are outlined. The surveyed evidence indicates that LMPA-based stiffness modulation is approaching engineering maturity for lumen navigation, while clinical translation still depends on rigorous thermal dose control and on long-term encapsulation reliability.

Keywords: low-melting-point alloy, variable stiffness, continuum robot, minimally invasive surgery, thermal management

1. Introduction

Minimally invasive surgery has progressively replaced open exposure in cardiothoracic, abdominal, and head-and-neck procedures [1]. Dominant robotic architectures remain essentially rigid: a straight shaft pivots about the insertion port, while distal dexterity is delivered by wristed linkages of limited diameter [1, 2]. In narrow or tortuous anatomies such shafts cannot reach the target without displacing tissue. Continuum robots bend with continuously distributed curvature and follow such pathways better, yet the compliance that grants safe navigation deprives the tip of the reaction force needed for dissection or ablation [2]. Variable stiffness is therefore the mechanism most capable of resolving this contradiction [1].

Variable stiffness may be realised by jamming, by structural means, or by phase transition, and the choice governs how much stiffness a millimetre-scale device gains and how fast it switches [1].

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Phase-transition materials are attractive because a reversible solid-liquid change alters rigidity by orders of magnitude without extra hardware [1, 2]. Three questions motivate this review: which material and structural choices govern stiffness gain, transition speed, and thermal load, in which anatomical domains such devices have passed bench demonstration, and which obstacles still block clinical use. Low-melting-point alloys are the focus because their transition temperatures lie near the range tolerated by tissue [1, 2]. Table 1 compares the four candidate mechanisms in stiffness gain and transition speed.

Table 1. Comparison of representative variable-stiffness mechanisms for surgical continuum robots

Mechanism	Working principle	Stiffness gain	Principal limitation
Granular and layer jamming	Vacuum-induced friction between particles or layers	Low to moderate	Vacuum line and fill occupy the lumen, gain falls at small diameter, response set by evacuation rate
Shape memory alloy and polymer	Thermally induced martensitic or glass transition	Moderate	Actuation strain small, transition temperature often above the tissue limit, cooling slow and cycle fatigue marked
Low-melting-point alloy	Reversible solid-liquid phase transition	Very high	Heating and cooling both required, with cooling setting the cycle time, some alloys contain lead or cadmium
Tendon-driven and nested-tube structures	Cable tension or tube interaction	Limited	Extra diameter for cables or nested tubes, friction and hysteresis, range narrow without preload

2. Core technologies of LMPA-based variable-stiffness continuum robots

2.1. Material properties and fabrication

The functional core of an LMPA-based robot is a sealed channel, typically a silicone or thermoplastic tube, filled with a fusible alloy and equipped with a heating element and, in most designs, a temperature sensor. The early variable-stiffness fibre demonstrated the principle: above 62 degrees Celsius it softened by more than 700 times and its deformability increased by more than 400 times, while the encapsulating polymer restored integrity after mechanical damage, giving the structure a self-healing capability [3]. Material selection is constrained by three interrelated requirements. The melting point must exceed body temperature so that accidental softening cannot occur, yet remain low enough for the heating power and surface temperature to stay within safety limits. The solid-state modulus determines the maximum transmissible force. The toxicity of the constituent elements determines whether encapsulation may ever fail, since widely used fusible alloys including Cerrolow 117 and Cerrolow 136 contain lead or cadmium and must be treated as permanently sealed hazards [4, 5]. Comparative studies of gallium, rubidium, Cerrolow, and Field's metal have documented microstructural change after repeated thermal cycling, indicating that composition and thermal history jointly determine long-term stability [5]. Manufacturing consequently centres on leak-tight encapsulation: alloy injection under vacuum, thermal or adhesive sealing of the end caps, and an additional outer barrier layer where biocompatibility is critical [3, 5].

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The compliant and rigid states of such a channel, together with the heating and cooling paths that connect them, are illustrated in Figure 1.

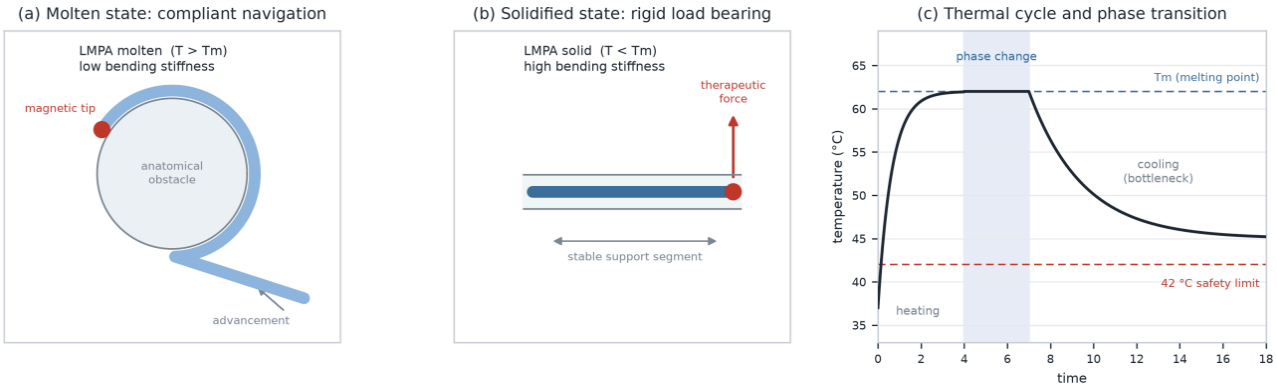


Figure 1. Operating principle of LMPA-based stiffness modulation: compliant navigation in the molten state, rigid load bearing in the solidified state, and the corresponding heating and cooling cycle

2.2. Structural design and actuation schemes

Three structural paradigms have been established. In the monolithic paradigm a single alloy-filled lumen runs the length of the device and the robot alternates globally between compliant and rigid states, a flexible manipulator exploiting hydraulic transport of molten alloy realised a rigid-to-flexible transition in 9.2 to 10.3 s and a flexible-to-rigid transition in 15.4 s, with lateral and flexural stiffness gains of 13.15 and 477.05 and an ultimate force above 1.36 N in the bent configuration [6]. In the segmented paradigm, independent heating zones permit simultaneous stiffening of a proximal support section and softening of a distal steering section, enabling inchworm advancement and selective shape locking [5, 6]. The alloy may also serve as the working fluid of hydraulic actuation so that one channel performs shape actuation and stiffness modulation and, through the electrical resistance of the alloy or of a co-fabricated conductor, shape detection [7]. In the hybrid paradigm the alloy is coupled to an external actuation field, most commonly magnetic, so that a permanent magnet or electromagnetic coil steers the tip while the LMPA sets the mechanical boundary condition [8]. Because the alloy is dense and conductive, embedding it modifies mass distribution and hence the dynamic response of the magnetic tip, an effect increasingly treated as an additional degree of freedom [2].

2.3. Modeling, thermal management, and control

Predicting the stiffness of an LMPA-based continuum robot is difficult, because the constitutive behaviour depends on the spatial distribution of solid and liquid phases, which in turn depends on the transient temperature field. Quasi-static models relating tip deflection to applied load through an effective bending stiffness have proved usable when augmented by a learning-based compensation term: one variable-length endoscopic robot held the average tip position change at 1.1 mm under external disturbance and supported a contact force controller for mucosal ablation [9]. Thermal management is the binding constraint on all such designs. Heating is straightforward, since resistive elements and the alloy itself dissipate power locally, but cooling relies on conduction to surrounding tissue or perfusion fluid, which is slow and sets the dominant time constant [6, 8]. Reported

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transition times therefore cluster between ten and thirty seconds, and the associated thermal dose must be judged against the widely cited 42 degrees Celsius threshold for irreversible tissue injury [5, 8]. Closed-loop regulation based on an embedded thermistor holds the surface below the safety limit while maintaining the solid state [8]. Recent work addresses both halves of the problem at once: antimony doping at 2.5 weight percent accelerates the phase transition and improves stiffness recovery, an active cooling circuit shortens the cooling phase and improves repeatability, and a thermochromic polydimethylsiloxane epidermis converts internal temperature into a colour signal readable by the endoscope, removing the need for an electrical sensor at the tip [10].

3. Surgical and medical applications

An LMPA-based device is ultimately judged at the anatomy, where a stiffness schedule realised on a bench must survive the constraints of a real pathway and a real task. Four application domains have dominated published research, each imposing distinct performance priorities: endovascular intervention requires atraumatic navigation followed by a stable platform, ophthalmic microsurgery imposes the tightest limits on diameter and force, gastrointestinal endoscopy requires long collapsible lumens to be traversed without wall trauma, and percutaneous access inverts the sequence, demanding stiffness first and steerability second. Sections 3.1 to 3.4 examine each in turn.

3.1. Endovascular and cardiac intervention

The strongest clinical motivation is endovascular navigation, where a device must cross attenuated and heavily branched vessels atraumatically and then resist the reaction force of an interventional tool. A magnetically steerable continuum device with an outer diameter of 2.33 mm illustrates the operating principle: the body stays compliant during magnetic guidance and is solidified at the target to provide a stable platform for cardiac ablation, with closed-loop thermal control protecting the vessel wall [8]. The same device class has been demonstrated in gastrointestinal endoscopy, where the compliant state allows the tip to follow the lumen without distending it [8]. Eversion-based tip-growing robots address the related problem of buckling under compressive load: localised heating of an alloy medium inside the everting membrane produced a stiffness ratio of 43, a fifteenfold increase in transmissible force, and hybrid soft-rigid morphologies [5].

3.2. Ophthalmic and microsurgery

Ophthalmic surgery imposes the tightest dimensional and force constraints of any surgical domain, since retinal tissue tolerates only tens of millinewtons and physiological tremor further degrades instrument stability. A submillimetre catheter with an outer diameter of 1 mm made stiffness continuously adjustable rather than binary: tip force ranged from 20 mN in the compliant state to 8 N in the rigid state, a ratio of approximately 400, with the transition occurring at 47 degrees Celsius [11]. The compliant state absorbs tremor and limits contact pressure during navigation, whereas the rigid state suppresses deflection when a deliberate manipulation force must be transmitted. Robot-assisted epiretinal membrane peeling was demonstrated with this device, indicating that LMPA-based compliance control can satisfy the safety requirements of microsurgery and not merely its dimensional requirements [11].

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3.3. Endoscopic and gastrointestinal interventions

Gastrointestinal endoscopy requires an instrument to traverse a long, collapsible, and often contaminated lumen while retaining the ability to lift, resect, or ablate mucosa. Two strategies dominate. The first stiffens discrete segments of an otherwise compliant endoscope so that a proximal section forms a stable anchor while a distal section explores, variable-length designs combine axial extension with LMPA solid-liquid transition to obtain two independent stiffness channels in one device, and have been validated in gastrointestinal phantom demonstrations of mucosal ablation [9]. The second separates navigation from manipulation inside the same body: one robot uses a rigid skeletal section for support and a liquefied section for tip extension, allowing the tip to grow through tortuous and fragile passages under clinical imaging [12], while a cooperative guider-follower architecture alternates softening and stiffening between a coaxial outer guider and inner follower so that the device advances without sliding contact against the lumen wall [13]. Reducing wall contact is clinically significant because friction and lateral pressure are principal sources of perforation and postoperative pain.

3.4. Percutaneous tumour ablation and needle steering

Percutaneous access demands the opposite sequence: the instrument must be stiff enough to penetrate tissue along a planned trajectory, yet steerable enough to correct that trajectory around vessels and bone. Alloy-filled needles with tunable stiffness segments address this by stiffening the proximal shaft while the distal segment remains compliant and deflects under asymmetric tip loading, producing large-curvature manoeuvres inside tissue [6]. Because the LMPA channel can also carry hydraulic pressure, the same structure supplies both the steering moment and the rigid support needed for subsequent instrument passage [6, 7]. Once at the target, solidifying the shaft converts the device into a stable conduit for biopsy forceps or an ablation probe, suppressing the tip deflection that otherwise degrades targeting accuracy [7, 13].

Collectively, these four application domains share a fundamental trade-off rather than presenting isolated results. The stiffness gain is consistently large, but it is paid for with heating time and thermal load, and the demonstrations remain at the level of phantoms, explanted tissue, or a single task under imaging. What differs between domains is which constraint binds first: outer diameter in ophthalmic work, lumen length and wall contact in endoscopy, penetration force in percutaneous access, and thermal dose in endovascular navigation. Table 2 collects the prototypes discussed above against the constraint that binds each of them so that the shared trade-off and the domain-specific limits can be read at a glance.

Table 2. Summary of the LMPA-based variable-stiffness prototypes discussed in Sections 3.1 to 3.4

Device	Scale	Reported performance	Surgical task	Ref.
Variable-stiffness fibre	Millimetre	Softening above 700 times, self-healing	Concept validation	[3]
Magnetic continuum device	2.33 mm diameter	Compliant-to-rigid switching, closed-loop thermal control	Cardiac ablation, GI endoscopy	[8]
Submillimetre catheter	1 mm diameter	20 mN to 8 N, about 400 times	Epiretinal membrane peeling	[11]

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Table 2. (continued)

Eversion tip-growing robot	Millimetre	Stiffness ratio 43, fifteenfold force gain	Intraluminal navigation	[5]
Variable-length endoscopic robot	Endoscopic	Average tip deviation 1.1 mm with force control	Mucosal ablation	[9]
Guider-follower robot	Millimetre	Alternating softening and stiffening, non-contact	Transluminal navigation	[13]
Magnetic steering robot	Millimetre	Solid skeleton with liquid tip extension	Transluminal procedures	[12]
Flexible manipulator	Millimetre	Transition 9.2 to 15.4 s, flexural gain 477	Minimally invasive manipulation	[6]

4. Key challenges and future directions

4.1. Thermal safety and tissue protection

The transition temperatures of practical fusible alloys lie above the widely accepted 42 degrees Celsius threshold for irreversible tissue injury. Accordingly, all designs must ensure that heat supplied to the alloy does not propagate to the tissue interface at hazardous levels. Reported mitigation includes closed-loop regulation from an embedded thermistor [8], thermal isolation of the alloy channel by low-conductivity encapsulation and aerogel layers, and spatial and temporal profiling of heating cycles so that only the segment requiring stiffening is heated [5]. Because thermal dose depends on duration as well as on temperature, slow cooling may be as damaging as fast heating, and future work should report cumulative thermal dose rather than peak surface temperature alone. Standardised phantom-based thermal testing comparable across laboratories would accelerate regulatory acceptance [5, 8].

4.2. Response speed and cooling efficiency

Cooling constitutes the rate-limiting step of the cycle, as heat must be dissipated into tissue or perfused fluid. Reported transition times ranging from 10 to 15s restrict the frequency of stiffness reconfiguration during a procedures [6]. Approaches under investigation include microfluidic channels circulating coolant through the device, phase-change materials absorbing latent heat adjacent to the alloy, and thermoelectric elements integrated at the proximal end [10]. Antimony doping at 2.5 weight percent has been shown to accelerate the phase transition and improve stiffness recovery, which demonstrates that composition engineering matters as much as thermal hardware [10]. A clinically useful target is to compress the complete soft-hard-soft cycle into a few seconds, so that stiffening can be synchronised with the cardiac or respiratory cycle [10].

4.3. Cyclic durability and material stability

Repeated melting and solidification changes the microstructure of fusible alloys and progressively degrades the sealed interface, which is the principal reliability concern for any reusable or long-indwelling device [5]. Encapsulation leakage is not merely a performance failure, because lead- and cadmium-bearing alloys are cytotoxic and containment must be demonstrated over the full service

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life rather than at delivery [4, 5]. Priority directions include low-toxicity formulations that retain a melting point near 50 degrees Celsius, barrier layers with matched thermal expansion, and accelerated cycling protocols that correlate laboratory ageing with clinical reuse [4, 5].

4.4. Intelligence and sensing integration

Stiffness modulation becomes most valuable when the controller knows the phase state of every segment without adding sensors at the millimetre scale. Thermochromic composites report temperature optically through the endoscope and remove the need for electrical leads at the tip [10], while the electrical resistance of the alloy or of a co-fabricated conductor has been used for simultaneous stiffness variation and shape detection [7]. Learning-based compensation of quasi-static stiffness models further reduces reliance on direct force sensing [9]. Integrating these modalities into one closed-loop controller, together with imaging-based tip localisation, is the most plausible route towards autonomous stiffness scheduling [7, 9, 10].

5. Conclusion

Low-melting-point alloys provide a physically compact route to the stiffness modulation that surgical continuum robots require, and the experimental record assembled over the past decade is now substantial. The material case is well established: melting points between 47 and 62 degrees Celsius are accessible with low-power heating, solid-state moduli of several gigapascals support therapeutic forces, and the molten state contributes no bending resistance, which permits stiffness gains of roughly 25 to 9000 times in devices as small as 1 mm in outer diameter [3, 4, 11]. Structurally, the field has progressed from monolithic fibres that switch globally [3, 6], through segmented bodies that lock selected sections [5], to hybrid magnetic platforms in which the alloy sets the boundary condition while an external field provides steering [8, 12, 13]. Clinically relevant demonstrations now span endovascular and cardiac intervention, ophthalmic microsurgery, gastrointestinal endoscopy, and percutaneous access [8, 9, 11-13]. The remaining obstacles are engineering rather than conceptual. Thermal dose must be reported and controlled against the 42 degrees Celsius threshold, since transition temperatures necessarily exceed it [5, 8]. Cooling, rather than heating, sets the cycle time, and compressing the cycle to a few seconds requires simultaneous progress in alloy composition and in active cooling [10]. Cyclic durability and encapsulation integrity determine whether lead- and cadmium-bearing alloys can ever be used clinically, which makes low-toxicity formulations an urgent priority [4, 5]. Stiffness modulation will deliver its full benefit only when phase state, shape, and contact force are available to the controller without bulky sensing, a direction already opened by thermochromic feedback, resistive shape detection, and learning-based compensation [7, 9, 10].

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