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Hybrid Continuum Robot Designs and Architectures for Healthcare Applications

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ABSTRACT

Continuum robots offer enhanced flexibility and dexterity compared to traditional rigid-link systems, making them well-suited to minimally invasive and endoluminal interventions. Numerous design and actuation configurations have been proposed, spanning from hard yet flexible robotic structures to passively adaptable monolithic soft-bodied designs. However, unimodal approaches often face trade-offs between compliance, range of motion, and control precision. Recently, hybrid continuum robots that integrate multiple design and/or actuation strategies within a single architecture have emerged. By spanning a broader range of materials and actuation approaches, hybrid continuum robots aim to overcome the limitations of single-modal systems and present new capabilities suited to challenging clinical applications. The presented review specifically focuses on the designs, architectures, and configurations of this emerging field, emphasizing how distinct structural and actuation combinations present significant diversity in performance and application. We first stratify hybrid continuum robot architectures by their material composition, capturing hard- and soft-bodied designs in exclusive or combined configurations. Within each high-level grouping, we consider the range of associated actuation methods and clinical applications presented to date. Adjacent approaches that achieve hybrid performance through active adaptability are also considered. Finally, we discuss the open challenges and opportunities for continuum robot hybridization in the context of clinical applications and future translation.

1 | Introduction

Continuum robots (CRs) represent a well-established alternative to traditional rigid-link robotic manipulators, offering slender bodies with enhanced flexibility and dexterity to complete complex navigation and manipulation tasks within confined and delicate environments [1–3]. Coupling robotic capabilities with broad design freedom across scales, materials, and actuation modes has made CRs of particular interest for medical applications such as minimally invasive surgery (MIS) [4], endoscopy [5, 6], and endovascular interventions [7, 8], as detailed in associated reviews on the topic [1, 2].

Many traditional CR design approaches combine a flexible backbone formed from hard components with mechanical actuation using tendons [9, 10], rods [11], shape-memory alloys (SMAs) [12] or the interaction of concentric pre-bent [13, 14] or notched tubes [15]. The development of suitable modeling and sensing approaches for hard CRs has facilitated precision control and allowed development into commercial continuum robotic systems such as the da Vinci SP [16] and Ion systems [17] (Intuitive Surgical, USA). However, hard CRs typically retain a higher overall stiffness relative to biological tissues, which must be taken into account to provide safe interaction with delicate anatomy during diagnostic or interventional procedures [2, 18].

As an alternative approach, researchers have explored the use of soft materials to form the CR's structure, offering the potential for enhanced dexterity and better conformation to anatomical shapes due to large actuation ranges and passive adaptation during interaction [19, 20]. Soft CRs can be designed from materials such as silicone [21] and hydrogels [22], and actuated via methods including pneumatic/hydraulic networks [23], cables/tendons [24], and smart materials such as dielectric elastomer actuators [25], ionic polymer–metal composites [26], liquid crystal elastomers [27], and magnetics [28]. Although beneficial for safer interaction, the low stiffness of soft CRs limits their ability to apply forces for functional manipulation of tissue [29] and makes them challenging to model and precisely control [30].

Clear trade-offs exist when developing robots based on individual hard or soft CR strategies in isolation. However, approaches based on hybrid architectures have recently been proposed that combine established CR designs and actuation modalities into a variety of configurations. Hybrid CR (HCR) strategies most commonly arise as a direct combination of multiple design and/or actuation approaches that seek to decouple degrees of freedom, modulate length-wise compliance, or improve workspace, payload, or navigational capabilities.

However, to more formally define the scope of HCR approaches, Figure 1 illustrates key characteristics with respect to established rigid-link and continuum approaches. In conventional rigid-link robotics, the terms serial and parallel refer to kinematic topology, with serial manipulators consisting of a single open kinematic chain (Figure 1A) and parallel manipulators being formed by multiple closed-loop chains (Figure 1B) [31]. Analogous configurations exist for CRs, where rigid links are replaced by continuously deformable flexible robotic elements. Serial configurations arise from stacking continuum segments end-on-end (Figure 1C), while parallel CRs result from multiple continuum elements, each connected to a rigid base, sharing a common end-effector platform (Figure 1D) [32]. Emerging HCR approaches introduce an additional level of architectural complexity due to the integration of a variety of possible subsystem when combining numerous subsystems within a single robot. At a high level, we consider serial hybridization as the stacked combination of two or more distinct CR segments (Figure 1E), whereas parallel hybridization refers to the intra-segment integration of multiple distinct CR elements that share a common end-effector connection (Figure 1F). It should be noted that more complex HCRs are also possible by combining multiple HCR segments in serial and/or parallel assemblies.

The presented review aims to provide a classification for the range of HCR design architectures proposed to date, and capture the current state of HCR research in the context of clinical applications. We specifically consider the term hybrid, in the context

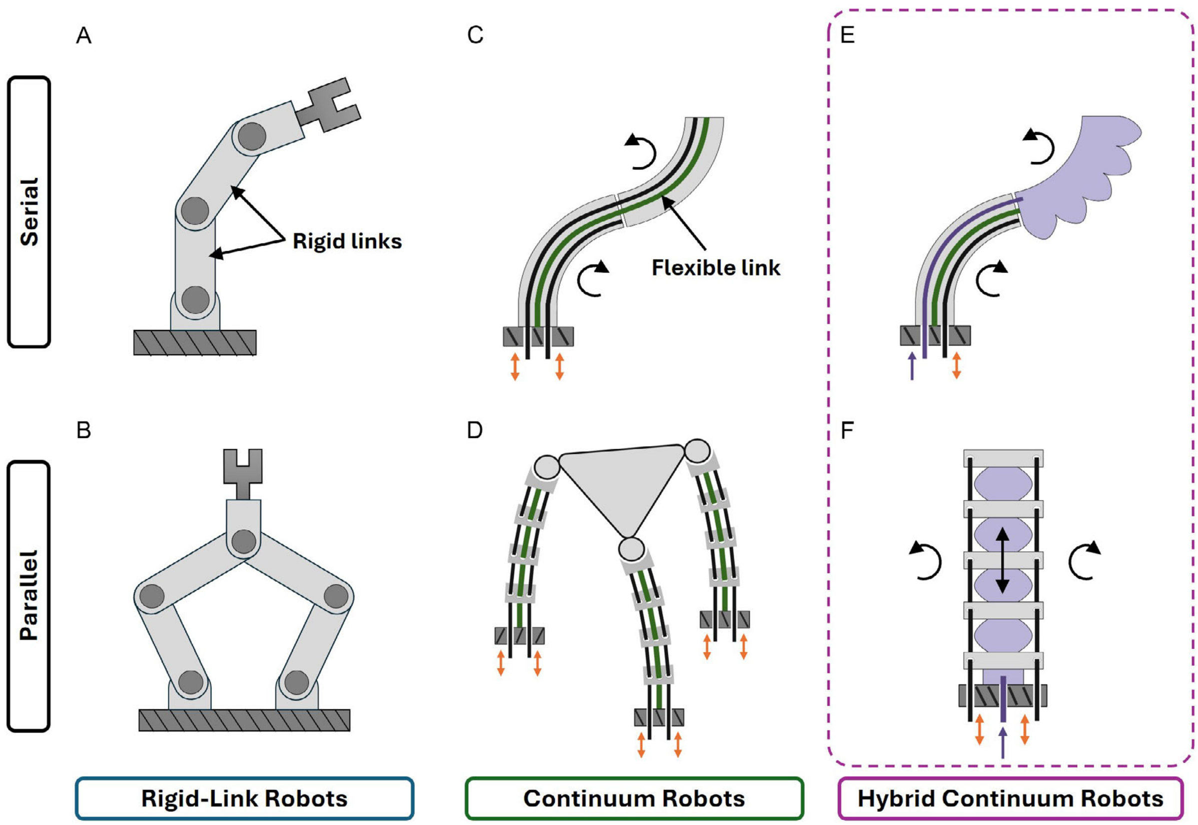

FIGURE 1 | Conceptual illustrations of serial and parallel configurations in traditional rigid-link, continuum, and hybrid continuum robotic architectures. Traditional rigid-link robotic manipulators: (A) serial open-chain mechanisms and (B) parallel closed-chain mechanisms. Continuum robot architectures: (C) serially connected flexible segments forming a continuous backbone and (D) parallel continuum structures composed of multiple interacting continuous robotic backbones. Hybrid continuum robots: (E) hybrid serial configurations integrating distinct actuation or material CR domains in series, and (F) hybrid parallel configurations with intra-segment integration of multiple actuation or material CR domains coupled to a common end-effector.

of HCRs, as architectures that integrate two or more established CR designs or actuation modalities within a single CR structure. This definition intentionally excludes CR designs that commonly maintain a uniform structural layout and actuation approach across multiple segments (e.g., multi-segment tendon-driven continuum robots). Likewise, robots that achieve hybrid-like behavior through adaptable mechanisms rather than CR approaches (e.g., jamming- or thermally responsive stiffness tuning) are categorized as having active adaptability rather than being structurally hybrid, and are discussed separately. Accordingly, the review covers hybridization arising from the deliberate integration of heterogeneous mechanical and/or actuation CR subsystems. A specific focus is given to emerging HCR designs, architectures, and configurations, with aspects of sensing, modeling, and control still predominantly aligned with established CR research and covered in other reviews [1–3].

In Section 2, we first extend the classification of HCRs, considering stratification by materials, configurations, and modes of action. Subsequently, in Section 3, we provide an overview of the broad range of HCRs proposed to date for application in challenging clinical scenarios. An overview of key adaptable CR approaches aligned to HCRs is given in Section 4, before summarizing the presented review in Section 5 and concluding with consideration of the open challenges and future outlook in Section 6. Providing this focused synthesis of HCR strategies aspires to guide future research toward the most promising opportunities and to support the identification of technical challenges that must be addressed for successful translation.

2 | Classification of Hybrid Continuum Robot Architectures

At the highest level, we consider CR classification based on the material structures employed in their design; although alternative distinctions can be reasonably made (e.g. actuation type). As introduced above, we categorize CRs on the basis of including primarily hard or soft components. In general, hard CRs can provide higher structural stiffness for tasks that require greater precision and/or high-force transmission [1], while soft CRs offer passive adaptability for potentially lower-risk interaction with delicate environments [19]. As depicted in Figure 2, we extend material type categorization to the consideration of hybridization strategies. As such, we consider hybridization as falling within the spectrum of existing CR designs, ranging from hard-bodied (HB) (Figure 2A) to soft-bodied (SB) (Figure 2C) in exclusive or combined HB/SB configurations.

As depicted in Figure 2B, we therefore consider a HCR as a conceptual aggregation of distinct constituent subsystems, with three subsets based on material composition, as:

$$\mathrm{HCR} = \begin{cases} \sum_{j=1}^{N} \mathrm{HB}_j, & \text{hard-only, } N > 1 \\ \sum_{k=1}^{M} \mathrm{SB}_k, & \text{soft-only, } M > 1 \\ \sum_{j=1}^{N} \mathrm{HB}_j + \sum_{k=1}^{M} \mathrm{SB}_k, & \text{mixed, } N,\ M \geq 1 \end{cases}$$

where combinations of N hard and M soft CRs are considered. This notation is intended only as a high-level abstraction, and does not indicate aspects including CR cross-coupling, actuation type or serial versus parallel interconnections, as introduced in Figure 1E,F.

However, based on these groupings, hard-only HCRs represent configurations with exclusive combinations of hard CR approaches. This allows retention of relatively high stiffness while potentially improving robot scaling and dexterity through efficient combinations of actuation modes and differing segment stiffness. This strategy delivers strong candidates for applications such as robotic-assisted surgeries, where load-bearing capacity and force application are critical.

Conversely, soft-only HCRs represent exclusive combinations of soft CR approaches, which can extend soft CR capabilities by

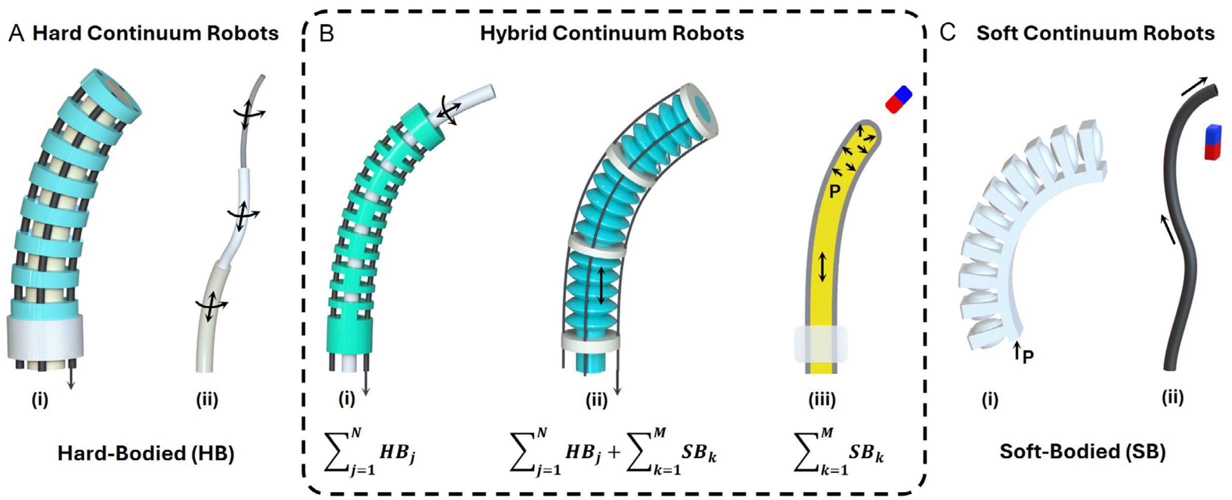

FIGURE 2 | Conceptual illustration of materials configurations for HCRs in the context of Hard-Bodied (HB) and Soft-Bodied (SB) CRs, illustrating their structural and actuation diversity. (A) HB CR examples, showing: (i) a tendon-driven CR, and (ii) a concentric tube CR; (B) HCRs of different materials compositions, showing: (i) a hard-only HCR design example of a tendon-driven and concentric tube combination, (ii) a mixed (HB and SB) HCR combination example of a tendon-driven and pneumatic design, and (iii) a soft-only HCR design example of a pneumatic and magnetic combination; and (C) SB CR examples, showing: (i) a pneumatically actuated soft CR, and (ii) a magnetically actuated soft CR. The dashed outline indicates the scope of HCR designs considered in the context of review.

decoupling and distributing actuation degrees-of-freedom (DOFs) for improved dexterity and control at small scales. This strategy is therefore potentially advantageous for delicate environments, such as in endoluminal procedures, where passive adaptation, scalability, and high dexterity are advantageous [19].

The mixed HCR combinations maximize intra-robot design diversity, offering potential for the broadest selection of passive compliance and actuation approaches. This can deliver self-supporting robotic structures with dexterous end effectors and decoupled actuation. These characteristics are well-suited to applications such as endoscopic diagnostic and interventional tasks, where competing requirements of navigation and task execution exist simultaneously [33].

A comparative summary of materials-based classifications, highlighting their key characteristics, primary applications, and associated challenges, is provided in Table 1. However, considering hybrid categorization based on materials alone does not capture the broad range of actuation approaches available, or the different methods of integration, including serial (→) or parallel (⊕), discussed previously. Serial configurations (e.g., HB → SB, such as in [34]) involve proximal-distal stacking of sequential robot segments (Figure 1E). This can offer benefits of reducing scale, increasing compliance or dexterity, and decoupling of DOFs. Conversely, parallel configurations (e.g., HB ⊕ HB, such as in [35]) combine different robot approaches directly, exploiting their simultaneous interaction to deliver enhanced motion and compliance characteristics within a unified robotic structure (Figure 1F). Figure 2B highlights a non-exhaustive selection of possible HCR approaches pertaining to the criteria outlined, while the following sub-sections cover the three high-level materials-based classifications outlined in detail.

2.1 | Hard-Only Architectures

Hard CRs, which serve as the foundation for hard-only HCRs, are designed primarily with higher-stiffness structures, which provide the essential characteristics of stability, precision, and high-force transmission [2]. Hard CRs will include a flexible backbone structure with actuation via tendons, rods, or self-interaction.

Commonly, a hard but flexible backbone element in the form of an elastic/superelastic rod or notched tube will be combined with either integrated disks or design features to guide separate drive tendons (in the case of tendon-driven CRs) or flexible rods (in the case of multi-backbone CRs) along the robot's length. This approach allows for variation in number, routing pathway, and termination locations for tendons/rods to suit desired kinematic behavior and deliver single- or multi-segment designs [36]. As an alternative to actuation tendons/rods, multiple structural backbones can interact to induce deformation. The most common approach of this type is Concentric Tube Robots, which consist of nested, pre-curved tubes, typically made of superelastic NiTi, that rotate and extend relative to one another. The interaction between the actuated tubes establishes the robot's configuration and can provide multi-degree-of-freedom motion [13]. A recent related variant in the form of a concentric push-pull robot combines opposing nested notched tubes connected at their distal end to allow bending via relative push-pull motion applied at the robot's base [37]. In both cases, combining the flexible mechanical structure and transmission together allows for a compact configuration with an open central lumen and high dexterity.

The advantage of hard CR systems lies in their ability to transmit greater forces while maintaining control precision, which is

TABLE 1 | Comparative summary of the three main hybrid CR classifications, highlighting their mathematical formulation, key characteristics, primary medical applications, and associated challenges.

Hybrid classification	Key characteristics & capabilities	Primary medical applications	Key challenges
Hard-Bodied Combinations $\mathrm{HCR} = \sum_{j=1}^{N} \mathrm{HB}_j$	• High Stiffness and Stability • Precision & High Force–Force • Structural Integrity	• Neurosurgery • Orthopedic Surgery • Single-Port Surgery	• Low Compliance • Risk of Tissue Trauma
Soft-Bodied Combinations $\mathrm{HCR} = \sum_{k=1}^{M} \mathrm{SB}_k$	• High Compliance and Safety • Passive Adaptability • Large Deformations	• Delicate Tissue Biopsy • Fragile Lumen Navigation • Soft Tissue Gripping	• Low Force Application • Control & Modeling Complexity
Hard + Soft Combinations $\mathrm{HCR} = \sum_{j=1}^{N} \mathrm{HB}_j + \sum_{k=1}^{M} \mathrm{SB}_k$	• Balanced Stiffness and Compliance • Variable/Tunable Stiffness • Synergistic Functionality	• Gastrointestinal Endoscopy • Endovascular Interventions • Catheter-Based Procedures	• Design and Integration Complexity • Stiffness Discontinuities

particularly critical in many surgical applications [3]. The variety of hard CR approaches allows rigidity and flexibility to be balanced through materials, design optimization, and actuation approach to suit a wide range of clinical tasks [38]. Combining multiple hard CR approaches, in the form of hard-only HCRs (e.g. [39],), extends the opportunity to improve clinical task suitability.

However, the integration of multiple hard-bodied subsystems also introduces unique engineering challenges that must be addressed to fully exploit their potential. Many of these challenges are not exclusive to hybrid architectures; they also appear in conventional hard multi-segment continuum robots, where transmission friction, inter-segment coupling, and alignment sensitivity similarly degrade performance [1, 40]. First, in terms of force transmission, the coexistence of multiple actuation paths, such as tendons, rods, or concentric tubes, can result in internal friction, backlash, and transmission losses that reduce the effective output force at the distal end. These effects become more pronounced in compact or highly curved configurations, where tendon routing and tube–tube contact increase energy dissipation [15]. Second, maintaining accuracy and repeatability is inherently difficult when rigid transmission components are coupled through compliant or nonlinear interfaces. Small alignment errors between nested or serially connected backbones can accumulate, leading to tip pose deviations that are difficult to calibrate or model accurately [41]. Finally, motion coupling between adjacent segments or actuation channels represents a major source of control complexity. In parallel hybrids (e.g., concentric or eccentric tube designs), torsional interactions between pre-curved elements can cause unintended secondary motions, while in serial architectures, bending of proximal sections can alter the mechanical boundary conditions of distal ones [42].

It is important to note, however, that hybridization can also alleviate some of these limitations by expanding the design space. By combining heterogeneous actuation modes, hard-only HCRs may reduce routing constraints or mechanical interference; for example, tendon-driven and concentric-tube actuation can be combined in a non-competing manner, enabling more efficient use of internal space, as demonstrated in systems such as [43]. Such mixed strategies offer opportunities for improved packaging, redundancy, and selective task-oriented actuation.

2.2 | Soft-Only Architectures

Soft CRs, which serve as the foundation for soft-only HCRs, are built entirely from compliant materials, such as elastomers or hydrogels. They are designed to leverage passive adaptability for improved conformation to their environment and reduced risk of damage during interaction with delicate structures [44].

Typical soft CRs include designs based on pneumatic/hydraulic actuation, cable/tendon transmission, and stimuli-responsive smart materials. Pneumatic or hydraulic networks, often implemented as embedded chambers within elastomeric bodies, enable large deformations through internal pressure control [20]. Cable- or tendon-driven soft structures provide similar actuation with simple, robust designs and the potential for precise steering or load-bearing capacity [24]. Smart material-based soft robots using approaches such as dielectric elastomer actuators, ionic polymer–metal composites, or shape-memory polymers to achieve electrically or thermally driven deformations, offering compact actuation without bulky external hardware [25, 26]. A prominent example within this category is magnetic actuation, where elastomers embedded with ferromagnetic particles enable wireless control of manipulators for highly constrained anatomical environments [28, 45].

The advantage of SB systems lies in their ability to achieve large bending, twisting, and elongation while maintaining intrinsic compliance, making them well-suited to applications that prioritize safety over precision. This is particularly critical in delicate medical procedures requiring endoluminal navigation, where rigid or hard CR approaches may pose a higher risk of tissue damage [18, 46, 47]. Furthermore, their deformable and highly adaptable nature enables them to operate effectively in unstructured and tortuous anatomical pathways, offering unique advantages over more rigid architectures.

However, the same properties that make soft CRs advantageous also introduce limitations. Their low stiffness restricts their capacity for forceful tissue manipulation or payload delivery, while non-linear material behavior and distributed actuation complicate modeling and control [30]. These challenges have motivated the development of soft-only HCRs, where multiple soft actuation modalities are integrated within a single robot (e.g., pneumatic chambers combined with dielectric elastomers, or soft magnetic steering integrated with fluid-driven elongation). Such combinations can decouple actuation DOFs, increase dexterity, and overcome the limitations of using a single soft actuation strategy in isolation.

By combining different soft CR approaches, soft-only HCRs extend the capabilities of compliant robots. For instance, parallel integration of magnetically active fluid within growing robots allows for independent length control and wireless steering within a compact fully soft CR body [48], while serial integration of multiple soft modules (e.g., soft tendon-driven segments with deployable growing robots) can allow position and orientation control coupled with navigation into tortuous vasculature [49]. These soft-only HCR strategies demonstrate the potential of soft materials not only to reduce operational risk, but also to provide controllable deployment and dexterity suitable for variable demands across clinical interventions.

2.3 | Mixed Architectures

HCRs that combine HB and SB elements aim to leverage the advantages of flexibility and softness [33]. These specific configurations allow robots to achieve the structural stability and precision associated with hard CRs while benefiting from the adaptability, flexibility, and safe interaction of soft CRs [19]. Within this class, hard and soft subsystems may be arranged in serial or parallel forms, or in multi-level combinations where, for example, a hard backbone supports embedded soft actuators, or a soft distal segment is deployed from a stiffer proximal platform.

Beyond their conceptual combination of hard and soft components, mixed HCRs introduce engineering behaviors that are not present in hard-only or soft-only systems. However, challenges can arise from the mismatch in mechanical properties between rigid and compliant elements. Differences in elastic modulus, energy storage, and deformation modes can lead to non-uniform strain distribution at the interfaces, which may induce local stress concentrations or reduce motion transmission efficiency. As a result, mixed HCRs often require carefully designed mechanical interfaces, such as graded stiffness transitions, reinforced bonding layers, or mechanically interlocking geometries, to maintain structural integrity during large deformations [3].

From a control perspective, mixed architectures blend the more predictable kinematics of hard CRs with the highly nonlinear, distributed compliance of soft CRs. When these subsystems interact in either a serial or parallel configuration, their boundary conditions dynamically influence one another, resulting in configuration-dependent coupling that complicates model-based control. This has motivated hybrid control strategies that combine model-based estimation for hard segments with data-driven or adaptive controllers for soft sections [50].

The benefit of such mixed integration is the ability to achieve distributed stiffness shaping along the robot's body. Hard elements can support load transmission or provide shape-holding behavior, while adjacent soft elements enable local dexterity, compliance, or safe interaction. Serial arrangements (e.g., hard-to-soft distal transitions) are advantageous when a stiffer proximal structure must deliver and orient a softer, more compliant tip, whereas parallel arrangements (e.g., soft actuation superimposed on a tendon-driven backbone) can facilitate decoupling of bending, elongation, or twisting DOFs within a single segment. These architectural synergies underpin many of the medical applications discussed in Section 3, where mixed hybrids are employed to reconcile competing demands on navigation, task execution, and safety.

3 | Applications of Hybrid Continuum Robot Designs in Healthcare

Building upon the architectural classifications introduced in Section 2, this section focuses on how different HCR designs have been applied within medical and surgical contexts. The discussion highlights representative examples where hard-only, soft-only, and mixed hybrid architectures have been tailored to meet distinct clinical requirements such as navigation through tortuous anatomy, safe tissue manipulation, and precise tool deployment. By analyzing these application domains, we emphasize the relationship between each hybrid architecture's structural design and its corresponding functional advantages. Figure 3 shows representative HCR designs for a range of targeted medical applications across the body, highlighting significant variety in materials, actuation, configuration and scale. A complete summary of the representative clinical applications, grouped by HCR classification, is also presented in Table 2.

3.1 | Hard-Only Hybrid Design Approaches and Applications

Hard-only HCR architectures ($HB \oplus HB$ or $HB \rightarrow HB$), have merged tendon-driven systems [43], concentric tube mechanisms [15], rods [52], backbones [42], and SMAs [12]. As summarized in Table 2 (upper section), these combinations have been explored in a variety of dimensions and applications, from neuroendovascular interventions to endoscopic approaches. Figure 4 presents a range of hard-only HCR examples from the literature.

Parallel configurations ($HB \oplus HB$) in hard-only HCRs typically involve the concentric nesting or direct integration of different mechanisms to augment a primary actuation method or add new functionality. A common theme is the combination of tendon or backbone structures with other mechanisms. For instance, combining tendon actuation and concentric tubes is used to achieve critical follow-the-leader motion for delicate endonasal surgery [43], as illustrated in Figure 4A. In orthopedic surgery, a flexible backbone is combined with tendon actuation for precise tasks such as drilling curved paths within bone for screw placement [83]. Another key theme in parallel designs involves integrating multiple interacting tubes and rods, often arranged concentrically or eccentrically around a central backbone to augment motion control. The concentric push-pull robot shown in Figure 4B enhances motion control by integrating a flexible backbone within concentric tubes [15]. This concept is extended in the eccentric tube robot (Figure 4C), which uses a central backbone to guide multiple rotatable, pre-curved tubes for neuroendoscopy [42], and in the Concentric-Tube-Eccentric-Rod (CTER) mechanism, which enables high-precision linear motion for micro-vascular surgery [35]. Finally, parallel hybridization is a powerful method for adding functionality, such as incorporating SMAs to dynamically modulate stiffness, which is crucial for safer tissue interaction in applications like MRI-compatible neurosurgery [84, 55].

Serial configurations ($HB \rightarrow HB$), in contrast, involve the proximal–distal stacking of different hard CR segments to create multi-segment manipulators. This architecture is particularly useful for tasks requiring complex navigation followed by precise manipulation. For example, multisegment catheters based on concentric, notched tubes actuated via push-pull motion have been developed for neuroendovascular interventions, where each segment can be independently controlled to traverse tortuous vasculature [52]. A similar serial strategy is used in multi-segment backbone-driven robots for transurethral bladder resection, which allows for both navigation and stable positioning for surgical tasks [41]. As seen in Figure 4D, another serial approach integrates a distal rigid-joint wrist with a flexible tendon-driven body to optimize dexterity and payload capacity, making it particularly suitable for minimally invasive surgical tasks in confined spaces [39]. More complex serial designs, such as the combination of concentric tube and tendon-driven segments, have been explored for procedures such as optic nerve sheath fenestration [56] and general minimally invasive surgery [57], and multi-mode hybrid architectures that integrate a distal concentric-tube section with a proximal cable-driven notched continuum segment to enhance trajectory planning and operational accuracy [85].

Across hard-only HCRs, representative trends and approaches have already emerged for both serial and parallel integration patterns. As summarized in Table 2, serial hard-only hybrids most commonly combine tendon-, backbone-, or rod-driven segments with concentric or notched tube mechanisms [56, 57]. Serial stacking of heterogeneous hard-bodied subsystems allows for sequential tuning of stiffness, dexterity, and force-transmission characteristics along the robot's length, while maintaining compact designs. Such combinations have demonstrated benefits for tasks that require follow-the-leader motion in tortuous anatomy [15, 43], high–force interaction for drilling or resection [41, 83], and precise multi-segment dexterity for confined minimally

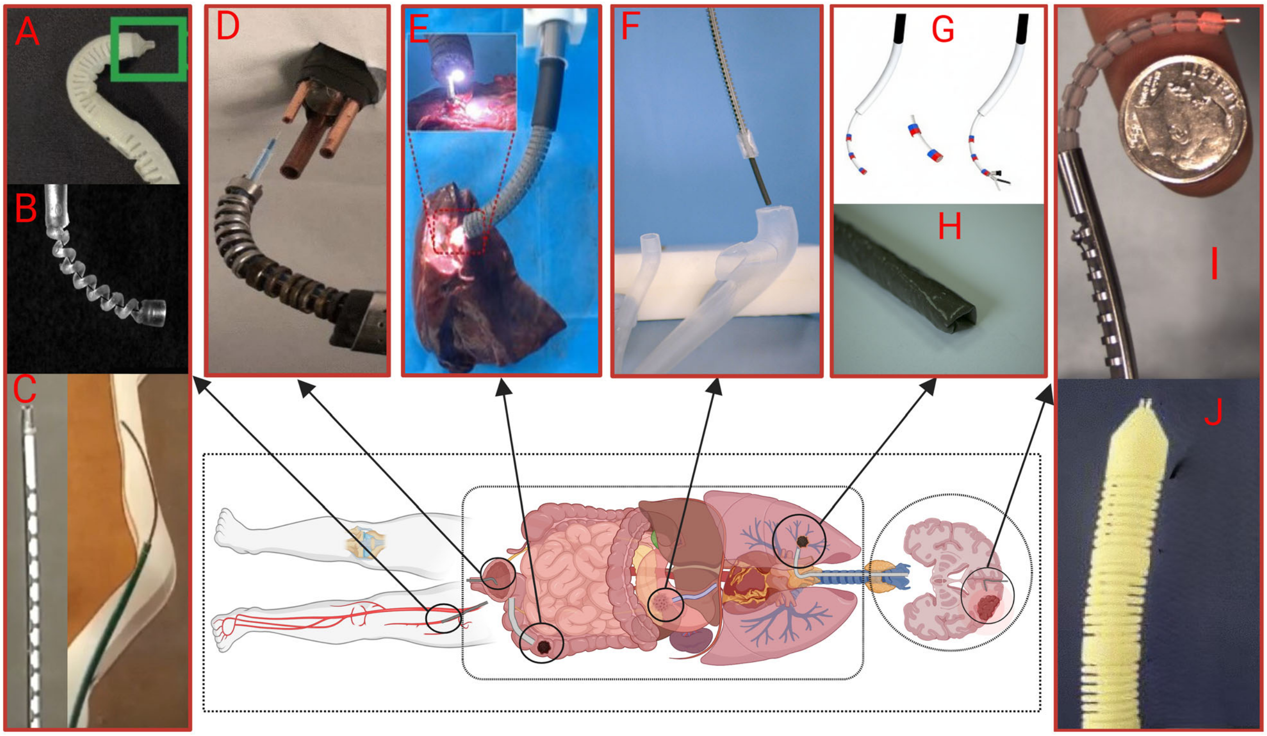

FIGURE 3 | Representative examples of HCR architectures for targeted medical applications. The figure highlights the versatility of these systems, showcasing examples for vascular, urological, gastrointestinal, pancreatic, pulmonary, and neurosurgical interventions. For the vascular system, representative robots are shown. (A) Endovascular procedures (SB → SB). Adapted with permission from ref. [49]. Copyright 2025, IEEE. (B) Aneurysm interventions that require navigating tortuous paths (HB ⊕ SB). Adapted with permission from ref. [51]. Copyright 2025, IEEE. (C) Neuroendovascular interventions for stroke treatment (HB → HB). Adapted under the terms of the CC-BY license [52]. Copyright 2024, The Authors, published by IEEE. (D) A multi-segment CR is depicted for transurethral bladder resection and surveillance in urology (HB → HB). Adapted with permission from ref. [41]. Copyright 2013, IEEE. For gastrointestinal endoscopy. (E) A hybrid manipulator is shown navigating the intestines (HB ⊕ SB). Adapted under the terms of the CC-BY 4.0 license [53]. Copyright 2023, The Authors, published by Wiley. (F) A specialized CR for accessing the pancreas and surrounding ducts via a single port (HB → SB). Adapted with permission from ref. [34]. Copyright 2025, IEEE. In pulmonary medicine, (G) a bronchoscope robot for deep lung examination (HB → SB). Adapted with permission from ref. [54]. Copyright 2024, IEEE. (H) A device for minimally invasive tissue biopsy sampling (SB ⊕ SB). Adapted under the terms of the CC-BY 4.0 license [48]. Copyright 2025, The Authors, published by Wiley. Finally, for neurosurgery, (I) endoscopic endonasal approaches to the skull base (HB ⊕ HB). Adapted with permission from ref. [43]. Copyright 2025, World Scientific Connect. (J) An MRI-compatible neurosurgical tool (HB ⊕ SB). Adapted with permission from ref. [55]. Copyright 2017, IEEE. The illustration was created in BioRender. [51] https://BioRender.com/ka9ni2j.

invasive procedures [39, 56, 57]. In contrast, parallel hard-only hybrids predominantly rely on concentric or eccentric geometric layouts to integrate multiple CR subsystems within a single segment. This includes designs such as concentric push-pull mechanisms, eccentric tube arrangements, and tendon-concentric tube pairings. Parallel integrations, although less common, offer high motion precision, enhanced torsional controllability, and increased structural redundancy, making them particularly effective for delicate operations such as neuroendoscopy [42] and skull-base surgery [43].

3.2 | Soft-Only Hybrid Design Approaches and Applications

In soft-only HCRs (SB ⊕ SB or SB → SB), combinations involve the integration of different soft actuators to enhance adaptability, control, and safety beyond that of unimodal soft systems. These designs merge a variety of approaches, including pneumatic actuators [61], integrated tendons [63], magnetic particles [48], growing mechanisms [49], and smart materials approaches such as shape memory polymers (SMPs) [64]. Table 2 (middle section) highlights a range of soft-only HCR systems that leverage these different actuation approaches in diverse and unique combinations. Figure 5 presents a range of soft-only HCR examples from the literature.

Parallel configurations (SB ⊕ SB) combine different soft actuation methods to work simultaneously, often to decouple degrees of freedom or introduce multi-modal control. A common approach is to augment soft pneumatic actuators with other mechanisms. For instance, pneumatic systems have been combined with integrated tendons to achieve enhanced control and variable stiffness for applications like human–robot collaboration and intra-bronchial interventions [61, 63]. Similarly, combining pneumatic and magnetic actuation enables multi-stimuli response for tasks in neurosurgery or creating intelligent bionic hands [58, 60, 62]. Another distinct parallel soft-only HCR approach, exemplified in Figure 5A, is magnetic vine robots that uses an eversion growing mechanism for advancement and a magnetic skin or internal magnetic fluid for steering to support navigation of the bronchial tree [48, 86].

TABLE 2 | Summary of example studies on hybrid actuation systems, grouped by their core classification and classified into parallel (⊕) and serial (→) configurations. Actuation key: T = Tendon, P = Pneumatic, C = Concentric Tube, B = Backbone, R = Rod, M = Magnetic, SMA = Shape Memory Alloy, SMP = Shape Memory Polymer, G = Growing, H = Hydraulic.

Refs	Hybridization	Configuration type	DOF	Diameter, mm	Length, mm	Application
Hard-Only Combinations						
[52]	$C \to C$	Serial	4	1.2	95	Neuroendovascular Interventions
[41]	$B \to C$	Serial	5	<8	—	Transurethral Bladder Resection
[43]	$T \oplus C$	Parallel	3	<4	—	Endoscopic Endonasal Approaches
[39]	$T \to T$	Serial	3/6	12.4/4.5	50/110	Minimally Invasive Surgery
[56]	$T \to C$	Serial	2/4	9	83/40	Optic Nerve Sheath Fenestration
[15]	$T \oplus C$	Parallel	5	4	—	Endoscopic Deployment
[57]	$C \to T \to C$	Serial	6	—	100/100/100	Minimally Invasive Surgery
[55]	$T \oplus$ SMA	Parallel	2/2/2	12.6	65	MRI-Compatible Neurosurgery
[35]	$R \oplus C$	Parallel	—	2.1	—	Microsurgery
[42]	$B \oplus C$	Parallel	—	18	65	Neuroendoscopy
Soft-Only Combinations						
[49]	$T \to T \to G$	Serial	2	7.6/2.67	-/445	Endovascular Emergencies (Stroke)
[48]	$G \oplus M$	Parallel	3	5	145	Minimally Invasive Tissue Biopsy
[58]	$P \oplus M$	Parallel	—	4	30	Neurosurgery
[59]	$P \to P \to G$	Serial	3	3.5	—	Lung Tissue Biopsy
[60]	$P \oplus M$	Parallel	—	18	113	Intelligent Bionic Hand / Medical Rehabilitation
[61]	$P \oplus T$	Parallel	3	—	—	Human-Robot Collaboration
[62]	$P \oplus M$	Parallel	3	3	18	Biomedical Applications
[63]	$P \oplus T$	Parallel	2	15	84	Robot-assisted Intra-bronchial Intervention
[64]	$P \oplus$ SMP	Parallel	—	22	110	Minimally Invasive Surgery
[65]	$H \to H$	Serial	—	13	600	Gastrointestinal Tract Screening
[66]	$P \oplus P$	Parallel	3	45	45	—
[67]	$P \to P$	Serial	—	18	1600	Colonoscopy
Mixed Combinations						
[51]	$T \oplus M$	Parallel	3	2.4	11.3–24.4	Aneurysm Interventions
[53]	$T \oplus P$	Parallel	2	18	110	Flexible Gastrointestinal Endoscopy
[34]	$T \to M$	Serial	—	2.8/1.3	250/60	Pancreatic Applications
[54]	$T \to M$	Serial	>6	4.5/2.4	460	Deep Lung Examination / Bronchoscopy
[68]	$T \oplus P$	Parallel	3	—	40–115	—
[69]	$R \oplus P$	Parallel	—	66	200–248	—
[70]	$T \oplus P$	Parallel	—	23	47	Minimally Invasive Surgery
[71]	$T \oplus P$	Parallel	>6	10–40	300	Surgical Applications
[72]	$T \oplus P$	Parallel	6	90	310–950	Remote Exploration and Operation
[73]	$T \to M$	Serial	—	3.3	30	Biomedical Robotics
[74]	$T \to M$	Serial	—	3.1	132	Medical Interventions
[75]	$C \to M$	Serial	—	0.8–7	150	Endovascular Intervention
[76]	$C \to M$	Serial	—	1.8/3.5	300/250	Vasculature Intervention
[77]	$(T \oplus P) \to (T \oplus P)$	Serial	2	—	—	Minimally Invasive Surgery

(Continues)

TABLE 2 | (Continued)

Refs	Hybridization	Configuration type	DOF	Diameter, mm	Length, mm	Application
[78]	$(T \oplus P) \rightarrow (T \oplus P)$	Serial	—	42–100	270/160	Assistive Human Applications
[79]	$G \oplus T$	Parallel	—	6.4	60	Intraluminal Applications
[80]	$P \rightarrow P$	Serial	4	55	—	—
[81]	$T \oplus P$	Parallel	—	3	95	Mammary Duct Inspection
[82]	$P \rightarrow P \rightarrow T$	Serial	7	12/12/7	35/35/40	Lower Gastrointestinal Interventions

Serial configurations (SB → SB) involve the proximal-distal stacking of different soft robotic segments, which is ideal for procedures with distinct sequential phases. A clear example of this architecture is the system developed for endovascular emergencies shown in Figure 5B, which connects a tendon-driven soft robot proximally with a soft growing robot distally [49]. This allows the tendon-driven section to perform active steering in larger vessels, which then precisely positions the growing robot to navigate through extremely tortuous and delicate distal anatomy. Similarly, a low-cost endoscope for gastrointestinal screening combines a proximal hydraulically actuated soft body for primary bending with a distal water-jet propulsion system for an expanded steering workspace [65]. Growing–pneumatic combinations have also been demonstrated, such as the soft everting colonoscopy robot, which is augmented via a pneumatic omnidirectional steering soft tip [67]. Finally, as seen in Figure 5C, hybridizing multiple soft actuation systems allows a complex, multi-stage medical task to be achieved that would not be possible via a single-function soft robot [59]. This soft-only HCR serially integrates three distinct soft actuators, each with a specialized function: steering, stabilization, and needle deployment. This hybrid design allows the robot to sequentially navigate to a target, anchor itself to increase its effective stiffness and counteract reaction forces, and then transmit sufficient force to puncture tissue for a biopsy.

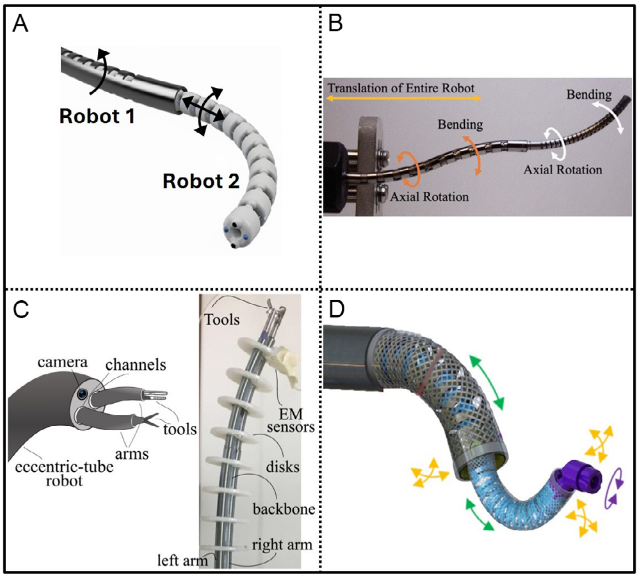

FIGURE 4 | Examples of HCRs composed of HB elements. (A) A parallel hybrid (HB ⊕ HB) combining two tendon-actuated robots concentrically for endonasal surgery. Adapted with permission from ref. [43]. Copyright 2025, World Scientific Connect. (B) A parallel hybrid (HB ⊕ HB) concentric push-pull robot integrating a flexible backbone to enhance planar control. Adapted with permission from ref. [15]. Copyright 2022, IEEE. (C) An eccentric tube robot, a parallel hybrid (HB ⊕ HB) that functions as a multi-arm steerable sheath by combining a central backbone with multiple pre-curved concentric tubes. Adapted with permission from ref. [42]. Copyright 2022, IEEE. (D) A tendon-driven hybrid robot (HB → HB) with integrated rigid segments designed to optimize dexterity and payload capacity. Adapted with permission from ref. [39]. Copyright 2023, IEEE.

Across the soft-only hybrid category, the designs surveyed in Table 2 indicate a clear trend of pneumatic actuation as a key [58–65]. This is largely due to its natural compatibility with elastomeric materials, ability to achieve large deformations at low pressure, and the ease of integrating additional subsystems within soft robotic bodies. Within this landscape, parallel pneumatic–tendon combinations emerge as the most prominent approach [61, 63]. These designs exploit pneumatics for global deformation while tendons provide directional control or localized stiffness tuning, resulting in multi-DOF segments capable of 3D bending and adaptable mechanical response. Although potentially advantageous for deployment or navigation in constrained anatomical environments, these systems have typically been restricted to relatively large diameters. In addition to tendon-based systems, modular vacuum-powered platforms such as the V-SPA robot demonstrate a fully soft parallel architecture that integrates pneumatic actuation, suction-based manipulation, and jamming-enabled stiffness control within a single soft module (Figure 5D) [66]. In comparison, parallel fluid-magnetic hybrids illustrate how tendon-free steering methods can provide advantages such as reduced diameter and improved remote control in constrained neurosurgical, intraluminal, or vascular environments [58, 60, 86]. Serial soft-only hybrids, while fewer in number, represent an emerging direction aimed at extending workspace or distributing specialized functions along the robot body. Multi-stage architectures, such as proximal steering modules coupled with distal growing or stabilizing segments [49], illustrate how serial integration can effectively separate navigation, stabilization, and task execution.

3.3 | Mixed Hybrid Design Approaches and Applications

In mixed HCR architectures (HB ⊕ SB or HB → SB) designs often merge distinct CR architectures and modes of actuation, such as

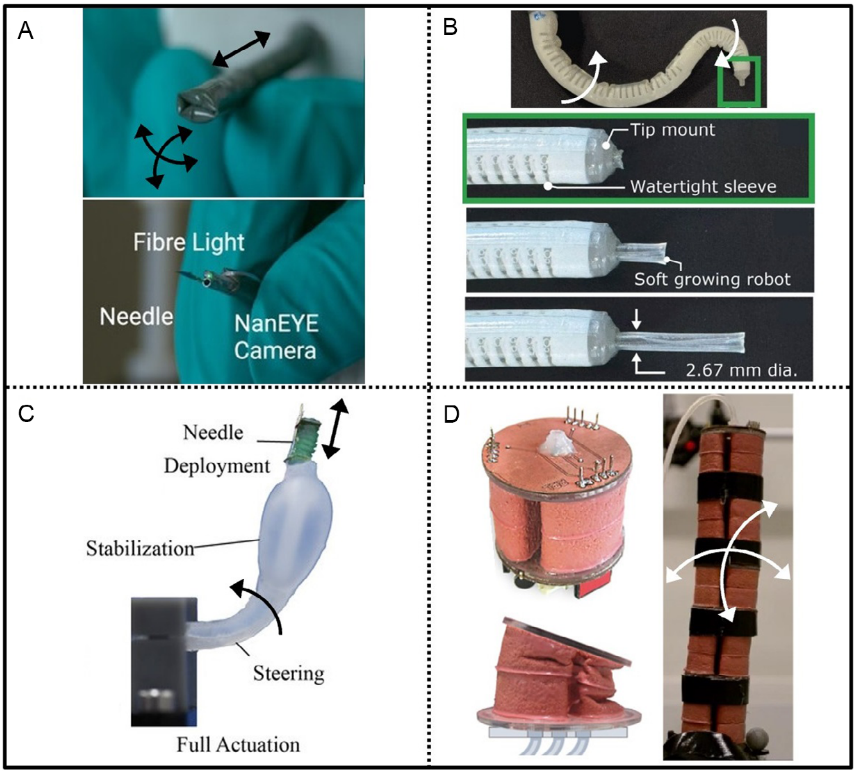

FIGURE 5 | Examples of HCRs composed primarily of SB elements. (A) A parallel hybrid (SB ⊕ SB) vine robot using hydraulic pressure for growth and an internal magnetic fluid for steering. Adapted under the terms of the CC-BY 4.0 license [48]. Copyright 2025, The Authors, published by Wiley. (B) A hybrid (SB → SB) platform for endovascular emergencies, combining a proximal tendon-driven soft robot with a distal soft growing robot. Adapted with permission from ref. [49]. Copyright 2025, IEEE. (C) A millimeter-scale serial hybrid (SB → SB) robot for tissue biopsy, which serially integrates three fluidic actuators for steering, stabilization, and needle deployment. Adapted under the terms of the CC-BY 4.0 license [59]. Copyright 2023, The Authors, published by Wiley. (D) A modular vacuum-powered (SB ⊕ SB) hybrid actuator system (V-SPA), integrating soft pneumatic actuation, suction-based manipulation, and jamming-based stiffness control. Adapted with permission from ref. [66]. Copyright 2017, AAAS.

combining stiffer tendon-driven structures with soft pneumatic actuators [53, 80], integrating magnetic elements with either hard or soft components [34, 51], or pairing growing mechanisms with other actuation types [81]. Table 2 (lower section) presents a range of mixed HCRs developed for a variety of medical applications. Figure 6 presents a range of mixed HCR examples from the literature.

Parallel configurations (HB ⊕ SB) typically integrate soft actuators into a higher-stiffness flexible skeleton/structure to create multi-functional end-effectors with tunable properties. The most common parallel approach combines pneumatic actuators and tendon-driven higher-stiffness flexible elements. This design is seen in various manipulators for minimally invasive interventions and surgical applications, where hard, flexible elements provide precision and soft actuators offer compliance [53, 68–72]. For instance, the modular hybrid manipulator in Figure 6A uses soft pneumatic actuators alongside hard, flexible joints for controlled stiffness modulation [80]. In a similar but distinct approach, the motion-decoupled joint combines a stiffer skeleton with soft pneumatic muscles to enhance dexterity [87]. Other parallel hybrids combine different materials, such as the variable-length catheter tip for aneurysm interventions, which pairs a soft tendon-driven helical body for extension/contraction with a hard permanent magnet for steering [51] (Figure 6B). Similarly, as shown in Figure 6C, the MAMMOBOT [81] is a mixed hybrid system for mammary duct inspection that integrates a hard, tendon-driven steerable catheter with a soft eversion growing sheath. This combination uses the precise steering of the hard catheter to guide the soft sheath, which can then navigate delicate and tortuous ducts by growing at its tip without creating frictional forces at the tissue walls.

Serial configurations (HB → SB) typically involve a smaller, softer CR being deployed from a larger, stiffer platform. This allows the proximal robot to navigate to a target area before the soft robot is deployed/engaged to safely explore delicate or tortuous distal anatomy. An illustrative example is the combination of a tendon-driven rigid manipulator deploying a soft magnetic robot. This approach has been offered for a robotic platform for pancreatic applications, as shown in Figure 6D [34], a hierarchical bronchoscope for deep lung examination [54], and a millimeter-scale robot for biomedical applications [73]. This serial deployment strategy is also effective for decoupling the control of position and orientation; for instance, a hybrid design combining a proximal tendon-actuated tube for positioning with a distal, telescoping magnetic ball chain for orientation has been shown to create a highly dexterous workspace, allowing the robot tip to approach a target from an arbitrary direction [74]. More complex serial designs involve stacking multiple parallel-hybrid segments. For instance, manipulators composed of serially connected segments have been developed for dexterous manipulation and assistive applications [77, 78]. A related serial mixed configuration has also been demonstrated for colorectal ESD, combining proximal soft pneumatic segments with a distal tendon-driven tip [82].

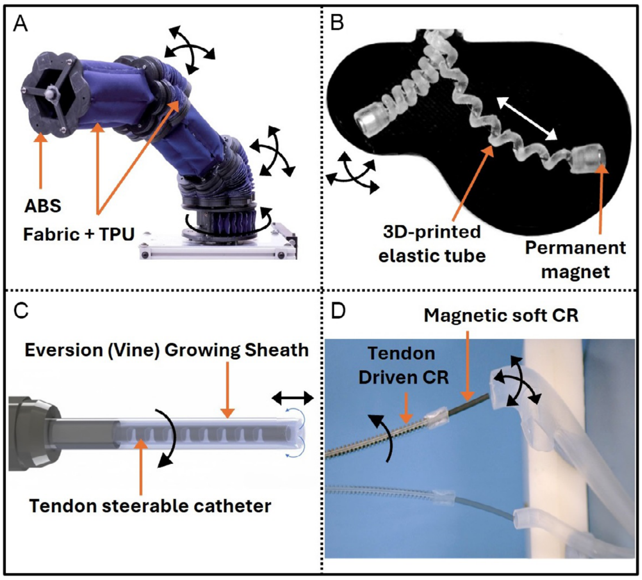

FIGURE 6 | Examples of HCRs combining HB and SB components. (A) A modular parallel hybrid (HB ⊕ SB) manipulator combining soft pneumatic actuators and rigid joints. Adapted with permission from ref. [80]. Copyright 2020, IEEE. (B) A parallel hybrid (HB ⊕ SB) catheter tip combining a tendon-driven soft helical body for variable length with a hard permanent magnet for steering. Adapted with permission from ref. [51]. Copyright 2025, IEEE. (C) A parallel hybrid (HB ⊕ SB) growing robot for mammary duct inspection, which combines a tendon-driven steerable catheter with a soft eversion sheath. Adapted with permission from ref. [81]. Copyright 2023, IEEE. (D) A serial hybrid (HB → SB) platform where a tendon-driven robot deploys a soft magnetic catheter for pancreatic applications. Adapted with permission from ref. [34]. Copyright 2025, IEEE.

Mixed HCR architectures from the literature, presented in Table 2, show the broadest versatility in design variation and application. However, for serial designs, a consistent trend is noted as the use of a stiffer hard-bodied proximal segment to provide structural support, load-bearing capacity, and precise proximal positioning, with a softer distal element enabling safe interaction, local dexterity, and adaptability within confined or delicate anatomical environments [34]. Common integration patterns of this type employ a tendon-driven or backbone-based proximal segment followed by a soft distal pneumatic or magnetic segment [54]. This division of roles allows mixed hybrids to reconcile the competing requirements of precision, compliance, and dexterity in many clinical applications; as seen in systems for pancreatic access [34], deep bronchoscopy [54], and millimeter-scale task-specific modules [59]. Parallel mixed hybrids, although diverse, typically embed soft pneumatic or magnetic actuation directly into a higher-stiffness flexible backbone [68]. This configuration leverages the stability of the hard structure while enabling distributed deformation, variable stiffness, or field-based directional control.

4 | Adaptable Approaches for Hybridization

Beyond combining physically distinct CR subsystems, hybrid-like performance can also be realized through active adaptability within a single robotic structure. This section, therefore, consolidates the enabling technologies that allow CRs to achieve hybrid behavior without physically integrating multiple CR architectures. These approaches, collectively referred to here as functional hybridization, focus on mechanisms or control strategies that dynamically adjust stiffness, compliance, or interaction behavior to emulate the dual characteristics of hard and soft systems. Unlike the structurally hybrid designs reviewed in previous sections, which integrate heterogeneous subsystems at the hardware level, the techniques discussed below achieve hybrid performance through material tuning or algorithmic control. Such adaptability is particularly valuable in medical applications, where a robot may require compliance for safe navigation yet sufficient stiffness for effective task execution. This adaptability can be primarily realized through either (i) dynamic adjustment of the robot's structure, or (ii) implementation of advanced control approaches that algorithmically manage the robot's behavior to emulate compliance. These aspects have attracted considerable research attention in their own right [88], but are summarized here as aligning technologies for implementing hybrid performance in CRs.

Variable stiffness CRs propose the integration of materials and design elements that facilitate on-demand adaptation to the robot's mechanical properties. This approach allows a structurally uniform CR to exhibit both hard and soft characteristics. Several key physical principles have been proposed to deliver stiffness modulation, which are often tailored to suit the restrictions of specific actuation methods such as tendons [79, 89], pneumatics [90], hydraulics [65], or magnetics [91, 92].

One of the most prominent approaches to achieve rapid stiffness change is the use of jamming mechanisms. These rely on controlling the internal friction between elements such as particles, fibers, or layers, typically by subjecting them to vacuum pressure within a confined elastic structure. For example, granular (particle) jamming was successfully employed in the STIFF-FLOP manipulator, where a flexible membrane filled with granular material was able to stiffen on-demand alongside pneumatically actuated steerable segments [90]. This allows the robot to be flexible during navigation through delicate anatomy and to become rigid to perform surgical tasks. Using a related principle, fiber jamming replaces particles with parallel fibers that can freely slide relative to each other under normal operation but lock together under application of a vacuum to cause reversible stiffening. This approach was recently implemented in a slender magnetically steered cardiovascular catheter to provide on-demand stiffening without the delays associated with alternative methods [91]. Similarly, the use of layers instead of fibers has also proven effective in creating tubular stiffening sheaths. The thin, overlapping material flaps used in layer jamming significantly increase rigidity against lateral loads while naturally preserving a central lumen for the robot [93]. As a promising alternative to vacuum-based actuation, magnetically induced stiffening has also been explored, which combines magnetorheological fluids with jamming scaffolds to achieve rapid, electronically controlled stiffness changes without pneumatic lines [94]. Recent advancements have further expanded the jamming category to include novel approaches such as 3D printed fabrics [95], granular chains [96], and hybrid jamming [97], which combine multiple jamming principles to achieve more versatile stiffness tuning [88].

Another major category for stiffness modulation relies on thermally responsive materials (TRMs), which leverage temperature-induced phase transitions to alter their mechanical properties [88]. This principle has been demonstrated using a range of materials, including SMA [98], SMP [64], low melting point alloys (LMPAs) [83], and thermoplastics (TPs) [99], which all transition from a solid high-stiffness state to a more malleable low-stiffness state upon moderate heating. For instance, SMA springs have been integrated into soft robotic arms, where they act antagonistically against driven cables to modulate the arm's overall stiffness [98]. Similarly, SMPs, valued for their biocompatibility, have been integrated as a stiffening backbone in pneumatic soft arms [64], with recent innovations, including thermoset SMPs that eliminate the need for an encapsulation layer, thereby improving manufacturability and enabling further miniaturization [100]. To further simplify the design, conductive SMPs have been developed to serve simultaneously as the heating element, temperature sensor, and variable stiffness structure [101]. LMPAs have also served as temporary skeletons in tendon-driven manipulators for minimally invasive surgery [83] and have been used to create sub-millimeter scale catheters that exhibit a high stiffness variation via a controlled radial temperature gradient [102]. More recently, TPs like graphene-polylactic acid have been used in magnetically steerable manipulators, where stiffness is modulated via Joule heating of the composite material [99]. While TRMs can offer a very high stiffness change ratio, they face two primary drawbacks. The first is a characteristically slow response time due to thermal dynamics, although this can be mitigated with hybrid control strategies integrating both active heating and cooling [103]. The second is the challenge of safely and effectively delivering the required thermal energy to the material, particularly for devices intended for use within the human body [88].

Stiffness can also be modulated through the integration of movable mechanical elements that physically constrain, lock, or apply antagonistic forces to the robot's body. A primary example of this is tendon antagonism, where the co-contraction of opposing tendons compresses the robot's structure to increase its overall stiffness [88]. This technique has been applied to manipulators for minimally invasive surgery, using a variable neutral-line mechanism to precisely control stiffness during procedures [89], and in bioinspired designs such as a robotic tail where adjustable tendon tension allows for precise stiffness control [104]. Other mechanical approaches include shape-locking mechanisms, as demonstrated in a hydraulic endoscope where a pneumatically-driven balloon locks alloy wires to provide a stable platform [65], and sliding backbones, where a movable NiTi rod selectively defines the flexible and rigid sections of a magnetically actuated soft robot [92]. Further innovative mechanical approaches include friction change mechanisms, where an SMA spring is used to alter the friction between internal wires to control stiffness [105], and variable stiffness ball joints, in which pneumatic actuators adjust the clearance within the joint to modify its effective rigidity [106].

While physical stiffness modulation provides an effective method of adaptation, managing CR's effective compliance via algorithmic control approaches represents an efficient alternative that does not necessitate alteration of the CR's underlying design architecture. Sophisticated control strategies have been developed to address challenges in force regulation [107], motion coordination [108], and adaptive responsiveness [109], enabling CRs to perform with the precision and compliance required for medical interventions. Effective force and motion control can be crucial to prevent tissue damage in delicate procedures [110], and advanced systems often combine force feedback with precise motion control to dynamically adjust their behavior [111]. Recent work has also explored hybrid control strategies that combine learning-based kinematic estimation with model-based feedback control to improve accuracy and robustness in soft robotic manipulators [50].

The broad range of variable stiffness techniques contributes to the enhanced design versatility of CRs in medical applications, enabling them to adapt their stiffness to the task at hand, whether it involves passive tissue interaction or the application of controlled forces. Similar to hybridization through design, stiffness modulation plays a critical role in enabling CRs to potentially perform a wide spectrum of surgical procedures with a balance of precision and safety.

5 | Summary

In this review, we have classified and reviewed various HCR architectures in the context of their proposed medical applications. This covers integration variety across HB and SB components and adaptable design approaches, and has emphasized the importance of underlying materials selection and collaborative actuation modes as key considerations in expanding the capabilities of CRs through hybridization. Hard-only HCRs leverage the benefits of established high-stiffness CR approaches to maintain high precision and load-bearing capacity, which are beneficial characteristics in many robot-assisted surgical applications. In contrast, soft-only HCRs are constructed entirely from combinations of soft CR approaches, maximizing flexibility and passive compliance. These hybrid designs have demonstrated suitability for tasks that involve delicate tissue, particularly at small scales. Finally, HCRs that combine HB and SB elements facilitate a balance between stiffness and compliance, where higher stiffness backbones can support soft, high-dexterity actuators, or where multiple actuation modes may be tightly integrated to provide enhanced adaptability. Mixed HCR approaches offer broad suitability for applications such as endoscopy and catheter-based interventions, as combinations can allow passive adaptability while maintaining control precision.

It is also important to recognize that several hybrid continuum robots [78, 79] identified in this review exhibit both serial and parallel hybrid characteristics at different levels of their architecture. In these systems, parallel hybridization is often implemented within a segment; for example, through the integration of tendon actuation with pneumatic, magnetic, or stiffness-modulating components, while serial hybridization emerges at the robot level through the sequential stacking of heterogeneous segments. In addition to this segment-vs-system layering, some architectures use a serial continuum mechanism to structurally support, constrain, or guide an embedded parallel subsystem; an approach exemplified by eccentric multi-arm concentric-tube sheaths, in which the coordinated rotation of multiple precurved tubes drives the deformation of the overall structure while the central backbone passively maintains disk spacing and geometric coupling [42]. This multi-level 'hybrid of parallel and serial' organization allows designers to combine complementary advantages across scales, achieving local dexterity or stiffness modulation alongside large-scale workspace shaping and navigational capability.

Some of the key performance benefits of hybrid approaches are mirrored in dynamically adaptable, variable stiffness designs.

Techniques such as structural jamming, antagonistic actuation, and integration of TRMs embody CRs with the ability to switch between compliant and rigid states as needed. In addition, advanced control strategies can be employed in fixed robot architectures to balance motion precision and compliance under external loading.

HCRs offer a broad category of versatile CRs that represent a promising pathway to overcome limitations associated with conventional CR approaches. The possibility of tuning and adapting designs across a wide range of materials, actuation approaches, and integration strategies offers the potential for custom HCRs to be developed to meet the requirements of many challenging healthcare applications, with the potential to improve patient safety and provide more dexterous robotic tools. However, HCR approaches still represent a minority within CR research, and many challenges and opportunities remain to maximize their potential.

6 | Open Challenges and Future Vision

Although HCRs have shown significant potential, the added complexity inherent in many designs poses several challenges. In particular, where a significant mismatch in materials exists, attention is required to achieve seamless and/or robust integration between elements. For HCRs with fixed relative arrangements of elements, discontinuities in material stiffness at joins can create regions susceptible to breakdown or failure. In the alternative case of elements allowing deployable motions, friction and self-interaction may restrict design freedom or influence performance. Integration challenges can also exist where the supply of multiple modes of actuation is required within the same HCR design. For example, attempting to co-supply mechanical tendons and pneumatic supply lines places additional restrictions on minimum robot dimensions, passive compliance, and can limit the possibility for auxiliary working channels or functional component integration. Beyond the body of the robot, external actuation hardware, including motors, regulators, or external magnetic field generation systems, adds complexity and cost relative to single-mode CR systems, and must compete for space in the context of healthcare settings.

Additional challenges are also presented through added manufacturing requirements, especially due to the level of miniaturization required for many minimally invasive tools. The materials used in hard and soft CRs typically necessitates the use of different manufacturing approaches. This makes direct co-fabrication challenging and thus often requires researchers to formulate novel assembly processes for each HCR. Employing modular design approaches may alleviate some of these challenges and provide options for rapidly reconfiguring blends of hard and soft CR components to suit different applications. However, looking to the future, the expansion of material options and multi-material 3D-printing may offer more freedom to solve challenges around HCR manufacture, assembly, and actuation integration. This may also help address the challenges of miniaturization and biocompatibility that must be overcome for HCRs to realize their impact as medical devices.

In addition to the complexities of physical design in HCRs, a major challenge lies in their control. Coupling between rigid and soft components introduces non-linearities that are difficult to model, potentially requiring different approaches. Furthermore, the integration of multiple actuation systems demands robust synchronization and management of undesired interactions. Improved multi-physics simulation tools, design optimization tools, and adaptive control algorithms will be essential to ensure HCRs can operate effectively in safety critical environments. Looking ahead, artificial intelligence and machine learning will likely play a critical role in handling the added complexity of HCR control to better adapt to unstructured environments, improve and maintain their performance over time, and make real-time decisions.

As with general CR research, the development of HCRs for healthcare applications will need to employ appropriate sensing approaches. Many sensor types are currently well-suited to either hard or soft CR designs, such as fiber Bragg grating sensors versus soft optical waveguides, respectively. There is a dearth of approaches that can be readily integrated across certain HCR designs without impacting on the stiffness or scale of the robot. This functional component integration problem is also present when modes of active stiffness modulation are included. To enable HCRs to switch between soft and rigid states dynamically, existing techniques, such as pneumatic actuation, granular jamming, and TRMs usually require additional space allocation within the robot's body for energy supply and can be slow to respond when required. Integration of onboard logic and embodied intelligence approaches may allow robots to sense and respond to the environment without reliance on off-board components for more rapid and seamless transitions between states.

In conclusion, while HCRs are still in an early stage of development, they hold great promise for transforming fields such as healthcare. The maturity and breadth of CR research has prepared the way for a rapid and creative future of HCR developments. However, with the significant diversity in potential approaches, it is critical that HCRs are co-designed with appropriate clinical oversight to target the specific requirements relating to key healthcare applications. Overcoming current challenges related to design, fabrication, integration, and control will be essential for unlocking their full potential.

The future outlook is optimistic, with emerging enabling technologies and materials likely to push the boundaries of what HCRs can achieve in terms of adaptability, precision, and safety. Looking ahead over the next three to 5 years, the most significant breakthroughs are expected to emerge from mixed hard–soft hybrid architectures and functionally adaptive continuum systems. In particular, modular tendon–pneumatic designs that exploit multi-material 3D printing and embedded sensing may achieve clinically appropriate scales while offering controllable stiffness. These approaches would be well suited to endoluminal applications such as bronchoscopy, pancreatic access, and gastrointestinal diagnostics. At smaller scales, soft-only HCRs combining mechanical-magnetic and fluidic-magnetic approaches are also likely to gain momentum due to their ability to efficiently integrate high dexterity remote magnetic steering with higher force actuation. These may enable navigation and task execution in previously inaccessible anatomical regions for neurosurgical or intravascular interventions. Converging advancements in additive manufacturing, smart materials, and AI-assisted modeling and control are anticipated to accelerate HCR development and provide a pathway from laboratory prototypes to clinically deployable tools supporting minimally invasive diagnosis and intervention.

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Conflicts of Interest

The authors declare no conflicts of interest.

References

1. J. Burgner-Kahrs, D. C. Rucker, H. Choset, "Continuum Robots for Medical Applications: A Survey," *IEEE Transactions on Robotics* 31, no. 6 (2015): 1261–1280.

2. T. da Veiga, J. H. Chandler, P. Lloyd, et al., "Challenges of Continuum Robots in Clinical Context: A Review," *Progress in Biomedical Engineering* 2, no. 3 (2020): 032003.

3. M. Russo, S. M. H. Sadati, X. Dong, et al., "Continuum Robots: An Overview," *Advanced Intelligent Systems* 5, no. 5 (2023): 2200367.

4. A. Bajo, R. E. Goldman, L. Wang, D. Fowler, and N. Simaan, "Integration and preliminary evaluation of an Insertable Robotic Effectors Platform for Single Port Access Surgery," in *2012 IEEE International Conference on Robotics and Automation*, (IEEE on IEEE Xplore, 2012), 3381–3387.

5. J. Zhao, X. Zheng, M. Zheng, A. J. Shih, and K. Xu, "An endoscopic continuum testbed for finalizing system characteristics of a surgical robot for NOTES procedures," in *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, (IEEE on IEEE Xplore, 63–70.

6. N. Garbin, L. Wang, J. H. Chandler, K. L. Obstein, N. Simaan, and P. Valdastri, "Dual-Continuum Design Approach for Intuitive and Low-Cost Upper Gastrointestinal Endoscopy," *IEEE Transactions on Biomedical Engineering* 66, no. 7 (2018): 1963–1974.

7. C. Heunis, J. Sikorski, and S. Misra, "Flexible Instruments for Endovascular Interventions: Improved Magnetic Steering, Actuation, and Image-Guided Surgical Instruments," *IEEE Robotics & Automation Magazine* 25, no. 3 (2018): 71–82.

8. S. Jeon, A. K. Hoshiar, K. Kim, et al., "A Magnetically Controlled Soft Microrobot Steering a Guidewire in a Three-Dimensional Phantom Vascular Network," *Soft Robotics* 6, no. 1 (2019): 54–68.

9. T. Kato, I. Okumura, S.-E. Song, A. J. Golby, and N. Hata, "Tendon-Driven Continuum Robot for Endoscopic Surgery: Preclinical Development and Validation of a Tension Propagation Model," *IEEE/ASME Transactions on Mechatronics* 20, no. 5 (2014): 2252–2263.

10. S. Geng, Y. Wang, C. Wang, and R. Kang, "A Space Tendon-Driven Continuum Robot," *Advances in Swarm Intelligence*, eds. Y. Tan, Y. Shiand Q. Tang(Springer International Publishing, 2018), pp. 25–35.

11. W. S. Roneand P. Ben-Tzvi, "Mechanics Modeling of Multisegment Rod-Driven Continuum Robots," *Journal of Mechanisms and Robotics* 6, no. 4 (2014): 041006.

12. C. Cheng, J. Cheng, and W. Huang, "Design and Development of a Novel SMA Actuated Multi-DOF Soft Robot," *IEEE Access* 7 (2019): 75073–75080.

13. H. Alfalahi, F. Renda, and C. Stefanini, "Concentric Tube Robots for Minimally Invasive Surgery: Current Applications and Future Opportunities," *IEEE Transactions on Medical Robotics and Bionics* 2, no. 3 (2020): 410–424.

14. D. C. R. Jessica Burgner, H. B. Gilbert, P. J. Swaney, P. T. Russell, K. D. Weaver, and R. J. Webster, "A Telerobotic System for Transnasal Surgery," *IEEE/ASME Transactions on Mechatronics* 19, no. 3 (2013): 996–1006.

15. K. Oliver-Butler, J. A. Childs, A. Daniel, and D. C. Rucker, "Concentric Push–pull Robots: Planar Modeling and Design," *IEEE Transactions on Robotics* 38, no. 2 (2021): 1186–1200.

16. R. W. Dobbs, W. R. Halgrimson, I. Madueke, H. T. Vigneswaran, J. O. Wilson, and S. Crivellaro, "Single-Port Robot-Assisted Laparoscopic Radical Prostatectomy: Initial Experience and Technique with the DA Vinci SP Platform," *BJU International* 124, no. 6 (2019): 1022–1027.

17. J. Reisenauer, M. J. Simoff, M. A. Pritchett, et al., "Ion: Technology and Techniques for Shape-Sensing Robotic-Assisted Bronchoscopy," *The Annals of Thoracic Surgery* 113, no. 1 (2022): 308–315.

18. M. Cianchetti, C. Laschi, A. Menciassi, and P. Dario, "Biomedical Applications of Soft Robotics," *Nature Reviews Materials* 3, no. 6 (2018): 143–153.

19. D. Rusand M. T. Tolley, "Design, Fabrication and Control of Soft Robots," *Nature* 521, no. 7553 (2015): 467–475.

20. P. Polygerinos, N. Correll, S. A. Morin, et al., "Soft Robotics: Review of Fluid-Driven Intrinsically Soft Devices; Manufacturing, Sensing, Control, and Applications in Human-Robot Interaction," *Advanced Engineering Materials* 19, no. 12 (2017): 1700016.

21. O. D. Yirmibesoglu, J. Morrow, S. Walker, et al., "Direct 3D printing of silicone elastomer soft robots and their performance comparison with molded counterparts," in *2018 IEEE International Conference on Soft Robotics (RoboSoft)*, (IEEE on IEEE Xplore, 2018), 295–302.

22. Y. Lee, W. J. Song, and J.-Y. Sun, "Hydrogel Soft Robotics," *Materials Today Physics* 15 (2020): 100258.

23. B. Sparrman, C. Du Pasquier, C. Thomsen, et al., "Printed Silicone Pneumatic Actuators for Soft Robotics," *Additive Manufacturing* 40 (2021): 101860.

24. F. Renda, M. Giorelli, M. Calisti, M. Cianchetti, and C. Laschi, "Dynamic Model of a Multibending Soft Robot Arm Driven by Cables," *IEEE Transactions on Robotics* 30, no. 5 (2014): 1109–1122.

25. M. Franke, A. Ehrenhofer, E.-F. M. H. Soumyarup Lahiri, T. Wallmersperger, and A. Richter, "Dielectric Elastomer Actuator Driven Soft Robotic Structures with Bioinspired Skeletal and Muscular Reinforcement," *Frontiers in Robotics and A* I7 (2020): 510757.

26. A. Benouhiba, K. Rabenorosoa, P. Rougeot, M. Ouisse, and N. Andreff, "A Multisegment Electro-Active Polymer Based Milli-Continuum Soft Robots," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, (IEEE on IEEE Xplore, 2018), 7500–7506.

27. E. R. Blackert, P. Scaccia, M. Barnes, et al., "Spatiotemporally Controlled Soft Robotics with Optically Responsive Liquid Crystal Elastomers," *Advanced Intelligent Systems* 7, no. 6 (2025): 2500045.

28. Z. Yang, H. Yang, Y. Cao, Y. Cui, and L. Zhang, "Magnetically Actuated Continuum Medical Robots: A Review," *Advanced Intelligent Systems* 5, no. 6 (2023): 2200416.

29. J. Duan, K. Zhang, K. Qian, J. Hao, Z. Zhang, and C. Shi, "An Operating Stiffness Controller for the Medical Continuum Robot Based on Impedance Control," *Cyborg and Bionic Systems* 5 (2024): 0110.

30. C. D. Santina, C. Duriez, and D. Rus, "Model-Based Control of Soft Robots: A Survey of the State of the Art and Open Challenges," *IEEE Control Systems Magazine* 43, no. 3 (2023): 30–65.

31. A. Antonov, "Parallel–Serial Robotic Manipulators: A Review of Architectures, Applications, and Methods of Design and Analysis," *Machines* 12, no. 11 (2024): 811.

32. S. Lilge, K. Nuelle, J. A. Childs, D. C. R. Kefei Wen, and J. Burgner-Kahrs, "Parallel-Continuum Robots: A Survey," *IEEE Transactions on Robotics* 40 (2024): 3252–3270.

33. S. Li and G. Hao, "Current Trends and Prospects in Compliant Continuum Robots: A Survey," *Actuators* 10, no. 7 (2021): 145.

34. B. Calmé, A. Metcalf, M. Brockdorff, et al., "Hybrid Tendon-Actuated and Soft Magnetic Robotic Platform for Pancreatic Applications," *IEEE Robotics and Automation Letters* 10, no. 2 (2025): 1784–1791.

35. L. Zeng, S. M. Hadi Sadati, M. Ismayilov, L. Lindenroth, and C. Bergeles, "Concentric-Tube-Eccentric-Rod: a Continuum Actuator for Macro-/Micro-Scale Translational Actuation," in *2024 IEEE. 20th International Conference on Automation Science and Engineering (CASE)*, (IEEE on IEEE Xplore, 2024), 2052–2058.

36. B. Ozdemir, P. Valdastri, and J. H. Chandler, "Towards Accurate Shape Prediction for Compact Spring Backbone Tendon-Driven Continuum Robots," *Towards Autonomous Robotic Systems*, eds. A. Cavalcanti, S. Fosterand R. Richardson (Springer Nature Switzerland, 2026), pp. 210–222.

37. K. Oliver-Butler, Z. H. Epps, and D. C. Rucker, "Concentric Agonist-Antagonist Robots for Minimally Invasive Surgeries," *Medical Imaging 2017: Image-Guided Procedures, Robotic Interventions, and Modeling*, eds. R. J. WebsterIIIand B. Fei, (International Society for Optics and Photonics, SPIE) 10135 (2017): pp. 1013511.

38. P. E. Dupont, N. Simaan, H. Choset, and C. Rucker, "Continuum Robots for Medical Interventions," *Proceedings of the IEEE* 110, no. 7 (2022): 847–870.

39. X. Ma, X. Wang, Z. Zhang, P. Zhu, S. S. Cheng, and K. W. S. Au, "Design and Experimental Validation of a Novel Hybrid Continuum Robot With Enhanced Dexterity and Manipulability in Confined Space," *IEEE/ASME Transactions on Mechatronics* 28, no. 4 (2023): 1826–1835.

40. R. J. Webster IIIand B. A. Jones, "Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review," *The International Journal of Robotics Research* 29, no. 13 (2010): 1661–1683.

41. A. Bajo, R. B. Pickens, S. D. Herrell, and N. Simaan, "Constrained motion control of multisegment continuum robots for transurethral bladder resection and surveillance," in *2013 IEEE International Conference on Robotics and Automation*, (IEEE on IEEE Xplore, 2013), 5837–5842.

42. J. Wang, J. Peine, and P. E. Dupont, "Eccentric Tube Robots as Multiarmed Steerable Sheaths," *IEEE Transactions on Robotics* 38, no. 1 (2022): 477–490.

43. K. K. Yamamoto, T. J. Zachem, P. Kheradmand, et al., "Tendon-Actuated Concentric Tube Endonasal Robot (TACTER," *Journal of Medical Robotics Research* 10, no. 03n04 (2025): 2550002.

44. M. Manti, V. Cacucciolo, and M. Cianchetti, "Stiffening in Soft Robotics: A Review of the State of the Art," *IEEE Robotics & Automation Magazine* 23, no. 3 (2016): 93–106.

45. A. Bacchetti, P. Lloyd, S. Taccola, et al., "Optimization and Fabrication of Programmable Domains for Soft Magnetic Robots: A Review," *Frontiers in Robotics and AI* Volume 9 (2022): 1–10.

46. M. Chauhan, J. H. Chandler, A. Jha, V. Subramaniam, K. L. Obstein, and P. Valdastri, "An Origami-Based Soft Robotic Actuator for Upper Gastrointestinal Endoscopic Applications," *Frontiers in Robotics and AI* Volume 8 (2021): 1–15.

47. C. M. Hofmair, K. Bhakhri, and M. Chauhan, "Design and Optimisation of Soft Robotic Actuators for Augmented Lung-Ventilation," *Biomimetic Intelligence and Robotics* 4, no. 3 (2024): 100172.

48. J. Davy, T. P. Dean, N. J. Greenidge, et al., "Magnetic Fluid-Driven Vine Robots for Minimally Invasive Tissue Biopsy Sampling," *Advanced Intelligent Systems* 7, no. 8 (2025): 2400827.

49. A. Mangan, S. Kim, N. Jones, et al., "Serially-Connected Soft Continuum Robots for Endovascular Emergencies," *IEEE Transactions on Medical Robotics and Bionics* 7, no. 3 (2025): 1029–1040.

50. A. Garriga-Casanovas, F. Shakib, V. Ferrandy, and E. Franco, "Hybrid Control of Soft Robotic Manipulator," *Actuators* 13, no. 7 (2024): 242.

51. M. A. Khalid, P. Valdastri, and J. H. Chandler, "3D-Printed Variable-Length Magnetically Steered Catheter Tip for Enhanced Access in Aneurysm Interventions," in *2025 IEEE. 8th International Conference on Soft Robotics (RoboSoft)*, (2026), 1–7.

52. C. Abah, J. P. Lawson, R. Chitale, and N. Simaan, "Self-Steering Catheters for Neuroendovascular Interventions," *IEEE Transactions on Medical Robotics and Bionics* 6, no. 4 (2024): 1726–1737.

53. X. Luo, D. Song, Z. Zhang, S. Wang, and C. Shi, "A Novel Distal Hybrid Pneumatic/Cable-Driven Continuum Joint with Variable Stiffness Capacity for Flexible Gastrointestinal Endoscopy," *Advanced Intelligent Systems* 5, no. 6 (2023): 2200403.

54. J. Zhang, Q. Fang, P. Xiang, R. Xiong, Y. Wang, and H. Lu, "Soft Hybrid Actuated Hierarchical Bronchoscope Robot for Deep Lung Examination," *IEEE Robotics and Automation Letters* 9, no. 1 (2024): 811–818.

55. Y. Kim, S. S. Cheng, and J. P. Desai, "Active Stiffness Tuning of a Spring-Based Continuum Robot for MRI-Guided Neurosurgery," *IEEE Transactions on Robotics* 34, no. 1 (2018): 18–28.

56. Z. Mitros, S. M. Hadi Sadati, S. Nousias, L. Da Cruz, and C. Bergeles, "Design and Quasistatic Modelling of Hybrid Continuum Multi-Arm Robots," in *2022 International Conference on Robotics and Automation (ICRA)*, (IEEE on IEEE Xplore, 2022), 9607–9613.

57. L. Wu, R. Crawford, and J. Roberts, "Dexterity Analysis of Three 6-DOF Continuum Robots Combining Concentric Tube Mechanisms and Cable-Driven Mechanisms," *IEEE Robotics and Automation Letters* 2, no. 2 (2016): 514–521.

58. Z. Koszowska, M. Brockdorff, P. Lloyd, J. H. Chandler, and P. Valdastri, "A Pneumatic Anchoring Mechanism for Improved Stability in Soft Magnetic Manipulators for Surgery*," in *2025 IEEE. 8th International Conference on Soft Robotics (RoboSoft)*, (IEEE on IEEE Xplore, 2025), 1–7.

59. D. Van Lewen, T. Janke, H. Lee, R. Austin, E. Billatos, and S. Russo, "A Millimeter-Scale Soft Robot for Tissue Biopsy Procedures," *Advanced Intelligent Systems* 5, no. 5 (2023): 2200326.

60. W. Xiao, D. Hu, H. Zhou, and X. Du, "A Self-Sensing Intelligent Soft Pneumatic Actuator with Soft Magnetic Structures," *International Journal of Mechanical Sciences* 250 (2023): 108279.

61. J.-Y. Lee, E.-Y. Go, W.-Y. Choi, W.-B. Kim, and K.-J. Cho, "Development of soft continuum manipulator with pneumatic and tendon driven actuations," in *2016 13th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, (IEEE on IEEE Xplore, 2016), 377–379.

62. J. E. Lee, Y. Sun, Y.-C. Sun, I. R. Manchester, and H. E. Naguib, "Design of Multi-Stimuli Responsive Hybrid Pneumatic–magnetic Soft

Actuator with Novel Channel Integration," *Applied Materials Today* 29 (2022): 101681.

63. M. Roshanfar, J. Dargahi, and A. Hooshiar, "Design Optimization of a Hybrid-Driven Soft Surgical Robot with Biomimetic Constraints," *Biomimetics* 9, no. 1 (2024): 59.

64. J. Liu, J. Wei, G. Zhang, S. Wang, and S. Zuo, "Pneumatic Soft Arm Based on Spiral Balloon Weaving and Shape Memory Polymer Backbone," *Journal of Mechanical Design* 141, no. 8 (2019): 082302.

65. J. Liu, L. Yin, J. H. Chandler, X. Chen, P. Valdastri, and S. Zuo, "A Dual-Bending Endoscope with Shape-Lockable Hydraulic Actuation and Water-Jet Propulsion for Gastrointestinal Tract Screening," *The International Journal of Medical Robotics and Computer Assisted Surgery* 17, no. 1 (2021): 1–13.

66. M. A. Robertsonand J. Paik, "New Soft Robots Really Suck: Vacuum-Powered Systems Empower Diverse Capabilities," *Science Robotics* 2, no. 9 (2017): eaan6357.

67. J. Shi, K. Borvorntanajanya, K. Chen, E. Franco, F. Rodriguez, and Baena, "Design, Control, and Evaluation of a Novel Soft Everting Robot for Colonoscopy," *IEEE Transactions on Robotics* 41 (2025): 4843–4859.

68. Z. Zhang, S. Tang, W. Fan, Y. Xun, H. Wang, and G. Chen, "Design and Analysis of Hybrid-Driven Origami Continuum Robots with Extensible and Stiffness-Tunable Sections," *Mechanism and Machine Theory* 169 (2022): 104607.

69. C. Sun, L. Chen, J. Liu, J. S. Dai, and R. Kang, "A Hybrid Continuum Robot Based on Pneumatic Muscles with Embedded Elastic Rods," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 234, no. 1 (2020): 318–328.

70. A. Shiva, A. Stilli, Y. Noh, et al., "Tendon-Based Stiffening for a Pneumatically Actuated Soft Manipulator," *IEEE Robotics and Automation Letters* 1, no. 2 (2016): 632–637.

71. F. Maghooa, A. Stilli, Y. Noh, K. Althoefer, and H. A. Wurdemann, "Tendon and pressure actuation for a bio-inspired manipulator based on an antagonistic principle," in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, (IEEE on IEEE Xplore, 2015), 2556–2561.

72. W. McMahan, B. A. Jones, and I. D. Walker, "Design and implementation of a multi-section continuum robot: Air-Octor," in *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, (IEEE on IEEE Xplore, 2005), 2578–2585.

73. T. Zhang, L. Yang, X. Yang, R. Tan, H. Lu, and Y. Shen, "Millimeter-Scale Soft Continuum Robots for Large-Angle and High-Precision Manipulation by Hybrid Actuation," *Advanced Intelligent Systems* 3, no. 2 (2021): 2000189.

74. G. Pittiglio, M. Mencattelli, A. Donder, Y. Chitalia, and P. E. Dupont, "Hybrid Tendon and Ball Chain Continuum Robots for Enhanced Dexterity in Medical Interventions," in *2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, (IEEE on IEEE Xplore, 2023), 8461–8466.

75. H. Liu, X. Teng, Z. Qiao, H. Yu, S. Cai, and W. Yang, "A Concentric Tube Magnetic Continuum Robot with Multiple Stiffness Levels and High Flexibility for Potential Endovascular Intervention," *Journal of Magnetism and Magnetic Materials* 597 (2024): 172023.

76. Z. Liand Q. Xu, "Multi-Section Magnetic Soft Robot with Multirobot Navigation System for Vasculature Intervention," *Cyborg and Bionic Systems* 5 (2024): 0188.

77. J. Hu, J. Zhang, Y. Zheng, et al., "Hybrid-Driven Continuum Robot With Decoupled Motion Patterns for Dexterous Manipulation," *IEEE Robotics and Automation Letters* 9, no. 9 (2024): 7437–7444.

78. X. Li, Q. Xiong, D. Sui, et al., "Disturbance-Adaptive Tapered Soft Manipulator With Precise Motion Controller for Enhanced Task Performance," *IEEE Transactions on Robotics* 40 (2024): 3581–3601.

79. S. M. H. adi. S. Shamsa Al Harthy, Z. Wu, C. A. Seneci, and C. Bergeles, "Variable Stiffness Soft Eversion Growing Robot via Temperature Control of Low-Melting Point Alloy Pressurised Medium," in *2024 International Symposium on Medical Robotics (ISMR)*, (IEEE on IEEE Xplore, 2024), 1–7.

80. H. D. Yangand A. T. Asbeck, "Design and Characterization of a Modular Hybrid Continuum Robotic Manipulator," *IEEE/ASME Transactions on Mechatronics* 25, no. 6 (2020): 2812–2823.

81. Z. Wu, M. De Iturrate Reyzabal, S. M. Hadi Sadati, H. Liu, et al., "Towards a Physics-Based Model for Steerable Eversion Growing Robots," *IEEE Robotics and Automation Letters* 8, no. 2 (2023): 1005–1012.

82. F. F. Leung, K. Borvorntanajanya, K. Chen, et al., "Hybrid Manipulator With Force Estimation for Lower Gastrointestinal Interventions," *IEEE Robotics and Automation Letters* 9, no. 11 (2024): 9709–9716.

83. F. Alambeigi, R. Seifabadi, and M. Armand, "A continuum manipulator with phase changing alloy," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*, (IEEE on IEEE Xplore, 2016), 758–764.

84. Y. Kim, S. S. Cheng, M. Diakite, R. P. Gullapalli, J. M. Simard, and J. P. Desai, "Toward the Development of a Flexible Mesoscale MRI-Compatible Neurosurgical Continuum Robot," *IEEE Transactions on Robotics* 33, no. 6 (2017): 1386–1397.

85. G. Zhang, F. Du, P. Qi, et al., "A Hybrid Continuum Manipulator for Minimally Invasive Surgery: Design, Modeling, and Validation," *IEEE Transactions on Medical Robotics and Bionics* 7, no. 3 (2025): 1317–1328.

86. J. Davy, N. J. Greenidge, S. Kim, et al., "Vine Robots With Magnetic Skin for Surgical Navigations," *IEEE Robotics and Automation Letters* 9, no. 8 (2024): 6888–6895.

87. W. Wenbiao, J. Shi, K. Wu, et al., "A Motion-Decoupled Pneumatic Rigid-Flexible Hybrid Joint With Variable Stiffness for Continuum Robot," *Chinese Journal of Mechanical Engineering* 38, no. 125 (2025): 1–11.

88. Y. Fan, B. Yi, and D. Liu, "An Overview of Stiffening Approaches for Continuum Robots," *Robotics and Computer-Integrated Manufacturing* 90 (2024): 102811.

89. Y.-J. Kim, S. Cheng, S. Kim, and K. Iagnemma, "A Stiffness-Adjustable Hyperredundant Manipulator Using a Variable Neutral-Line Mechanism for Minimally Invasive Surgery," *IEEE Transactions on Robotics* 30, no. 2 (2013): 382–395.

90. M. Cianchetti, T. Ranzani, G. Gerboni, I. De Falco, C. Laschi, and A. Menciassi, "STIFF-FLOP surgical manipulator: Mechanical design and experimental characterization of the single module," in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, (IEEE on IEEE Xplore, 2013), 3576–3581.

91. Y. Sun, Y. Piskarev, E. H. Hofstetter, et al., "Instant Variable Stiffness in Cardiovascular Catheters Based on Fiber Jamming," *Science Advances* 11, no. 6 (2025): eadn1207.

92. P. Lloyd, T. L. Thomas, V. K. Venkiteswaran, et al., "A Magnetically-Actuated Coiling Soft Robot with Variable Stiffness," *IEEE Robotics and Automation Letters* 8, no. 6 (2023): 3262–3269.

93. M. Langer, E. Amanov, and J. Burgner-Kahrs, "Stiffening Sheaths for Continuum Robots," *Soft Robotics* 5, no. 3 (2018): 291–303.

94. L. T. Gaeta, K. J. McDonald, L. Kinnicutt, et al., "Magnetically Induced Stiffening for Soft Robotics," *Soft Matter* 19, no. 14 (2023): 2623–2636.

95. Y. Zhaoand Y. Wang, "A Palm-Shape Variable-Stiffness Gripper Based on 3D-Printed Fabric Jamming," *IEEE Robotics and Automation Letters* 8, no. 6 (2023): 3238–3245.

96. S.-Q. An, W.-H. Li, J.-H. Li, H.-L. Zou, and Z.-C. Deng, "Tuning Stiffness with Granular Chain Structures for Versatile Soft Robots," *Soft Robotics* 10, no. 3 (2023): 493–503.

97. E. Amanov, T.-D. Nguyen, F. I. So Markmann, and J. Burgner-Kahrs, "Toward a Flexible Variable Stiffness Endoport for Single-Site Partial Nephrectomy," *Annals of Biomedical Engineering* 46, no. 10 (2018): 1498–1510.

98. C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador, and P. Dario, "Soft Robot Arm Inspired by the Octopus," *Advanced Robotics* 26, no. 7 (2012): 709–727.

99. J. Park, H. Lee, H. Kee, and S. Park, "Magnetically Steerable Manipulator with Variable Stiffness Using Graphene Polylactic Acid for Minimally Invasive Surgery," *Sensors and Actuators A: Physical* 309, (2020): 112032.

100. M. Mattmann, C. De Marco, F. Briatico, et al., "Thermoset Shape Memory Polymer Variable Stiffness 4D Robotic Catheters," *Advanced Science* 9, no. 1 (2022): 2103277.

101. Y. Piskarev, J. Shintake, C. Chautems, et al., "A Variable Stiffness Magnetic Catheter Made of a Conductive Phase-Change Polymer for Minimally Invasive Surgery," *Advanced Functional Materials* 32, no. 20 (2022): 2107662.

102. J. Lussi, M. Mattmann, S. Sevim, et al., "A Submillimeter Continuous Variable Stiffness Catheter for Compliance Control," *Advanced Science* 8, no. 18 (2021): 2101290.

103. M. Mattmann, Q. Boehler, X.-Z. Chen, S. Pané, and B. J. Nelson, "Shape memory polymer variable stiffness magnetic catheters with hybrid stiffness control," in *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, (IEEE on IEEE Xplore, 2022), 9589–9595.

104. A. Sadeghi, A. Mondini, E. D. Dottore, A. K. Mishra, and B. Mazzolai, "Soft-Legged Wheel-Based Robot with Terrestrial Locomotion Abilities," *Frontiers in Robotics and A* I3, (2016): 73.

105. H. Jeon, Q. N. Le, S. Jeong, et al., "Towards a Snake-Like Flexible Robot with Variable Stiffness Using an SMA Spring-Based Friction Change Mechanism," *IEEE Robotics and Automation Letters* 7, no. 3 (2022): 6582–6589.

106. J. Guo, J.-H. Low, J. Liu, Y. Li, Z. Liu, and C.-H. Yeow, "Three-Dimensional Printable Ball Joints with Variable Stiffness for Robotic Applications Based on Soft Pneumatic Elastomer Actuators," *Polymers* 14, no. 17 (2022): 3542.

107. M. Mahvashand P. E. Dupont, "Stiffness Control of Surgical Continuum Manipulators," *IEEE Transactions on Robotics* 27, no. 2 (2011): 334–345.

108. C. Wang, C. G. Frazelle, J. R. Wagner, and I. D. Walker, "Dynamic Control of Multisection Three-Dimensional Continuum Manipulators Based on Virtual Discrete-Jointed Robot Models," *IEEE/ASME Transactions on Mechatronics* 26, no. 2 (2020): 777–788.

109. M. C. Yipand D. B. Camarillo, "Model-less Hybrid Position/Force Control: A Minimalist Approach for Continuum Manipulators in Unknown, Constrained Environments," *IEEE Robotics and Automation Letters* 1, no. 2 (2016): 844–851.

110. Y. Ueda, S. Miyahara, K. Tokuishi, et al., "Impact of a Pneumatic Surgical Robot with Haptic Feedback Function on Surgical Manipulation," *Scientific Reports* 13, no. 1 (2023): 22615.

111. A. Bajoand N. Simaan, "Hybrid Motion/Force Control of Multi-Backbone Continuum Robots," *The International Journal of Robotics Research* 35, no. 4 (2016): 422–434.