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Surgical Applications of Compliant Mechanisms: A Review

Current surgical devices are mostly rigid and are made of stiff materials, even though their predominant use is on soft and wet tissues. With the emergence of compliant mechanisms (CMs), surgical tools can be designed to be flexible and made using soft materials. CMs offer many advantages such as monolithic fabrication, high precision, no wear, no friction, and no need for lubrication. It is therefore beneficial to consolidate the developments in this field and point to challenges ahead. With this objective, in this article, we review the application of CMs to surgical interventions. The scope of the review covers five aspects that are important in the development of surgical devices: (i) conceptual design and synthesis, (ii) analysis, (iii) materials, (iv) manufacturing, and (v) actuation. Furthermore, the surgical applications of CMs are assessed by classification into five major groups, namely, (i) grasping and cutting, (ii) reachability and steerability, (iii) transmission, (iv) sensing, and (v) implants and deployable devices. The scope and prospects of surgical devices using CMs are also discussed. [DOI: 10.1115/1.4049491]

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1 Introduction

Compliant mechanisms (CMs) are designed to achieve transfer or transformation of motion, force, or energy through elastic deformation of flexible elements. Devices that implement CMs can be traced back to as early as 8000 BC in the form of bows, which were the primary hunting tools [1]. While reviewing the history of urethral catheterization, Bloom et al. [2] noted that ancient Chinese medical procedures used lacquer-coated compliant tubular leaves of allium fistulosum (bunched onion) as catheters. They also mention that Sushruta, the author of an ancient Indian surgical text, described tubes of gold and silver coated with ghee (clarified butter) used for catheterization. Ancient Greek and Roman surgeons too are known to have used flexible silver tubes in surgery. Over the years, CMs have seen several applications in surgical procedures. Furthermore, the applications of CMs have been extended to aerospace and automotive industries, microelectromechanical systems (MEMS), actuators and sensors, high precision instruments, and robots [3,4].

CMs have gained significant attention in the last few decades as they offer many advantages over traditional rigid-body mechanisms. A CM has monolithic structure, which reduces the number of assembly steps, thus simplifying the fabrication process and requiring reduced maintenance [5]. High precision is attained, and the need for lubrication is eliminated due to the absence of contact among members that causes wear, friction, backlash, and noise [6].

The merits of CMs have led to a proliferation of studies that implement CMs, especially in the medical field [7]. Many variants of CMs have been designed as surgical devices to perform various functions. The structural compliance integrated in the main body of a device is exploited to perform object manipulation tasks such as grasping, cutting, retracting, and suturing for surgical procedures in the form of ablation, laparoscopy, endoscopy, and biopsy, to mention a few. In addition, easy miniaturization of CMs enables the device to reach remote difficult-to-access surgical sites as seen in the design of several continuum manipulators [8]. CMs also serve a secondary function in the device to transmit force/motion, as observed in some surgical robots [9,10]. Applications of CMs are found in microactuators, MEMS, and micro-scale surgical devices as well [11–14]. Force sensing using CMs to monitor tool–tissue interaction has also been demonstrated, which serves as a feedback for safe operation of the device inside the human body [15,16]. The potential of CMs made using biocompatible materials has been realized in the development of biomedical implants, stents, and deployable devices [17–19].

There is a growing body of literature that provides a useful account of the design process of CMs [6,20]. However, there is no detailed investigation into different aspects to be considered while designing surgical devices using CMs. It poses a problem for those with little to no experience in the medical field on what approach to follow, to go from initial concept to final prototype. This article aims to provide an overview of this process, which

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Table 1 Description of synthesis methods for compliant mechanisms, stating their applications and limitations

Synthesis method	Description	Applications and limitations
Freedom and constraint topologies (FACT) [**23–25**], *[none]*	Provides topological solution for known freedom space and constraint space based on screw theory, in which twists and wrenches are used to represent constraints and degrees-of-freedom of compliant elements.	• Synthesizing CMs with small to intermediate deflections. • Research on large deformation analysis and representation of elastomechanics, dynamics characteristics, and parasitic errors is limited.
Building blocks [**28,29**],*[26,27]*	Two main approaches based on: (i) instant centers and compliance ellipsoids, and (ii) flexible building blocks and optimization.	• Synthesizing CMs with intermediate to large deflections. • Infeasible geometry may result depending on the chosen basic building block.
Topology optimization [**34–36**],*[18,30–33]*	Uses optimization algorithms to search for best CM topology to realize the design objective, subject to desired requirements and constraints generally through finite element methods.	• Most widely used CM synthesizing method within surgical devices, with its ability to generate solutions from a wide design space. • Difficult to account for localized stresses and buckling. Resulting topologies are sometimes difficult to manufacture, warranting 3D printing or postprocessing for manufacturing.
Rigid-body replacement [**1,39–41**],*[27,37,38]*	Utilizes the pseudo-rigid-body model to replace compliant members and joints with equivalent rigid links and movable joints, with springs for capturing elastic deformation energy.	• Reduced-order method that relies on established rigid-body kinematics methods, providing more intuitive analysis. • Accuracy of analysis suffers with increase in the complexity of CM.
Selection maps [**21,22,42–44**], *[none]*	Uses a catalog of CMs whose inherent stiffness and inertia characteristics are captured in two-port spring-lever and spring-mass-lever models for matching the user specifications for the purpose of selection.	• Can incorporate practical considerations of material selection, manufacturability, strength, and scaling. • Limited to single-input-single-output CMs at present.

Note: References of work relevant to each method are provided in square brackets. Numbers in **bold** refer to the papers that describe the general approach of the method and numbers in *italics* refer to the surgical devices reviewed in this paper which are designed using the particular method.

involves five major aspects: (i) CM conceptual design and synthesis, (ii) analysis, (iii) material selection, (iv) fabrication methods, and (v) actuation methods. Furthermore, this article also reviews the existing literature on surgical devices that use CMs by classification into five major groups: (i) grasping and cutting, (ii) reachability and steerability, (iii) transmission, (iv) sensing, and (v) implants and deployable devices. We conclude this article by addressing the associated challenges and provide an outlook on future scope.

2 Design Aspects

This section presents the various methods used during the design process of surgical devices that use CMs. The process begins with the synthesis of the CM, followed by optimization to satisfy the intended functional requirements and identification of constraints. Various methods of generating or synthesizing CMs have been explored by researchers. Howell et al. [4] describes four techniques used in the synthesis of CMs: freedom and constraint topologies (FACTs), building blocks, topology optimization, and rigid-body replacement. Hegde and Ananthasuresh [21,22] introduced a selection maps method for conceptual design and synthesis of CMs. The five aforementioned synthesis methods are explained briefly in Table 1. However, many compliant surgical devices are designed without explicit use of these conventional synthesis methods. This may be because the synthesis methods developed for CMs mostly apply to input–output transmission characteristics rather than guiding and maneuvering. The scope of the expected functions of surgical devices, described later in the article, offers a huge opportunity for designers. Therefore, the synthesis methods and the subsequent classification of devices is not discussed in detail in this review.

During synthesis of a CM, selection of suitable material is crucial to ensure failure prevention. It is generally desirable to have large deformation of a CM, while ensuring the strain to be small and the stress stays within limits. This depends on the Young's modulus and the failure strength of the material. From a clinical standpoint, other criteria that need to be considered are the biocompatibility, chemical resistance, elasticity, transparency, strength, temperature resistance, and most importantly, sterilizability of the chosen material [45]. Table 2 describes the materials and different fabrication methods that are suitable for making surgical devices. The four commonly used 3D printing technologies for rapid prototyping compliant surgical devices are also described in Table 2. While punching and blanking technique is used in meso-scale compliant grippers, electrical discharge machining (EDM) is most widely used for micro-scale fabrication of flexure-based continuum manipulators and grippers. Pop-up book MEMS fabrication is an emerging multi-material technique of fabricating MEMS and micro-scale surgical devices. Milling and laser cutting are conventional subtractive manufacturing methods used for surgical manipulators and their constituent parts like wrist and end-effector. Although injection molding was not typically used in the making of surgical devices reviewed in this article, it is an economical way of mass manufacturing implants and medical plastics.

The method of actuation is an important aspect to be considered in the design of a CM. Based on the specific function that the CM serves in the design, various actuation methods have been demonstrated in literature. Table 3 presents commonly used actuation methods of CMs, which are suited to surgical applications, along with their advantages and limitations. Cable-driven actuation is the most widely used method among continuum manipulators and steerable instruments. SMAs and piezoelectric materials are seen more in high precision devices and for micro/nano manipulation. While fluidic actuation is used in a few flexible surgical instruments, there is a gradual increase toward the use of magnetic actuation in designing surgical devices for precise contactless control.

3 Surgical Applications

This section presents a review of the different surgical applications of CMs. The applications of CMs in surgical devices can be broadly classified into five major groups: (i) grasping and cutting, (ii) reachability and steerability, (iii) transmission, (iv) sensing, and (v) implants and deployable devices. Figure 1 is an overview of this classification showing examples of surgical devices designed for each of these groups of applications, while Fig. 2 depicts the distribution of the number of surgical devices in each group. These are explored in detail in the remainder of this section.

Table 2 Description of fabrication methods and materials suitable for compliant mechanisms in surgical applications

Fabrication method		Materials	Surgical devices	Pros and cons
Rapid prototyping	PolyJet [46–52]	Biocompatible materials like MED625FLX, MED610 and MED620.	Flexible surgical manipulators, tooltips and catheters.	+ Suitable for small parts with intricate details and printed with high precision. – Vulnerable to heat and light degradation. – Provides limited mechanical strength.
	Stereolithography [53–55]	Photopolymer resins.	Flexible surgical instruments and surgical robot joints.	
	Selective laser sintering [9,30,56–58]	Biocompatible polymers such as polyetheretherketone (PEEK), poly(vinyl alcohol), polycaprolactone and poly(L-lactic acid).	Surgical robot joints.	+ Uses a wide variety of materials that provide good mechanical performance.
	Selective laser melting [59–61]	Biocompatible metals like steel, titanium alloys and cobalt-chrome.	Surgical continuum manipulators with flexure hinges and bone implants.	– Expensive. – Produces rough surface finish.
Subtractive manufacturing	Milling [61–67]	Metals like stainless steel, aluminum and titanium. Plastics like nylon, acrylonitrile butadiene styrene (ABS), PEEK, polyvinyl chloride (PVC).	Surgical manipulators and associated supports like wrist, fixtures and end-effector.	+ Accurate, precise, and repeatable machining applicable on a wide variety of materials. – High initial machinery and tooling costs. – Difficult to model complex 3D parts.
	Laser cutting [68–71]	Plastics like acrylic, ABS, and delrin. And metals like stainless steel, aluminum, and titanium.	Endoscopic manipulators and surgical tooltips with intricate patterned cuts.	+ Contactless cutting with accuracy and speed. – Not suitable for cutting parts with very wide thickness. – Releases toxic fumes that needs good ventilation provision.
Micro-scale fabrication	Electrical discharge machining (EDM) [37,62,66,72–82]	Conductive materials like titanium, inconel, and kovar.	Miniature components like coronary stents, implants, grippers, and micro-scale flexures for compliant manipulators.	+ Suitable to fabricate biocompatible surfaces as it can create an oxide layer on the surface to enhance biological attachment. – Expensive. – Fabricating parts with complex shapes require specially designed fixtures and takes more time.
	Pop-up book MEMS fabrication [13,14,83]	3D multi-material fabrication using a flexible polyimide layer (Kapton®, by DuPont de Nemours, Inc.) and structural layers (304 Stainless Steel), with adhesive (Dupont FR1500 acrylic adhesive).	MEMS and micro-surgical devices.	+ Monolithic meso- and micro-structures made can be inserted through small incisions and "pop-up" to perform their function. + Soft fluidic micro-actuators can also be integrated in the fabrication process. – Risk of peel failure. – Castellated hinge failure due to stress concentrations.
	Punching and blanking [84]	Sheet form of metals like steel, aluminum, and plastics like PEEK, nylon, and delrin.	Meso-scale compliant grippers.	+ Low-cost and fast process. – Cutting complex geometry is difficult. – Negatively affects the quality of edges of cut-out part.
Mass Manufacturing	Injection molding [45,85–87]	Plastics like PVC, styrene acrylonitrile copolymer (SAN), polycarbonate, and polyester. Metals like titanium alloys.	Surgical implants and medical plastics.	+ Efficient and economic manufacturing method that is automated to produce high output in one step. – High inital tooling costs and long lead times. – For high fatigue resistance and increased lifetime, mold designs for CMs should orient the polymer chain in specific directions.

Note: The pros (+) and cons (–) of each method are described, along with examples of surgical devices made using the given method. Numbers of references are given in square brackets.

Table 3 Description of actuation methods for surgical devices, stating their advantages (+), and limitations (–) in surgical applications and integration with CMs

Actuation method	Surgical applications	Integration with compliant mechanisms
Cable-driven actuation [10,56,74,75,88–92]	Surgical robotic systems and flexible surgical instruments. + Uses lightweight and flexible cables for deformation of the structure. – Miniaturization is challenging due to the associated cables and moment arms.	+ Ability to transmit force/motion to remote joints and application points enables convenient location of the actuation unit away from the workspace of the device. – High pretension in cable is necessary to reduce backlash and hysteresis.
Shape memory alloys (SMAs) [93–99]	Internal actuators for instruments like biopsy forceps, hingeless graspers, and endoscopic and laparoscopic instruments, among others. Also used in stents, stent grafts and in orthopaedics as correction rods and fracture fixators. + Similar hysteresis behavior with bone and tendons and low sensitivity to MRI. + Shape memory effect provides a collapsible form during insertion and expands after deployment. – Limited by rise in temperature caused by heating.	+ Reliable control on actuating CM by training the SMA to fine-tune the performance. + Offers high power-to-weight ratio. + Easy to embed in complex structures. – Generally activated by Joule heating while deactivation takes place via convection heat transfer, which leads to a slow response time.
Piezoelectric materials [46,73,100–103]	Actuators for micro/nano manipulation. + Delivers sub-nanometer positioning accuracy and is compact in size. – Expensive to fabricate.	+ Offers high response speed. + Large force-to-weight ratio. – Limited by low strain range. – Transmission of forces to remote location is challenging.
Magnetic actuation [37,48,104–107]	Endoscopic devices and surgical instruments with inherent compliance. + Precise positioning and control.	+ Enables contactless actuation of CM. – Adversely affected upon scaling to large surgical workspace.
Flexible fluidic actuators [14,62,108]	Flexible surgical instruments. + Safe to operate under radiation and magnetic fields. + Ability of the inflatable membranes to lose and regain their shape facilitates the insertion of instrument inside a patient's body.	+ Causes no relative motion between parts, no wear and there is no need for lubrication. – Risk of leakages, and controlling pressure is more complex when compared to electrical signals used in motors and other conventional actuators.

Note: Numbers of references are given in square brackets.

3.1 Grasping and Cutting. CMs have been used to develop forceps, scissors, graspers, and needle holders for performing different surgical tasks such as grasping, cutting, suturing, and holding tissue. For instance, Frecker et al. [114,121] designed a multifunctional compliant instrument with forceps and scissors using topology optimization and fabricated a 5.0 mm diameter stainless steel prototype. Subsequently, a miniaturized prototype was developed by applying size and shape optimization [113,122]. Recently, a compliant forceps with serpentine flexures was designed to overcome the problem of parallel motion found in traditional forceps with "U"-shaped flexure [123]. Cronin et al. [112] demonstrated an endoscopic suturing instrument by optimizing a compliant design that provides sufficient puncture force with maximum distal opening of the suture arms.

Several forms of grasping tools have been investigated, which utilize the flexibility and stiffness that a CM can offer with different geometry, materials, and fabrication techniques. For example, an underactuated compliant gripper made of five phalanges was designed to have large shape-adaptation capability and the deformation was shared by many joints so as to increase the lifetime of the device [72]. A polymer-based minimally invasive surgery (MIS) shaft instrument was developed using a hybrid effector mechanism combining compliant joints and conventional pin joints [62]. A three-fingered laparoscopic grasper for finger articulation was designed using flexures, leading to distribution of the grasping force and thereby minimizing tissue perforation [124]. A multi-material design was utilized for a compliant narrow-gauge surgical forceps for laparoscopic and endoscopic procedures [125]. Large grasping forces were realized through a hybrid design approach by having some regions with high stiffness and other regions with greater flexibility to provide larger jaw openings. In subsequent work, a design optimization routine was carried out to maximize the tool performance, validating the grasping potential of a meso-scale contact-aided compliant forceps [126,127]. Recently, the grasping performance of a compliant surgical grasper was enhanced by functional grading, which introduces material with elastic nonlinearity at certain segments of the grasper, while reducing the maximum overall stress [109].

The introduction of robot-assisted surgery has led to many designs of CM-based grasping end effectors, to deliver efficient manipulation with high dexterity. Piccin et al. [111] showed that a flexible needle grasping device for medical robots has a higher threshold force and stiffness before slipping, compared to a rigid-body needle grasping device. In another work by Forbrigger et al. [104], the distal dexterity of a brain tissue resection robot was enhanced by a magnetically driven forceps made with flexible beams and eliminating the need for an external mechanical or electrical transmission to actuate the end-effector.

The monolithic nature of CMs makes them easier to fabricate when compared to the pivoted jaw configurations of current grasping tools [128]. Hence, CM was used in developing a disposable compliant forceps for HIV patients in which, the Q-joints

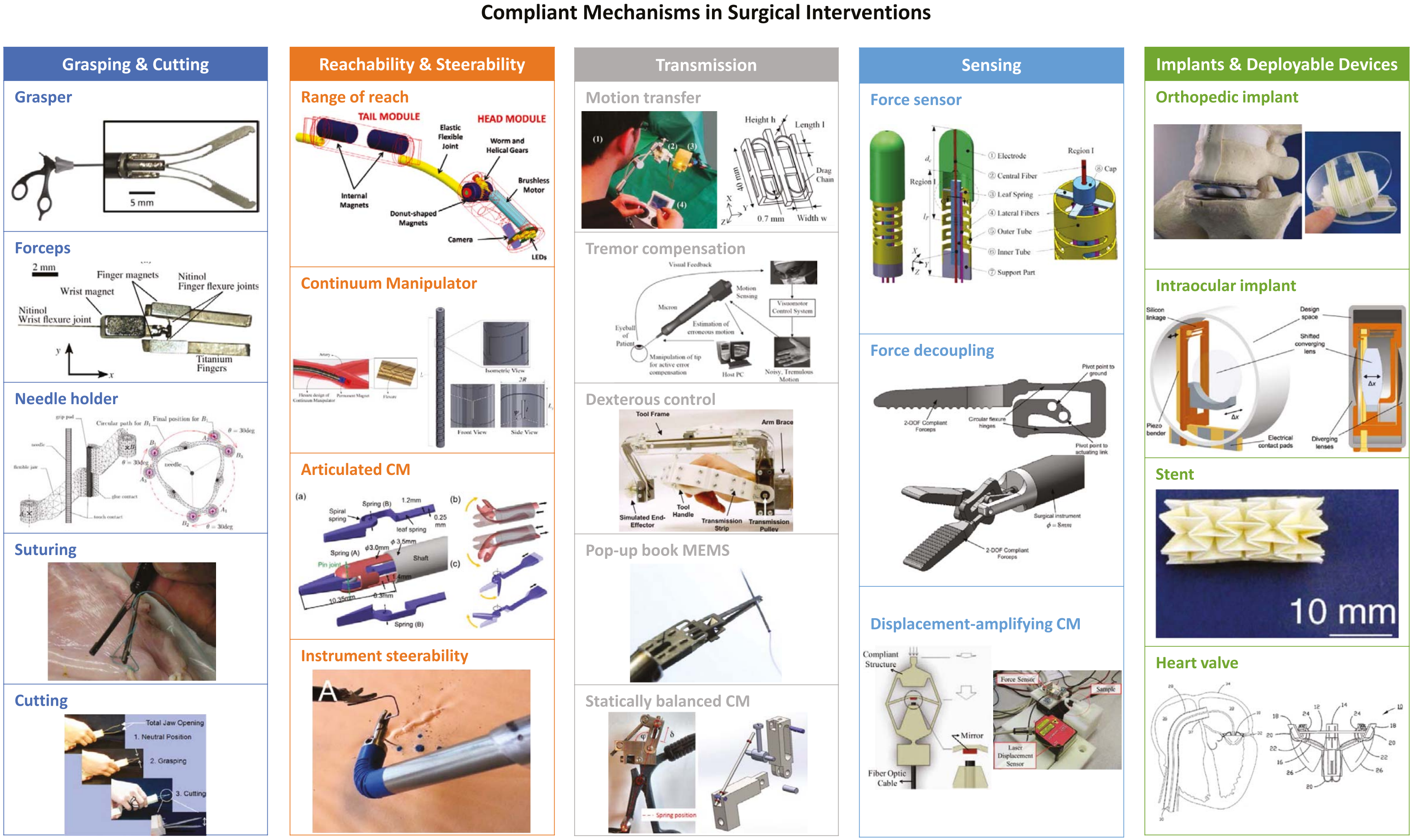

Fig. 1 An overview of different surgical applications of CMs. Images: Grasper (© 2018 IEEE. Reprinted with permission from Ref. [109], originally from Ref. [110]); forceps (© 2019 IEEE. Reprinted with permission from Ref. [104]); needle holder (republished with permission of ASME from Ref. [111]; permission conveyed through Copyright Clearance Center, Inc.); suturing (republished with permission of ASME from Ref. [112]; permission conveyed through Copyright Clearance Center, Inc.); cutting (republished with permission of ASME from Ref. [113]; permission conveyed through Copyright Clearance Center, Inc., originally from Ref. [114]); range of reach (© 2019 Simi et al., reproduced from Ref. [105], Licensed under CC BY 4.0); continuum manipulator (© 2020 Thomas et al., reproduced from Ref. [37]); articulated CM (© 2019 IEEE. Reprinted, with permission from Ref. [115]); instrument steerability (© 2014 by Dewaele et al. from Ref. [68], reprinted by permission of SAGE Publications, Inc.); motion transfer (© 2014 IEEE. Reprinted with permission from Ref. [9]); tremor compensation (© 2005 IEEE. Reprinted with permission from Ref. [54]); dexterous control (republished with permission of ASME from Ref. [116]; permission conveyed through Copyright Clearance Center, Inc.); pop-up book MEMS (© 2013 IEEE. Reprinted with permission from Ref. [83]); statically balanced CM (republished with permission of ASME from Ref. [110]; permission conveyed through Copyright Clearance Center, Inc.); force sensor (© 2018 IEEE. Reprinted with permission from Ref. [117]); force decoupling (© 2012 IEEE. Reprinted with permission from Ref. [16]); displacement-amplifying CM (© 2013 IEEE. Reprinted with permission from Ref. [118]); orthopedic implant (Image courtesy of Halverson et al. (Brigham Young University, USA) from Ref. [17]); intraocular implant (reprinted from Ref. [119], © 2012, with permission from Elsevier); stent (reprinted from Ref. [95], © 2006, with permission from Elsevier); heart valve (© 2009 Herrmann et al., reproduced from Ref. [120]).

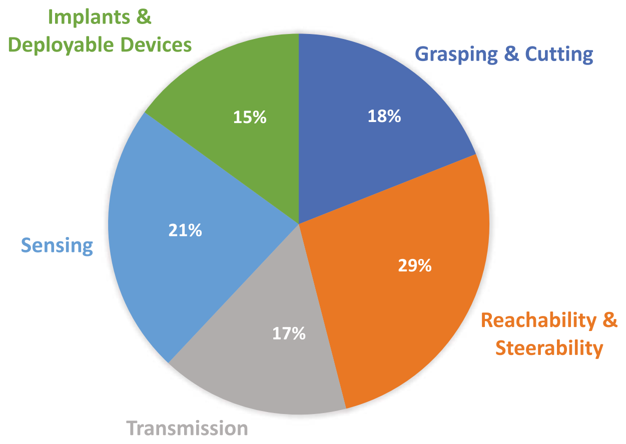

Fig. 2 Contribution of different surgical applications of compliant mechanisms, showing the distribution of the number of surgical devices reviewed in this paper in each application group

methods was employed to replace a conventional pin-joint [129]. Later, Sun et al. [30] synthesized the shape of a disposable compliant forceps for traditional open surgical applications using topology optimization. Subsequently, an adaptive grasping function of the forceps to overcome damaging sensitive organs during both open surgery and robot-assisted minimally invasive surgery (MIS) was devised using topology optimization [88].

At micrometer scale, CM-based microgrippers and micromanipulators have been developed based on flexure hinges and cantilever beam structures. A microgripper made up of piezoelectric bending unimorphs was demonstrated by Haddab et al. [100]. Accurate manipulation of a hybrid compliant gripper was achieved using a combination of flexure hinges and a bias spring [73]. Ease in grasping and accurate tool positioning of a micro-forceps was provided by optimizing the jaw design to minimize actuation force, internal stresses, and size [130]. Yang et al. [131] demonstrated the opening and closing of the jaws of a compliant micrograsper and microcutter for ophthalmic surgery by using a cylindrical package tube pulled through the device. While the use of CMs contributes to the elimination of Coulomb friction and backlash, they have some inherent drawbacks. As noted in the design of a low cost flexure-based hand-held mechanism for micromanipulation, a drift in the major axis is caused by the imperfect rotation of most compliant joints [46]. Flexure hinges have limited range of angular motion depending on the geometry and material properties of the hinge, and cantilever structures fail to produce perfect parallel motion [73,132]. However, topology optimization aided by intuition has been used to design CM grippers with parallel-jaw motion.

3.2 Reachability and Steerability. This section describes applications of CMs to increase the range of motion and enhance steerability of the surgical instruments to reach difficult to reach surgical sites inside the body. Single-port laparoscopic and endoscopic procedures are adversely affected by limited maneuverability of surgical instruments through confined spaces and narrow visual view inside the human body. Therefore, a steerable endoscopic instrument was developed using three coaxial tubes that slide together concentrically to form a single tube [68]. The design offers additional flexibility due to narrow cuts in the tube and more room in the lumen as the steering mechanism resides in the tubular wall. A review on the different joint types used in the steerable tips of MIS instruments is described by Jelínek et al. [133]. To maximize the span of an endoscopic camera, Simi et al. [105] modeled a compliant joint in a magnetic levitation system and potential to reduce instrument collision inside the body was shown. Similarly, a flexure-based foldable and steerable CM was reported for providing stereo vision capture in laparoscopic surgery with a pair of miniature cameras [134].

Continuum manipulators are devices that can be precisely steered inside the body to reach difficult-to-access surgical sites. CMs have been used to design flexible miniaturized continuum manipulators for robot-assisted surgery. For example, a 2 degree-of-freedom (DoF) flexible distal tip for enhanced dexterity of endoscopic robot surgery was constructed with a flexible tube cut into a structure consisting of a series of rings connected by thin elastic joints [74,135]. A similar design was used in a flexible micro manipulator for neurosurgery [75,136]. A two-section tendon-driven continuum robot with a backbone cut into flexures from a pipe was designed to enhance tip positioning and offer large viewing angles in endoscopic surgery [137,138]. A multi-arm snake-like robot for MIS was developed using flexible overtube structure as a spine, which guides endoscope and other instruments, and two manipulator arms at its tip made of three separate flexure hinge sections [56]. Since beam flexure structures suffer from stress concentrations in the corners, as well as fatigue, a snake-like surgical robot composed of flexible joints based on helical spring was designed [59]. Furthermore, to prevent axial compression, circular rolling contacts were introduced at each turn of the helix. Recently, a contactless mode of actuation and steering of a monolithic metallic compliant continuum manipulator with flexures using magnetic fields was demonstrated [37].

Notched-tube compliant joint mechanisms are variants of aforementioned continuum manipulators, where different shapes, sizes, and patterns of notches made on tubes can enable different DoFs and range of motion [139]. For instance, a flexible manipulator arm for single-port access abdominal surgery was made from a superelastic nitinol tube with triangular notches [140–143]. A needle-sized wrist made from a nitinol tube with rectangular cutouts was developed to increase the DoF and dexterity of needle laparoscopic surgery (needlescopy) surgical tools [63,144]. Eastwood et al. [145] designed asymmetric notch joints for surgical robots and noted that decreasing the joint's tube diameter and increasing notch depth favors compact bending of the manipulator, but leads to significant reduction in stiffness. Hence, a contact-aided compliant notched-tube joint for surgical manipulation was introduced to improve the stiffness and bending compactness, while operating in confined workspaces [139]. In another work, a cable-driven dexterous continuum manipulator (DCM) comprising two nested superelastic nitinol tubes with notches was designed for removing osteolytic lesions with enhanced volumetric exploration [76,146–153]. In subsequent work, a flexible ring currette made of thin and long pre-curved ring nitinol strips was designed to pass through the open lumen of the DCM [154]. The integration of DCM to a da Vinci actuation box (Intuitive Surgical, Inc., USA) as a hand-held actuator was also shown [77,155]. In the related work, a flexible cutter and an actuation unit to control the DCM were designed to study its buckling behavior during the cutting procedure [156]. The designs of a debriding tool that passes through the lumen of DCM and a steerable drill following a curved-drilling approach to remove lesions were also investigated [157,158]. Subsequently, by using the curved-drilling technique, a bendable medical screw made of two arrays of orthogonal notches along its shaft was devised for internal fixation of bone fractures [78,159].

Concentric tube robots (CTRs) are a special type of continuum manipulators that are made of multiple precurved elastic tubes that are concentrically nested within one another [160]. CTRs have been deployed for "follow-the-leader" insertion, and their steering is not affected by the tissue interaction forces [161]. Thus, they have found several applications as steerable needles and miniaturized surgical manipulators [162].

Some surgical manipulators rely on CMs to enhance articulation. For instance, a compliant articulation structure for surgical tool tips using nitinol was designed to increase the functional workspace and deliver a large blocked force [163]. Other work studied the use of corner-filleted flexure hinge-based compliant joints in a compliant grasper integrated to a 2-DoF surgical tooltip, and circular guide members were added to strengthen the load carrying capacity of the slender compliant joints [47]. Later, a 3-DoF surgical tooltip with modified serpentine flexures and magnetic coupling was developed [48]. Arata et al. [164] designed a prototype of 2-DoF articulated laparoscopic surgical instrument using a CM to move two spring blades at the tip. Thereafter, a 4-DoF compliant manipulator was proposed consisting of springs designed to deform locally, reducing the bending radius [115]. A subsequent study on the variation of range of motion and rigidity of elastic moments revealed that to achieve a higher range of motion, there will be a trade-off with the lower values of output force and the precision, and vice versa [165].

The flexibility provided by CMs can be extended to positively affect some specific surgical applications. For instance, a compliant endoscopic ablation probe composed of an array of compliant tines was designed to generate target spherical heating zones and improve the distribution of heat in the ablation zone [166,167]. A 3 DoF microrobotic wrist for needlescopy was fabricated using MEMS technology [79,93]. It was based on a CM derived from a reference parallel kinematics mechanism architecture with three legs, which offered increased instantaneous mobility. A compliant instrument for preparing the subtalar joint for arthroscopic joint fusion was developed, having a shaft design that was compliant in only one direction and stiff in the other two directions to resist and transmit machining forces [168]. In the subsequent works, a sideways-steerable instrument joint was designed for meniscectomy that increases the range of motion and reachability within the knee joint while operating through small portal of the body [169,170]. It consisted of a compliant rolling-contact element (CORE), which was rotated by flexural steering beams configured in a parallelogram mechanism. Steerability of kinked bevel-tip needles was improved through the use of a flexure-based needle tip design while minimizing tissue damage, as the flexure keeps the needle in place during insertion [171].

3.3 Transmission.

Transmission refers to the use of CMs in augmenting an actuator in the transfer of force, displacement, or energy. In some surgical devices, CMs made for force or displacement transmission serve as an input or feedback for the principal function of the device. For example, the translation motion of a medical robot for ENT (ear, nose, and throat) surgery was provided using compliant linear joints fabricated by 3D printing [9]. Yim and Sitti [106] showed passive deformation and recovery of a magnetically actuated compliant capsule endoscopic robot by having its structure based on a Sarrus linkage and circular flexure hinges.

The traditional CORE joint involves joining two half cylinders with flexures. Derived from CORE, the Split CORE was integrated to a wrist design provided by Intuitive Surgical Inc. to create a 3 DOF gripping mechanism [53]. Lan and Wang [10] developed an adjustable constant-force forceps for robot-assisted surgical manipulation to aid in grasping soft tissues. It employs a compliant constant-torque mechanism made using flexible arms to transmit the required force to forceps tips. The motion of a flexure-based parallel manipulator for an active hand-held micro-surgical instrument was tracked to cancel the hand tremors using piezo-actuators [54]. Awtar et al. [116] developed FlexDex™, a minimally invasive surgical tool frame, that is attached to the surgeon's forearm to enhance dexterity and provide intuitive control. The design projects a 2-DOF virtual center of rotation for the tool handle at the surgeon's wrist using transmission strips, making it stiff about one axis and compliant in the orthogonal axis.

In microsurgery applications, the concept of pop-up book MEMS has found a few applications. For example, pop-up components made of flexible hinges were designed to realize an articulating micro-surgical gripper and a flexural return spring to passively open the gripper [13]. A multi-articulated robotic arm was fabricated by introducing soft elastomeric materials into the pop-up book MEMS process, and mounted on top of an endoscope model demonstrating potential surgical applications such as tissue retraction [14].

A drawback of CMs is that energy efficiency is challenged due to energy storage in the flexible members of the mechanism [172]. Herder and Van Den Berg [173] introduced the principle of a statically balanced compliant mechanism (SBCM) to circumvent this problem for a partially compliant statically balanced laparoscopic grasper (SBLG), in which a negative stiffness mechanism negates the elastic forces of the CM. Drent and Herder [174] developed a numerical optimization model for total range of motion of a SBLG with normal springs (with non-zero free length) and a constant-force transfer function. Powell and Frecker [175] designed a compensation mechanism of a compliant forceps for ophthalmic surgery using a rigid link slider-crank mechanism with a nonlinear spring, which balances the potential energy of the CM. de Lange et al. [31] used topology optimization for a SBCM, which resulted in reduced actuation force of a SBLG. Tolou and Herder [38] modeled a partially compliant SBLG using pairs of prestressed initially curved pinned-pinned beams made of linear elastic material that resulted in reduced Von Mises stress and balancing error. Hoetmer et al. [26] investigated a building block approach in designing SBCM since the pseudo-rigid-body method and the topology optimization did not consider an optimization process and the stress constraints, respectively. Subsequently, the first physical demonstration of SBCM with fully compliant elements was shown by taking into account stiffness, range of motion, and stress [176]. Lassooij et al. [177] used precurved straight-guided beams that are preloaded collinear with the direction of actuation of a fully compliant SBLG with a near zero stiffness, also demonstrating its bistable behavior. Earlier, Stapel and Herder [178] had carried out a feasibility study of a fully compliant SBLG using the pseudo-rigid-body method. In the subsequent work, Lamers et al. [27] developed a fully compliant SBLG with zero stiffness and zero operation force.

3.4 Sensing.

Sensing application refers to the use of CMs in detecting or measuring physical quantities. Several kinds of sensors rely on the change in deflection or stiffness of CMs in conjunction with other transducers like optical sensors and strain gauges to measure physical parameters. Alternatively, vision-based force sensing integrated with miniature grippers was reported by Reddy et al. [179]. Subsequently, a compliant end-effector to passively limit the force in tele-operated tissue-cutting using the vision-based force sensing for haptic feedback was demonstrated [64].

Force sensing forms an integral part of different surgical applications that involve tissue palpation, pulling, and pushing of tissue during biopsy, to name a few. A miniature micro-surgical instrument tip force sensor during robot-assisted manipulation was developed using a double-cross flexure beam configuration [180]. It can provide uniform force sensitivity in all directions at the instrument tip by altering the vertical separation between the beam crosses. A force-torque transducer based on flexural-jointed Stewart platform was integrated to an MIS instrument's tip to enable six-axis force sensing capability [181].

Magnetic resonance imaging (MRI)-compatible force sensors, in particular, benefit from a CM-based design as the metallic and electric elements can be placed outside MRI. The force sensing element typically consists of an elastic body which deforms under the influence of an applied force, which in turn is measured by a transducer like optical fiber. For example, high accuracy and high sensitivity to displacement were demonstrated using optical micrometry by supporting the force detector with thin annular plates, which convert applied force into minute displacement [182]. Later, a parallel plate structure was chosen to design a uniaxial force sensor due to its directionality and simplicity, offering better accuracy including hysteresis characteristics and axial interference than the previous design [183].

Different types of flexible elements can be adapted in the design of force sensors. Analyzing the mechanical design of sensing elements, a polymer torsion beam guided in rotation by a ball bearing and supported by compliant linkages was proposed in the development of an MRI-compatible torque sensor [65]. The sensor design was further improved for a 2-DOF haptic interface by using a sensing body made of two blades fixed between the optical head and the reflective target [69]. The blade causes a displacement of the optical head upon application of force by the subject and prevents deformation in other directions, thereby minimizing cross-sensitivity. Later, an ultrasonic motor torque sensor using flexible hinges was also developed [66]. A three-axis optical fiber force sensor for MRI applications was designed using a 3-DOF compliant platform made of three identical cantilever beams with their supports, offering flexibility in response to axial forces and bending moments and high stiffness to withstand axial torque [184]. A three-axis optical force sensor made of two parallelogram-like segments of helical circular engravings that can provide intrinsic axial/ lateral overload protection during prostate needle placement was developed [185]. Similarly, a triaxial catheter tip force sensor having flexures and integrated reflector was developed for cardiac procedures [49]. The flexures are designed so that the axial and lateral forces cause different deformation of the flexures which leads to different amounts of light getting reflected and detected by the photo detectors.

A challenge with multi-axial force sensors lies in the decoupling of forces along the axes as observed in the study by Gao et al. [117]. Linear decoupling methods proved to be inaccurate since local deformation of flexures affects the strains measured. A method to decouple pulling and grasping forces of a 2DOF compliant forceps was derived using the serial connections of two torsional springs, which was realized by optimizing the shape of two circular-type flexure hinges [16]. However, rotational perturbation of forceps, sideway forces acting at the forceps, and fabrication errors introduced disturbances in the force measurement. Gonenc et al. [130] demonstrated axial-transverse force decoupling in their flexure design of micro-forceps for robot-assisted vitreoretinal surgery. Peirs et al. [80] decoupled the deformations caused by axial and radial forces of a micro optical force sensor for minimally invasive robotic surgery, using four identical parallelograms placed in an axisymmetric arrangement. Fifanski et al. [186] developed a flexure-based in-vivo force sensor that can measure forces in 3D using individual optical fibers. As flexure-based force sensors cause undesirable transverse moments, twists and lateral deflections, making it difficult to measure forces along the different axes, Tan et al. [32] presented a potential solution of decoupling the force measurements using topology optimization to design the elastic frame structure.

Other factors to be considered while designing force sensors include thermal sensitivity, hysteresis, plastic deformation and friction due to contact between internal components that can alter the elastic behavior of flexures [50]. Kumar et al. [187] developed a force sensor using a compliant version of the Sarrus mechanism and strain gauges. Their elastic model could not address the hysteresis, viscoelastic effects, and nonlinearities in the prototype caused by fabrication process. To increase the sensitivity of force sensors, Krishnan and Ananthasuresh [188] evaluated several displacement-amplifying compliant mechanisms (DaCMs) and proposed a general design methodology using application-specific topology optimization. Furthermore, a study by Turkseven and Ueda [118,189] showed that a DaCM-based force sensor with lower sensitivity can enhance the performance of the sensor by reducing hysteresis and improving signal-to-noise ratio. CMs can also be used to passively sense force and respond in surgical situations. An instance of this was discussed in the context of endoscopy simulation [190], which could also be used in virtual surgical trials. In this work, a CM was designed to convert radial force experienced by the inner rim of a ring into circumferential motion of the ring that can be measured using an encoder.

3.5 Implants and Deployable Devices.

Implants are medical devices embedded inside the body via surgery to replace or enhance damaged biological tissue. Within this review, different applications of implants designed using CMs are discussed. FlexSuRe™ a spinal implant based on the geometry of lamina emergent torsional (LET) joint was developed to restore normal motion to the degenerate spine [191]. The LET joint is made from a lamina, and torsion of beams results in flexibility in multiple directions similar to the intervertebral disc. An intraocular implant with CM-based silicon linkages was designed to amplify the displacement of a piezoelectric bender and provide an almost tilt-free translational displacement of the lens for optical imaging quality [119]. Krucinski et al. [101] showed that the flexural stresses of bioprosthetic heart valves can be reduced by incorporating a flexible or expansile supporting stent into the valve design.

Within the context of this article, deployable devices refer to CMs designed to change in shape and size that facilitate insertion of the surgical device in a compact form to reduce invasiveness of the procedure. For example, Chen et al. [192] designed an intracardiac magnetic resonance imaging catheter consisting of folded imaging coil during vascular navigation (4.5 mm in diameter). Upon deployment, it forms a circular loop (40 mm in diameter) to image a 40 mm field of view. Herrmann et al. [120] developed a bistable heart valve prosthesis that can be folded inside a catheter and percutaneously inserted for delivery to the patient's heart for implantation. In designing cardicovascular stents, topology optimization was used to generate optimal geometry of stent cells and maximize the stiffness of the point of application of forces, thereby maintaining structural integrity [33]. However, plastic strains can cause nonuniformity in the expanded portion of the stent. Hence, James and Waisman [18] used topology optimization to design a bistable stent that snaps-through to a stable expanded configuration, relying on the geometric nonlinearity of the structure.

Origami-based designs have emerged as a powerful tool in developing deployable devices for MIS [19]. According to Edmondson et al. [193], "Origami can be viewed as a compliant mechanism when folds are treated as joints and panels as links." A pair of origami-inspired surgical forceps was developed to ease the fabrication and sterilization process of robotic forceps. An increase in flexibility while maintaining rigidity was achieved by utilizing multi-layer lamina emergent mechanisms (MLEMs) in the design process. (MLEMs are a type of CM made from multiple sheets (lamina) of material with motion out of plane of fabrication to achieve specific design objectives [194].) Subsequently, small grippers (3 mm in diameter) were developed for the Intuitive Surgical's da Vinci robotic surgical systems, which can be deployed inside the body during surgery [195]. Salerno et al. [94] integrated an origami parallel module to generate rotations and translation of a compliant gripper. Recently, Kuribayashi et al. [95] designed a self-deployable origami stent graft using hill and valley folds. Bobbert et al. [196] fused the origami, kirigami, and multi-stability principles to fabricate deployable meta-implants. It was also shown that the mechanical properties of the implant can gradually increase depending on the design of kirigami cut patterns that determine the porous structures allowing bone regeneration. Halverson [17] developed a disc implant based on CORE to mimic the biomechanics of human spine. Later, Nelson et al. [197] demonstrated a deployable CORE joint (D-CORE) using curved-folding origami techniques to enable transition from a flat state to a deployed functioning state. Origami works well with flexible nonmetallic materials, thus making them ideal for MRI-guided procedures, which is hazardous in the presence of magnetic materials. Recently, an MR-conditional SMA-based origami joint using CORE for potential applications in endoscopy was demonstrated [96].

4 Discussion

This study began with the aim of assessing the utility of CMs in designing surgical devices. There are some challenges that hinder the further development and implementation of these devices in clinical practice. A drawback concerning CMs is the adverse effect of stress concentrations and fatigue, especially in flexure-based designs under cyclic loading. This is a major challenge in the medical field where device failure is not acceptable. To tackle this issue, there is a growing interest towards developing multi-material CMs [85,198–200] and functional grading of CMs [109,201] to enhance structural integrity. The emerging concept of the so-called 4D printing ushers in many more possibilities for using CMs in surgical applications [202]. This technology can strengthen mechanical properties and create multi-material programmable structures made of elastomers and soft active materials such as shape memory polymers, which react to environment stimuli such as temperature, moisture, and magnetic field. Soft robotics is another emerging field of interest, which utilizes flexibility to function but is not classified under CMs. Inspired by the softness and body compliance of biological systems, continuum devices based on soft robotics systems are designed using compliant materials [203].

The behavior of CMs with geometric nonlinearity caused by large deflections is disregarded in many studies described in Sec. 3. Researchers have investigated this behavior of CMs using topology synthesis and other nonlinear modeling methods. It is beyond the scope of this article to discuss these approaches, and readers are advised to refer to the following studies: Refs. [204–208]. An interesting finding of this study is the pivotal role of CMs in developing a new class of force sensors for surgical procedures. However, much uncertainty still exists on the underlying convoluted issues of hysteresis, plastic deformation, among others as discussed in Sec. 3.4. There is scope for improvement by analyzing and understanding the deformation of flexible members of CMs under these complex conditions.

This review highlights the merits of CMs over conventional rigid body mechanisms due to elimination of joint friction, backlash, wear, and need for lubrication. This aspect is leveraged by integration of CMs with modern actuators such as magnets, SMAs, and piezoelectric materials [209]. However, a major challenge lies in analyzing an overall system of CM consisting of multiple flexible members. While the monolithic nature of most of the CMs simplifies the fabrication and assembly processes, the flip side is that the whole design may fail if even one part of the mechanism breaks. It is infeasible to restore and modify CM-based designs for quick testing and improvement. Since the key functioning of CMs depends on the stiffness and the resulting deformation, accurate fabrication is critical, which can lead to higher production costs and lead time.

From a clinical standpoint, the protection of instruments from contamination due to contact with fluids is important. As a potential solution, some researchers have suggested soft elastic coating of the instrument [37,49,210]. However, further analysis of the implications of *in-vivo* operating conditions on the instrument's performance, while maintaining sterilization, is necessary.

5 Conclusions

An overview of the design aspects of CMs in surgical interventions is presented in this article, discussing design methodology, material selection and failure prevention, fabrication, and actuation methods. CMs provide many advantages such as reduction of assembly steps, high precision, accuracy, and repeatability with the elimination of backlash, friction, and wear. This study has identified the virtues of elastic deformation of compliant members in achieving desired functions tailored for diverse surgical applications including but not limited to laparoscopy, endoscopy, ablation, ENT surgery, vitreoretinal surgery, to robot-assisted surgical interventions. The challenges associated with these applications related to biocompatibility of surgical instrument, fatigue, stress concentration, energy efficiency, fabrication, and complex modelling methods of CMs are discussed. The domain of CMs is a niche area of research that has seen tremendous growth in the last few decades and has raised many questions in need of further investigation. The analysis undertaken here extends our existing knowledge of CMs and offers valuable insights for future research. This would help in paving the way towards seamless integration of CMs in designing safe, dexterous, efficient, and cutting-edge surgical devices.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request. The authors attest that all data for this study are included in the paper.

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