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Polymers' Novel Roles in Improving Minimally Invasive Surgery

I. INTRODUCTION

Robotic surgery and endoscopic instrumentation has become one of the most significant advances in minimally invasive surgery (MIS) in recent years, having seen massive improvements in patient recovery times, reducing pain, reducing cost, allowing for better average patient outcomes, and having a more precise platform for complex procedures [1]. However, such advances are still in their infancy, and significant improvements must be made in order to propel the benefits of robotic surgery to reach both a larger patient population—mainly pediatric, fetal, and low-income patient groups—as well as extending its uses to even more complicated operations—such that traditional surgery is not strictly required for such procedures. This paper serves as a review of three distinct, prominent angles of research that improve upon robotic surgery through exploiting the unique properties of polymers. First, is a review of pneumatic endoscopic devices which employ shape memory polymer (SMPs) backbones in order to actuate a flexible snake-like arm throughout the body, while also reducing costs and complex sterilization procedures found in modern MIS endoscopes. Then, we will focus our attention more directly to polymers' role in robotic surgery with the promising uses of Ionic Polymer-Metal Composites (IPMCs) as an extremely biocompatible material which can reduce the complexity, size, and operation of traditional wire-driven robotic surgery instruments via its unique ability to precisely deflect upon applying a voltage. Finally, we will review the usage of ferromagnetic polymers for soft robots which can extend robotic surgery to the smallest scales of the human body—specifically, cerebrovascular endoscopy. All three of the design approaches discussed are aimed at the usage of polymers to improve upon MIS devices by providing a novel means to actuate safely and precisely within the body while eliminating some of the problems of traditional actuation methods.

II. REVIEW

SMPs provide a unique advantage for robotic surgery in that they can utilize temperature in order to force the polymer to return back to its original shape, owing its properties to better crosslinks which allow the polymer to repeatedly recover deformation extremely efficiently while in the rubbery state. This property is utilized in Liu et. al. with an SMP backbone to produce an inch-worm-like actuation algorithm, allowing for the material to point an endoscope device within the stomach of a patient without utilizing a wire-driven mechanism prominent in most other endoscopes [2]. The traditional wire-driven platforms for endoscopes use a bulky external robot to house multiple motors and opposing wires, which are pulled in order to give the endoscope 6 DOF motion within the body, then locking its position via increasing joint friction [1]. Usage of SMPs, however, can provide an alternative actuation method that boasts ‘‘high power-to-weight ratio, soft and low-cost materials, easy manufacturing process, decent force output, and good safety for human interaction’’ compared to the wire-driven model [2]. Additionally, the SMP model is much cheaper, and doesn't require overly-complex sterilization procedures.

The two parts of the endoscopy procedure are first to navigate to the target site safely and in a time-efficient manner, then to hold a rigid position in place as a platform for the endoscopic instrument to do its operation. This requires extreme flexibility within the tortuous shapes of the human body for navigation, while requiring moderate stability and high stiffness for the actual operation portion. Since this is quite rare for a material to possess both qualities, great attention has been placed on the Polyurethane SMP MM3520, which has a glass transition temperature of 35° C (*see:* **Fig. 1**)—just slightly below human body temperature. Both Liu et. al. and Yin et. al. utilize this specific polymer to keep an SMP backbone in the highly flexible rubbery state (T > Tg) while in the navigation portion of endoscopy, then inject cooling fluid into the endoscope to return the SMP back to glassy state such that its elastic modulus is increased enough to hold a camera in place for the procedure [2][3]. Thus, since the body is above 35° C, the endoscope will *passively* remain in its flexible ‘navigation’ phase—withstanding plastic strains of up to 400%—and can be *actively* transitioned into its rigid ‘operation’ phase with coolant [2].

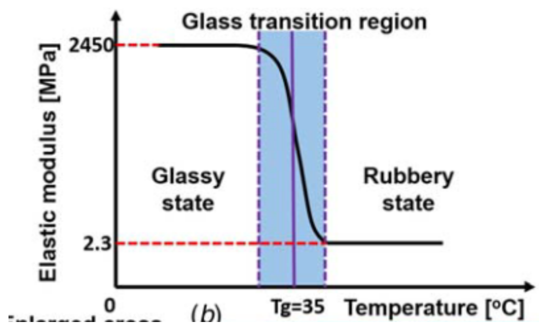

Figure 1: Glass transition range for the shape memory polymer MM3520, [2]

While regular polymers may exhibit the same glass transition temperature as the SMP, SMPs in particular are preferred for their biocompatibility and increased efficiency of deformation recovery in the ‘inch-worm’ style actuation, despite the motion being technically possible with non-SMP polymers [3][4]. The SMP therefore allows for motion to automatically return to its original position, rather than requiring pneumatic or hydraulic actuation to do so, thus increasing the device’s efficiency.

Both Yin et. al. and Liu et. al. utilize 6 and 3 tubes respectively, spiraled in a helix around the SMP backbone with embedded wires for resistive heating; although Yin et al. utilize hydraulic actuation to have more power (and use water as coolant), while Liu et. al utilize pneumatic tubes and gas coolant. Liu et. al. provides a derivation for a mapping function between the input pressure of the tubes and the corresponding helical coordinates of the endoscope tip; this is then implemented into a LabVIEW control system in order to allow for actuation of the endoscope in one direction or another via the inch-worm motion proven experimentally from the data in **Fig. 2** [2]. Liu et. al. then continue to demonstrate the

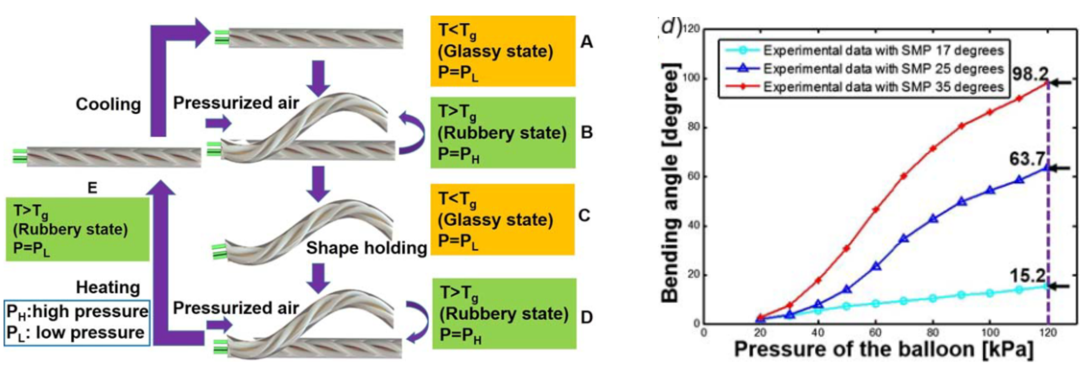

Figure 2: Inch-worm motion of SMP endoscope from Liu et. al. actuated by temperature change & direction-controlled via pneumatic pressure [2]

efficacy of their actuation method by experimentally testing the max force (without noticeable deflection) as 5x larger for the rigid phase than the rubbery navigation phase, as well as the stiffness being approximately double that of the rubbery phase. Notably, the pressure-position relationship exhibited nonlinear hysteresis, making accurate modeling of the position potentially unreliable with repeated cycling. Consequently, the navigation of the endoscope is somewhat clunky, and the time required for a full procedure was not specified in the paper, leaving some doubts about the practical implementation of such a design.

These criticisms are addressed by a slightly different control scheme in Yin et. al. which jets the water in each tube selectively in any of the six directions (60° apart) at the endoscope tip (rather than using the inch-worm actuation of the Yin et. al. model), thus by adjusting flow rates through each jet, a full range of motion is afforded to the end effector. When tested against traditional endoscopes with a professional gastroenterologist, the procedure took nearly 3.5x as long, however this is likely due to the control system interface being ill-equipped for a consumer audience. Potential solutions to increase the speed of operation are included in the "future outlook" section below, however the researchers stress that the total time of operation is under 15 minutes, which is the average time for endoscopy procedures anyways [3]. Thus, the low cost platform that Yin et. al. propose is still quite viable and extremely useful for extending robotic surgery to lower-income groups which suffer heavily from undiagnosed GI cancer.

While endoscopes are an important area of MIS, equally as important is the actual surgical implements themselves. A surgical forcep which utilizes a 2 DOF IPMC base was proposed by Bahramzadeh and Shahinpoor in order to significantly reduces the complexity of sterilization with wire-driven forceps as well as miniaturize the implements used in robotic surgery such that they can be used on pediatric and fetal procedures [1]. IPMCs were chosen particularly because of their "low actuation voltage, large bending deformation, excellent functionality in aqueous solution and alkaline environment in the body and their biocompatibility" that allows them to be an ideal material for soft robotic manipulation. Most importantly, the IPMC has so-called "biomimetic flexibility" in that relatively low voltages can cause the ions embedded within the IPMC to create a force which deflects the IPMC to such a degree that it can be snaked throughout the most tortuous portions of the human body (*see:* **Fig. 3**) [1].

Figure 3: Cantilevered IPMC being actuated with low voltage [1]

A circular beam is created from the IPMC and four electrodes are placed 90° apart from one another; supplying a voltage to the electrodes forces the structure to bend according to the Nernst-Planck equilibrium equation, thus if a control system were implemented, then the actuation of the end effector (blue region in **Fig. 3**) could be controlled entirely without wires [1]. The IPMC would bend in-plane but rotation of the rigid tube which the end effector is connected to will allow the tip of the device to effectively have 6 DOF within the body cavity.

In addition to the proposed functionality of IPMCs as miniaturizeable actuators for MIS operating devices, IPMCs also exhibit a reverse-functionality in that any deformation applied to them will result in a small voltage difference being created across the material. Thus, it is further proposed that a second IPMC layer could be placed upon the actuator which has low stiffness, and thus easily deforms upon interaction with tissues and organs; this would then be transmitted as a voltage, and could be transformed into tactile feedback for the teleoperator surgeon. This could reduce unnecessary force being applied to organs by ~50% and thus result in dramatically more precise MIS procedures via force-sensor feedback for the surgeon [1]. Such a proposal, however, may still suffer from the base failing under stress, as IPMCs have significantly lower elastic moduli than would the metal and wire-driven models of present day; recent research indicates that carbon nanotube "bucky paper" may provide an alternative solution using the same principles as the proposed design, with much greater structural integrity [5].

Finally, we explore the usage of ferromagnetic soft robots demonstrated by Kim et. al., which provides an endoscope platform free of the manufacturing complexities of the pneumatic SMP models, remains much smaller than wire-driven models, and affords more accurate controls due to its magnetic operation not relying on nonlinear behavior as the SMPs do. While previous designs for magnetic endoscope operation have been successful, they are not miniaturizeable due to the embedded magnets being damaged or breaking off entirely at small scales [6]. Kim et. al. remedy this through the use of a NdFeB and PDMS ferromagnetic polymer composite, therefore allowing for the magnetic properties of the endoscope to be distributed throughout the actual structural material itself. The NdFeB particles were evenly distributed through the PDMS resin at a volume fraction of ~20%, as their analytical calculations utilizing Ashby material indices indicated would result in the max deformation for a given magnetic field applied perpendicular to the axis of the robot. This was done using **Eq. 1** based on the applied magnetic

$$\frac{\delta}{L} = \frac{16}{9}\left(\frac{MB}{G}\right)\left(\frac{L}{D}\right)^2 \tag{1}$$

stress and the elastic stress of a Neo-Hookean solid (although shear modulus was modeled using the Mooney model) [6]. The mixture was then magnetized to turn it into a thixotropic paste, such that the system can be modeled as a continuum and therefore give accurate analytical solutions for its behavior. The mixture is then injection molded around a functional core which includes either an optical camera, laser for laser ablative surgery, or nitinol core for structural support (the size of this mold can be miniaturized to sub-millimeter scale with this process) [6]. A hydrogel layer 10-25 μm thick is then grown on the surface of the robot, which decreases the friction coefficient ten-fold, a necessary property for the robot's proposed application: cerebrovascular endoscopy [6]. If the robot were to get snagged on an aneurysm in an artery, there would be a high likelihood of rupture and subsequent hemorrhagic stroke, thus this step is imperative for effective material composition. Finally, the entire device is magnetized a second time along its axial axis and silica is added to prevent corrosion of the ferromagnetic particles. The silica's efficacy at preventing both corrosion and cytotoxicity from the metal particles was proven by the researchers by using an acid bath [6].

The soft robot's functionality was then demonstrated using small rings and various objectives such as shining a light at specific dots on a wall or pointing a laser at specific locations (*see:* **Fig. 4**). Additionally, Kim et. al. utilized a silicone phantom cerebrovascular artery with multiple aneurysms to simulate operation, and proved that the robot could endoscopically inspect each aneurysm without making contact with the walls of the aneurysm lumen (arterial wall) in a time-efficient manner [6]. This is a marked improvement over traditional endoscopic guidewires, as they are usually solely passively controlled, in that a skilled operator will twist the end of the wire outside the body, and push the wire such that it conforms by pushing on the walls of the artery and deforming to its shape as a result. The soft robot

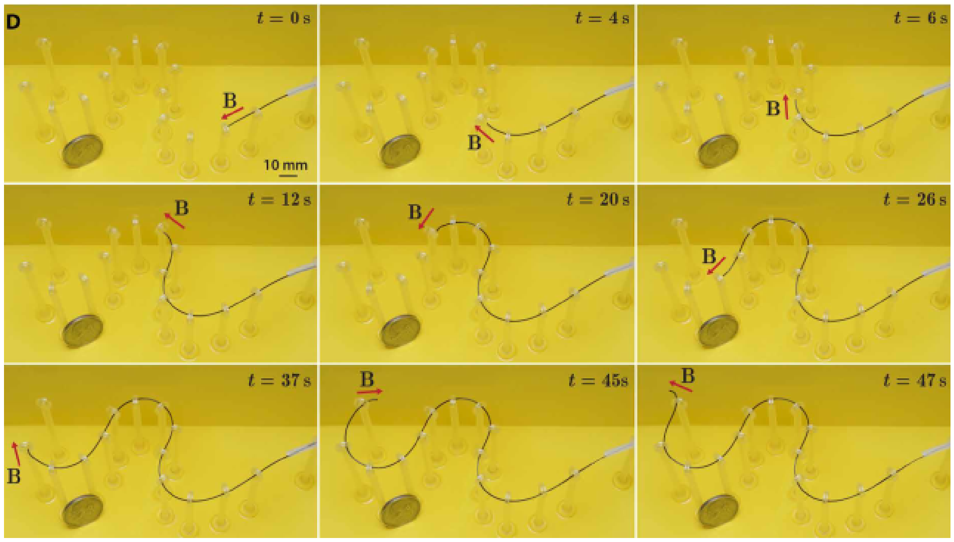

Figure 4: Ferromagnetic soft robot traversing small ring course [6]

design of Kim et. al.. however, provides a novel solution utilizing the high flexibility of the PDMA, the low friction of the hydrogel, and the magnetism of the NdFeB in order to provide an *active control* endoscope for cerebrovascular procedures with minimal possibility for damage of the artery itself.

III. FUTURE OUTLOOK

All of the polymer-based actuation methods provide intriguing solutions for lowering the cost of MIS as well as miniaturizing common robotic surgery or endoscopic devices such that MIS can be extended to larger patient populations. Improvements upon the proposals discussed in this review will likely focus in large part on making the control system design practical enough to actually use in a surgery setting. For the pneumatic and hydraulic SMP devices, this would require more research into faster cooling mechanisms to reduce time spent actuating the device, as well as researching methods by which to increase the thermal conductivity of SMPs (which are quite low usually) [2][3]. Additionally, due to the high fluidity of the SMPs, they are quite complex and difficult to manufacture precisely, causing unreliable and asymmetrical controls to develop; thus, research into a more easily manufacturable SMP matrix will be necessary before this particular design becomes ready for surgical use. The implementation of the IPMC-driven model for the robotic surgical instruments will likely be taken over by some form of carbon nanotube-driven models which utilize the same basic concept of a deformation-voltage relationship to actuate; carbon nanotubes have recently been proven to provide the same effect, and are orders of magnitude cheaper to manufacture while also being much more structurally sound [5]. Finally, the ferromagnetic soft robot design could be implemented into industry much sooner than the other designs, as it has been thoroughly demonstrated to function extremely well inside cerebrovascular arteries, and may actually be further used for angioplasty endoscopy within patients. Additionally, a more robust control system should be developed for the design, utilizing 3-dimensional magnetic field control systems which have been researched and proposed separately from this proposal. The internal functional core of the soft robot will also likely undergo further research to determine additional functionalities and further test the laser ablation functionality for atherosclerosis. With future research in the controls of these three different approaches to polymer-based MIS, robotic surgery and endoscopic procedures can be brought to more and more patients, improving our healthcare, and reducing its strain on individuals' finances in the process.

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