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Soft Robots in Cardiac Interventions

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ABSTRACT

Cardiovascular diseases are the leading cause of death worldwide, underscoring the need for safer and more effective interventions that improve patient outcomes. The success of traditional open-heart surgery and catheter-based procedures are limited by the heart's constant motion and the fragility of cardiac tissues. Rigid robotic systems like the da Vinci platform improve precision and flexibility but remain limited in their ability to safely interact with the soft, delicate anatomy of cardiac structures. Soft robots offer a compelling alternative as compliant systems that conform to cardiac tissue, apply gentle forces, and navigate complex anatomy while minimizing the risk of injury. This review summarizes recent progress in the field of soft robotics across three domains: tools aiding cardiac surgery, functional support of the heart, and organ replacement, drawing on studies of catheter-deployed soft platforms, epicardial sleeves and direct compression systems, and hybrid total artificial hearts. Finally, the use of a technology readiness level (TRL) assessment will be used to assess current barriers and discuss future directions of soft robotic technologies in cardiovascular medicine

I. INTRODUCTION

A. Cardiac Conditions and Procedures

According to the World Health Organization (WHO), cardiovascular diseases (CVDs) are the leading cause of death worldwide, accounting for an estimated 19.8 million deaths in 2022 and nearly one-third of mortality worldwide.[1] The American Heart Association identifies coronary artery disease (CAD), associated with the narrowing of blood vessels in the heart, as the leading contributor to cardiovascular mortality, causing approximately 235.2 deaths per 100,000 people annually [2]. Globally, 64 million people are impacted by heart failure [3], while atrial fibrillation (AF), which occurs when the electrical signals are no longer synchronous across the heart, impacts over 33 million individuals globally [4], [5], [6]. These cardiac conditions pose unique and complicated clinical challenges that highlight the urgent need for more safe and novel interventions.

Although mechanical devices and surgical advances such as ventricular assist devices (VADs) and total artificial hearts (TAHs) have extended survival for select patients, they also carry significant risks including thrombosis (blood clotting), infection, and end-organ injury [7], [8]. The approval of the da Vinci Surgical System by the U.S. Food and Drug Administration for laparoscopic procedures in 2000 and thoracoscopic-assisted cardiac surgery in 2002 mark important milestones in robotic medicine [9].

Early adoption of this and other rigid robotic platforms, including the Corindus CorPath platform for endovascular interventions, the Sensei robotic catheter, and the ZEUS telemanipulation robot improved operator ergonomics and surgical precision, thereby promoting procedural efficiency and surgical success. Despite these advances, rigid robotic instruments still lack much needed adaptability to the dynamic and deformable nature of cardiac tissues and pose risks to the delicate environment of the beating heart [9], [10], [11]. An overview of soft-robotic modalities spanning catheter mapping, intracardiac stabilization, epicardial sleeves, and artificial heart muscle concepts is shown in Figure 1.

B. Soft Robotics and Modes of Actuation

Soft robotics is an emerging field of robotics that introduces a fundamentally different paradigm. Built from compliant and deformable materials such as silicones, elastomers, and shape memory alloys (SMAs) [12], soft robots conform to anatomy, apply gentle forces, and navigate complex structures safely. These qualities are particularly advantageous for the heart, which is in perpetual motion and highly sensitive to mechanical damage. Emerging soft robotic systems now span multiple applications, including catheter-deployed mapping devices for arrhythmia treatment [13], implantable epicardial sleeves that augment cardiac function without contacting blood [14], [15], and hybrid artificial hearts that combine soft actuation with physiological pumping. The transition from rigid to soft robotic systems represents a potential opportunity to reduce surgical complications, expand minimally invasive treatment options, and transform cardiovascular care across three domains: aiding in various forms of cardiac surgery supporting function, and enabling replacement. Soft robots perform tasks through various means of activation called *actuation*. Common types of activation for soft robots are electrical-, magnetic-, thermal-, light-, pressure-, flow-, and explosive-based actuation [16].

Magnetic, pressure, and hydraulic actuation are the most relevant types of actuation for cardiac medicine and intervention. Magnetic actuation allows soft robots to be highly controllable with complex movements at small scales, making them effective to operate within the human body. External magnetic fields allow these systems to achieve both magnitude and directorial control, varying levels of stiffness, and enhanced degrees of safety in delicate cardiac environments [17], [18], [19]. Pressure-based actuation has shown promise in the development of TAHs, where chambers can reproduce the contractile motion of the heart’s ventricles, supporting physiologic hemodynamics [20], [21]. Hydraulic actuation further enhances these systems by providing fine force-sensing and improved stability, preventing tissue injury during cardiac procedures [22], [23].

With these various forms of actuation, soft robots can address major cardiovascular problems such as CAD, heart failure, and atrial fibrillation, which are characterized by blood vessel narrowing, inadequate cardiac output, and abnormal rhythm, respectively. By advancing safety, performance, and functional cardiac support, soft robots offer an improved, reliable alternative to modern rigid robotic systems and conventional surgical approaches. Through innovative applications such as catheter-based tools, cardiac sleeves, and hybrid artificial hearts, these technologies enhance safety, precision, hemodynamic recovery, and ultimately improve both patient survival and quality of life.

Figure 1. Overview of Soft Robotic Devices for Cardiac Applications

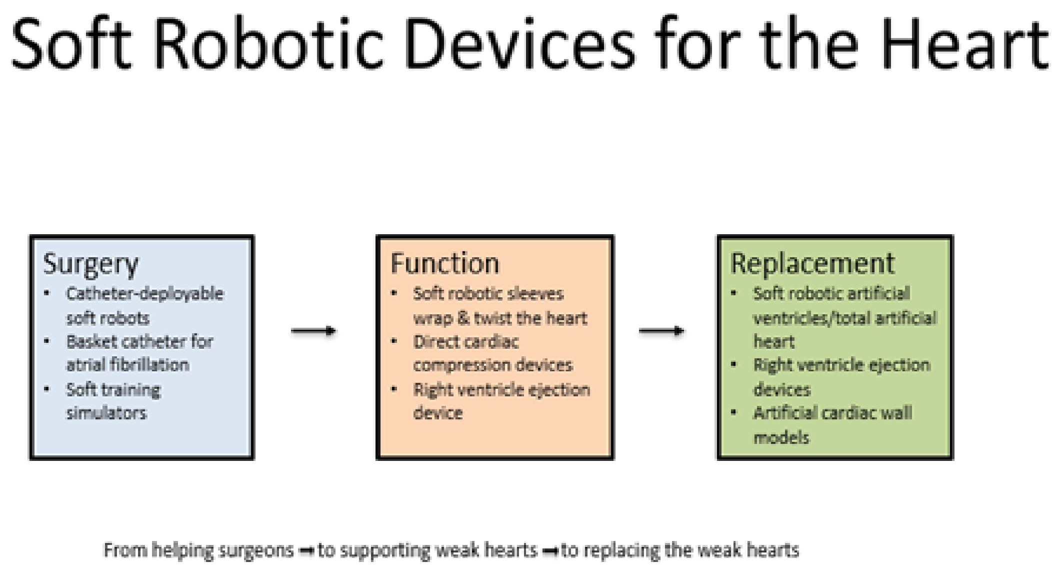

Figure 1. Devices can be grouped into three categories: those aiding with surgery (catheter-deployable soft robots, basket catheters, and simulators), those supporting cardiac function (soft robotic sleeves, direct cardiac compression devices, and ventricular assist tools), and those intended for full heart replacement (hybrid soft total artificial hearts). The figure highlights the progression from surgical tools to mechanical support and ultimately to organ replacement.

II. METHODOLOGY

A targeted review was conducted using PubMed, Google Scholar, and the Web of Science. Search terms included "hard robotics", "soft robotics", "cardiac surgery", "epicardial sleeve", "direct cardiac compression", "catheter mapping", and "artificial heart". Priority was given to peer-reviewed studies reporting device design, bench or ex vivo testing, and in-vivo validation. Review articles that contextualize the materials used in soft robotics, their diverse actuation strategies, and the surgical use that highlight their promise and current limitations were also included. More than forty sources were screened across the three domains of interest: cardiac surgery, function, and replacement, with attention to reported technology readiness levels (TRLs) and translational considerations. TRLs provide a standardized framework for assessing the maturity of emerging technologies. Based on definitions from the National Aeronautics and Space Administration (NASA) and the United States Department of Defense (DoD), TRLs in the field of biomedical devices generally progress from levels 3–4, which correspond to proof-of-concept and laboratory prototypes, to levels 5–6, where validation occurs in animal models or in vivo studies, and finally to levels 8–9, which represent regulatory approval and widespread clinical deployment. During this review, the Human Readiness Level (HRL) scale was also identified as an additional framework to the technology readiness system. Similar in structure to the TRL scale, HRL evaluates whether a device is ready for safe and computable use in humans. A comparison of the two scales revealed that most devices achieved comparable TRL and HRL ratings, though HRL scores were generally lower (3-4) because most technologies reviewed remain at the prototype stage without extensive human testing. ([35])

The quality of studies on cardiac soft robotics *varies* widely, ranging from early design and feasibility reports of benchtop or 3D-printed heart models to more advanced, large-animal experiments. While these investigations have established fundamental safety, compliance, and integration in anatomically relevant settings, most TLR scores for these devices are mid-range, with limited evidence for their durability, sustained performance, and long-term biocompatibility. Hybrid concepts combining soft robotics with artificial heart technologies such as total artificial hearts (TAHs), ventricular assist devices (VADs), and biohybrid ventricular simulators show promise, but the absence of extended in-vivo testing and human feasibility trials represent hurdles for their use clinically.

III. SOFT ROBOTICS IN CARDIAC SURGERY

Soft robotics is introducing new possibilities for safer and less invasive heart surgery. Traditional “open-heart” procedures defined as surgical operation in which the chest is surgically opened and the heart is directly accessed, often requiring cardiopulmonary bypass along with rigid robotic systems are challenged by the delicate, perpetual movement of the cardiac environment. Soft robotic systems, built from compliant materials, can navigate such complex anatomy with reduced risk of tissue damage and greater adaptability.

One major innovation is the development of catheter-deployed soft robotic platforms. These inflatable “basket” catheters expand gently to match the shape of the atrium, helping physicians map irregular heart rhythms like atrial fibrillation more accurately during ablation procedures. Unlike stiff metallic baskets, which often fail to provide complete tissue contact with a success rate of about 60%, soft robotic catheters conform to the curved walls of the atrium. When tested in patient-specific models such as custom 3D models of real patients hearts built from imaging scans, they achieved up to 85% sensor coverage [13].*This improved conformability increases the accuracy of identifying arrhythmogenic tissue and reduces the risk of procedure-related complications*.

An additional promising advance is the use of soft robotic systems for the delivery of coiled anchors, which enable stable deployment within moving cardiac tissue while minimizing risk of injury [23], [24]. This system enables anchor deployment in moving cardiac tissue with low positional error and clinically relevant force output, helping to stabilize devices inside the heart with less risk of injury. Such anchor systems add to soft robotics’ toolkit by enabling support for tools or sensors that need stable attachment inside beating cardiac tissue.

Another important application of soft robotics is in surgery, particularly through the development of conformable catheters. In minimally invasive surgery, magnetically actuated catheters are useful as they can withstand the complex cyclical movements of a beating heart. Soft robotics is also being used to develop stabilization platforms for intracardiac procedures. These devices can brace themselves against moving cardiac tissue and guide surgical tools with precision, enabling interventions without the need for open-chest access [12], [25]. Building on this concept, Rogatinsky et. al developed a soft robotic device that autonomously stabilizes inside the heart, assisting surgeons with reaching their intended target by attaching securely to the target site without damaging or puncturing cardiac tissue and precisely localize their intervention and improving the likelihood of procedural success [23]. Similarly, another team of researchers developed a soft force-sensing catheter with the ability to actively monitor and regulate the applied force ensuring that safe and consistent pressure is maintained throughout the operation [9]. Furthermore, training simulators made from soft robotic materials provide realistic practice environments for practicing procedures such as transseptal puncture, helping physicians build skills safely before working with patients [26].

Altogether, these advances demonstrate how soft robotics can transform cardiac surgery and catheter interventions by combining minimal invasiveness, adaptability, and precision. While most of these systems are in preclinical stages of development, their potential to enable safer, faster and more effective interventions is increasing evident

IV. SOFT ROBOTICS IN AIDING CARDIAC FUNCTION

Heart failure occurs when the heart becomes too weak to pump blood effectively. Traditional mechanical devices used to help the heart come into direct contact with blood, which increases the risk of complications such as clotting and infection. Soft robotics offers a safer alternative by supporting the heart externally rather than inside the bloodstream. Many devices supporting cardiac function can be grouped into two categories: soft robotic sleeves and cardiac compression devices.

A. Cardiac Sleeves and VADs

Soft robotic sleeves are a form of cardiac assistive devices that wrap around the heart to mimic the natural fiber orientation of heart muscle that contracts with a twisting motion during each beat [14]. Other designs, such as pneumatic muscle systems, can be shaped to fit around the heart and restore normal pumping volumes without damaging fragile tissue [14], [22].

Soft robotic concepts have also been applied to ventricular assist device (VAD) design. VADs support patients with heart failure by improving blood circulation and restoring ejection fraction (EF), which is the percentage of blood pumped out of the heart's left ventricle with each heartbeat. The average EF is around 50-60%. Despite their clinical value, conventional VADs are hindered by moving components that remain in direct contact with the blood flow of the heart, increasing risk of thrombosis and infection [27]. To overcome these challenges, one group of researchers developed magnetically actuated patches designed to augment cardiac ventricular function without directly contacting blood flow [27]. In preclinical testing of these magnetically actuated patches in a porcine model, this device achieved ejection fraction 37% in the left ventricle and 63% in the right ventricle [27]. While there is still room for improvement, these increased EFs highlight the promise of soft robots in cardiac assistance and recovery.

B.Cardiac Compression Devices

Cardiac compression devices (CCDs) are designed to support the heart by applying external forces that aid in contraction when cardiac function is impaired. Traditional CCDs often compress the entire heart rather than targeting the region(s) of the heart affected by underlying disease, which can reduce efficacy and increase complications. The integration of soft robotics and their diverse actuation strategies offer a more precise and clinically applicable. For example, researchers have developed buckled foam actuators that can be incorporated into an existing direct cardiac compression device (DCCD) [28]. These actuators increase durability and elasticity, making the device a more permanent solution [28]. Importantly, the use of soft, biocompatible materials allows the device to mimic the mechanical properties of native cardiac tissue [28]. The incorporation of soft robotics in cardiac compression devices has allowed for increased safety, improved biocompatibility, and further innovations in mechanical cardiac support.

V. SOFT ROBOTICS IN HEART REPLACEMENT

In severe cases of heart failure, when the heart is no longer able to pump blood adequately even with medical or mechanical support, heart replacement becomes the only option. Soft robotic heart replacements aim to mimic the elasticity, adaptability, and dynamic pumping action of native cardiac tissue.

A.Artificial Heart Muscles

Recent advances have focused on artificial muscle filaments capable of twisting, squeezing, and stretching motions to produce patterns that resemble a beating heart [29]. In one study, pneumatic actuation was used to create a device operable at rates of up to 200 beats per minute, with software control enabling highly precise regulation. Durability testing demonstrated functionality from one day to four months at 60 beats per minute, suggesting a potential bridge therapy option for patients awaiting a heart transplant [30].

Building on these developments, researchers have designed an artificial left ventricle simulator that replicates the complex twisting and elongation motions to produce systolic compression comparable to native cardiac tissue [31]. Soft robotics has also been explored for right-sided cardiac support. The right ventricular ejection device (RVED) is designed to approximate the right ventricular wall toward the septum, thereby enhancing ventricular contraction in cases of right-sided heart failure [32]. Importantly, such devices can be synchronized with the patient’s own heartbeat, improving safety and efficiency with blood circulation [15].

B.Major/Complete Heart Replacement

When the heart fails completely, treatment options are limited to donor transplantation or mechanical total artificial hearts TAHs. Unfortunately, current TAHs are large, rigid, and associated with significant complications such as clotting and infection. Soft robotics offer a promising new direction by creating artificial hearts that are smaller, safer, and more adaptable.

Recent advances in heart replacement include hybrid artificial hearts that combine soft pneumatic pumps with biocompatible linings designed to minimize clot formation. In preclinical studies, these devices demonstrate the ability to pump blood at physiological rates of 5–6 liters per minute, nearly matching a healthy human heart [20]. Further efforts have produced biohybrid right-ventricle platforms that replicate septal motion, valve dynamics, and blood flow, enabling testing of soft robotic replacements for right-sided heart failure [33]. One example is the development of a biohybrid heart that integrates magnetic imaging, engineered biological tissue, and soft robotic actuators within a synthetic myocardial band designed to mimic the heart’s complex motion. The engineered tissue, derived from living cells or biomimetic scaffolds, was incorporated to reproduce the intricate anatomy and mechanical behavior of native cardiac structures [34].

Another approach to heart replacement focuses on building major cardiac structures. A recent study used an artificial cardiac wall that mimics left ventricular wall using pneumatic artificial muscle actuators, often referred to as McKibben actuators. These actuators contract when pressurized, closely imitating the natural behavior of heart muscle fibers. Arranged in a double-helix configuration and combined with a flexible silicone inner lining, the system replicates the twisting and squeezing motions of the native cardiac wall. Compared with rigid mechanical designs, this approach is more cost-efficient while maintaining physiologic performance. In early laboratory testing, the artificial wall achieved ejection fraction values within the normal physiological range, underscoring its potential for use in anatomically constrained spaces and as a foundation for future implantable cardiac replacement devices [21].

Further progress has been achieved through compact soft robotic TAH designs that integrate lightweight actuators with optimized chamber geometry. Early in vitro studies show that these systems can generate near-physiological pressures and cardiac output while offering improved portability compared to conventional rigid devices [20]. *Although still preclinical, these technologies represent an important step towards the long-term goal of replacing failing hearts with soft robotic systems that are safer, more durable, and less dependent on scarce donor organs*

VI. CONCLUSION, PERSPECTIVE, AND FUTURE DIRECTIONS

Despite encouraging progress, significant gaps remain in the quantitative knowledge base for soft robotic cardiac devices. Most studies rely on short-term benchtop or small-scale animal models, which do not fully capture the durability, fatigue resistance, or biocompatibility challenges associated with long-term human use. A recurring but often untested assumption is that materials performing well in vitro will maintain safety and compliance under chronic hemodynamic loads and within the heart's complex electrical and immune environment. This assumption may not hold.

We agree that quantitative consistency is essential to enable meaningful comparison across studies. However, reported performance metrics such as ejection fraction, durability, actuation force, and cardiac output vary substantially across the literature due to differences in experimental conditions, including animal model selection, device configuration, actuation strategy, synchronization with native cardiac motion, and duration of testing. As a result, these values should be interpreted primarily as proof of concept benchmarks rather than directly comparable indicators of clinical efficacy.

Compounding this challenge is the absence of standardized outcome metrics across soft robotic cardiac platforms. Current studies emphasize heterogeneous endpoints, including force generation, displacement, or tissue contact quality, but rarely align these measures with clinically meaningful outcomes, including clot resistance, arrhythmia prevention, or tissue remodeling [12], [13], [20]. This lack of standardization limits reproducibility, hinders cross-study comparison, and slows translational progress.

To address these gaps, future research should adopt multi-scale computational modeling, incorporate long-term in vitro perfusion systems and large-animal testing, and prioritize closed-loop control systems that synchronize with native electrophysiology [31], [34]. Collaborative frameworks linking material science, engineering, and clinical cardiology will be essential to advancing from mid-range readiness levels to safe clinical application..*From a translational and regulatory perspective, clinical adoption will require staged regulatory pathways, including Investigational Device Exemptions (IDEs), rigorous preclinical durability testing, and clinically meaningful endpoints aligned with cardiovascular outcomes. Early integration of regulatory considerations may accelerate progression from preclinical validation to first in human feasibility studies, supporting the safe translation of soft robotic cardiac technologies*.

As summarized in Figure 1, these gaps, assumptions, and potential research trajectories highlight the key steps required to advance soft robotic cardiac devices from experimental prototypes toward clinical translation.

Figure 2. Illustration of Soft Robotic Devices in the Heart

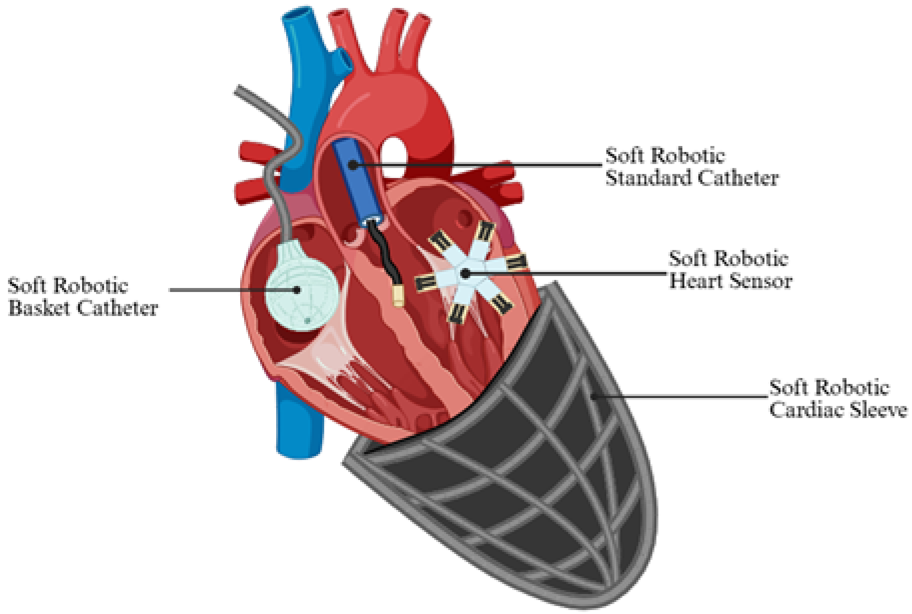

Figure 2. Illustration of Soft Robotic Devices in the Heart. This figure illustrates how soft robotics can be integrated into the heart to improve both interventional and replacement strategies. Inflatable basket catheters and sensor-enabled baskets provide conformable mapping of atrial tissue. A soft robotic six-armed sensor is shown and can be used inside the heart to identify and respond to motion. A soft robotic sleeve encasing the ventricles delivers external compression to augment pumping function. Together, these systems highlight how soft robotics can enhance safety, adaptability, and precision while paving the way toward viable heart replacement therapies.

Among the three primary applications, catheter-based surgical tools (baskets, anchors, stabilization platforms) are at the highest Human Readiness Level (HRLs of ~3–4), supported by benchtop and animal validation, making them the closest to translation. Their most significant impact will likely be assisting surgeons by improving mapping, precision, and safety in delicate interventions such as ablation. Soft robotic sleeves and compression devices occupy the mid-range HRLs (HRLs of 2–3), with promising animal data suggesting they could support failing hearts externally without blood contact, thereby reducing the risks of clotting and infection compared to conventional VADs. Full heart replacements, however, remain at the lowest HRL (HRLs of 1–2), with evidence mostly limited to prototypes or in vitro systems, though their potential impact could be transformative as alternatives to scarce donor hearts [7], [20], [21], [22].

From a cost perspective, catheter-deployed tools are likely the most affordable, since they extend existing workflows and could reduce expenses for procedures such as atrial fibrillation ablation by shortening duration and improving accuracy. Sleeves and compression platforms may be more expensive to manufacture, but they could reduce hospitalization costs by lowering the incidence of complications. In contrast, hybrid artificial hearts are likely to remain costly and initially confined to tertiary centers [7], [14], [15], [20].

Regarding risk, catheter-based devices are the safest option in the near term, as they avoid blood contact and conform gently to the cardiac anatomy. Sleeves and compression devices carry moderate risks of tissue irritation or long-term mechanical wear, while full replacements face the highest hurdles, including thrombosis, infection, and biocompatibility challenges [7], [13], [14], [15], [20], [23], [28]. Current systems primarily employ silicones, elastomers, and shape-memory alloys, materials that promise compliance but still require validation for chronic implantation.

Table 1. Current Gaps, Implicit Assumptions, and Proposed Research Trajectories in Soft Robotic Cardiac Devices.

Current Gaps	Implicit Assumptions	Proposed research trajectories
Short-term in vitro and small-animal studies are the primary focus of current research	Establishing safety through bench-top or acute animal studies provides a valuable foundation for ensuring long-term safety in humans.	Conduct long-term animal studies and perform chronic durability testing while under physiological conditions
Limited availability of standardized outcome metrics, with a focus on force and precision	The technical performance directly correlates with clinical success.	Create standardized endpoints, such as thromboresistance, arrhythmia risk, and tissue remodeling.
Mid-range technology readiness levels (TRLs 4–6) with minimal human data	Prototypes with limited functionality are nearing readiness for clinical use.	Advance through multi-center translational studies and human simulation platforms
Material compliance tested independently	Soft materials will respond the same way to hemodynamic stress and immune environment conditions	Utilize multi-scale modeling, cell culture systems, and fatigue tests to evaluate long-term biocompatibility
Actuation is synchronized only in controlled settings	Device control will naturally synchronize with native heart rhythms	Integrate closed-loop control algorithms that are synchronized with electrophysiology
The interdisciplinary work is fragmented	Advancements in robotics and cardiology can develop independently of each other	Promote the development of interdisciplinary research teams that include experts in materials science, control engineering, and cardiology

This table provides an overview of the current gaps that exist with the usage of soft robotic devices. The second column provides possible implications that stem from these gaps. Finally, the third column provides potential ways to fill these gaps and make the integration of soft robotics more reliable.

Artificial intelligence (AI) represents an underutilized but highly relevant avenue. While not yet integrated into most cardiac soft robotics studies, AI has been demonstrated to support design optimization of soft actuators and image-guided navigation in cardiac robotics [35], [36]**.** Generative AI methods have also shown promise in proposing novel actuator geometries [37]. In future work, AI-driven control systems synchronizing device actuation with cardiac signals could enhance safety, personalization, and longevity

While soft robotic systems remain mostly at mid-range Technology Readiness Levels (TRLs of 4–6) with corresponding HRLs one step lower, they are steadily progressing toward clinical translation. Catheter-based platforms are the closest to reality and are likely to impact surgical precision first, followed by supportive devices for failing hearts, with full replacements as a long-term, transformative goal [7], [13], [14], [15], [20], [21], [23]. Advancing feasibility will require rigorous durability testing, standardized outcome metrics, robust biocompatibility validation, and integration of computational and AI-driven design strategies.

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