

REVIEW

Triboelectric Property in Implantable Bioelectronic Systems

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ABSTRACT

Incorporating triboelectricity into implantable bioelectronic systems offers a distinctive pathway for enabling autonomous electrical functions within dynamic biological environments. Despite rapid progress over the past decade, existing implantable triboelectric devices are often discussed in a fragmented manner, with limited differentiation among excitation sources, functional roles, and intended implantation durations. Moreover, current studies predominantly emphasize electrical output metrics while lacking clinically meaningful performance benchmarks, constraining systematic comparison and translational evaluation. This review examines the development of triboelectricity-based implantable bioelectronic systems with an emphasis on *in vivo* operation and therapeutic relevance. Mechanical excitation sources are organized into endogenous and exogenous categories, encompassing intrinsic physiological motions as well as externally applied stimuli. The functional landscape of implantable triboelectric devices is further clarified by delineating power supply, *in situ* sensing and signal transmission, and *in situ* therapeutic intervention as distinct operational modalities. Implantable operation cycles are also discussed in relation to durable implantation and temporary implantation therapeutic objectives. Building on these classifications, forward-looking design considerations are proposed with a focus on site-specific integration, function targeting, and outcome-oriented performance metrics. Together, this structured framework aims to support rational device design, enable meaningful cross-study comparison, and facilitate the clinical translation of triboelectric implantable bioelectronic systems.

1 | Introduction

Diagnostic, therapeutic, and rehabilitative implantable medical devices play a central role in modern healthcare, yet their clinical deployment remains constrained by limitations in power supply, device longevity, and mechanical compatibility with living tissues [1–3]. Conventional implantable systems typically rely on batteries or wired power delivery, which restrict device miniaturization and often necessitate secondary surgical procedures for replacement or maintenance [4–6]. Furthermore, the mechanical mismatch between rigid electronic components and soft, dynamic biological environments poses challenges for long-term stability and functional reliability [7–9].

To address these challenges, a variety of physical transduction platforms have been explored to enable self-responsive or self-powered operation in bioelectronic systems [10, 11]. Broadly, these platforms aim to couple mechanical, thermal, magnetic, or electrical interactions with functional electronic outputs, thereby reducing reliance on conventional batteries and rigid power architectures [12–16]. While each platform offers distinct advantages, they also entail inherent trade-offs in terms of material constraints, signal adaptability, structural complexity, or integration flexibility within dynamic biological environments [17, 18]. Among these emerging approaches, triboelectricity represents a fundamentally different paradigm, as it enables direct charge generation and signal formation from ubiquitous interfacial

mechanical interactions without requiring predefined material polarization, continuous biasing, or complex transduction pathways [19–26]. This intrinsic simplicity, together with its high sensitivity to weak and irregular motions, mechanical compliance, and compatibility with soft material systems, positions triboelectric mechanisms as uniquely suited for biointerface-driven electronic functions [27, 28]. As a result, triboelectric platforms offer opportunities that are not readily achievable by other transduction strategies, motivating increasing interest in their use for implantable bioelectronic applications.

Implantable triboelectric nanogenerators (TENGs) were initially explored as *in vivo* energy harvesters that exploit physiological motions such as cardiac activity, respiration, and musculoskeletal movement [29]. More recently, triboelectric interactions have enabled self-driven sensing, signal transmission, and localized therapeutic stimulation, extending the role of triboelectric devices beyond power generation [30]. Nevertheless, implantable triboelectric systems remain underexplored relative to other bioelectronic platforms, and their design principles and functional boundaries are not yet clearly established. Mechanical excitation mechanisms are often discussed without distinguishing whether they originate from endogenous physiological activity or from externally applied sources such as ultrasound. Similarly, implantable triboelectric devices are frequently grouped under the broad label of “energy harvesting,” obscuring important functional differences between power supply, sensing, and therapeutic operation. In addition, many studies do not explicitly consider whether a device is intended for durable implantation or temporary, purpose-driven therapy, despite the profound implications for material selection, encapsulation strategies, and evaluation criteria.

In this review, we adopt a structured and application-oriented framework to examine triboelectricity-based implantable bioelectronic systems, as schematically summarized in Figure 1. Starting from key ambiguities in the existing literature, we disentangle the mechanical interaction mechanisms underlying triboelectric operation by distinguishing endogenous physiological excitation from externally applied mechanical stimuli. We then reorganize reported devices according to their dominant functional roles, spanning autonomous power supply, *in situ* sensing and signal transmission, and localized therapeutic intervention. Finally, implantation duration is treated as a defining design parameter, enabling a clear differentiation between long-term operation and temporary intention, purpose-driven therapeutic use. Together, this workflow provides conceptual clarity and establishes practical guidelines for the rational design and translational development of implantable triboelectric bioelectronic systems.

2 | Bioelectronic Platforms

Implantable bioelectronic platforms provide a direct interface between electronic systems and the physiological environment, enabling *in vivo* sensing, signal transduction, and therapeutic intervention. By exploiting mechanical, electromagnetic, thermal, and optical interactions with biological tissues, these platforms support autonomous or externally assisted operation without reliance on bulky internal power sources.

Since the emergence of minimally invasive and self-sustained implantable systems, a diverse range of bioelectronic platforms has been developed, each defined by its dominant physical transduction mechanism and functional role within implanted devices.

2.1 | Electromagnetic Platforms

Electromagnetic platforms utilize magnetic fields and electromagnetic coupling to enable wireless power transfer and signal communication with implanted devices. By decoupling energy delivery from local energy conversion, these platforms support stable operation of implants requiring continuous or relatively high power, such as neural stimulators and active therapeutic systems. Their capability for deep-tissue penetration and external programmability has made electromagnetic approaches a cornerstone of clinically deployed implantable bioelectronics [31].

2.2 | Magnetoelasticity Platforms

Magnetoelastic platforms utilize the coupling between mechanical stress and magnetic state variations in magnetically responsive materials. Mechanical deformation alters magnetic permeability or domain configuration, which can be transduced into electrical signals through inductive or resistive readout schemes. Recent advances in soft magnetoelastic materials have enabled implantable systems capable of converting biomechanical stimuli into electrical outputs without direct electrical contact, offering an emerging route for motion sensing and energy transduction in complex *in vivo* environments [32].

2.3 | Thermoelectric Platforms

Thermoelectric platforms harvest electrical energy from temperature gradients via the Seebeck effect and have been explored for implantable applications leveraging intrinsic heat dissipation in the body. Although physiological temperature differences are typically modest, advances in thermoelectric materials and device integration have enabled low-power sensing and auxiliary energy supply in long-term implants. These platforms offer a passive, maintenance-free transduction strategy suitable for anatomically thermally heterogeneous regions [33].

2.4 | Piezoelectric Platforms

Piezoelectric platforms transduce mechanical deformation into electrical signals through stress-induced polarization and have been extensively investigated for implantable sensing and energy harvesting. By responding to physiological motions such as cardiac contraction, respiration, and musculoskeletal activity, piezoelectric devices enable self-powered monitoring and localized electrical stimulation. Their deterministic electromechanical coupling and material maturity make piezoelectric platforms well suited for stable, repeatable transduction of biomechanical signals *in vivo* [34].

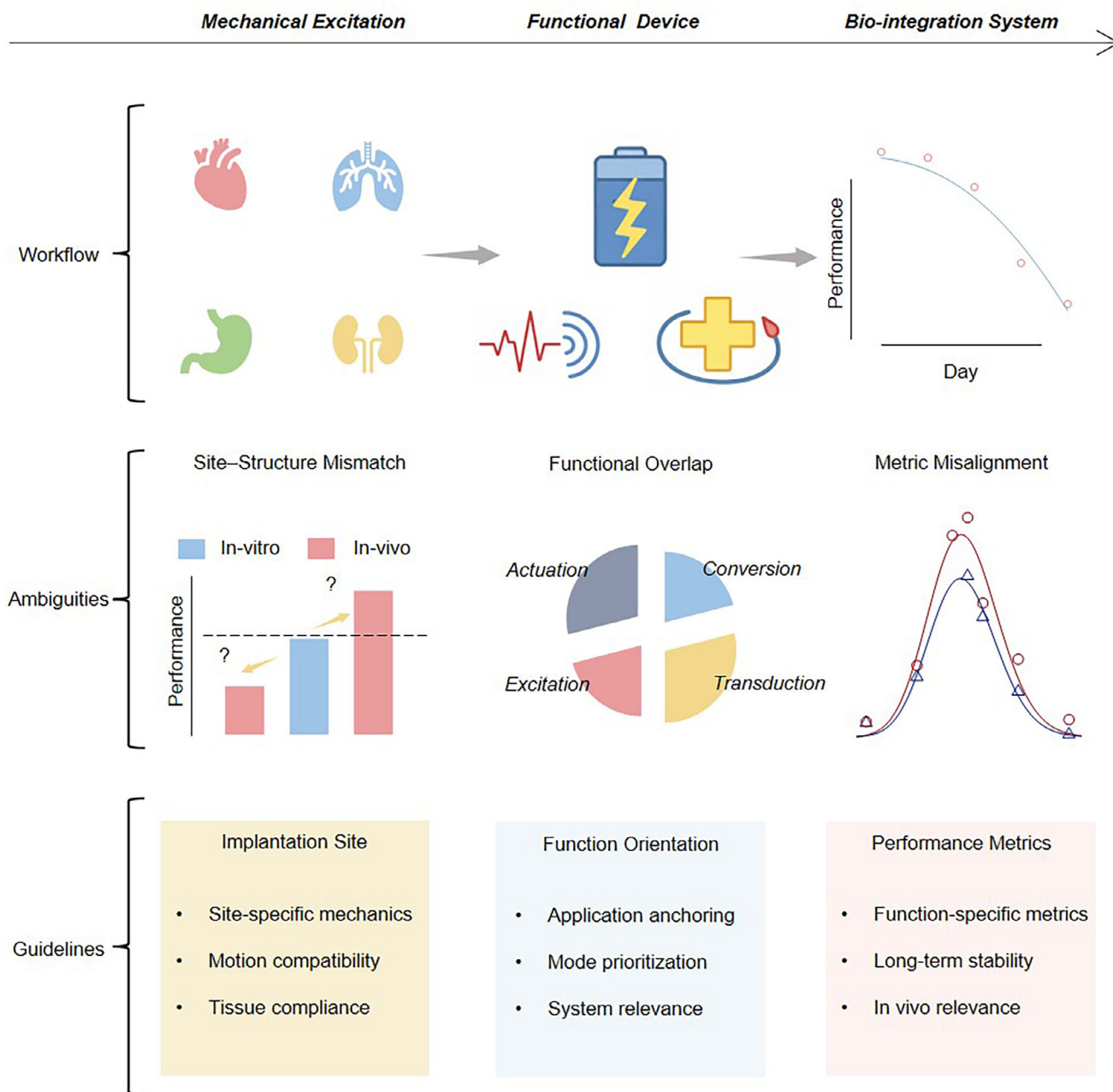


FIGURE 1 | Workflow and conceptual roadmap of this review. Schematic overview of the analytical framework with major ambiguities and the resulting guideline-oriented classification of triboelectric implantable bioelectronic systems.

2.5 | Piezoresistivity Platforms

Piezoresistive platforms rely on stress-induced changes in electrical resistivity to transduce mechanical deformation into measurable electrical signals. Unlike generator-based platforms, piezoresistive systems do not primarily function as energy harvesters but instead enable direct and highly sensitive mechanical-to-electrical signal conversion with minimal power overhead. In implantable bioelectronics, piezoresistive mechanisms have been employed for precise monitoring of pressure, strain, and tissue deformation, supporting continuous physiological sensing with simplified device architectures [35].

2.6 | Capacitive Platforms

Capacitive platforms exploit deformation-induced variations in capacitance arising from changes in electrode separation, overlap area, or dielectric properties. Mechanical stimuli within the body modulate the local electric field distribution, producing electrical signals that reflect physiological motion or pressure. Owing to their high linearity, fast response, and low hysteresis, capacitive transduction mechanisms are particularly attractive for implantable biomechanical sensing applications, where signal fidelity and long-term stability are critical [36].

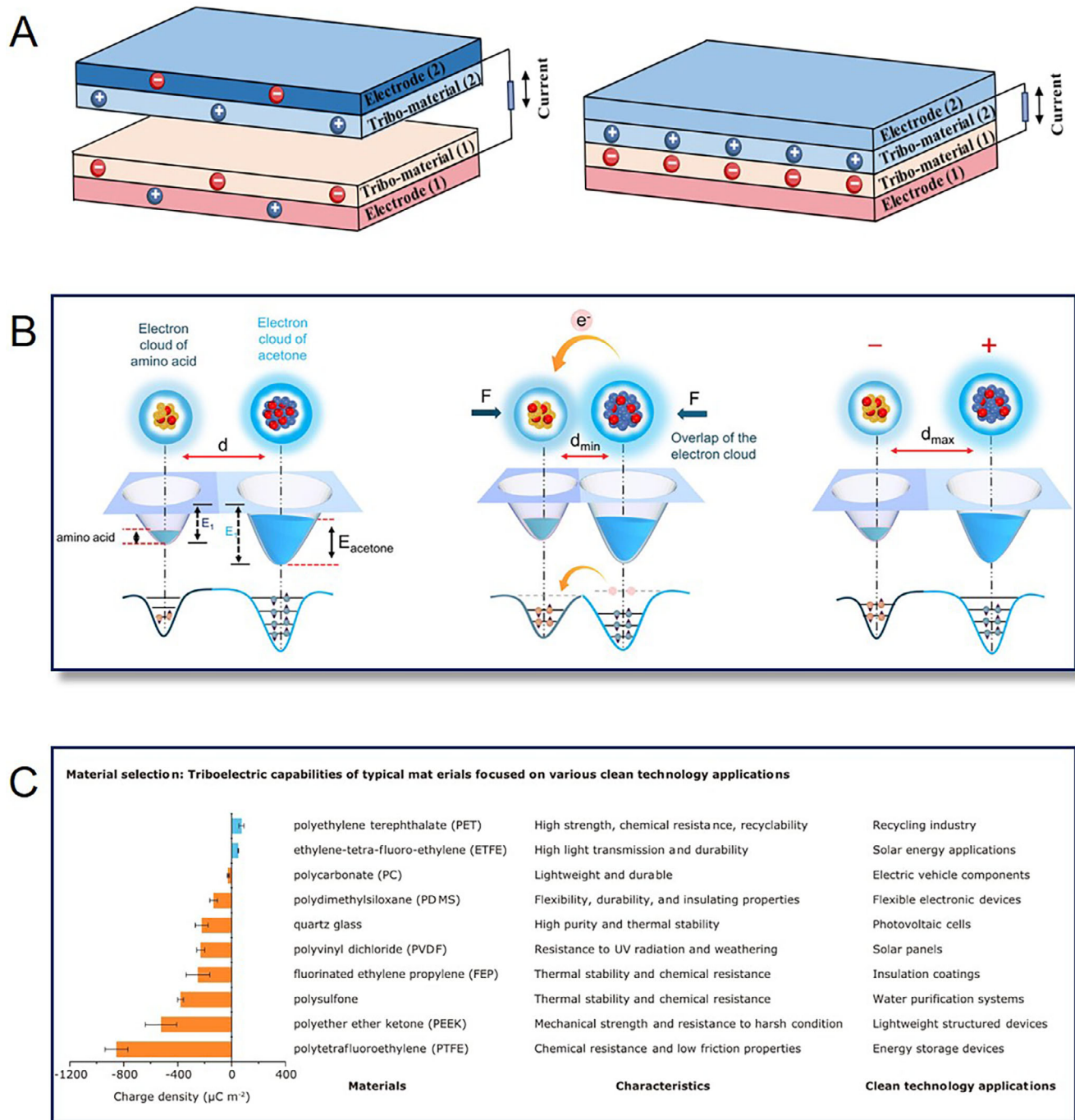


FIGURE 2 | Conceptual framework of triboelectric systems. (a) Working mechanism of contact-separation mode TENG. (b) Electron cloud interactions between the two materials drive interfacial charge transfer during the contact-separation cycle. Reproduced with permission [37]. Copyright 2026, American Chemical Society. (c) Enhancing TENG's output performance through optimization of material selection. Reproduced with permission [38]. Copyright 2022, Springer Nature.

2.7 | Triboelectric Platforms

Triboelectric platforms rely on contact electrification and electrostatic induction to convert relative motion or deformation into electrical output (Figure 2a). At the microscopic level, charge generation originates from interfacial electronic interactions during the contact-separation cycle, where transient electron cloud overlap and relaxation between two surfaces drive net charge

transfer (Figure 2b) [37]. Owing to this interfacial origin, the electrical output can be effectively modulated through material selection and interface design, as differences in triboelectric polarity and electronic affinity directly govern charge density and voltage generation (Figure 2c) [38].

As a result, TENGs are distinguished by high output voltage and pronounced sensitivity to low-frequency mechanical

excitation, making them particularly effective for harvesting subtle motions that are difficult to access using other transduction mechanisms. Beyond energy generation, triboelectric platforms have been extended to self-powered sensing, signal modulation, and electrical stimulation, enabling multifunctional bioelectronic operation in dynamic environments. Compared with many other bioelectronic transduction mechanisms, triboelectric transduction can operate in a bias-free and interface-dominated manner, enabling direct electrical signal generation from mechanical interactions without reliance on bulk polarization or field-mediated induction. From a clinical perspective, these characteristics translate into distinct advantages, including simplified system architectures without continuous power supply, effective utilization of intrinsic physiological motion, and compatibility with mechanically dynamic implantation sites. These physical characteristics collectively make triboelectric platforms well suited for low-frequency, mechanically rich environments and provide a clear physical basis for their focused discussion in this Review. Figure 3 outlines the conceptual triboelectric platform workflow, progressing from mechanical excitation mechanisms of implantable TENGs (Figure 3a), to their functional roles (Figure 3b), and finally to bio-integration considerations governing *in vivo* suitability (Figure 3c) [29, 39–44]. At the same time, several translational challenges remain to be addressed, such as site-dependent performance variability, long-term operational stability under physiological loading, and the need for evaluation frameworks that extend beyond electrical output metrics toward function- and outcome-oriented benchmarks. Addressing these challenges requires an integrated consideration of excitation mechanisms, functional intent, and biointegration, which are systematically examined in the following sections.

3 | Physical Interaction Mechanisms Between TENGs and Biological Systems

The operation of implantable TENG fundamentally relies on the conversion of mechanical interactions occurring within the body into electrical signals. Unlike *ex vivo* or wearable systems, where excitation conditions can be externally defined or standardized, *in vivo* mechanical excitation is intrinsically heterogeneous, spatiotemporally constrained and tightly coupled to anatomy and physiology. As a result, the excitation and transduction mechanisms of implantable TENGs must be understood not merely as material-level phenomena, but as system-level processes shaped by organ motion, tissue mechanics and implantation context.

From a mechanistic perspective, *in vivo* triboelectric excitation can be broadly classified according to the origin of mechanical input. Endogenous biomechanical excitation arises from intrinsic physiological motions, such as cardiac contraction, respiration, muscle deformation and visceral peristalsis, which provide continuous or quasi-continuous mechanical stimuli. In contrast, exogenous excitation is introduced intentionally from outside the body, most commonly via acoustic or ultrasound waves, enabling wireless, on-demand activation of implanted devices. These two excitation paradigms impose fundamentally different constraints on device architecture, transduction efficiency and functional deployment, and therefore warrant separate consideration.

3.1 | Endogenous Biomechanical Excitation

Endogenous biomechanical excitation exploits naturally occurring physiological motions as the driving force for triboelectric transduction. In this mode, relative motion, deformation or contact-separation between triboelectric layers is induced directly by organ dynamics or tissue movement. Cardiac pulsation, respiratory expansion of the thoracic cavity, skeletal muscle contraction and smooth muscle peristalsis have all been demonstrated as effective excitation sources for implantable TENGs [45].

A defining characteristic of endogenous excitation is its intimate dependence on implantation site and local mechanical environment. Motion amplitude, frequency, directionality and mechanical impedance vary significantly across anatomical locations, leading to large differences in triboelectric output even for identical device structures. For example, cardiac implantation sites experience periodic, high-frequency deformation with relatively small displacement, whereas thoracic or diaphragmatic regions provide larger-amplitude but lower-frequency motion. Moreover, multiple physiological motions may coexist and interact, such as respiratory modulation of cardiac displacement, resulting in composite excitation patterns that are reflected in the electrical output.

From a transduction standpoint, endogenous excitation often favors flexible, compliant device architectures capable of conformal integration with soft tissues. Contact–separation and sliding modes are commonly employed, but gap generation is frequently constrained by surrounding tissues, motivating designs that either minimize reliance on predefined spacers or leverage tissue-induced deformation to dynamically create interfacial separation. Importantly, because endogenous excitation is inherently persistent over time, this mode is particularly suited to long-term implantation scenarios, supporting continuous sensing, baseline monitoring or sustained low-power operation.

However, reliance on endogenous excitation also introduces limitations. Mechanical input is not externally controllable and varies with physiological state, activity level and disease progression. Consequently, triboelectric output under endogenous excitation is best interpreted as context-dependent, emphasizing relative changes and physiological correlation rather than absolute or constant power delivery.

3.2 | Exogenous Acoustic and Ultrasound-Mediated Excitation

Exogenous excitation circumvents the variability of physiological motion by introducing mechanical energy from outside the body, most prominently through acoustic or ultrasound waves. In this paradigm, incident acoustic energy induces micrometer-scale vibration or deformation of triboelectric structures, triggering contact electrification and interfacial charge transfer without requiring direct mechanical coupling to organ motion [46].

Ultrasound-mediated excitation offers several advantages for implantable TENGs. First, acoustic waves can penetrate biological tissues with relatively low attenuation, enabling wireless

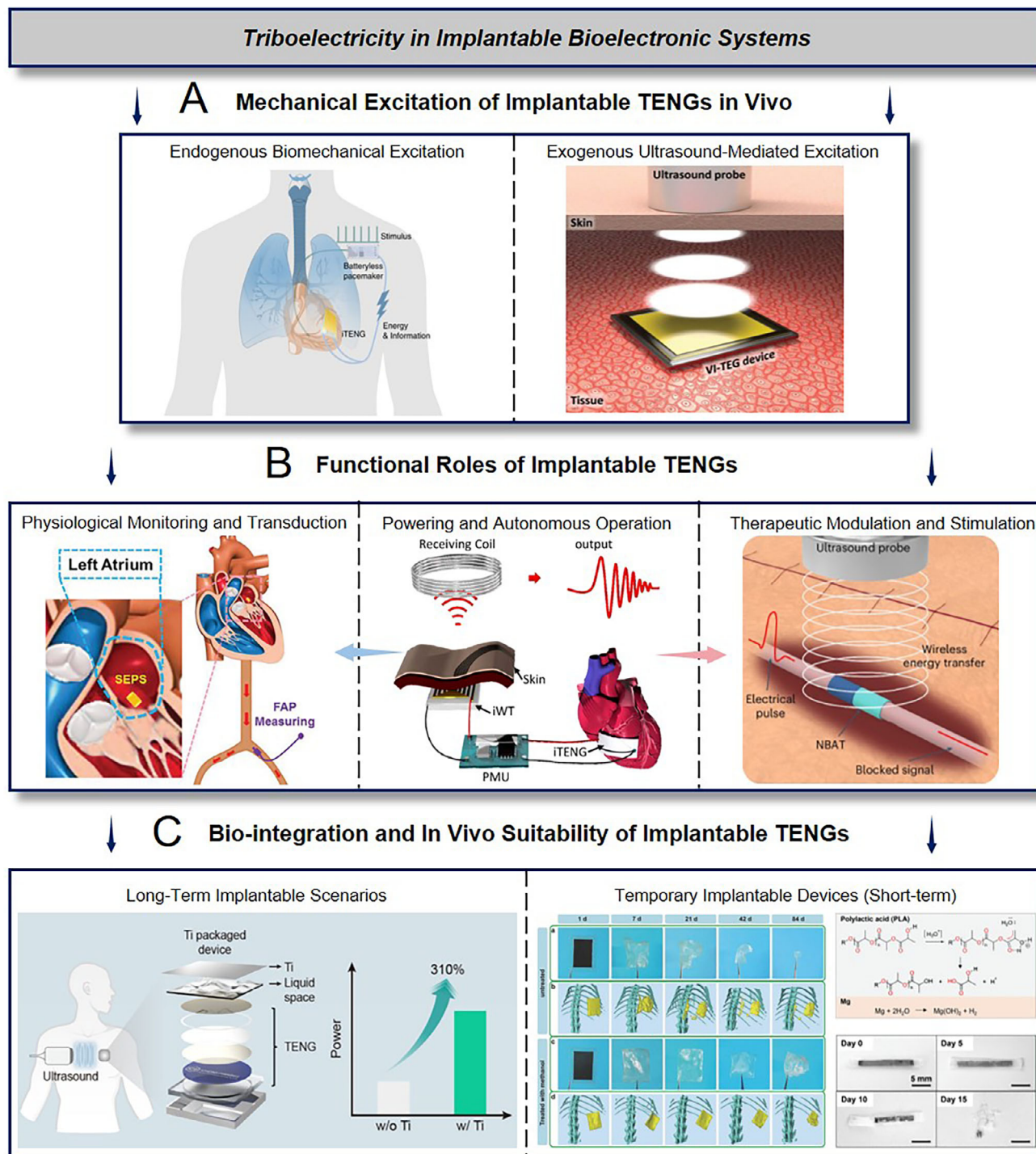


FIGURE 3 | Workflow of implantable TENGs: (a) mechanical excitation of implantable TENGs in vivo converts physiological motions. Reproduced with permission [29]. Copyright 2019, Springer Nature. Reproduced with permission [39]. Copyright 2019, American Association for the Advancement of Science. (b) Functional roles of implantable TENGs in energy harvesting, self-powered sensing, signal transmission, and therapeutic intervention. Reproduced with permission [40]. Copyright 2018, John Wiley and Sons. Reproduced with permission [41]. Copyright 2016, American Chemical Society. Reproduced with permission [42]. Copyright 2026, Springer Nature. (c) Bio-integration and in vivo suitability of TENGs. Reproduced with permission [43]. Copyright 2024, Elsevier. Reproduced with permission [44]. Copyright 2018, John Wiley and Sons.

activation of deeply implanted devices. Second, excitation parameters – including frequency, intensity, and duty cycle – can be precisely controlled externally, allowing on-demand operation and temporal modulation of triboelectric output. Third, ultrasound excitation decouples device function from local physiological

motion, expanding the range of viable implantation sites beyond mechanically active organs.

From a transduction perspective, ultrasound-driven TENGs primarily operate through acoustically induced structural vibration

and displacement amplification, which govern the efficiency of contact–separation dynamics under oscillatory loading. Low-frequency ultrasound is typically used to maximize mechanical displacement and energy transfer, favoring energy harvesting or stimulation applications, whereas higher-frequency ultrasound enables rapid signal modulation and has been leveraged for wireless sensing and signal transmission. Notably, triboelectric transduction under ultrasound excitation has demonstrated robustness to tissue thickness, angular misalignment and device deformation, highlighting its compatibility with complex in vivo geometries.

Exogenous excitation is particularly well suited to temporary or task-specific applications, such as episodic therapy, controlled drug release or temporally gated stimulation, where continuous operation is neither required nor desirable. In addition, ultrasound-mediated excitation enables the integration of biodegradability and programmed lifespan into implantable devices, as excitation intensity can be used to accelerate mechanical degradation after therapeutic completion.

4 | Functional Roles of Implantable TENGs

Implantable TENGs have often been broadly categorized as energy harvesters; however, such a unifying description obscures the diverse functional roles that triboelectric devices can assume within biological systems. Unlike conventional implantable electronics that rely on predefined power architectures, implantable TENGs directly transduce mechanical interactions at the tissue-device interface into electrical signals whose utility depends strongly on the physiological context, implantation site and intended clinical objective. It should also be noted that in vivo performance is inherently influenced by the choice of experimental model, as differences in anatomical scale and biomechanical environment across species may affect signal magnitude and functional interpretation. As a result, the same triboelectric transduction process may underpin fundamentally different in vivo functions, ranging from autonomous power provision to direct physiological readout and active therapeutic modulation.

In practice, the electrical outputs generated by implantable TENGs do not necessarily serve as general-purpose power sources. In some scenarios, accumulated electrical energy is harvested, conditioned and stored to sustain the autonomous operation of implantable electronics, enabling battery-free or self-recharging systems. In other cases, the triboelectric signal itself constitutes the functional output, encoding biomechanical information for real-time physiological monitoring or signal transduction without intermediary amplification or power management. Beyond passive roles, triboelectric outputs can also be deliberately harnessed as therapeutic actuators, where localized electric fields or pulsed stimulation are applied to excitable tissues or used to trigger controlled drug release, thereby directly intervening in pathological processes.

Accordingly, the functional roles of implantable TENGs can be understood along three interrelated but distinct dimensions. First, triboelectric transduction can be exploited to supply electrical energy for autonomous or self-recharging implantable

systems, where mechanical inputs are converted into usable power under defined physiological conditions. Second, the triboelectric output itself can serve as an information carrier, enabling direct physiological monitoring and signal transduction by encoding biomechanical dynamics into electrical signals without the need for external bias or continuous power consumption. Third, the generated electrical outputs may be applied as active stimuli, either to modulate excitable tissues or to trigger therapeutic interventions such as electrical stimulation or controlled drug release. Importantly, throughout this section, electrical output parameters are discussed in the context of functional sufficiency, emphasizing whether reported values meet physiological or therapeutic thresholds rather than absolute magnitude alone. The following sections examine these roles in detail, focusing respectively on powering, sensing and therapeutic modulation (Several representative applications of in vivo triboelectric systems across power, sensing and therapy is shown in Table 1).

4.1 | Powering and Autonomous Operation

Implantable TENGs were initially explored as in vivo power sources capable of harvesting biomechanical energy directly from physiological motions, with the aim of enabling autonomous operation of implantable electronics. Unlike conventional battery-powered systems, triboelectric approaches leverage the inherent mechanical dynamics of organs and tissues, offering a pathway toward self-sustained implantable platforms without wired connections or frequent battery replacement. Early proof-of-concept studies demonstrated the feasibility of harvesting biomechanical energy in vivo using triboelectric mechanisms. One representative work first showed that the periodic expansion and contraction of the rat thorax could be converted into electrical energy by an implantable TENG. The harvested energy was rectified and stored in a capacitor, and was sufficient to drive a prototype pacemaker to regulate the heart rate of the animal [47]. Although modest by today's standards, the output was considered substantial for powering implantable microelectronic devices at the time, establishing triboelectricity as a viable in vivo energy source [41]. Following this initial demonstration, subsequent studies began to recognize that implantation site plays a critical role in determining harvesting efficiency. Systematic evaluation of multiple cardiac implantation locations—including the right ventricular outflow tract, left atrial appendage, cardiac base, left ventricular lateral wall, inferior wall, and apex—revealed pronounced differences in electrical output. Among these sites, the left ventricular lateral wall delivered the highest performance, attributed to its larger motion amplitude and greater interfacial gap variation during the cardiac cycle. Notably, respiratory motion was also found to modulate electrical output, as chest wall expansion and diaphragmatic movement induce subtle deformation of the pericardial cavity, highlighting the coupled influence of multiple physiological motions on triboelectric energy harvesting [41]. Building on these insights, triboelectric powering was further advanced toward fully implantable and functionally autonomous cardiac systems. Li Zhou and co-workers reported a fully implantable symbiotic pacemaker that integrated energy harvesting, storage, and cardiac pacing in a large-animal model. The implantable TENG generated an open-circuit voltage of up to 65.2 V and

TABLE 1 | Representative in vivo applications of implantable triboelectric systems across power, sensing, and therapy.

Device	Classification	Application	Feature	Year	Refs.
iTENG	Power supply	Harvesting rat thorax mechanical energy	Drive a prototype pacemaker	2014	[47]
iTENG	Power supply	Fabricating a self-powered, wireless healthcare monitoring system	Systematic evaluation of multiple cardiac implantation locations	2016	[41]
iTENG	Power supply	Correcting sinus arrhythmia and preventing the deteriorating condition	A type of symbiotic device	2019	[29]
SICP	Power supply	Self-powered intracardiac pacemaker	Being leadless, battery-free, transcatheter-intervention, and lightweight	2024	[48]
I-TENG	Power supply	Charging a lithium-ion battery	Inertia-driven device	2021	[49]
VI-TEG	Power supply	Collecting little vibration energy	Established US-based TENG	2019	[39]
FUTUD	Power supply	Demonstrating a passive wireless sensor	Ultra-wideband triboelectric ultrasonic device	2023	[50]
US-TENG	Power supply	Remote charging	Producing a high output charge with low-intensity ultrasound and a long probe distance	2025	[51]
iTEAS	Sensing	Monitoring of heart rate and respiratory frequency	Estimating blood pressure and flow velocity	2016	[52]
SEPS	Sensing	Endocardial pressure sensors	Harvested mechanical energy from intracardiac blood flow	2019	[40]
NSTENG	Sensing	Sensitive to subtle motions	Non-spacer	2021	[53]
BCMC	Sensing	Precise monitoring and early diagnosis of CVDs.	Zero-power consumption and implantable bias-free	2024	[54]
TRI-TENG	Sensing	Functional heart patch and self-powered e-care remote diagnostic sensor	Unified 3 kinds of function in one patch.	2024	[30]
TENGs	Stimulation	Direct muscle stimulation	Proof-of-concept devices toward neuromuscular therapies	2019	[58]
MV-TENG	Stimulation	Addressing diaphragm paralysis resulting from spinal cord injury	Sensitive to micro-vibration	2024	[59]
FNC	Stimulation	Mechanical neuromodulation of pelvic autonomic nerves	Only a small number of low-frequency (~1 Hz) stimulation pulses was sufficient to induce urination	2019	[60]
NBAT	Stimulation	Pain modulation	Immediate pain control by alternating triboelectric potential	2026	[42]
MH-TTD	Stimulation	Electric-field-based cancer therapies	Neuro-oncological therapy to treat glioblastoma	2025	[64]

harvested 0.495 μJ per cardiac cycle, exceeding the endocardial pacing threshold energy. Notably, this example demonstrated functional sufficiency rather than merely high electrical output. As a result, the triboelectric-powered pacemaker successfully corrected sinus arrhythmia and prevented disease progression, demonstrating that triboelectric energy harvesting can meet clinically relevant energy demands (Figure 4a) [29]. Parallel efforts have focused on miniaturization and minimally invasive implantation strategies. A self-powered capsule-type intracardiac pacemaker was designed to harvest biomechanical energy from cardiac motion and was delivered to the right ventricle via a transvenous catheter. The leadless and battery-free system harvested approximately 0.026 μJ per heartbeat, with a maximum

output power of 0.039 μW . Although the energy harvested per cycle was lower, theoretical analysis indicated that energy accumulated over several cardiac cycles could surpass the pacing threshold of commercial leadless pacemakers (Figure 4b) [48]. Importantly, this analysis relates the harvested energy directly to the clinically defined pacing threshold, indicating that the device output is functionally sufficient for effective cardiac stimulation rather than merely demonstrating nominal electrical generation. These findings underscore the feasibility of compact, self-sustained cardiac implants. Meanwhile, a TENG based on human motion and neutral inertial drive has also been developed. It is about the size of a button cell and can charge lithium batteries to realize a self-functional cardiac pacing system

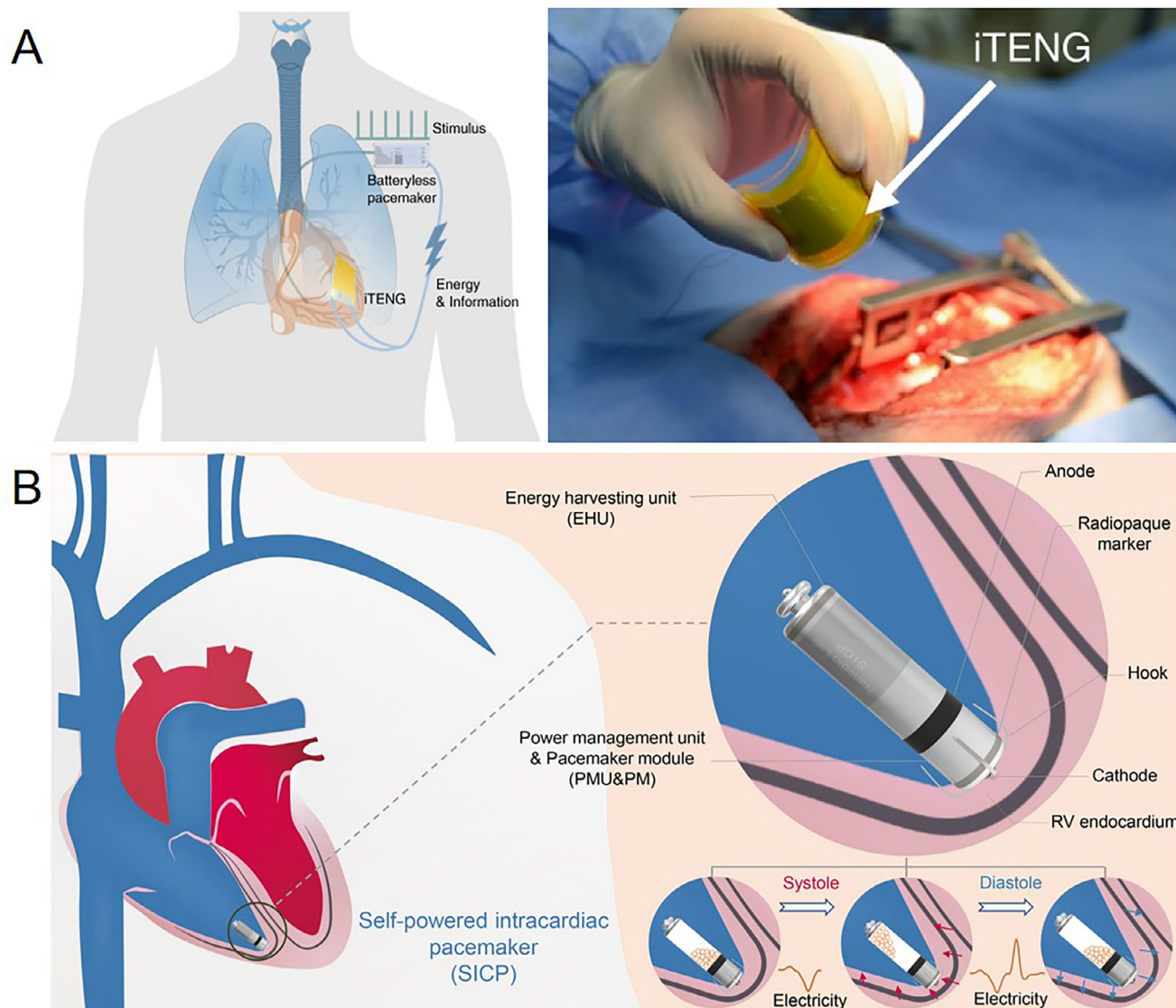


FIGURE 4 | Powering application of implantable triboelectric systems. (a) A TENG-powered cardiac pacemaker that harvests biomechanical energy to enable autonomous pacing for the treatment of cardiac arrhythmia. Reproduced with permission [29]. Copyright 2019, Springer Nature. (b) A capsule-type, TENG-based intracardiac pacemaker implanted in the right ventricle, demonstrating localized energy harvesting and self-sustained pacing in vivo. Reproduced with permission [48]. Copyright 2024, Springer Nature.

[49]. Beyond direct biomechanical excitation, external stimuli have also been introduced to extend the operational flexibility of implantable TENGs. Kim and colleagues demonstrated that ultrasound waves can induce micrometer-scale displacement in polymer films, generating electrical output through contact electrification. Even through 5–10 mm of intervening fat and skin tissue, the device produced currents of 98–156 μA and power outputs approaching 98.6 μW , sufficient for charging batteries in small implantable devices. These results established capacitive triboelectric electrets as one of the first triboelectric platforms capable of harvesting ultrasound energy in vivo with performance comparable to piezoelectric systems [39]. Further studies expanded the functional scope of ultrasound-driven triboelectric systems across a wide frequency range. Under low-frequency ultrasound (20–200 kHz), triboelectric devices functioned as efficient acoustic energy harvesters,

generating voltages of up to 1.2 V and currents of 150 μA through 10 mm of porcine tissue and charging capacitors to 3.2 V. At higher ultrasound frequencies (0.2–10 MHz), integration with flexible electromagnetic coils enabled passive wireless sensing, allowing physiological information to be transmitted from implanted devices to external receivers [50]. Importantly, these ultrasound-powered triboelectric systems demonstrated robust performance under mechanically challenging conditions, including large bending deformations, angular misalignment, and implantation depths of up to approximately 6 cm. Such tolerance to geometric mismatch and tissue-induced attenuation highlights the compatibility of triboelectric devices with complex organ geometries and nonideal alignment between implanted devices and external excitation sources, further supporting their potential for autonomous and adaptable implantable operation [51].

4.2 | Physiological Monitoring and Transduction

TENGs have also emerged as a distinctive class of self-powered sensors for physiological monitoring, not by acting as energy suppliers for downstream electronics, but by directly transducing subtle biomechanical activities into measurable electrical signals. Unlike conventional implantable sensors that rely on external bias or rigid power architectures, TENG-based systems leverage intrinsic physiological motions as both the stimulus and the signal source, enabling continuous, bias-free and highly sensitive monitoring in complex in vivo environments.

Early demonstrations focused on multifunctional cardiac monitoring, exemplified by a self-powered implantable triboelectric active sensor (iTEAS) constructed from multilayer thin-film structures with excellent flexibility and minimized thickness, allowing implantation via minimally invasive procedures. Implanted in the pericardial cavity of live pigs, the device achieved real-time and continuous monitoring of heart rate and respiratory frequency, while also enabling the detection of life-threatening arrhythmias. By correlating triboelectric outputs with arterial pressure catheter measurements, the system further demonstrated the capability to estimate blood pressure and flow velocity, highlighting the potential of TENGs for comprehensive physiological signal transduction rather than single-parameter sensing [52]. Subsequent studies advanced this concept toward intracardiac applications, where miniature, flexible and ultrahigh-sensitivity self-powered endocardial pressure sensors (SEPS) were developed. These TENG-based devices harvested mechanical energy from intracardiac blood flow; however, the generated electrical output was used exclusively as a sensing signal rather than as a power source. In vivo experiments revealed excellent linearity ($R^2 = 0.997$) and high sensitivity ($1.195 \text{ mV mmHg}^{-1}$), enabling the identification of diverse physiological and pathological cardiovascular states, including electrophysiological abnormalities, ventricular fibrillation, and premature ventricular contractions. This work underscored the ability of TENG signals to encode rich hemodynamic and electromechanical information (Figure 5a) [40]. Structural innovations have further expanded the sensing bandwidth of implantable TENGs. Using an in situ gap-generation strategy, Yang and co-workers developed a non-spacer TENG (NSTENG), eliminating conventional spacers that can impede the detection of subtle motions. When implanted onto the hearts of Sprague–Dawley rats, the NSTENG achieved a heart-rate monitoring accuracy of up to 99.73% and simultaneously captured respiratory motions. Notably, the triboelectric signals provided complementary information on fine cardiac mechanical activities that are not accessible through conventional electrocardiography, revealing a unique sensing dimension of implantable TENGs beyond electrical cardiac signals [53]. Miniaturization and system integration have also enabled catheter-deliverable, bias-free cardiac monitoring devices. A self-powered cardiac monitoring capsule, measuring only 6.5 mm in diameter and 20 mm in length, was implanted into the right ventricle of adult pigs for continuous monitoring of myocardial contractility. Although the triboelectric output was not used for powering auxiliary electronics, its self-powered nature eliminated the need for energy consumption at the sensing interface. Combined with a subcutaneous acquisition and transmission module, the system successfully detected variations in contractile force

as well as pathological events such as premature ventricular contractions and ventricular tachycardia (Figure 5b) [54]. Beyond sensing alone, multifunctional triboelectric architectures have integrated diagnosis with therapeutic relevance. A biomimetic tri-functional TENG featuring a dual-spacer-layer structure combined energy harvesting, sensing and therapeutic capabilities within a single cardiac patch. Periodic contact and separation driven by cardiac contraction and relaxation enabled the device to function as a sensitive cardiac activity sensor. Importantly, reductions in myocardial contractility under ischemic conditions led to pronounced decreases in triboelectric output voltage, allowing precise identification of pathological cardiac states. Wireless signal transmission further enabled real-time monitoring on mobile platforms (Figure 5c) [30]. The applicability of implantable TENG-based sensing extends well beyond the cardiovascular system. In orthopedic contexts, where neither patients nor clinicians can readily assess cartilage regeneration in real time, implanted TENG sensors have been proposed to detect subtle mechanical changes associated with tissue repair [55]. Implantable triboelectric devices have also been demonstrated for monitoring muscle activity, enabling real-time tracking of neuromuscular processes without external power [56]. Moreover, under conditions of ultrashort working distance and strong electromagnetic interference, TENG-based implants have achieved accurate and real-time detection of extremely low-frequency gastrointestinal peristalsis, down to 0.3 Hz, a regime that remains challenging for conventional implantable sensors [57]. Collectively, these studies establish implantable TENGs as a versatile and distinctive platform for physiological monitoring and signal transduction. By directly converting biomechanical activities into self-generated electrical signals, TENG-based implants offer a complementary sensing modality that captures mechanical, hemodynamic and functional information inaccessible to traditional electrically biased sensors, thereby opening new avenues for continuous, minimally invasive and information-rich in vivo monitoring.

4.3 | Therapeutic Modulation and Stimulation

Neural interfaces represent one of the most functionally demanding application domains for implantable bioelectronics, owing to their stringent requirements on stimulation precision, signal fidelity, and long-term biocompatibility. TENGs have been increasingly explored as active therapeutic interfaces capable of delivering localized electrical stimulation and electrically mediated interventions. As discussed in Section 4.1, implantable TENGs can be driven either by endogenous physiological motions or by externally applied ultrasound, generating electrical outputs without conventional batteries. In therapeutic contexts, these self-generated signals are not primarily used for powering electronic circuits, but instead serve as direct actuators to modulate excitable tissues—such as peripheral nerves, muscle fibers, or cardiac tissue—or to trigger controlled therapeutic responses. In this regard, triboelectric-enabled stimulation has also begun to emerge as a promising strategy for neural interfaces, where battery-free, mechanically coupled electrical cues can be leveraged to achieve targeted neuromodulation with minimal device complexity and reduced implantation burden.

Loss of muscle function caused by neurological disorders or nerve injury remains a major clinical challenge, for which electrical

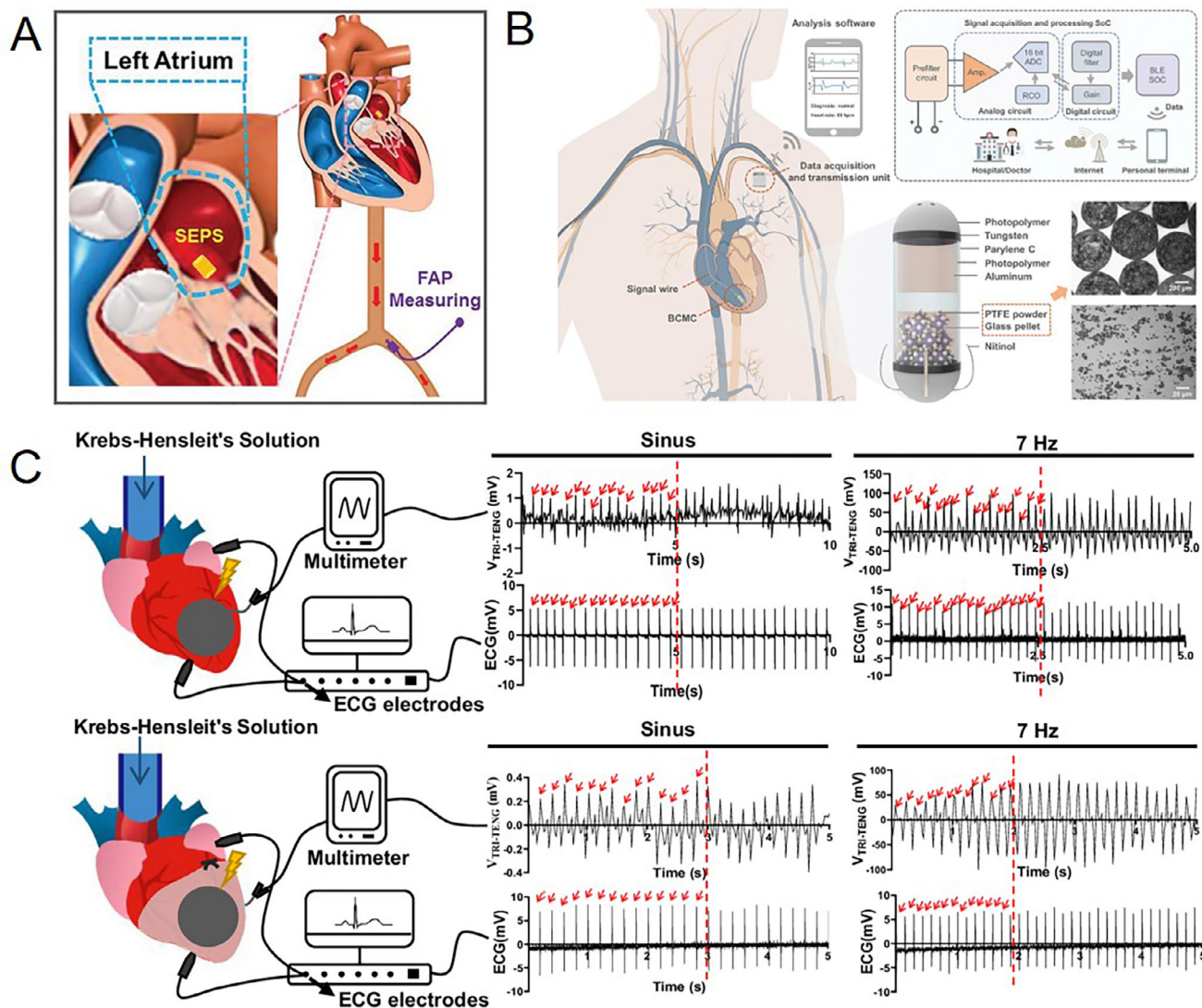


FIGURE 5 | Sensing applications of implantable triboelectric systems. (a) An ultrasensitive TENG-based device that converts intracardiac blood flow dynamics into electrical signals for self-powered physiological sensing. Reproduced with permission [40]. Copyright 2018, John Wiley and Sons. (b) A bias-free, capsule-type triboelectric device enabling continuous monitoring of cardiac contractile force without external power supply. Reproduced with permission [54]. Copyright 2024, John Wiley and Sons. (c) A TENG-based cardiac patch sensitive to myocardial contractility variations, allowing real-time monitoring of ischemia-associated mechanical dysfunction. Reproduced with permission [30]. Copyright 2024, Springer Nature.

stimulation of affected muscles is a widely adopted therapeutic strategy. Early work by Lee and co-workers demonstrated the feasibility of direct muscle stimulation using implantable TENGs, systematically examining stimulation efficiency and long-term stability under physiological conditions. These studies provided foundational guidance for translating triboelectric stimulation from proof-of-concept devices toward practical neuromuscular therapies [58]. Building on this concept, a micro-vibration-driven TENG (MV-TENG) was developed to address diaphragm paralysis resulting from spinal cord injury. Mechanical vibrations were converted into pulsed electrical outputs, rectified and temporarily stored before being delivered through a nerve cuff electrode anchored to the phrenic nerve. When implanted subcutaneously in rats, the system successfully induced diaphragm motor evoked potentials over a four-week period, leading to reliable diaphragm contractions and demonstrating sustained therapeutic efficacy [59]. Triboelectric stimulation has also been extended to auto-

nomous neuromuscular control. A flexible triboelectric nerve stimulator integrated with a neural clip interface enabled mechanical neuromodulation of pelvic autonomic nerves. Voluntary movements generated electrical outputs that were transmitted directly to target nerves, activating downstream muscles. In vivo experiments revealed that applying only a small number of low-frequency (~ 1 Hz) stimulation pulses was sufficient to induce urination, highlighting the high efficiency of mechanically driven triboelectric neuromodulation [60].

Electrical stimulation is known to promote axonal growth across multiple neuronal types, including dorsal root ganglion, hippocampal, cortical and spinal neurons, with therapeutic outcomes strongly dependent on stimulation parameters. In this context, Hao et al. introduced a TENG-based system that harvested mechanical energy from elbow joint movements and delivered the resulting electrical signals simultaneously to the sciatic nerve

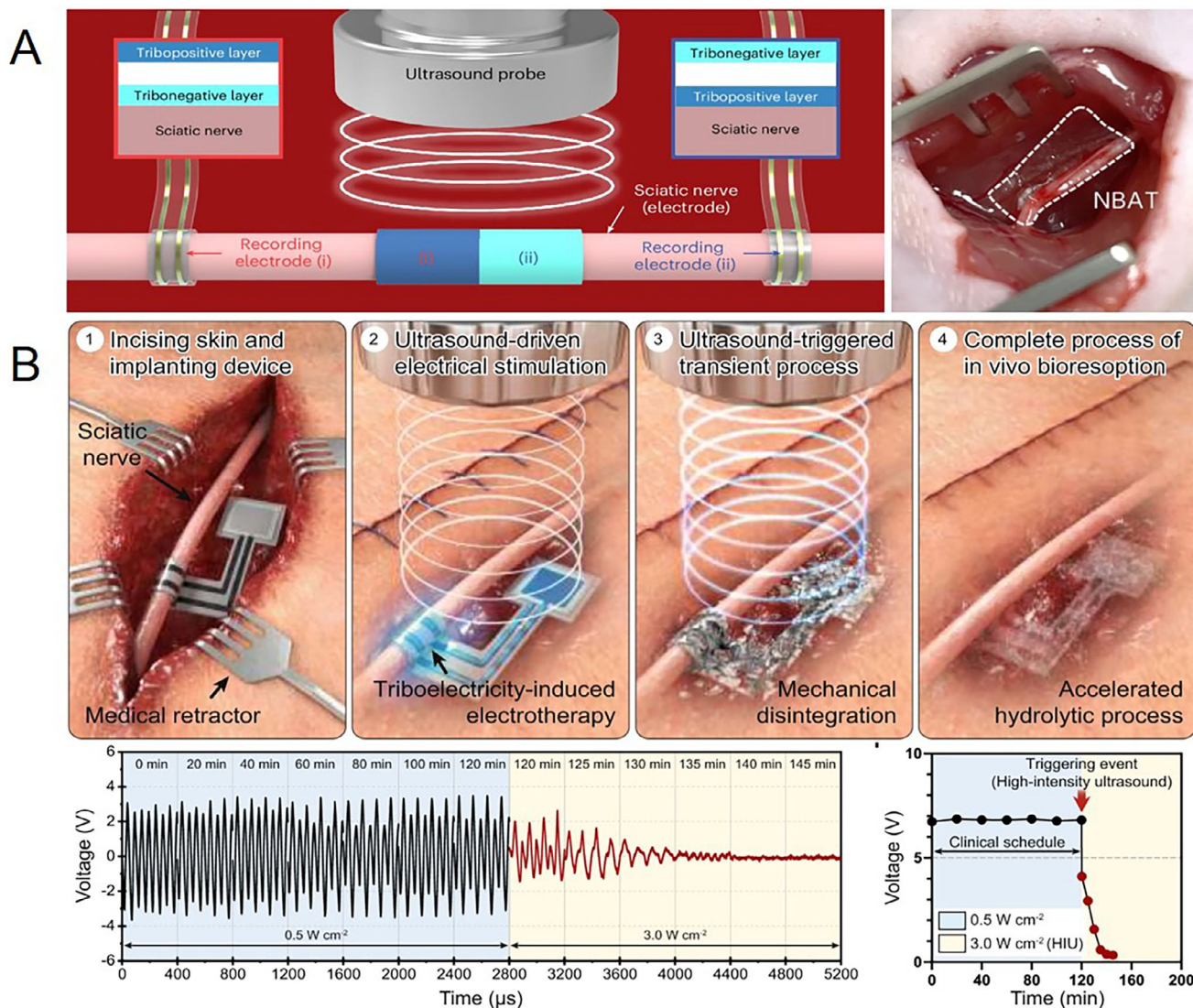


FIGURE 6 | In situ therapeutic applications of implantable triboelectric systems. (a) A bioresorbable TENG that generates localized triboelectric electric fields under ultrasound stimulation for pain modulation. Reproduced with permission [42]. Copyright 2026, Springer Nature. (b) An ultrasound-activated TENG-based neural stimulator capable of stimulating the sciatic nerve, enabling wireless and on-demand neuromodulation in vivo. Reproduced with permission [62]. Copyright 2023, Springer Nature.

and spinal collateral branches, enabling sensorimotor-coupled electrical stimulation. Importantly, the triboelectric stimulation did not induce neuronal damage and significantly enhanced axonal regeneration, demonstrating the therapeutic potential of motion-driven neural modulation [61]. The development of bioresorbable triboelectric devices has further expanded the scope of neural therapies. An ultrasound-activated, bioresorbable triboelectric nerve cuff was designed for pain modulation, in which target nerves were wrapped by polymers with opposite triboelectric polarities. Under ultrasonic excitation, alternating triboelectric fields were generated parallel to the nerve, effectively regulating pain perception. In vivo studies in rat and pig models showed immediate analgesic effects without affecting gait, and the device naturally degraded over time, eliminating the need for secondary surgical removal (Figure 6a) [42]. A related bioresorbable system employed magnesium-based cuff electrodes integrated with an ultrasound-driven TENG. Low-intensity ultrasound activated the device to generate stimulation

pulses for the sciatic nerve, while high-intensity ultrasound accelerated mechanical disintegration after completion of therapy (Figure 6b) [62]. Additional studies demonstrated that ultrasound-mediated triboelectric systems could produce stimulation pulses with tunable frequency, amplitude and pulse width through dual-electrode configurations, although achieving multifunctionality—such as simultaneous stimulation, sensing and communication—using ultrasound alone remains challenging [63].

Electric-field-based cancer therapies have attracted increasing attention due to their ability to interfere with cell mitosis. Implantable triboelectric systems provide a unique opportunity to generate localized, wireless and tunable electric fields directly at tumor sites. An implantable device designed for personalized neuro-oncological therapy applied precisely controlled electric fields to treat glioblastoma. The system disrupted cancer cell cycles and significantly inhibited tumor

proliferation in tumor-bearing mice. Notably, the frequency range required for modulating polar proteins (100–300 kHz) fell well within the tunable output range of the triboelectric device, suggesting adaptability across different tumor types [64]. Therapeutic efficacy has been further enhanced by combining triboelectric field stimulation with chemotherapy. A biodegradable implantable triboelectric device, wirelessly activated by ultrasound, generated alternating voltages while simultaneously releasing chemotherapeutic agents. This dual-action approach synergistically disrupted cytoskeletal assembly and cell division, leading to improved tumor suppression. Compared with conventional tumor treating field therapies, the triboelectric platform offered advantages in mechanical flexibility, wireless operation, accelerated biodegradation and significantly reduced treatment duration [65].

Implantable TENGs have also been employed as active triggers for on-demand drug delivery. In one approach, a biodegradable TENG connected to interdigitated electrodes generated localized electric fields that stimulated red-blood-cell-based drug carriers to accelerate the release of doxorubicin, thereby reducing off-target drug accumulation in healthy tissues [66]. More sophisticated systems integrated sensing, stimulation and drug release. An ultrasound-enabled, implantable triboelectric system was developed for real-time epilepsy monitoring and therapy. Upon detecting high-frequency mechanical signals associated with epileptic episodes, therapeutic molecules preloaded within the TENG matrix were automatically released via electrothermal activation, enabling closed-loop and intelligent treatment [67]. Similarly, an ultrasound-wirelessly controlled, electrically responsive implantable drug delivery system combined a triboelectric generator with an electro-responsive drug reservoir. Ultrasonic excitation induced high-frequency vibrations, producing pulsed electrical outputs that drove water electrolysis, locally increasing alkalinity to dissolve drug carriers and release antifolate anticancer agents. This strategy enabled spatially and temporally precise drug delivery without batteries or wired connections [68].

5 | Biointegration and In Vivo Suitability of Implantable TENGs

Successful implantation of TENGs requires more than efficient electromechanical transduction; it demands system-level biointegration that accounts for material biocompatibility, mechanical compliance, degradation behavior, encapsulation strategy and the intended in vivo working lifetime. Unlike external or wearable devices, implantable TENGs must operate within dynamic, chemically active and mechanically constrained biological environments, where long-term foreign-body responses, surgical burden and device retrieval all become critical considerations. Accordingly, current implantable TENGs can be broadly categorized into temporary systems and durable systems, each guided by distinct design priorities and clinical objectives. Temporary implantable TENGs are typically developed for task-specific interventions, where the device is required to function only during a defined therapeutic or diagnostic window. In this context, complete biodegradability, controllable lifetime and elimination of secondary removal surgery are prioritized over prolonged

operational stability. By contrast, durable implantable TENGs are designed to support sustained physiological interfacing, where structural robustness, encapsulation integrity and stable energy transduction dominate the design logic. Together, these two paradigms define the biointegration landscape of implantable triboelectric systems.

For temporary implantation scenarios, the primary design philosophy emphasizes complete bioresorbability, programmable operational lifetime, and elimination of secondary surgical removal. Early studies demonstrated that fully biodegradable TENGs (BD-TENGs), constructed from resorbable polymers such as PLGA, PCL, and PHB combined with absorbable metals like Mg, can effectively convert in vivo biomechanical energy while undergoing gradual degradation and absorption after task completion. These multilayer architectures establish a foundational paradigm for transient self-powered implants that minimize long-term adverse tissue responses [69]. Building upon this concept, injectable and minimally invasive transient systems further expand clinical applicability. Fully biodegradable, ultrasound-driven injectable TENGs (I-TENGs), fabricated from PLA, Mg, and PCL in a single-electrode configuration, achieve sufficient electric field intensity for localized electrical stimulation while enabling direct needle-based implantation. Such systems underscore how device miniaturization and transient material selection jointly enhance in vivo deployability [70]. At the material–triboelectric interface level, systematic investigations of natural biomaterials have clarified their triboelectric polarity ranking and output behavior, providing rational guidelines for transient TENG material selection. By modifying silk fibroin-based triboelectric layers, device operational lifetimes can be precisely tuned from days to weeks, achieving complete in vivo degradation without residual complications. These studies highlight that triboelectric performance and degradation kinetics can be co-engineered, rather than treated as competing requirements [44]. To enable active, on-demand termination of device function, externally triggered degradation strategies have been introduced. Near-infrared (NIR)-responsive biodegradable implantable TENGs incorporating gold nanorods (AuNRs) allow remote control over degradation behavior. Without optical stimulation, such devices remain functional in vivo for extended periods; upon NIR irradiation, rapid power decay and accelerated material resorption occur, offering unprecedented temporal control over transient implant lifetimes [71]. Complementary approaches exploit ultrasound as both an energy mediator and a degradation trigger. Ultrasound-responsive transient TENGs utilize biodegradable encapsulation layers whose degradation rates dramatically increase under elevated acoustic intensity, enabling demand-driven dissolution after therapeutic action [72]. More advanced designs integrate Bio-MOF-11/PLGA composite triboelectric films, where low-intensity ultrasound supports stable operation, while high-intensity focused ultrasound induces rapid pore formation, liquid infiltration, and oxidation-assisted degradation, culminating in complete device resorption within minutes [73]. Collectively, these studies establish temporary implantable TENGs as task-oriented, self-terminating bioelectronic systems, with degradation behavior engineered as a functional parameter rather than a passive consequence.

For semi-permanent implantable bioelectronic systems, durable safety and encapsulation reliability often outweigh maximal

energy conversion efficiency. Rather than modifying the encapsulation material, one study demonstrated that a fully titanium-encapsulated triboelectric implant could still be effectively powered under clinically safe ultrasound intensities (500 mW cm^{-2}) through capacitive matching and system-level energy management. Despite the intrinsic acoustic attenuation of titanium, sufficient electrical output was generated to drive a battery-free, miniaturized wireless neural stimulator, highlighting that robust neuromodulation can be achieved without energy storage or material substitution when device architecture is appropriately engineered [74]. Building on the limitations imposed by titanium's acoustic impedance, subsequent work pursued impedance-matched material replacement as a complementary strategy. Poly(2-hydroxyethyl methacrylate) (HEMA), a clinically approved and mechanically tunable hydrogel polymer, was introduced to replace the titanium plate and serve simultaneously as a triboelectric layer. Owing to its acoustic impedance being adjustable toward that of biological tissue, the ultrasound transmission coefficient increased by nearly an order of magnitude compared with titanium. As a result, the implantable ultrasound-driven TENG exhibited substantially enhanced power output, charging a $100 \mu\text{F}$ capacitor 3.7 times faster *in vivo*, underscoring the importance of acoustic impedance matching in long-term implanted energy harvesters [75]. Beyond material substitution, device durability and mechanical stability under prolonged ultrasound exposure remain critical for chronic implantation. Addressing this, a reliable implantable ultrasound-driven TENG was developed using polyether ether ketone (PEEK) as the acoustic transmission encapsulation layer. Benefiting from its tissue-matched acoustic impedance and excellent mechanical robustness, PEEK enabled an ultrasound transmission rate of up to 99.94%, in stark contrast to the high reflectivity of titanium. The resulting device sustained stable electrical output for over 300 min, demonstrating that long-term performance can be achieved through encapsulation materials that balance acoustic transparency with structural integrity [76]. More recently, a distinct interfacial engineering strategy was introduced that retains titanium encapsulation while mitigating its acoustic limitations. By incorporating a liquid coupling layer between the titanium shell and the triboelectric membrane, elastic waves generated within the titanium plate were transformed into a more controlled single-mode vibration. The elimination of trapped air gaps enabled efficient elastic-wave transmission to the triboelectric layer, leading to a 310% increase in power density. This architecture supported durability and enabled *in vivo* Bluetooth communication, demonstrating that wave-mode regulation and interfacial coupling can compensate for material-level constraints in chronic implantable TENG systems [43]. Beyond sealed implants, a fundamentally different strategy abandons encapsulation altogether. Bioabsorbable triboelectric scaffolds integrate tissue engineering architectures with TENG functionality, directly coupling biomechanical motion to therapeutic electrical stimulation. Using biodegradable elastomers such as PGS and multiscale porous structures fabricated via 3D printing, these scaffold-based TENGs operate reliably in wet biological environments without waterproof packaging [77]. Subsequent studies extended this concept to regenerative medicine, demonstrating effective bone defect repair and cartilage regeneration, thereby confirming the feasibility of encapsulation-free, tissue-integrated triboelectric systems for long-term implantation [78].

Beyond complete TENG systems, parallel advances in biointegrated materials and functional bioelectronics further enrich the design space of implantable triboelectric platforms. Biodegradable metallic glasses based on Mg, Zn, and Ca alloys exhibit enhanced stretchability, fatigue resistance, and biocompatibility compared to conventional transient metals, offering mechanically robust interconnects for deformable implantable electronics [79]. At the application interface, self-powered bioelectronic sutures leveraging triboelectric principles enable real-time monitoring of suture tension during wound closure, providing surgeons with quantitative feedback to reduce postoperative complications. Such devices illustrate how triboelectric mechanisms can be embedded into clinically familiar forms, enhancing acceptance and translational potential [80]. Innovative electrode architectures based on triboelectric field propagation further reduce electrode density requirements in implantable cardiac monitoring and pacing systems, improving durability and tissue compatibility while minimizing stimulation-induced damage [81]. Humidity-driven shape-morphing materials introduce a novel dimension to biointegration. By exploiting body-fluid-induced swelling, rolled or compact TENG structures can autonomously deploy into functional configurations after catheter-based delivery and subsequently degrade *in situ*. This strategy exemplifies how mechanical adaptability and transient behavior can be synergistically integrated for minimally invasive implantation [82].

6 | Conclusion and Perspective

Triboelectricity has emerged as a versatile and increasingly mature transduction mechanism for implantable bioelectronic systems, enabling direct coupling between mechanical dynamics and electrical functionality within living tissues. By systematically organizing recent advances, this review clarifies how implantable triboelectric devices operate across distinct mechanical excitation sources, functional roles, and implantation timeframes. Differentiating endogenous and exogenous mechanical stimuli provides a unified framework for understanding how triboelectric systems interface with biological environments, while a refined functional classification highlights that implantable triboelectric devices extend well beyond power supply to support *in situ* sensing, signal transmission, and therapeutic intervention. Furthermore, explicitly distinguishing durable implantation from temporary implantation, purpose-driven therapy underscores the importance of aligning device architecture with clinical intent, material stability, and evaluation strategy. Collectively, these perspectives reveal that the performance and translational potential of implantable triboelectric systems are governed not only by materials or electrical output, but by how effectively device design is integrated with anatomical context, functional objectives, and therapeutic timelines. Viewed from a broader perspective, triboelectricity can be regarded as an emerging biointerface-level transduction paradigm, in which mechanical interactions inherent to physiological environments are directly converted into functional electrical cues. Such a paradigm is particularly well suited for future implantable bioelectronic systems that are adaptive, closed-loop, and context-aware, where continuous coupling between tissue dynamics and electronic response is essential. Looking forward, as demonstrated in Figure 7, the continued development of implantable triboelectric

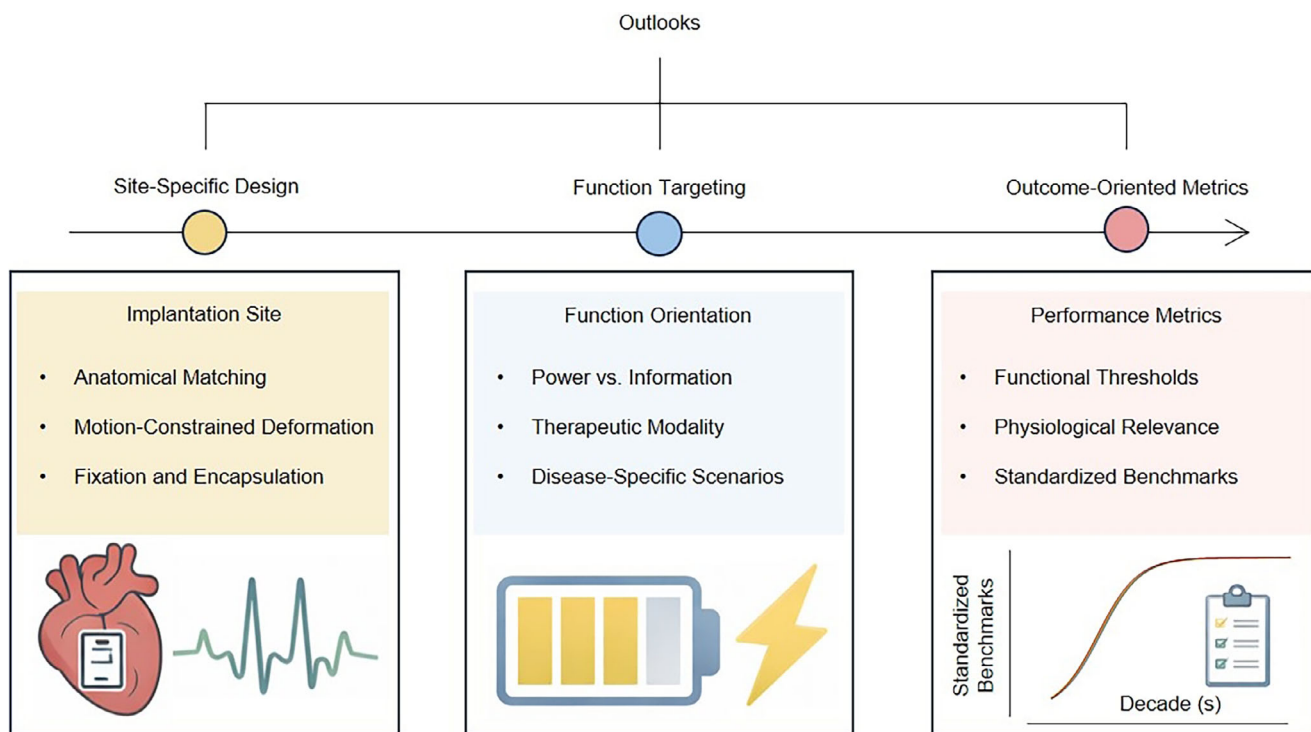


FIGURE 7 | Schematic perspectives highlighting future directions in site-specific device design, function-targeted system integration, and outcome-oriented performance metrics to guide the clinical translation of implantable TENG-based bioelectronic platforms.

bioelectronic systems will benefit from a shift toward three below considerations:

6.1 | 6.1 Site-Specific Design Consideration

Site-specific design paradigms will be foundational to the next generation of implantable triboelectric bioelectronic systems. Rather than adopting generic device architectures, future designs must explicitly align device geometry, mechanical compliance, and deformation modes with the anatomical and biomechanical characteristics of the intended implantation site. Precise anatomical matching can significantly enhance mechanical coupling efficiency, improve signal robustness, and reduce mechanical mismatch-induced attenuation. Moreover, motion-constrained or directionally selective deformation strategies enable devices to preferentially harvest or transduce relevant physiological dynamics—such as cardiac motion, respiratory cycles, or localized tissue displacement—rather than indiscriminately responding to ambient mechanical disturbances [83, 84]. Equally important is the co-design of fixation and encapsulation strategies with implantation sites. Stable anchoring methods must accommodate continuous tissue motion while minimizing stress concentration and inflammatory response. Encapsulation materials and geometries should provide sufficient mechanical protection and biocompatibility without suppressing triboelectric interactions or altering interfacial charge transfer dynamics. Together, these considerations emphasize that site-specific design is not merely a geometric optimization problem, but a system-level integration challenge that links anatomy, mechanics, materials, and triboelectric functionality into a unified design framework.

6.2 | 6.2 Function Targeting Consideration

Beyond anatomical adaptation, implantable triboelectric systems must be anchored to clearly defined functional targets. Moving forward, it will be increasingly important to distinguish between power-oriented and information-oriented operation modes at the earliest stages of device design. Rather than broadly classifying implantable TENGs as energy harvesters, future systems should explicitly define whether their primary role is to supply electrical power, enable self-powered sensing and signal transmission, or actively modulate physiological processes through electrical stimulation. For therapeutic applications in particular, triboelectric-enabled functions should be directly mapped onto specific disease scenarios and clinical intervention strategies [85]. Such functional anchoring allows device architectures, operating frequencies, stimulation waveforms, and implantation strategies to be tailored to concrete therapeutic objectives rather than generalized demonstrations of feasibility [86]. By integrating functional targeting into the design logic, triboelectric systems can evolve from multipurpose prototypes into purpose-driven bioelectronic platforms with clearly delineated clinical roles.

6.3 | 6.3 Outcome-Oriented Metrics Consideration

The evaluation of implantable triboelectric bioelectronic systems must also evolve toward outcome-oriented performance metrics that more accurately reflect physiological relevance and therapeutic efficacy. While conventional electrical output parameters—such as open-circuit voltage, short-circuit current, and power density—remain useful for benchmarking device physics, they are insufficient for assessing *in vivo* functionality or



FIGURE 8 | Outlook of implantable triboelectric platforms for precision bioelectronic therapy. The workflow illustrates the progression from targeted material and device design to integrated multifunctional operation and ultimately clinical outcomes. Key milestones include precision, site-adaptive therapy, autonomous in situ bioelectronic intervention, disease-specific bioelectronic modulation, clinically interpretable performance evaluation, and translation into implantable TENG platforms with real-world therapeutic relevance.

clinical potential. Future studies should prioritize defining functional thresholds required for effective sensing, stimulation, or signal transmission within specific physiological contexts. Establishing disease-relevant benchmarks and adopting standardized evaluation protocols will be critical for enabling meaningful cross-study comparison and long-term reproducibility. Metrics should account for factors such as signal stability under physiological motion, long-term performance degradation, tissue-device interaction dynamics, and functional outcomes at the system level. Importantly, evaluation frameworks aligned with regulatory and translational requirements will facilitate the transition from laboratory demonstrations to clinically viable technologies.

Looking forward, these platforms are expected to transition from device-level innovations to clinically translatable systems. Achieving this transition requires addressing several key challenges, including site-dependent performance variability, long-term operational reliability under physiological conditions, and alignment with clinically meaningful evaluation criteria. By leveraging targeted material and structural design, they can achieve site-adaptive and disease-specific interventions, providing autonomous, in situ modulation of physiological processes. Integration of multiple functionalities enables not only energy harvesting and sensing but also clinically interpretable performance evaluation. If these directions are coherently advanced, implantable triboelectric bioelectronic systems could evolve from isolated functional demonstrations into clinically integrated platforms with clearly defined roles and measurable therapeutic impact. Importantly, rational classification frameworks—such as the differentiation of excitation sources, functional roles, and implantation timeframes proposed in this review—play a critical role in guiding clinical translation and advancing intelligent bioelectronic systems. By aligning device design more closely with anatomical context and intended clinical objectives, triboelectric systems may operate as embedded components of the physiological environment rather than externally imposed energy or sensing units. The establishment of evaluation frameworks grounded in physiological relevance and therapeutic outcomes would further enable meaningful comparison across studies, support regulatory translation, and accelerate the integration of triboelectric platforms into adaptive and context-aware medical technologies. Collectively, such progress would position

triboelectricity as a mature and versatile transduction mechanism within implantable bioelectronics, enabling more adaptive, minimally invasive, and purpose-driven medical technologies (Figure 8).

Author Contributions

Y.H. was responsible for conceptualization, investigation, and original draft writing. C.L. contributed to review and editing. C.L. and X.L. provided project administration, supervision, and funding acquisition.

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Conflicts of Interest

The authors declare no competing interests.

Data Availability Statement

All data needed to evaluate the conclusions in the paper are presented in the paper. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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