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Perspective

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Organoids in motion: biohybrid robotics futures

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1. Introduction

A driving motivation for merging organoids with robotics is to overcome the limitations of each technology alone. Organoid technology has rapidly progressed as a cutting-edge tool to recapitulate organ complexity for research and clinical applications. Yet, organoids in isolation lack the vascular perfusion, mechanical stimuli, and system-level inputs of a living body, which can limit their maturation and long-term functionality. Soft robots, on the other hand, excel at simulating physiological motions and environments—from gentle pumping to peristaltic flows—but lack the cellular metabolism, sensing, and adaptive responses of living tissue.[1] The integration of organoids with soft robots could create biohybrid systems that are greater than the sum of their parts: robots endowed with the functional intelligence of living cells and organoids supported by the dynamic environment and control of robotics.[2] Such biohybrid systems may address unmet needs in medicine—for example, more predictive disease models that respond to drugs and stimuli in real time, smarter drug delivery devices that adapt to patient physiology, and active implants that promote tissue regeneration through living interfaces. In the following sections, we discuss current progress in organoid science and soft robotics, examine strategies for interfacing organoids with robots, highlight application opportunities across biomedicine, outline key technical hurdles, and present a forward-looking vision for the next decade of organoid-integrated biohybrid robotics (Figure 1).

2. Advances in organoid technology and soft robotics

Organoid technology has seen tremendous advances over the past decade, yielding ever more complex and physiologically relevant mini-tissues. From tiny cerebral organoids that model aspects of human brain development, to cardiac organoids (cardioids) that beat spontaneously, to intestinal organoids that form crypt-villus structures, researchers can now generate a spectrum of mini-organs in vitro. This includes advanced techniques, such as realizing engineering large-scale self-mineralizing bone organoids and woven bone organoid formation.[3,4] These organoids capture key features of their in vivo counterparts—for instance, brain organoids exhibit diverse neuron types and network activity and gut organoids form polarized epithelial layers with nutrient absorption and secretion functions.[5,6] Indeed, brain organoids have provided unprecedented insights into neurodevelopment and disease, and they hold promise for drug screening in neurological disorders. Similarly, patient-derived tumor organoids are used to test cancer drugs ex vivo, and liver and kidney organoids model metabolic diseases and toxicity.[7] Efforts are underway to improve organoid maturity and scalability, addressing current limitations. For example, microfluidic and bioreactor systems provide perfusion to support larger organoids with sustained viability, and bioengineering strategies (such as embedding endothelial cells or biomaterial scaffolds) aim to vascularize organoids.[8] Additionally, combining multiple organoids to form "assembloids" is an emerging approach to model interactions between organs (eg, brain-region assembloids or gut–liver axis).[9] These developments reflect an increasing demand for organoids in disease modeling, drug testing, and even as building blocks for future organ replacements. In summary, organoids have evolved into sophisticated in vitro avatars of human organs, yet they typically remain static, lacking the dynamic mechanical and electrical cues of a living organism.

Concurrently, soft robotic systems have matured to become powerful platforms for biomedical interaction. Soft robots are constructed from compliant materials (elastomers, hydrogels, textiles) and employ gentle actuation mechanisms (pneumatic, hydraulic, dielectric, magnetic, etc) that are inherently suited for interfacing with delicate biological tissues.[10] Their flexibility and adaptability enable capabilities ranging from minimally invasive surgical tools to implantable assistive devices. For instance, soft robotic catheters and endoscopes can navigate the body's tortuous pathways for targeted interventions, and implantable soft actuators have been developed to augment organ function (such as a robotic sleeve that assists heart pumping or a diaphragmatic actuator that aids breathing in respiratory failure). A recent example demonstrated an implantable soft robotic ventilator wrapped around a pig's diaphragm to effectively increase inspiratory motion.[11] Advances in stimuli-responsive

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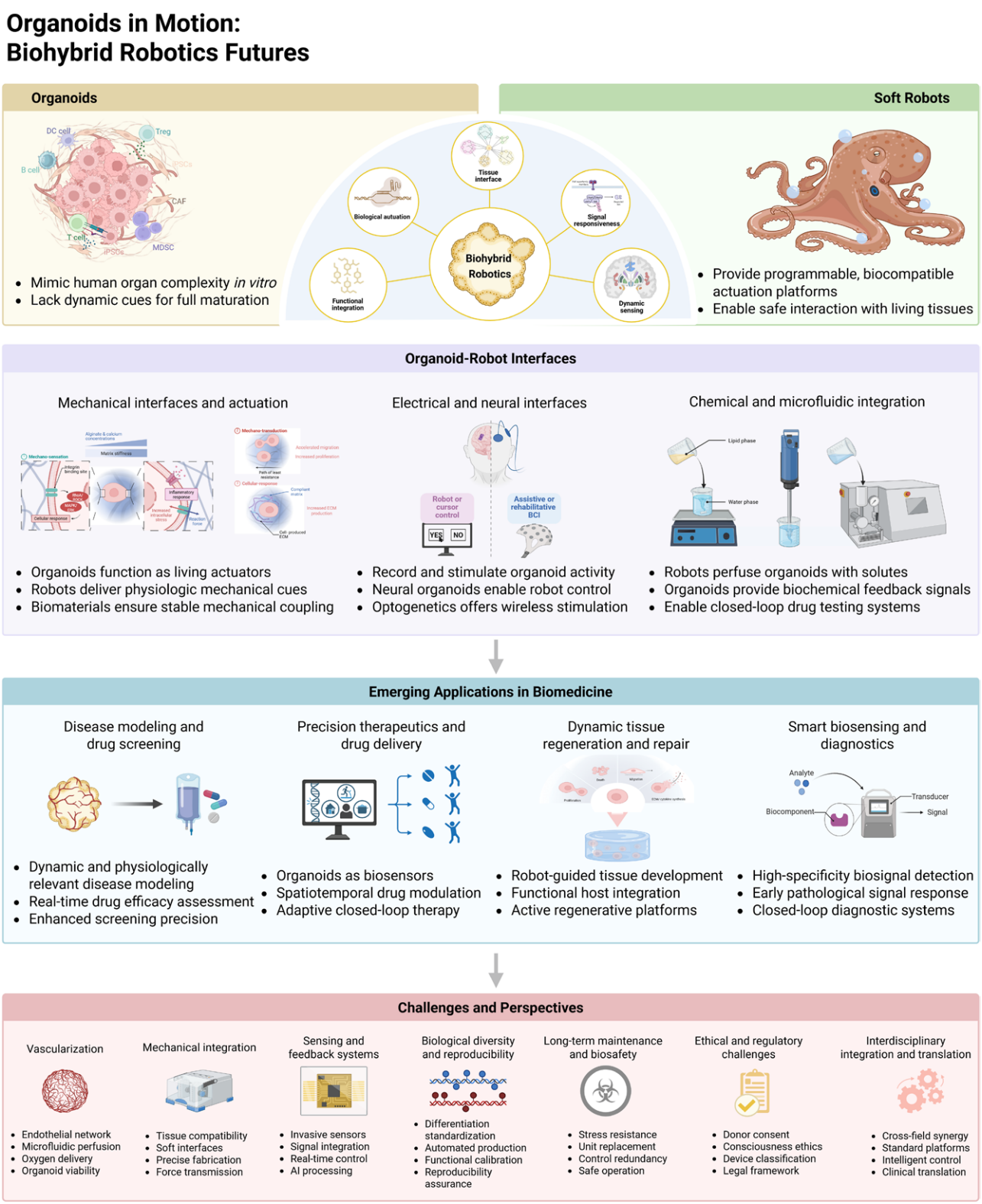

Figure 1. Organoids integrated with soft robots enable dynamic biomedical applications, including disease modeling, drug screening, and tissue regeneration, while addressing challenges in mechanical integration and long-term maintenance (brain–computer interface [BCI]).

materials (eg, shape-memory polymers, liquid crystal elastomers) and additive manufacturing are expanding the design space of soft robots, allowing custom geometries and programmable motions. Importantly, soft robots can operate in close contact with living tissues without causing damage, due to their compliant nature and high biocompatibility. This makes them ideal platforms to integrate with organoids. Moreover, the field of biohybrid robotics has begun to incorporate living cells as actuators or sensors in robots—for example, skeletal muscle strips or cardiac tissues have been used to power small

locomoting devices.[12] These early biohybrid "biobots" showcase the potential synergy: living muscle cells provide efficient, self-healing actuators, while the engineered scaffold provides structure and direction. Notably, one milestone was the development of a biohybrid fish powered by human cardiac muscle cells, which achieved self-propelled swimming by replicating the heart's mechanoelectrical feedback loops.[12] In this system, 2 layers of cardiomyocytes were arranged antagonistically; each contraction stretched the opposite layer, triggering it to contract in turn, producing an autonomous rhythmic motion. An embedded pacemaker-like node maintained the cycle, enabling the fish to swim continuously. This remarkable example, published in *Science* 2022, illustrates how insights from cardiac biology can inform robotic design and result in a self-regulating biohybrid machine.[12] It also hints at broader applications—such a system provides a platform to study cardiac physiology and diseases (like arrhythmias) in a dynamic setting.

Together, these advances in organoid biology and soft robotics set the stage for organoid-integrated robotics. Organoids bring authentic biological function—beating heart tissue, firing neural circuits, and secreting gut epithelium—while soft robots contribute controllable actuation, structural support, and the ability to interact with the physical world. The following sections delve into how these components can be interfaced and harnessed, and what new capabilities emerge as a result.

3. Organoid–robot interfaces: signal integration and actuation strategies

Creating a functional union between organoids and robots requires carefully engineered interfaces that allow 2-way communication: robots must deliver stimuli to organoids and receive signals or actions from them. Several modes of interface are conceivable, including mechanical coupling, electrical and chemical signal integration, and even optical or genetic control pathways. The overarching goal is to achieve seamless coordination such that the organoid and robotic components operate in concert as a single system. Here, we outline key interface and actuation strategies that underpin organoid–robot integration.

3.1 Mechanical interfaces and actuation

One straightforward approach is to use the organoid as a living actuator or mechanical sensor within a soft robot. Contractile organoids, such as cardiac or muscle organoids, can produce forces or motion that a robot can harness. For example, a cardiac organoid attached to an elastic robotic scaffold could generate pumping or locomotion when it beats. Conversely, a soft robot can apply controlled mechanical stimuli to an organoid—such as stretch, compression, or fluid flow—to influence its development or function. A well-known example is the biohybrid fish, in which human cardiomyocytes powered rhythmic swimming by coupling with a compliant fin structure.[12] This system demonstrated a 2-way mechanical feedback loop: the contractions of cardiomyocytes drove the fins, while the elastic tension of the fins paced the cells in return.

In a similar vein, researchers have built biohybrid robots where engineered skeletal muscle strips are anchored to flexible skeletons; when the muscle cells contract (induced by electrical pulses or light in optogenetic cells), the robot bends or crawls forward. The mechanical integration of organoids may involve embedding them in soft matrices or coupling them via connectors to the robot's movable parts. Critical to success is maintaining the organoid's viability and adherence during actuation. The success of such systems depends heavily on preserving organoid viability and stable attachment during actuation. To this end, innovations in biomaterials—such as collagen or fibrin gels—have enabled effective coupling between soft tissues and synthetic frameworks by forming a responsive mechanotransduction interface. Moreover, mechanical interfacing must account for differences in stiffness and strain tolerance: organoids are fragile and typically require gentle forces in physiologic ranges. The use of compliant materials and strain-limiting mechanisms in the robot can ensure that the organoid experiences lifelike mechanical cues without damage. Mechanical loading can also serve as a developmental cue-constant fluid pulsation or cyclic stretch can promote maturation of organoids (for instance, applying anisotropic stretch was shown to induce formation of multichambered, vascularized cardiac organoids mimicking an embryonic heart structure).

However, despite the promising prospects, organ-based actuators also face fundamental challenges. Compared with synthetic motor systems, they usually generate lower force output, have reduced durability, and offer lower control accuracy. Furthermore, biological tissues require continuous support, such as perfusion or nutrient delivery, to maintain vitality, and their functional lifespan is essentially limited by biological aging. From this perspective, the mechanical interface is not merely a driving pipeline. They also play an active role in supporting organoid health and guiding maturation through physiologically related forces.

3.2 Electrical and neural interfaces

Many organoids (especially neural, cardiac, and muscle types) communicate via electrical signals. Integrating these organoids with robots often entails reading and delivering electrical impulses. High-density microelectrode arrays or flexible electronics can be incorporated to record an organoid's electrophysiological activity (such as the spiking of neurons in a brain organoid or the field potential of a cardiac organoid) and to stimulate the organoid electrically to evoke activity. In an organoid–robot control loop, a neural organoid could serve as a biological processor: the organoid receives sensory input from the robot (translated into electrical pulses delivered via electrodes), processes this input in its neuronal circuits, and then outputs signals that are fed back to the robot's actuators. Early demonstrations of this concept are already appearing. In the DishBrain system, a 2D neural culture (a precursor to organoids) was embodied in a simulated game environment, and it was able to learn to play Pong by responding to electrical feedback—essentially functioning as a primitive biological computer.[13] Extending this to 3D brain organoids, one can envision living "brains" controlling robots. Indeed, researchers have reported that brain organoid cultures interfaced with microchips can drive mobile robots, adapting their activity based on feedback from the robot's sensors. A recent open-source platform called MetaBOC has been developed to connect brain organoids to external devices, showing that human neurons grown on chips can receive inputs from and send outputs to robotic systems. These findings highlight that organoid networks are capable of embodied learning and closed-loop control, given appropriate interface hardware and training feedback. Electrical coupling is equally powerful for actuation: for instance, a soft robotic gripper lined with muscle organoids could have embedded electrodes that trigger the organoids to contract on demand, causing the gripper to bend

and hold an object. Alternatively, light-based stimulation can be used if the organoid cells are genetically modified with optogenetic channels—light can penetrate soft tissues and avoid direct electrode contact, offering a wireless mode of control. In sum, electrical interfaces enable organoids to act as controllers and actuators in biohybrid robots, effectively merging biological neural networks with robotic systems in real time.

3.3 Chemical and microfluidic integration

Another interface modality involves the exchange of chemical signals (eg, metabolites, hormones, and neurotransmitters) between organoid and robot. Organoids, by nature, secrete a variety of biochemical factors and respond to their culture milieu. A robot equipped with microfluidic channels can perfuse an organoid with specific solutes (drugs, nutrients, and signaling molecules) under precisely regulated timing and conversely sample the organoid's secreted factors for analysis or feedback control. This type of interface is especially pertinent for metabolic organoids (liver, gut, pancreatic islets) and for drug testing applications. For example, a gastrointestinal organoid integrated in a robotic device could be exposed to varying concentrations of a drug via automated micropumps, while sensors measure the organoid's secreted enzymes or electrical responses, creating a closed-loop drug screening system. There are already organs-on-chips that incorporate human organoids or tissue constructs with flowing media to emulate blood flow and nutrient delivery, some even linking multiple organoid types in sequence to represent a physiological system. Robotic automation has been used to assemble and cultivate organoids on-chip, ensuring reproducible placement and connection of tiny tissue spheroids. In advanced setups, one could imagine a "robotic symbiote" where the robot provides life support to the organoid—continuous perfusion, waste removal, and even immune isolation—similar to a heart–lung machine but on the microscale. The organoid, in return, provides real-time biochemical sensing or production. A concrete illustration is a "robot-on-a-chip" human motor unit developed in 2024, which integrated a brain organoid with a network of motor neuron spheroids and a muscle tissue strip, all on a microfluidic chip.[14] In this device, microfluidic channels supplied nutrients and drugs (like levodopa [L-DOPA] for a Parkinson disease model) to the organoids, while the neurons relayed signals from the brain organoid to activate the muscle, effectively coupling chemical neurotransmission with mechanical actuation in one platform. This exemplifies how fluidic and chemical interfaces can connect organoid and robotic elements into a functional circuit.

3.4 Multimodal signal integration

Ultimately, effective organoid–robot interfaces will likely be multimodal—combining mechanical, electrical, and chemical linkages. Consider the challenge of connecting a cerebral organoid to a soft exoskeleton for neuroprosthetics: one might embed the organoid with electrode arrays (neural interface), enmesh it in a supportive hydrogel scaffold that transmits forces (mechanical interface), and perfuse it with a blood-mimicking fluid (chemical support). The signals flowing across these interfaces can be integrated via onboard electronics and software. Advanced signal processing and artificial intelligence (AI) algorithms can decode complex organoid outputs (eg, deciphering neural spiking patterns or metabolic readouts) and translate them into actionable instructions for the robot's actuators. Conversely, algorithms can determine the optimal stimulation patterns to elicit desired responses from the organoid (training it over time, akin to adaptive control). Achieving seamless integration also requires addressing the time-scale differences between biological responses and robotic control loops—for instance, neurons fire in milliseconds, hormonal changes occur over minutes, and tissue growth/remodeling happens over days. A robust interface will manage this by operating on multiple time scales, perhaps using faster electronic feedback for immediate control and slower chemical modulation for long-term adaptation.

A noteworthy aspect is that the organoid–robot interface need not be purely manmade; biological components can serve as connectors. For example, in the aforementioned human motor circuit chip, endothelial cells (human umbilical vein endothelial cells [HUVECs]) were introduced to promote neurite outgrowth between the brain organoid and muscle, essentially forming a vascularized neural bridge. The endothelial network not only helped sustain the neurons but also guided the integration of neural circuits, improving signal transmission from the organoid to the muscle. Such use of cellular components (vascular cells, glial cells, etc.) as living interfaces might greatly enhance the stability and integration of organoid and robot parts. This blurring of boundaries is intrinsic to biohybrid design—the interface is not a single point of contact but an engineered ecosystem where living and nonliving elements intermix.

In summary, organoid–robot interfaces require a convergence of bioengineering and robotics: flexible electronics, microfluidics, biofabrication, and computational control all come into play. With thoughtful design, it becomes possible to treat organoids as "brains," "hearts," or "guts" of a robotic system, enabling the robot to sense and act biologically. The following section explores concrete application areas where such organoid-integrated robots could be game changers, illustrating the concepts in practice.

4. Emerging applications in biomedicine

The fusion of organoids with soft robotics opens up a rich landscape of applications across biomedicine. In this section, we present in-depth examples spanning disease modeling, precision therapeutics, dynamic tissue regeneration, and smart biosensing. These examples highlight how organoid-integrated robots could function in each domain, leveraging the unique strengths of living organoids to solve pressing challenges.

4.1 Disease modeling and drug screening

Organoid–robot hybrids are reshaping disease modeling by introducing dynamic, physiologically relevant parameters absent in conventional static systems. A compelling example is the motor-system-on-a-chip platform, integrating cortical brain organoids, motor neurons, and contractile muscle tissue on a soft robotic substrate to replicate the neuromuscular axis in Parkinson disease.[14] The system quantifies therapeutic efficacy in real time, evidenced by enhanced muscle contraction following L-DOPA administration, providing patient-specific readouts with high translational value. Beyond neurology, soft robotic platforms enable mechanodynamic modeling of pulmonary or gastrointestinal diseases by mimicking breathing and peristalsis, revealing how physical forces shape pathophysiology and microbial interaction.[1] The addition of mechanical actuation to robotic screening systems augments throughput and precision, advancing phenotype-based drug discovery.

4.2 Precision therapeutics and drug delivery

Integrating organoids as intelligent biosensors within robotic systems enables a new class of therapeutic platforms that sense, decide, and actuate in real time. One envisioned application is a biohybrid artificial pancreas, where a pancreatic islet organoid embedded in a soft implant autonomously secretes insulin in response to glucose levels. In such a system, robotics through controllable actuation or programmable microfluidic channels can fine-tune the rate, timing, and localization of insulin release. This enhances delivery fidelity by reducing overshoot, synchronizing release with physiological demand, and minimizing off-target exposure. Similarly, tumor organoid-laden robotic catheters could preview chemotherapeutic responses intraoperatively. Screen out appropriate drugs using tumor organoids and adjust treatment decisions in real time based on immediate feedback. A soft robotic catheter embedded may be used intraoperatively to test microdoses of chemotherapeutics in real time, offering a personalized prediction of response before systemic administration. Advances in synthetic biology allow engineered organoids to secrete therapeutic agents on demand, while soft robotic components regulate spatial and temporal delivery. Such feedback-controlled systems—for instance, those in which neural organoids monitor electrophysiological activity to detect preseizure patterns, triggering soft robotic components to deliver targeted vagus nerve stimulation—demonstrate the feasibility of living devices for adaptive, closed-loop therapies.

4.3 Dynamic tissue regeneration and repair

Organoid-integrated soft robots offer an active paradigm in regenerative medicine, moving beyond inert scaffolds to devices that modulate the microenvironment during tissue repair. In muscle regeneration, robotic meshes embedded with stem cell–derived muscle organoids apply controlled stretch and stimulation, promoting alignment, fusion, and maturation into contractile tissue. In neuroregeneration, brain organoids coupled with microelectronic interfaces have been shown to integrate structurally and functionally with host circuits upon electrical stimulation, restoring impaired connectivity postinjury.[15] For cardiac repair, organoid-infused soft robotic patches synchronize with the heartbeat and deliver electrical pacing, enhancing functional integration and potentially enabling scarless myocardial regeneration.[16] These systems capitalize on developmental principles, where robotic-imposed geometry and force guide self-organizing organoids to form context-specific architectures.[17]

4.4 Smart biosensing and diagnostics

Organoid–robotic constructs offer unprecedented sensitivity and specificity in biosensing by combining the nuanced biological responsiveness of organoids with the precision of robotic transduction. In vitro, liver organoid robots linked to real-time metabolic sensors provide early toxicity alerts by tracking adenosine triphosphate (ATP) production or enzyme secretion. In vivo, soft wearable robots housing miniaturized immune or neural organoids could detect early cytokine surges or neurotransmitter imbalances, triggering automated therapeutic responses. For environmental surveillance, robotic platforms equipped with multiorganoid arrays (eg, lung, skin, and neural) serve as living detectors for chemical vapors, radiation, or neurotoxins, offering a sophisticated alternative to conventional sensors. These systems not only detect molecular presence but interpret physiological consequences, enabling closed-loop diagnostics and intervention—a foundational shift from static assays to embodied, intelligent monitoring.

From these examples, it is clear that organoid-integrated biosensors offer rich, human-relevant information. They bridge the gap between biochemical sensing and physiological interpretation: rather than just measuring a molecule's presence, they measure the tissue's response to that molecule. When combined with robotics, this becomes actionable information. For instance, detection of a certain stress response in a cardiac organoid sensor might trigger a wearable defibrillator to activate, or sensing a spike in glucose could command an insulin pump. This closes the loop for diagnostic and preventive action. In all application domains discussed—modeling, therapeutics, regeneration, and sensing—organoids act as central players, providing functions traditionally limited to living organisms (learning, metabolism, regeneration, and sensation). Integrated with soft robotics, they give rise to a new class of biohybrid machines that could transform medicine by being more lifelike in function and more personalized in operation.

5. Challenges and perspectives

Realizing organoid-integrated soft robotics demands overcoming a series of complex technical and biological challenges that span vascularization, mechanical integration, sensing-feedback systems, biological variability, and long-term maintenance. Ensuring sustained viability of organoids within robotic platforms necessitates vascularization strategies that integrate endothelial networks and microfluidic circuits to mimic in vivo perfusion and oxygenation. Simultaneously, mechanical compatibility between fragile organoids and actuating soft robotic elements requires compliant interfaces, viscoelastic hydrogels, and spatially precise biofabrication technologies such as RODEO to prevent structural damage and ensure functional transmission. For real-time control, the development of minimally invasive sensing architectures—ranging from optical and chemical sensors to flexible electrophysiology arrays—is vital for capturing organoid states and enabling adaptive robotic responses. These systems must navigate biological signal variability and latency, which differ significantly across organoid types (eg, fast-reacting neural vs. slow endocrine tissues), requiring robust AI-enhanced control frameworks. Variability in organoid morphology and function further complicates reproducibility, demanding standardized differentiation protocols, automated manufacturing, and in situ calibration routines. As organoids inevitably decline in function due to metabolic stress or senescence, strategies such as modular biocartridge replacement, redundancy, or fallback control logic must be implemented to ensure continuity and biosafety. Finally, as organoid-based systems edge toward cognitive or sensory functions, ethical and regulatory concerns surrounding sentience, donor consent, and device classification become increasingly urgent. For instance, the integration of neural organoids into responsive robotic systems raises unresolved questions about the emergence of sentience or moral status. While current models remain far from consciousness, any future scenario involving adaptive or learning behaviors will require careful ethical oversight. Similarly, the use of patient-derived tissues in biohybrid devices calls for robust frameworks ensuring informed consent, privacy protection, and long-term data stewardship. These challenges, while formidable, are active frontiers in interdisciplinary research and will define the roadmap toward clinically viable and ethically responsible biohybrid robotics.

The integration of organoids with biohybrid robotics is poised to revolutionize biomedicine over the next 5 to 10 years, progressing from in vitro demonstrations to clinically relevant platforms. Sophisticated prototypes—such as closed-loop systems where neural organoids control muscle actuation under metabolic input from liver organoids—are expected to validate the functional integration of multiple organoid types within robotic frameworks. Concurrently, standardization and high-precision biofabrication methods, including RODEO droplet platforms and laser-guided assembly, will support scalable production of organoids with defined actuation or sensing properties. The first in vivo applications, such as implantable insulin-secreting pancreatic organoid robots or vascularized neural interfaces, are likely to emerge through advances in perfusable architectures, immune protection strategies, and biodegradable robotic scaffolds. At the control level, AI will increasingly assist in decoding biosignals and optimizing robot–organoid interactions, while organoid intelligence—exemplified by neural tissues capable of learning tasks like Pong—may offer a novel biological computing substrate. These systems will catalyze new theoretical models of embodied intelligence, raising questions about developmental plasticity, computation, and sentience in engineered biological substrates. Ethical and regulatory frameworks will evolve in parallel, particularly for neural organoids approaching cognitive thresholds. Ultimately, interdisciplinary convergence—encompassing tissue engineering, robotics, neuroscience, synthetic biology, and ethics—will define the future of this field, supported by emerging institutional infrastructures and dedicated translational consortia.

In conclusion, the integration of organoids with soft robotics represents a bold and visionary frontier—one that could yield fundamentally new technologies for medicine and beyond. By combining the adaptive, self-organizing capabilities of living tissues with the precision and programmability of machines, we edge closer to creating devices that are not just bioinspired but truly biointegrated. Such devices might one day behave as an extension of the human body, capable of sensing, healing, and interacting in ways that restore or enhance natural function. However, along with this vision come biological and practical problems. Organoids require metabolism, have a limited lifespan, and are affected by functional variability. Ensuring long-term stability requires a powerful support system, such as vascularized stents, real-time monitoring, and modular replacement strategies, to maintain long-term viability and performance. Unlike synthetic components, living tissues can degrade, adapt to unpredictable conditions, or respond slowly to stimuli. All of these must be taken into account in design and control.

Over the next decade, we expect organoid-integrated biohybrid robots to transition from imaginative laboratory demonstrations to early translational applications, setting the stage for a new era of living therapeutic machines. The journey will require overcoming significant challenges and careful ethical navigation, but the potential benefits—finely-tuned disease models, smart implants that respond to the body, regenerating tissues, and intelligent biosensors—herald a transformative impact on biomedical engineering and human health. The convergence of organoids and robotics is more than an integration of 2 technologies; it is the inception of a new class of entities that straddle the boundary of living and synthetic, opening up possibilities as vast as they are exciting.

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Conflicts of interests

The authors declare that they have no conflicts of interest.

Author contributions

L.B.: conceived, organized, and wrote the manuscript. Y.W. and J.L.: organized and wrote the manuscript. P.S. and D.Z.: conceptualization. J.S.: conceptualization, funding acquisition, investigation, project administration, resources, supervision. All authors discussed and approved the final manuscript.

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