Biomedical AI: Evolving from digital to physical and biological intelligence

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Biomedical artificial intelligence (AI) is advancing toward integrated systems that bridge the digital, physical, and biological domains. What emerges from the convergence of these realms? This perspective article outlines the evolution of biomedical AI from digital models trained on vast biomedical datasets, to physically intelligent systems such as surgical robots that interact with and learn from their environments, and further toward biological intelligence that enables direct communication between human brains and AI. We explore how foundation models, physical embodiment, and brain-brain communications open new possibilities in predictive medicine and personalized intervention. These advances point toward a future in which AI not only comprehends biological processes but also actively collaborates with them, ushering in an era of proactive healthcare where diseases can be prevented, lifelong health maintained, and human capabilities enhanced through the convergence of digital, physical, and biological intelligence.

Biomedical artificial intelligence (AI) is undergoing a profound transformation, evolving from data-centric models toward integrated frameworks that bridge the digital, physical, and biological realms. This evolution begins with digital intelligence, built on data-driven feature extraction and deep learning algorithms that form the cornerstone of current AI.[1] It advances into physical intelligence, comprising embodied agents that interact with and learn from their environments, and extends further toward biological intelligence, characterized by seamless interfaces between human brain and AI systems. Rather than developing in isolation, these domains are now merging to create a new form of convergent intelligence that is poised to transform biomedical research and clinical practice. This perspective article explores the evolution of this integration, discussing key technologies, and applications that are driving the fusion of digital, physical, and biological AI (Figure 1).

THE AGE OF DATA INTELLIGENCE

The current AI development is increasingly defined by foundation models, which are pretrained on large-scale datasets through self-supervised learning techniques. These models demonstrate strong adaptability when applied to numerous diverse downstream tasks with minimal or no further training. In the general domain, large language models such as ChatGPT (https://chat.openai.com/) and DeepSeek (https://chat.deepseek.com/) exemplify this trend. In biomedicine, foundation models are rapidly applied to handle the distinctive complexities of biomedical and clinical data. They process multimodal inputs ranging from genomic sequences and molecular structures to medical images and electronic health records, enabling significant progresses in disease diagnosis, personalized treatment planning, and drug discovery.

Notably, large language models demonstrate state-of-the-art performance in processing unstructured texts from electronic health records.[2] By identifying patterns across massive textual datasets, these models can assess disease risk and recommend personalized treatment strategies based on clinically analogous cases. Meanwhile, vision-language models construct a unified representation space where visual and language embeddings are semantically aligned. Pretrained on vast collections of unlabeled images and corresponding text reports, these multimodal models can not only detect abnormalities in pathological images, X-rays, computed tomography (CT), and magnetic resonance imaging (MRI) scans but also classify diverse pathologies, predict patient outcomes, and even establish connections between imaging features and genomic markers for precision diagnosis of various cancer types.[3] In pharmaceutical research, AI-powered platforms are now transforming drug discovery. Based on molecular structure learning and binding affinity predictions, these models efficiently screen virtual compound libraries containing billions of molecules, significantly improving the efficiency of candidate discovery while minimizing dependence on high-throughput experimental screening.[4] By incorporating molecular dynamics simulations with toxicity assessment, researchers can further refine compounds for optimal efficacy and safety profiles prior to chemical synthesis. However, key challenges lie in the generalization ability and the gap between predicted molecular behavior and in-vivo performance. Nonetheless, such AI-aided approaches effectively compress traditional development timelines from several years to months.

However, models of data-centric AI are constrained by their inherent detachment from the physical world. These systems learn from digital datasets the representations that are effective within a purely computational domain but lack engagement with real-world. For example, a vision model may recognize an object in an image yet possess no understanding of how a robot would physically manipulate it. Recently, the field is now shifting toward the development of physical intelligence, where algorithms learn through direct interaction with and feedback from their environments.

THE FRONTIER OF PHYSICAL INTELLIGENCE

Physical intelligence represents a critical advancement in AI, shifting computational systems toward direct engagement with the physical world. This progress is primarily driven by embodied AI, which combines multimodal perception, action control, and task planning to operate effectively in real-world settings. A multimodal perception module aligns and fuses multimodal data from various sensors to construct environmental representations. This representation is continually refined through interactive perception and real-time sensory feedback. Subsequently, an adaptive motor control module translates these perceptual signals into precise physical manipulations. By incorporating vision-language-action models with robotic platforms, embodied intelligence is demonstrating increasing potential for adaptation to complex biomedical environments and clinical scenarios.

Rigid surgical robots represent a primary application of physical intelligence. For example, the RoboBrain project integrates visual and linguistic inputs with motion planning to enable precise instrument navigation and control in minimally invasive surgeries (https://github.com/FlagOpen/RoboBrain-X0). Complementing these rigid systems are soft robotic devices, which employ compliant, bio-inspired actuation mechanisms to achieve safe physical interactions with delicate biological tissues.[5] Such devices are particularly suited for endoscopic procedures and other manipulations where minimizing mechanical trauma is critical. Physical intelligence is also changing biomedical sensing and health monitoring. Advanced research is progressing in flexible, multimodal sensor systems, allowing for continuous tracking of multiple physiological modalities, including bioelectrical, biochemical, and biomechanical signals.[6] These devices leverage embedded AI not only to process complex data streams at the source but also to adaptively adjust sensing parameters in response to the user's state, enabling early anomaly detection and personalized monitoring in managing chronic diseases. Beyond clinical applications, physical intelligence also contributes to biological and biochemical automation.

Current embodied intelligence systems face several persistent limitations.

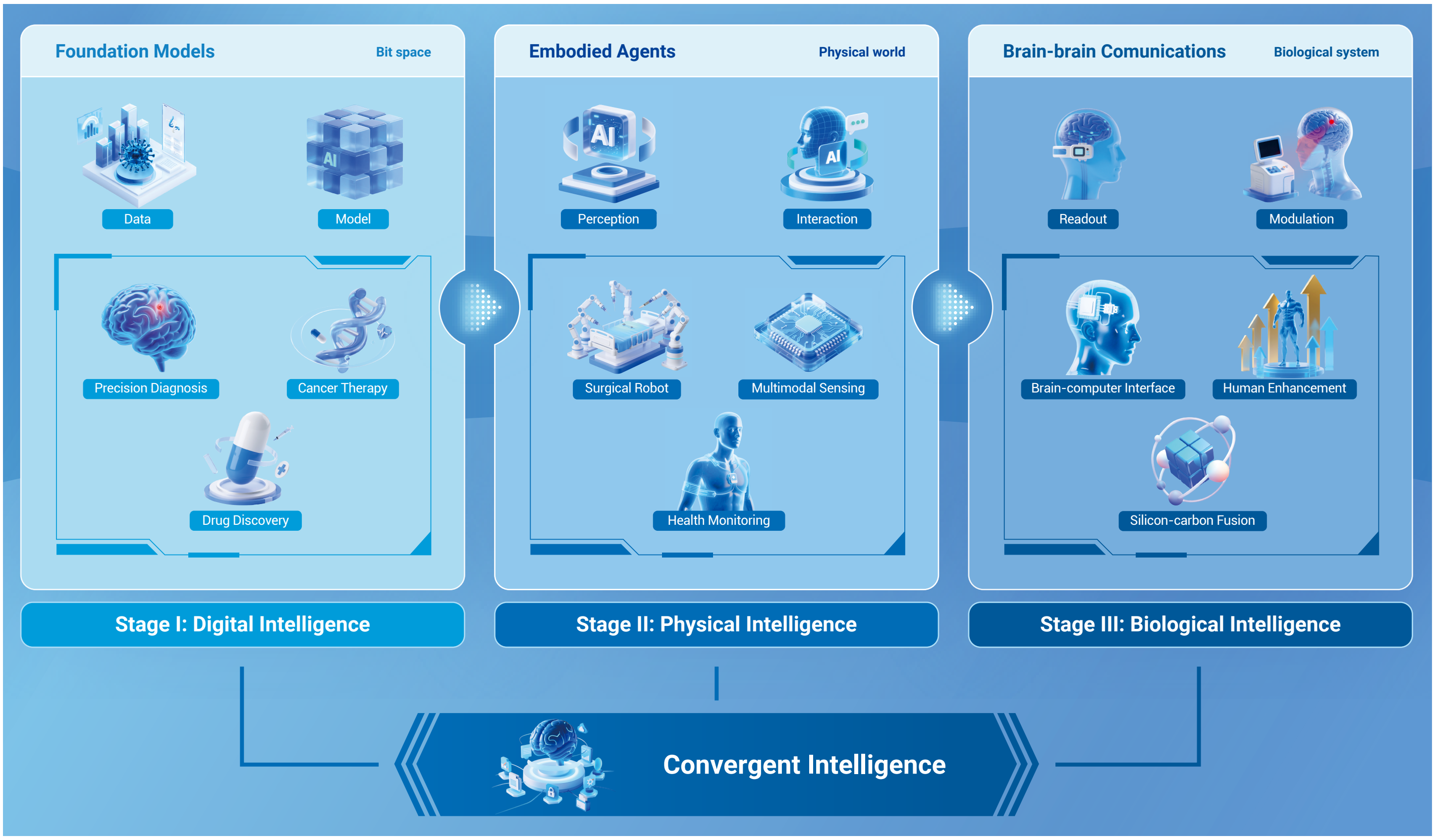

Figure 1. The evolution of biomedical AI from digital to physical and biological intelligence.

Most existing frameworks are designed for isolated subfunctions. For example, surgical robotics can perform precise operational tasks and monitor physiological parameters effectively, yet they still lack the cognitive autonomy needed to interpret nuanced anatomical variations or make real-time surgical decisions. Furthermore, training data rely heavily on visual or linguistic inputs, with limited incorporation of tactile, auditory, or other sensory modalities -a gap that constrains their adaptability in real-world clinical environments. Research directions include integrating high-density tactile arrays with force/torque sensing, deploying acoustic scene analysis, and developing multimodal benchmarks such as MultiPLY (https://github.com/UMass-Embodied-AGI/MultiPLY). Research should focus on the fusion with living biological tissues, especially neural systems, to support safe long-term implantation and brain-machine cooperation, which involves challenges such as reliable biocompatibility and bio-electronic interfaces.

THE HORIZEN OF BIOLOGICAL INTELLIGENCE

Biological intelligence represents the next frontier for biomedical AI, moving beyond conventional brain-computer interfaces (BCIs) to establish bidirectional partnerships between neural and artificial systems. This stage is defined by AI frameworks that dynamically connect and adapt to neural circuitry, surpassing the capabilities of simple read-only interfaces or passive stimulation. Here biological intelligence is distinguished from conventional BCIs by several key criteria, including bidirectional information flow between neural tissue and artificial systems, real-time adaptation to neural dynamics, and co-learning across neural and artificial substrates. It signifies the convergence of bits, atoms, and molecules that bridges the domains of silicon-based and carbon-based systems. Biological intelligence establishes new pathways that aim not only to enhance therapeutic efficacy but also to augment human cognitive and physiological capabilities, thereby paving the way for the next evolution of medicine and human potential.

The realization of biological intelligence may require direct brain-brain communication, a goal that depends on establishing bidirectional, high-bandwidth information exchange between human neural networks and computer system. Currently, invasive BCIs provide high-resolution neural decoding at the cost of surgical risk, while non-invasive approaches remain limited by poor signal resolution. A critical direction is therefore the coordinated development of non-invasive brain reading, precise neuromodulation, and possible writing technologies.[7] AI models for non-invasive brain activity readout are now able to reconstruct high-level cognitive states such as perception, intention, and semantic content into pictures or texts from functional neuroimaging data. Meanwhile, emerging technologies including functional MRI and non-invasive functional ultrasound imaging are granting access to previously unobservable neural activity across multiple scales, from single neurons to entire brain networks. These methods collectively transform neural dynamics into interpretable data, thereby creating a window into brain function in non-invasive manners.

In precise neural modulation, AI acts as the decision-making core, powering adaptive models that continuously optimize stimulation strategies using live neural feedback. As one promising approach, AI-guided ultrasonic neuromodulation leverages acoustic radiation force to selectively target specific ion channels. This technique is being progressively refined through miniaturized hardware such as flexible acoustic metasurfaces, which enable full spatial control of acoustic fields.[8] The combination of these reading, modulating, and possible writing capabilities establishes a foundation for non-invasive brain-brain communication. It thereby heralds a new phase in biological intelligence, poised to expand the frontiers of human cognition and collaboration.

Several key technical risks must be overcome, such as inadequate spatiotemporal resolution and data bandwidth, limited cross-subject generalization for both AI models and modulation protocols, and system latency that currently acts as a barrier to real-time communications.

TOWARDS A CONVERGENT FUTURE OF BIOMEDICAL AI

The most exciting potential of biomedical AI lies at the convergence of data, physical, and biological intelligence. Together, they establish a cohesive framework capable of both interpreting and modulating human biological processes. At the interfaces of these domains, novel capabilities are emerging: embodied systems that built upon large-scale datasets to interact with their environments; neural interfaces that facilitate collaboration between artificial and cognitive systems; and therapeutic platforms that translate diagnostic signals into personalized treatments. This may potentially redefine the boundaries of human health and capability. The progression involves an algorithmic shift from transformer-based foundation models to embodied models learn through continuous feedback loops with the physical environment, and towards neuromorphic computing and advanced deep learning enabling real-time interaction with neurobiological signals.

Several key trends are likely to shape this convergent future. A central direction is multi-scale data fusion, in which molecular, cellular, physiological, and behavioral data are combined with physical interactions and neural activity streams to build digital twins of biological systems.[9] Another key trend involves the advancement of convergent AI that continuously monitor physiological status, predict health trajectories, and deliver precisely targeted interventions via physical interfaces.[10] Further ahead, the maturation of brain-brain communication could enable collective neuro-intelligence networks, linking multiple individuals with AI agents to open new possibilities in collaborative problem-solving and creative expression.

It also raises important ethical considerations regarding neural privacy, personal integrity, and human agency through concrete technical and procedural measures. Key measures include implementing data minimization and on-device processing, establishing consent with revocable authorization and incorporating human-in-the-loop oversight with pre-specified stopping rules.

The vision for biomedical AI centers on integrating physical principles and biological mechanism with AI models. These next-generation agents may eventually decode biological processes across multiple scales, from molecular to organs. Through continued scientific advancement, we could move closer to an era in which diseases might be prevented, health maintained throughout life, and the aging process more intelligently guided, potentially ushering in a new paradigm of predictive, personalized, and proactive healthcare.

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AUTHOR CONTRIBUTIONS

H.Z. conceptualized and supervised this work. Z.-C.L. and H.Z. drafted the manuscript and created figures. W.Q. and D.L. reviewed and edited the manuscript. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

Hairong Zheng is the Editor-in-Chief of The Innovation Informatics and was blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of this member and their research group. The other authors declare no conflicts of interest.