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Digital twins in ophthalmology: Concepts, applications, and challenges

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Recent advances in digital technologies have unlocked unprecedented opportunities for high-fidelity simulations of complex biological systems.[1] Digital twins (DTs), which are dynamic digital replicas of physical entities, that mirror their behavior in real time, are poised to revolutionize medicine by enabling predictive modeling of disease progression and personalized interventions.[2] The eye, with its unique anatomical and physiological features such as optical transparency, immune privilege, and accessibility to non-invasive high-resolution imaging, emerges as an ideal frontier for DT innovation. As research in ophthalmic DTs accelerates, an understanding of their foundational principles, clinical applications, and unresolved challenges is urgently needed (Fig. 1).

Core components of ophthalmic digital twins

The development of DTs relies on three key components: data, devices, and modeling. Multimodal datasets integrating molecular profiles, imaging (e.g., fundus photography, optical coherence tomography), physiological metrics (e.g., intraocular pressure), and patient outcomes form the cornerstone of accurate simulations. Advanced Internet of Things (IoT)-enabled devices, including wearable sensors and next-generation imaging systems, facilitate continuous, real-time data capture. In computational modeling techniques, mechanistic models such as biomechanical and fluid dynamic models provide trustworthy simulating backbones, and artificial intelligence models such as deep neural networks, diffusion models, and large language models (LLMs) integrate individual heterogeneity and conduct clinical reasoning, which collectively enable the continuous predictive, patient-specific simulations.[3]

Preliminary efforts in ophthalmology

Although DTs have become important tools for advancing precision medicine in fields like cardiology and neurology,[2] their application in ophthalmology remains in early stages. Existing studies do not constitute full DT systems but offer useful insights and building blocks for future progress. For example, in patient care, a DT framework for glaucoma has been conceptualized, enabling real-time data processing to deliver actionable insights for both patients and specialists, thereby allowing for the ongoing refinement of treatment strategies to maintain stable intraocular pressure.[4] Virtual simulations of ophthalmic surgeries may incorporate DTs that reflect individual anatomical and physiological variations, enhancing surgical planning and training for procedures such as cataract extraction.[5] Additionally, it can function as a digital replica of practitioners or patients through role-playing, providing interactive responses to medical inquiries and immersive consultation training for students.[6] In research, a 3D modeling method has been developed to generate personalized eye shapes based on changes in fundus images, refractive errors, and axial lengths, offering new possibilities for trustworthy individualized myopia management.[7] Another study developed a virtual simulation of dynamic fundus fluorescein angiography, replicating vascular lesion changes without the need for contrast dye injection.[8] These advancements demonstrate how DTs provide a powerful platform for exploring disease mechanisms, optimizing examination and treatment strategies.

Persisting challenges and pathways forward

Despite this promise, critical barriers must be addressed: 1. Data limitations: Current models often rely on static, fragmented datasets. Longitudinal, multi-omics data streams enhanced by wearable biosensors (e.g., smart contact lenses) and generative AI for synthetic data augmentation are essential to capture disease dynamics. 2. Computational demands: Interpretable high-fidelity simulations require the integration of AI and mechanistic models. The rule-based parts provide essential restriction boundaries, and the data-driven parts perform elaborate fitting. The immense processing power gap can be relieved by innovations such as Mixture of Experts (MoE) and liquid neural networks. 3. Independence and interactivity: Ideal DTs can stably represent the dynamics similar to real entities and interact with various outer condition settings. Mechanistic models based on rules ensure stable simulations, while LLMs and AI agents translate contextual information to the system and allow easy access for clinical use. 4. Ethical and clinical validation: Algorithmic biases, if unaddressed, may exacerbate disparities in care. Rigorous validation against diverse populations, transparent model interpretability, and adherence to regulatory standards are imperative before clinical deployment.

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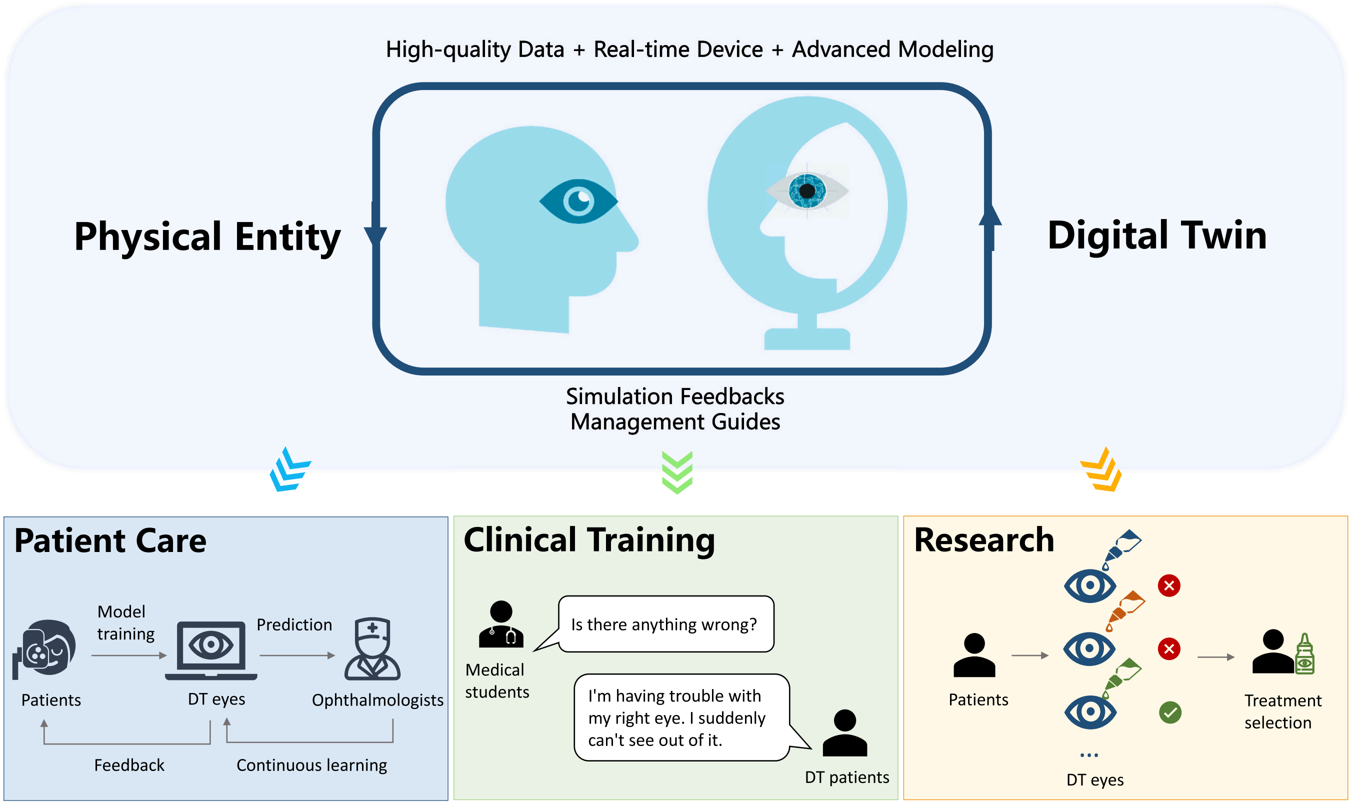

Fig. 1. Framework and applications of digital twins (DTs) in ophthalmology. DTs are virtual representations of physical entities, built using high-quality data, real-time monitoring, and advanced modeling techniques. In ophthalmology, DTs enable clinically meaningful simulations and decision support, with applications spanning patient care, clinical training, and research.

In summary, DTs in ophthalmology represent a transformative innovation for personalized eye care, redefining clinical training and advancing research. However, their ethical and equitable implementation requires collaborative frameworks that bring together ophthalmologists, data scientists, and policymakers. By emphasizing high-quality multimodal data collection, computational efficiency, and inclusive design, the field can leverage DTs to deepen our understanding of ocular health and disease—one digital twin at a time.

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Disclosure

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