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**· 述评 ·**

# 建立光-力-生物耦合新理论

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**摘要**：人眼视觉以光学为基础，是生物体对光学成像的感知与响应系统。近年来研究表明，力学通过调控眼球结构与材料属性，可以直接影响光学成像质量，是影响视觉功能的重要物理因素之一。然而，人眼本质上是生物组织，是具有主动生物反馈能力的生命结构，其光学与力学的作用过程并非纯粹的物理现象，而是伴随器官、组织甚至细胞等层面的多层次生物响应。基于光学、力学与生物反应三者之间存在耦合作用，本文提出光-力-生物（optics-mechanics-biology, OMB）耦合理论框架，系统探究光刺激、力学响应与生物组织作用形成多尺度反馈系统发挥最终效应。代表性疾病如圆锥角膜、青光眼的发展过程均体现光、力与生物耦合的作用。OMB 理论框架有望为阐明眼部疾病的发生发展机制、提高诊疗效能，以及推动基础研究与精准医学发展等提供新思路。

**关键词**：视觉；光学；力学；生物组织；耦合效应；光-力-生物耦合
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# Establishing a Novel Optics-Mechanics-Biology Coupling Theory

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**Abstract**: Human vision is fundamentally rooted in optics, and it is a biological system that perceives and responds to optical imaging. Recent studies have shown that mechanics can also directly influence optical image quality and is therefore one of the key physical determinants of visual function by regulating ocular structure and material properties. However, the eye is inherently a biological tissue and a living structure with active feedback capacity. The optical and mechanical processes it undergoes are not purely physical phenomena but are accompanied by multi-level biological responses at the organ, tissue, and even cellular scales. Built on coupling among optics, mechanics, and biological reactions, this study proposes an optics-mechanics-biology (OMB) coupling framework, in which optical stimuli, mechanical responses, and tissue-level biological processes form a multiscale closed-loop feedback system that produces the final functional outcome. Representative diseases such as keratoconus and glaucoma exemplify the role of this OMB coupling during disease development and progression. The OMB framework is expected to offer new perspectives for elucidating the onset and evolution of ocular diseases, enhancing diagnostic and therapeutic efficacy, and promoting basic research and precision medicine.

**Key words**: vision; optics; mechanics; biological tissues; coupling effects; optics-mechanics-biology (OMB)

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传统视角下,眼球常被简化为由前节屈光系统、视网膜光感受器和眼球壁支撑结构组成的光学成像装置。然而,真实的眼球在生长与发育过程中,经历持续力学作用驱动的形态与结构重塑;同时,还伴随光学刺激、神经调控、局部应力与几何约束等多种物理与生化信号的协同影响[1-2]。当前对于眼病的认识多停留在单一层面:光学强调曲率、折射率、散射与像差等变化[3],力学聚焦弹性、黏弹性、滞后性等特性[4],而生物学则关注器官形态、组织重塑及细胞骨架-细胞外基质(extracellular matrix, ECM)相互作用等从宏观到微观的过程[5-6]。相应地,对疾病的描述也是如此。例如,屈光不正更多聚焦单纯的屈光系统及介质特性[7];青光眼多围绕眼压与相关机械损伤[8];视网膜病变则主要关注出血、缺血及神经改变等[9]。然而,实际上眼球是高度复杂、具有主动调控能力的生物系统,其功能不仅涵盖单一的光学、单一的力学、单一的生物组织细胞反应,更关键的是这些因素之间存在广泛的相互作用。这些相互作用又受光与力、力与生物组织及各因素之间耦合作用的影响,最终产生新的综合效应。基于此,本文提出光-力-生物(optics-mechanics-biology, OMB)耦合理论框架,系统探究光刺激、力学响应与生物组织作用形成多尺度反馈系统发挥最终效应。

## 1　光学在 OMB 理论中的作用:从成像质量到组织重塑

在经典光学成像中,眼球常被视作由角膜与晶状体构成的屈光系统,将外界光线精准聚焦到视网膜。然而,基于从 OMB 耦合的视角,光学的功能远不止于成像。首先,眼球的几何形态与折射率分布直接影响光线在眼内的成像轨迹、焦点位置和能量分布[10]。反过来,眼球通过将成像质量(像差、离焦信号等)反馈至生物通路调节眼球重塑,例如远视性离焦促进眼轴延长、近视性离焦抑制眼轴生长,这一机制已经在动物实验和临床研究中得到反复验证[11-12]。光照周期和昼夜节律亦参与调控眼内代谢(如多巴胺、褪黑素水平),对眼轴控制、视网膜神经元存活产生重要影响[14]。由此可见,光学效应不仅是实现成像功能的物理过程,更是一种持续而精细的信息刺激,通过复杂的生物网络被转译为组织重塑与力学调控的指令。

光学并不只是简单的成像,通过提供可测量的物理量包括相位、频移、偏振态等,使眼组织力学从只能靠接触测试或离体检测变成了可活体检测的评估手段。相位敏感光学相干断层成像(optical coherence tomography, OCT)能把微小位移、波传播速度等检测出来,再采用波动理论、逆问题反演剪切模量、黏弹性参数[15];Brillouin 显微镜利用光谱测量把局部力学刚度信息编码到频移上,获取组织的纵向模量[16];基于应力-光学定律通过将偏振延迟与应力差联系起来,从而利用偏振光学量评估应力分布[17]。此外,偏振敏感光学相干断层成像(polarization sensitive optical coherence tomography, PS-OCT)给出双折射相关参数与光轴取向,用于推断胶原纤维取向,为各向异性本构模型提供理论基础[18]。

## 2　力学在 OMB 理论中的作用:从物理负荷到多尺度力学调控

眼球所处的整体力学环境由眼压、房水、外部机械负荷(如揉眼、手术牵拉、眼外肌张力)以及眼眶形状、眼球壁与视神经头的几何形态等多因素决定,共同塑造了眼球内高度异质的应力-应变分布场[19-20]。在这一背景下,组织弹性、黏弹性、滞后性、应力分布等直接决定眼球在生长、发育及视觉活动中的模式[21]。宏观受力会影响局部微环境的应力、应变分布,进而调控细胞、分子力生物学通路,改变 ECM 重塑状态,而 ECM 重塑又会改变组织材料参数,最终反馈到宏观形态与光学结局,形成跨尺度的调控。例如,巩膜和角膜在眼压、房水及眼球壁等的作用下,会改变眼轴长度和角膜曲率,并反馈影响光学成像质量[22]。本研究团队借助有限元建模分析,在视觉矫正中,力学不仅直接影响矫正效果[23],也会直接影响视觉中的高阶像差[24]。同时,这些力学变化也会通过改变前节光学界面的形态与稳定性,最终重构视网膜上的光学能量与像差分布,改变光感受器和视网膜神经网络接收的刺激模式。

长期的光刺激及其诱发的代谢负荷、氧化应激与炎症,会促使局部组织刚度下降,在相同眼压下产生更大的形变,这在圆锥角膜的局灶软化与向外

锥状突起、近视巩膜变薄与眼轴延长中均有体现[25-26]。临床上,角巩膜交联术通过提高局部组织力学性能,改变其抵抗变形的能力,进而改变眼球的屈光状态,实现干预角巩膜扩张性疾病的目的[27]。本研究团队应用光-力耦合理论,通过采用双光子飞秒激光技术实施角膜交联手术,在提升角膜硬度的同时实现了交联范围的精确控制[28-29]。力学不仅是眼球结构的物理基础,更是连接光学与生物响应、实现耦合调控的关键环节,为精准视觉矫正和疾病干预提供了重要的理论与方法依据。

## 3　生物学在 OMB 理论中的作用:光-力信息的主动响应核心与耦合的载体

眼球作为复杂生物组织,光学和力学作用过程通常伴随细胞、组织乃至器官层面的生物学响应。更重要的是,作为生命活体组织,眼球具有显著的可塑性,即细胞、基质与组织并非被动承受光学与力学刺激,而是依赖复杂的信号网络对这些刺激进行主动感知、响应与反馈,从而驱动组织结构、材料属性与功能状态的动态重塑。因此,生物学是构成光-力耦合效应的核心执行层,是载体的同时也是决定眼球健康与疾病发展的关键之一。

在近视发展过程中,巩膜成纤维细胞通过调控 ECM 状态,导致巩膜重塑[30];圆锥角膜的发病则与角膜基质细胞的氧化应激高敏感性、胶原交联减少、纤维间距增加密切相关,共同促进锥形前凸[31-32];青光眼中,筛板细胞的力学敏感性改变、炎症激活与 ECM 异常沉积,改变了视神经头的力学承载模式[33];而在视网膜退行性疾病中,则体现为光致代谢-炎症长期失衡带来的结构破坏[34]。这些实例表明,生物组织并非光学与力学刺激的被动承受者,同时还是主动感知外界信号、动态调控组织响应与重塑过程的核心。

## 4　总结

综上所述,OMB 理论将光学刺激-力学响应-生物学重塑整合为一个耦合系统,不仅为理解近视、圆锥角膜、青光眼及视网膜退行性疾病等复杂眼病提供了新的机制框架,也为基于耦合理论的新型干预策略奠定了理论基础。OMB 耦合理论框架强调,单一光学或力学指标难以全面反映并影响眼球状态,提示临床与科研工作需从传统的单域观察转向多域协同,从经验性现象解释迈向考虑多因素作用的机制驱动,进而建立更精准的预测模型,达到更精准的诊断与治疗,并在理论构建、实验验证与临床应用中持续推进多模态、多维度融合。

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