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Perspective

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Wearable health devices for pediatric ophthalmology

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The shortage of pediatric ophthalmologists presents an opportunity to leverage existing tools and re-imagine care delivery to support this patient population. By directly interfacing with the eye, wearable health devices provide a localized and potentially more accurate assessment of certain eye conditions. In addition to early detection, wearable health-based devices (wearables) can enable data collection over time and serve as adjuvant treatment to the standard clinic- or surgical-based solutions. We highlight some innovations in wearables targeted for common categories of pediatric eye disease: refractive errors, strabismus, dry eye disease, and glaucoma. In addition to integrating preventive medicine with ophthalmology, wearables generate data that can be funneled into addressing research questions and refining device development.

Wearables represent a broader shift in healthcare towards preventive medicine, specifically P4 medicine (personalized, preventative, participatory, and predictive), with the ultimate goal of earlier disease prediction[1]. Ophthalmology is among the many specialties to recently apply a P4 lens to care delivery. However, pediatric ophthalmology cannot be as inherently participatory compared to its adult counterpart. By re-imagining care delivery in pediatric ophthalmology with wearables, a P4 lens can be applied to the care of children with eye disease. Among digital medicine tools, wearables are particularly relevant as they directly interface with the eye to provide a localized, potentially more accurate assessment of conditions. In this perspective, we describe the need for integrating wearables into pediatric ophthalmic care and highlight some existing innovations in diagnosis and management.

Current challenges

The shortage of pediatric ophthalmologists in the United States widens with each passing year. The COVID-19 pandemic was a major disrupter, and since 2020, pediatric ophthalmology has remained understaffed and underfunded[2]. As of 2024, 90% of US counties lack pediatric ophthalmologists, with four states having none[3]. Exacerbating these disparities, pediatric patients are more vulnerable to loss to follow-up for ophthalmic care[4]. Due to the shortage of pediatric ophthalmologists, many children may not be seen at the correct interval or by an appropriate provider. In response, the American Academy of Ophthalmology urged Congress to increase the Pediatric Specialty Loan Repayment Program by 30 million in fiscal year 2025. While these efforts aim for long-term change in the pediatric ophthalmology landscape, the roll-out of innovations, especially wearable, is crucial. Those devices can reduce the burden on specialists by identifying the subset of children who especially need to be seen by a pediatric ophthalmologist versus those who can be appropriately treated by another provider. Care delivery could even be altered such that some patients can be seen remotely by an ophthalmologist. Since certain wearables can be used at home after instruction to parents, they can be applied as adjuvant treatments to clinic- or surgical-based solutions.

Alongside treating patients, wearables can refine diagnosis methods considering fluctuations of parameters during a pediatric appointment. Conduction of the eye exam significantly differs between adults and children. Since children tend to fidget, precisely capturing intraocular pressure measurement, retina visualization, and eye movements can be challenging. Accuracy is an aspiration, and the eye's size limits the margin for error. Capturing intraocular pressure, visual acuity, visual fields, eye movements, slit lamp findings is critical in therapeutic decision-making, yet many factors fluctuate in the span of a visit. For example, a child crying during intraocular pressure measurement may have a markedly elevated, overestimated recording. Similarly, a new clinical environment may stimulate greater wandering and fixation deficits, suggesting an increased degree of eye muscle misalignment than actuality.

Going beyond the clinic

To expand available data points, the pediatric ophthalmic exam discreetly starts from the waiting room, observing gaze, fixation, and interactivity, all while simultaneously building trust to hopefully achieve compliance in the exam chair[5–7]. By extension, data collection should begin even before the appointment and at home. Wearables facilitate data collection over time, enabling more accurate diagnosis and tailored treatment plans when integrated with routine clinical care[8]. Implementation of these devices would be useful for any child, but especially those with diseases requiring close, frequent monitoring, such as glaucoma, strabismus, amblyopia, and significant

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refractive errors[9,10]. Wearables encompass smart device sensors and headsets[11,12]. The plethora of collected data can subsequently be channeled into creating digital phenotypes, which synthesize an individual's interaction with technology into unique behavioral and biological profiles[13]. Wearables provide the unique opportunity to track and monitor biomarkers that can aid in diagnosis[14]. Other modes of diagnosis are not as reliable in children, such as questionnaires and interviews[15]. Having underlined the utility of wearable health devices, we highlight some innovations in wearables development for common pediatric ocular diseases. Across the wearable, the fundamental sensing will be eye tracking, such as fixation and saccades, with alterations based on unique additional aspects of the disease.

Refractive errors

The most common condition encountered in pediatric ophthalmology is refractive errors, traced to abnormalities in the shape of the cornea and/or lens[16]. Young children may not be able to express difficulties seeing, and such deficits may only manifest as gaze issues and irritability. Children who are non-verbal may not be able to respond to the phoropter, a device that presents different lens options to patients who then express which depicts the clearer image. Children who are too young may have trouble fixating on the autorefractor, which is a machine that measures the refractor error of the eyes. Bypassing these issues encountered at a visit, VisionFit® (www.optazoom.com/public/index.php/products/visionfit-sc-mobile-wireless-adaptive-optics-refraction-system-visionfit-sc-78603) and Clouclip (www.clouclip.com) are portable wearable refraction systems that measure refractive errors at distance, near, and with different gaze positions in children[17,18]. These devices have been used in clinic settings and could be implemented in settings without ophthalmologists or optometrists to remotely determine a refraction prescription[19]. Once a prescription is obtained, selecting glasses or contacts is the next decision point. Dual-focus soft contact lenses are more effective than single-vision lenses in slowing the progression of myopia, otherwise known as nearsightedness. MiSight® (www.misight.com) is a commercially available, dual-focus contact lens that has demonstrated a significant decrease in refractive prescription[20,21]. If glasses are preferred, Adspecs (www.engineeringforchange.org/solutions/product/adspecs/) adjustable-focus glasses have been tested in children, who were taught to self-refract and adjust the lenses at various distances. The accuracy of self-refraction by children was comparable to professional refraction in one study[22]. Though fully-automated glasses are not commercially available yet for children, many recent technological innovations are on this trajectory to enhance vision correction.

Strabismus

Strabismus is the misalignment of the eyes due to under-activation or over-activation of eye muscles. Vision development occurs throughout childhood and slows down around 6 to 9 years of age. Therefore, if not fixed in a timely manner, strabismus can lead to vision loss, known as amblyopia[23]. Interventions include strabismus surgery and non-surgical interventions (patching, dilating eye drops, blurring glasses) to help re-establish binocular vision.

Virtual reality (VR) experiences enable eye-tracking and vision re-training for near versus distance accommodation[24]. Luminopia® (www.luminopia.com) is an FDA-approved prescription therapy for patients with concern for amblyopia that entails a wearable VR headset streaming television shows to maintain proper eye alignment[25]. After 12 weeks of treatment (one hour a day, six days a week), there was a statistically significant improvement in baseline visual acuity of 62%[26]. CureSight™ (www.nova-sight.com/curesight-amblyopia-treatment/) is another available VR headset used to treat ambylopia. Both Luminopia® and CureSight™ are deemed to be cost-effective when considering gains in visual acuity during such a crucial vision developmental period[27]. In real-time, adherence can be monitored with alterations to the treatment itself. Beyond treatment, these VR headsets can also be applied to strabismus screening and diagnosis. In one study, pupil tracking over time with a wearable virtual reality headset estimated the angle of deviation comparable to measurements by doctors[20]. Piloted in children with strabismus, eye movement data from a wearable eye-tracking device was interpreted by an artificial intelligence-based algorithm to determine the severity of strabismus and referral for further intervention[28]. Pivothead® (www.pivotvision.com) are glasses equipped with a camera, enabling ophthalmologists to perform and record strabismus evaluations hands-free and in real-time, capturing angle measurement and ocular motility.

Dry eye disease

Though the name may suggest innocuity, dry eye disease is the leading cause of eye pain, resulting from an imbalance of tear production and lubrication of the cornea. The discomfort diminishes the quality of life and schoolwork productivity[29]. Dry eye disease is associated with the development of anxiety and depression, especially among younger patients[30]. In children, dry eyes are often linked to systemic health conditions, including allergic keratoconjunctivitis and juvenile idiopathic arthritis[31]. Usually, over-the-counter lubricating eye drops can fix the problem, but in refractory cases, there are commercially available devices, such as Lipiflow® (www.jnj.com/innovation/lipiflow-thermal-pulsation-system-a-new-dry-eye-treatment), TearCare® (www.tearcare.com), and iLux® (www.ilux.myalcon.com/). Each of these devices applies heat and/or pressure to the eyelids to release oils and enhance lubrication. Lipiflow was the first device approved by the US FDA. For severe cases, wearable prosthetic lenses can protect the eye from environmental damage, inducing dryness; these include Prokera® (www.biotissue.com/patients/prokera-for-patients/), PROSE® (www.bostonsight.org/patients/patient-prose-treatment/), and EyePrintPro® (www.eyeprintpro.com/)[32]. PROSE®, in particular, has been approved for pediatric patients, especially in those facing severe dry eye [33,34].

Glaucoma

Glaucoma is defined as the gradual death of the optic nerve. The incidence of congenital glaucoma in the US is 1 out of 10,000 to 18,000 births[35]. Elevated intraocular pressure is a major risk factor for disease development and guides medication initiation[36]. Smart contact lenses represent a recent innovation not yet tested in children. The smart contact lens is a wearable that captures intraocular pressure and biomarkers contained in tears[37]. Tears are less subject to contamination and contain higher biomarker concentrations than saliva and sweat[38,39]. Continuous measurement via a smart contact lens accounts for natural fluctuations of intraocular pressure over the course of the day. In addition to collecting diagnostics, some lenses are designed to be drug-eluting, which would make placing several eyedrops a day an easier task, especially for children [40].

Future directions

Many wearables have not been trialed in large groups of children, likely due to the limitations of such innovations (Table 1). Cost is a major limiting step to widespread implementation[41]. Although the accuracy of ocular biomarkers is increasingly being fine-tuned, data collection via wearable health devices still cannot replace the gold standard of in-person visits. In particular, there are no existing wearables for retina diseases, which means that in-person examination of the retina is necessary at this time. However, creation of wearables would be insightful as the retina presents a window to monitor biomarkers for systemic health, such as sickle cell retinopathy [42,43].

Regarding public perception, parents may be skeptical of these devices for their child in a way that they may not be as hesitant for themselves. Additionally, eye disease in children tends to either consist of a few, very severe cases or minimally pathologic, essentially well-child cases. With all of this in consideration, we advocate that the pediatric ophthalmic population is particularly suited for wearables given the unpredictability of the eye exam and biomarkers at a single visit and the present shortage of pediatric ophthalmologists. Wearables can serve as a bridge to in-person appointments, such that in the meantime, they can facilitate discussion of parameters over telehealth.

The current state of pediatric ophthalmology in the United States presents a gap in care delivery that wearables may help alleviate as

Table 1 | Overview of wearables designed to detect ocular conditions in children

Disease	Technology	Function	Commercial Examples	Technology	Function	Commercial Examples
Refractive errors	Portable wearable refraction system	Measures refractive errors at distance, near, and with different gaze positions in children	VisionFit® Clouclip	Adjustable-focus glasses	Enables a child to adjust the lens prescription in the glasses	Adspecs
Strabismus	Virtual reality headsets	Track eye movements and misalignment	Luminopia® CureSight™	Video recording-glasses	Enables ophthalmologists to record examination data hands-free	Pivothead®
Dry eye disease	Thermal pulsation system	Applies controlled heat and pressure to eyelids to enhance lubrication	Lipiflow® TearCare® iLux®	Prosthetic lenses	Protects the eye from dry air and other environmental insults	Prokera® PROSE® EyeprintPro®
Glaucoma	Smart contact lens	Determines intraocular pressure and tear biomarkers	Not yet available for children			

technology improves. As the rest of medicine becomes increasingly personalized, preventative, participatory, and predictive, so should pediatric ophthalmology. The resulting high-volume data generation is exciting as most pediatric ophthalmology research questions have been unanswered. In turn, a deeper understanding will inform innovations in device development. Further, the ubiquitous presence of technology has created a generational shift in technology acceptance, which may motivate children to integrate wearables into routine wear. These devices are additionally a daily reminder of health and well-being. Exposing children to these devices hopefully affirms the importance of health maintenance from an early age, creating a generation receptive to chronic disease management and behavioral change later as adults.

Data availability
No datasets were generated or analysed during the current study.

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Author contributions

N.I. and J.K. conceptualized the perspective, and all authors contributed substantively to revisions and approved the final manuscript for submission.

Competing interests

The authors declare no competing interests.

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