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From Outdoor Light Exposure to Physical Activity in Childhood Myopia Prevention: A Narrative Review of the Evidence and Multilevel Mechanisms

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Abstract

The global prevalence of childhood myopia poses a major public health challenge. Increasing time spent outdoors is an established preventive approach, particularly for reducing myopia onset, but the extent to which physical activity contributes beyond outdoor light exposure remains uncertain. This narrative review synthesizes epidemiological, mechanistic, and intervention evidence on physical activity and childhood myopia. Longer time spent outdoors is consistently associated with a lower incidence of myopia. Bright outdoor light may contribute through retinal dopamine signaling and regulation of axial growth. In a two-year prospective cohort study involving 4,306 children, one year of smartwatch monitoring showed that a higher composite activity-load measure was associated with less myopic shift and less axial elongation, with stronger associations outdoors than indoors. These observational findings do not establish an independent causal effect of physical activity. Intervention studies suggest that increasing outdoor time can reduce myopia onset and myopic shift, whereas evidence for slowing progression in children who are already myopic is less consistent. Proposed mechanisms include light-related neurobiological pathways, ocular hemodynamic and systemic

metabolic processes, and behavioral pathways such as reduced near work. Wearable technologies may support objective monitoring of activity and light exposure. Prevention strategies should prioritize sufficient daily outdoor time (often around two hours in current guidance) while promoting age-appropriate moderate-to-vigorous physical activity as part of an integrated strategy. Future studies should distinguish the effects of light exposure and physical activity through well-designed longitudinal studies and randomized trials and account for genetic susceptibility and family, school, and community environments.
Keywords: Myopia prevention; children; physical activity; outdoor light exposure; physical activity intensity; multilevel mechanisms; integrated interventions

1. Introduction: The Public Health Challenge of Childhood Myopia and the Preventive Potential of Physical Activity

1.1. The High Prevalence and Disease Burden of Childhood Myopia Globally and in China

Myopia has become a major global public health concern, with its prevalence continuing to rise and imposing a substantial burden, particularly among children and adolescents. Global estimates indicate considerable regional variation in myopia prevalence, reaching as high as 60% among school-aged children in Asia and approximately 40% in Europe, compared with less than 10% in Africa and South America [1]. The global myopia epidemic is expected to intensify, with nearly half of the world's population projected to be affected by 2050, making myopia one of the leading causes of blindness [2]. China is among the countries with the highest prevalence of myopia worldwide. Childhood and adolescent myopia represents a particularly serious concern in the country, characterized by a high and rapidly increasing prevalence, a growing proportion of high myopia, and an increasingly early age of onset [3]. Myopia progression also increases the risk of several potentially sight-threatening ocular complications, including macular disease, glaucoma, cataracts, and retinal detachment [4]. Children who develop myopia at an early age face a greater risk of progressing to high myopia and myopic maculopathy, potentially resulting in irreversible visual impairment or even blindness. These consequences impose long-term health and economic burdens on individuals, families, and society. A clear understanding of the epidemiological landscape of myopia is therefore essential for developing effective public health strategies to address this global challenge.

1.2. Limitations of Traditional Risk-Factor Models and the Emergence of Outdoor Activity

Research into the etiology of myopia has traditionally focused on genetic predisposition and near work. The contribution of genetics is well established, with parental myopia substantially increasing the risk of myopia in offspring [5]. Specific genetic variants may also interact with environmental factors to influence myopia susceptibility [6-7]. However, the rapid increase in global myopia prevalence against a relatively stable genetic background suggests that environmental and lifestyle factors may play a more prominent role in the current epidemic [8], highlighting the limitations of traditional explanatory models. Near work, including

prolonged reading and electronic device use, is a recognized risk factor, although its effects are complex and may be modified by factors such as time spent outdoors [9].

Longer time spent outdoors has been consistently associated with a lower incidence of myopia, particularly among children who are not yet myopic. Proposed explanations include light-related stimulation of retinal dopamine signaling and the contribution of a wider outdoor visual field to emmetropization [10]. Evidence suggests that sufficient time outdoors each day is important, and school policies that increase outdoor exposure during recess may reduce myopia incidence [11]. This shifts prevention efforts toward increasing protective exposures rather than focusing exclusively on risk reduction.

1.3. From Time Spent Outdoors to Physical Activity: Advancing Research and Mechanistic Hypotheses

Early studies suggested that increasing time spent outdoors could reduce the risk of childhood myopia [12]. Subsequent research, however, has indicated that the protective effects of outdoor exposure may reflect the combined contributions of several factors, including high-intensity natural light exposure, reduced sustained near work, and physical activity facilitated by outdoor environments [13]. Consequently, research has increasingly examined physical activity as a distinct component of this relationship. Physical activity encompasses activities performed both indoors and outdoors and may influence axial growth through mechanisms such as dopamine signaling and improved blood flow, thereby broadening the potential targets for myopia prevention.

A prospective cohort study in Shanghai quantified the study-defined “activity load” and found that higher activity loads were associated with less myopic shift in both indoor and outdoor settings, with a stronger association outdoors [14]. The association between activity load and myopic shift persisted after adjustment for measured light intensity. This finding is consistent with a possible contribution of physical activity beyond measured light exposure, but the observational design does not establish an independent causal effect. The relationship may also be influenced by socioeconomic conditions, family environments, and other contextual factors [15], and associations may differ across population subgroups, including children with overweight [16]. These considerations support more individualized prevention strategies.

Overall, the transition from studying time spent outdoors to examining physical activity represents a more refined and multidimensional stage of research. Further studies are needed to clarify the dose–response relationships between activity type, intensity, and myopia outcomes and to investigate the underlying neuroendocrine, vascular, and metabolic mechanisms. Physical activity interventions should also be considered within a broader socioecological framework encompassing families, schools, and communities to inform comprehensive prevention strategies.

1.4. Multilevel Evidence and Mechanisms of Physical Activity in Myopia Prevention

Childhood and adolescent myopia has become a global public health concern, with a particularly high and persistently increasing prevalence in China [17]. The Chinese government has issued the *Implementation Plan for the Comprehensive Prevention and Control of Myopia

in Children and Adolescents*, which emphasizes the importance of increasing physical activity and time spent outdoors to protect children's vision [18]. However, the specific contributions of physical activity to myopia prevention and control, as well as the mechanisms underlying these contributions, remain incompletely understood [13]. This narrative review synthesizes the relevant evidence and proposed mechanisms to inform the development of preventive interventions.

Epidemiological studies suggest that higher physical activity levels may be associated with more favorable myopia-related outcomes. A study of Chinese university students reported differences in myopia incidence between students who participated in sports clubs and those who did not [19]. Separately, a cross-sectional survey of primary and secondary school students in Ningxia found an association between physical activity level and visual status [20]. A dose–response meta-analysis of observational studies reported that each additional hour of daily physical activity was associated with approximately 12% lower odds of myopia [71]. In the Shanghai prospective cohort, the association between activity load and myopic shift persisted after adjustment for light intensity [14]. Together, these findings support further investigation of a potential contribution beyond outdoor light exposure, but they do not establish causality.

At the biological level, physical activity may affect myopia-related outcomes by improving ocular hemodynamics and metabolic status, including through changes in retinal vessel diameter [21]. Physical activity is also associated with systemic metabolic health, while myopia has been linked to an increased risk of metabolic syndrome and type 2 diabetes. Physical activity may therefore have the potential to mitigate some of these associated risks [22]. Genetic evidence also supports a possible relationship between lower physical activity and increased myopia risk [23]. Taken together, these findings suggest that physical activity may influence scleral remodeling and axial elongation, either directly or indirectly, through multiple pathways involving ocular blood flow, systemic metabolism, and inflammation.

Integrated prevention strategies may be more promising than isolated measures, although the effectiveness of specific combinations requires further evaluation. A school-centered cluster-randomized intervention protocol has proposed integrating family and clinical components into school-based prevention [24]. Schools also play an important role: promoting outdoor time and providing appropriately designed desks and chairs may help reduce myopia onset and progression [25]. Incorporating motor imagery training into physical education classes has been reported to improve children’s visual function [26]. Machine-learning models have also incorporated modifiable behavioral factors into multivariable myopia-risk prediction [27], although predictive importance does not establish a causal effect.

In summary, this narrative review integrates evidence from three complementary domains: epidemiological research, mechanistic studies, and intervention evaluations. It aims to develop a comprehensive and scientifically grounded account of the role of physical activity in myopia prevention, providing a theoretical and practical basis for the development and refinement of integrated prevention strategies spanning policy, environmental conditions, health behaviors, and education.

2. Epidemiological Evidence: The Effects of Physical Activity Duration, Intensity, and Environment

Epidemiological studies increasingly support an association between physical activity and childhood myopia-related outcomes, with observed associations varying according to activity duration, intensity, and setting. A two-year prospective cohort study in Shanghai followed children aged 6–9 years and used smartwatches to monitor physical activity over one year. The researchers introduced a composite measure termed "activity load," calculated by weighting time spent in light-, moderate-, and vigorous-intensity activities [14]. Higher activity loads in both indoor and outdoor settings were associated with a more favorable change in spherical equivalent refraction (SER) and less axial elongation. The association was stronger outdoors ($\beta = 0.18$) than indoors ($\beta = 0.06$). These associations persisted after adjustment for measured light intensity, but the observational design does not establish that physical activity itself causes the outcomes independently of light exposure.

The relationship between physical activity and myopia is embedded in children's overall 24-hour behavioral patterns rather than occurring in isolation. A cross-sectional study based on the Canadian 24-Hour Movement Guidelines examined the association between adherence to recommendations for moderate-to-vigorous physical activity, screen time, and adequate sleep and the risk of myopia [28]. Children who met both the screen-time and sleep recommendations, as well as those who met all three recommendations for physical activity, screen time, and sleep, had significantly lower odds of myopia (OR = 0.47 and 0.40, respectively). These findings suggest that myopia prevention should account for multiple behavioral factors, with adequate sleep itself (OR = 0.50) and its potential interaction with physical activity warranting particular attention. A separate large cross-sectional survey of Chinese students aged 7–18 years in Jiangsu Province further illustrated the complex relationships among sleep, physical activity, and myopia [29]. Sleep duration was inversely associated with myopia, and sleeping for at least 8 hours per day was identified as a protective factor. More importantly, vigorous-intensity physical activity was associated with a lower risk of myopia and mediated the inverse association between sleep duration and myopia. This finding suggests that adequate sleep may be associated with lower myopia risk partly through its relationship with greater participation in vigorous physical activity.

The setting in which physical activity occurs, particularly the school environment, is an important contextual factor that may influence its contribution to myopia prevention. A nationwide longitudinal study in China examined the association between the school physical activity environment and the co-occurrence of overweight/obesity and myopia in children and adolescents [30]. Compared with children attending schools with more favorable physical activity environments, those in less favorable environments had higher odds of overweight/obesity co-occurring with myopia (OR = 1.85) and higher odds of myopia progression (OR = 1.29). These findings highlight the potential importance of improving school sports facilities, scheduling, and the overall activity-promoting environment to support prevention of both obesity and myopia. A cohort study examining classroom visual

environments found that, after adjustment for multiple confounders, indicators including adequate floor area per student and sufficient mean blackboard illuminance were associated with more favorable changes in axial length and refraction [31]. A favorable school physical environment may therefore complement an activity-promoting behavioral environment, although these associations do not establish causality.

2.1. The Protective Association of Time Spent Outdoors

The association between time spent outdoors and childhood myopia prevention is supported by a substantial body of epidemiological evidence. Multiple studies have reported that longer time outdoors is associated with lower myopia prevalence and incidence, and some studies have also reported slower progression [32]. For example, a 2.5-year longitudinal cohort study conducted in Wenzhou found that children who remained non-myopic throughout the study spent more time outdoors per day than children who developed incident myopia (1.92 vs. 1.81 hours/day). Annual axial elongation was lower among children with high outdoor exposure (>2.5 hours/day; 0.22 ± 0.13 mm/year) than among those with low exposure (≤1.5 hours/day; 0.24 ± 0.14 mm/year) [33]. A study in Singapore found that each additional hour of self-reported outdoor time was associated with lower odds of myopia (odds ratio [OR] = 0.82) [34].

The association between outdoor exposure and myopia appears to follow a dose–response pattern, with longer outdoor duration generally associated with lower odds of myopia. A cross-sectional study of school-aged children in Chongqing, China, found that each additional hour spent outdoors was associated with lower odds of myopia on both weekdays and weekends (weekday OR = 0.811; weekend OR = 0.796) [35]. Multiple prospective cohort studies have reported that longer daily outdoor exposure, such as more than 2 hours, is associated with a lower incidence of myopia. A three-year cohort study in Vietnam found that greater time spent outdoors was associated with lower myopia incidence (adjusted OR = 0.499) [36]. In a study in Xi'an involving 15,046 primary school students aged 6–12 years, a 24-month follow-up found that outdoor exposure was associated with lower odds of myopia onset (OR = 0.47) [37]. Data from the Australian Raine Study indicated that, among young adults aged 20–28 years, a smaller area of conjunctival ultraviolet autofluorescence (CUVAF), indicative of lower outdoor sunlight exposure, was associated with higher odds of myopia onset and progression [38]. In Shenzhen, an analysis using high-resolution satellite imagery found that schools with greater green-space coverage, aggregation, and connectivity experienced slower increases in myopia prevalence [39].

The association between outdoor exposure and myopia may vary by age and may be particularly relevant in younger children and before myopia onset. A meta-analysis found that, among non-myopic children and adolescents, increased outdoor exposure was associated with a more favorable change in SER (weighted mean difference = 0.10 D) and less axial elongation (weighted mean difference = −0.05 mm). However, increased outdoor exposure did not significantly slow progression among children who were already myopic [40]. This distinction highlights the potential importance of intervention timing: increasing outdoor exposure before onset or during early refractive change may be more effective for preventing or delaying onset

than for controlling established myopia. A large cross-sectional study in Shanghai reported that the association between green environments around schools and myopia was strongest among children aged 7–12 years (OR = 0.223) [41].

2.2. Physical Activity Intensity and Myopia-Related Outcomes

Although the role of time spent outdoors in reducing myopia onset is well supported, the contribution of physical activity intensity beyond outdoor exposure remains an important research question. In the Shanghai cohort, children aged 6–9 years wore smartwatches for one year to record activity duration at different intensities indoors and outdoors. The researchers calculated "activity load" by weighting time spent at different intensities (light × 1, moderate × 2, and vigorous × 3). After adjustment for other factors, activity load was associated with more favorable changes in SER and axial length over the two-year study period, with a stronger association outdoors ($\beta = 0.18$). The association persisted after adjustment for light intensity [14]. Children in the highest quartile of indoor activity load (≥3.02 weighted hours/day) had 22% higher odds of limited myopia progression, whereas children in the two highest outdoor activity-load groups had 34%–77% higher odds [14]. These findings suggest that assessments should consider both activity duration and intensity, while recognizing that the study was observational.

A cross-sectional study of school-aged children in China examined adherence to the Canadian 24-Hour Movement Guidelines and myopia risk [28]. Meeting the recommendation for moderate-to-vigorous physical activity alone was not significantly associated with lower myopia risk, whereas meeting more recommendations—particularly screen-time and sleep recommendations together, or all three recommendations—was associated with lower odds of myopia. These findings suggest that physical activity may be more informative when considered alongside other health behaviors, including adequate sleep and reduced screen time. A separate study of Chinese children aged 11–14 years examining sugar-sweetened food consumption included weekly vigorous physical activity as a confounding variable [42]. This provides indirect evidence that vigorous physical activity is considered in multifactorial models of myopia, rather than proving an independent effect.

The association between activity intensity and myopia-related outcomes may vary according to individual characteristics and environmental conditions. In the Shanghai study, the association between outdoor activity load and less myopic shift was evident among non-myopic children ($\beta = 0.15$) and stronger among children who spent less than 120 minutes outdoors per day ($\beta = 0.22$) [14]. This raises the hypothesis that higher-intensity outdoor activity might partly offset insufficient outdoor duration, but the possibility requires direct testing. Indoor activity load was associated with favorable outcomes among second-grade students and children who already spent at least 120 minutes outdoors each day. These subgroup findings support considering refractive status, age, and habitual outdoor exposure when developing prevention strategies.

Intervention studies provide evidence that increasing time spent outdoors can reduce myopic refractive shift and axial elongation; they do not necessarily isolate the independent

contribution of physical activity intensity. A Cochrane systematic review found that interventions to increase outdoor time reduced myopic shift in refraction (mean difference [MD] = 0.13 D) and axial elongation (MD = −0.04 mm) at two-year follow-up [43]. A meta-analysis of 15 studies reported a mean reduction in annual axial elongation of 0.08 mm and a 0.16 D shift in SER toward hyperopia per year [44]. A meta-analysis of randomized controlled trials also found that outdoor-time interventions improved SER (MD = 0.19 D) and reduced axial elongation (MD = −0.09 mm) [45]. These interventions generally prescribed 40–120 minutes of additional outdoor exposure per day, although effects varied across studies.

2.3. Differences Between Indoor and Outdoor Environments and Their Interactions

Indoor and outdoor environments differ substantially in their physical visual characteristics, and these differences may influence the onset and progression of childhood myopia. Research suggests that the spatial frequency characteristics of outdoor visual environments differ markedly from those of indoor environments [46]. An analysis of images of children's rooms and frequently visited outdoor areas found that the spatial frequency slope was significantly lower indoors (−1.43 ± 0.18) than outdoors (−1.11 ± 0.23). The indoor spatial frequency slope was positively correlated with children's SER and negatively correlated with myopia risk. These findings suggest that the low-spatial-frequency visual information commonly encountered indoors, such as large expanses of blank walls and ceilings, may create a form of regional visual deprivation that contributes to myopia risk [47]. Further quantification indicated that as much as 29.5% of the indoor visual field might be subject to this form of visual deprivation, a proportion substantially higher than that observed outdoors.

Lighting conditions are an important difference between indoor and outdoor environments. Lower illuminance and less time spent in bright light have been associated with higher myopia prevalence [48]. In a cluster-randomized trial in Shanghai schools, the intervention group had a higher mean outdoor light-intensity index (3,557 ± 970 lux per outdoor minute) than the control group (2,984 ± 806 lux per outdoor minute). The trial also reported that 120–150 minutes outdoors per day at an intensity of 5,000 lux per outdoor minute, or a study-specific cumulative outdoor-light index of 600,000–750,000 outdoor lux/day, corresponded in model-based estimates to a 15%–24% reduction in the incidence rate ratio [49]. These values should be interpreted as study-specific exposure metrics and model estimates, not as universally validated thresholds. By comparison, indoor illuminance is generally much lower. A study in Israeli kindergartens reported a mean illuminance of 670.76 ± 3.73 lux even in the high-intensity group [50]. Animal experiments provide mechanistic clues: in a form-deprivation myopia model in chicks, bright light suppressed myopia development in an intensity-dependent manner, alongside increasing retinal dopamine levels [51].

The association between indoor activity load and less myopic shift was weaker than the association for outdoor activity load ($\beta = 0.06$ vs. $\beta = 0.18$), but it remained detectable among second-grade students and children spending at least 120 minutes outdoors per day [14]. These subgroup findings suggest that indoor physical activity may complement outdoor exposure for some children, but they do not show that indoor activity compensates for insufficient outdoor

time. Prevention programs should prioritize sufficient time outdoors and may include indoor physical activity as a supplementary component of broader health-promotion strategies.

Environmental conditions and behavioral changes can interact to influence myopia-related outcomes. During home confinement in the COVID-19 pandemic, increased screen time and reduced time outdoors may have contributed to greater myopic shifts. Children aged 6–8 years experienced a marked myopic shift in refraction (approximately −0.3 D) [52], while monthly axial elongation was reported to be 35% greater than during the corresponding normal period [53]. A systematic review and meta-analysis found more negative SER during home confinement than before the pandemic and identified increased screen time and reduced outdoor exposure as associated factors [54]. A separate follow-up study in Feicheng also examined myopia prevalence after home confinement [83]. These findings illustrate how changes in daily environments may alter behaviors relevant to childhood myopia, but they do not establish that any single behavior alone caused the observed changes.

3. Potential Multilevel Mechanisms Linking Physical Activity and Myopia

The onset and progression of childhood myopia constitute a complex process involving interactions among genetic, environmental, and behavioral factors. Excessive axial elongation is a central feature of myopia development, and physical activity, particularly when performed outdoors under bright light conditions, may influence this process through multiple pathways.

3.1. Proposed Neurobiological Pathway: Light–Dopamine Signaling

Proposed mechanisms linking outdoor exposure to lower myopia incidence include light-related modulation of retinal dopamine signaling. Dopamine is a neurotransmitter involved in the regulation of ocular growth [55]. The effects of light on dopaminergic signaling are complex and may depend partly on wavelength. Some optical accounts suggest that long-wavelength red light focuses behind the retina, whereas medium- to short-wavelength blue light focuses in front of the retina; proposed implications for myopia should be interpreted cautiously because wavelength effects are context-dependent [56]. A study of pupillary responses in children found that, during summer, children with shorter axial lengths showed stronger pupillary constriction responses to blue light than to red light, whereas this association was less evident in winter [57]. The authors hypothesized that greater summer light exposure might stimulate retinal dopamine release and thereby inhibit axial elongation; this proposed pathway requires further confirmation.

Recent studies have explored possible interactions between light-related dopamine signaling and other molecules. All-trans retinoic acid (atRA) and dopamine appear to exert opposing effects in experimental myopia. A preprint study using animal models suggested that ambient light can regulate ocular atRA levels, with higher illuminance and longer exposure associated with lower atRA levels in retinal and posterior eye tissues [58]. Systemic administration of levodopa (L-DOPA), a dopamine precursor, to mice produced a transient reduction in retinal atRA levels, whereas atRA treatment did not affect ocular dopamine levels. These findings suggest a possible interaction among ambient light, atRA, and dopamine, but the pathways and their relevance to human childhood myopia remain uncertain.

To objectively quantify the association between outdoor light exposure and myopia, conjunctival ultraviolet autofluorescence (CUVAF) area has been investigated as a biomarker of cumulative sunlight exposure. A meta-analysis found that individuals with myopia had significantly smaller CUVAF areas than those without myopia and also reported less outdoor activity by self-report [59]. These findings provide complementary objective and self-reported evidence supporting an association between lower outdoor sunlight exposure and myopia.

3.2. Potential Hemodynamic and Metabolic Pathways

Myopia-related changes may involve ocular hemodynamics as well as axial elongation. Studies using swept-source optical coherence tomography angiography (SS-OCTA) have found that longer axial length is associated with lower deep retinal vessel density in the macular region and reduced choroidal vascular and stromal volumes [60]. These observations have prompted hypotheses about the role of choroidal perfusion, but they do not demonstrate that improved perfusion mediates an effect of physical activity on myopia. Posterior scleral reinforcement surgery has been reported to stabilize axial length and refraction; improved posterior ocular perfusion has been proposed as one possible mechanism [61].

At the metabolic level, Mendelian randomization analyses have examined potential causal relationships between glycemic traits and myopia. Higher glycated hemoglobin (HbA1c) levels were associated with higher myopia odds (OR = 1.018), whereas higher adiponectin levels were associated with a potentially protective estimate (OR = 0.99) [62]. Adiponectin is an adipocyte-derived hormone with anti-inflammatory and insulin-sensitizing properties. These findings support further investigation of metabolic pathways, including whether physical activity-related changes in adiponectin contribute to ocular outcomes; they do not establish adiponectin as a mediator of any exercise effect.

Physical activity may influence systemic and ocular circulation, but direct evidence that these pathways prevent childhood myopia is limited. Studies in other ocular conditions have reported associations between regular physical activity and increased optic-disc vessel density in patients with primary open-angle glaucoma [63], transient reductions in intraocular pressure (IOP) and increases in ocular perfusion pressure (OPP) after aerobic exercise [64], and lower odds of visual-field progression among patients with glaucoma who performed moderate-to-vigorous physical activity in the evening [65]. Acute high-intensity exercise has also been associated with dynamic changes in retinal-layer thickness in young adults [66]. Outside the eye, voluntary wheel running has enhanced clearance of metabolic waste through the brain’s glymphatic system in animal research [67]. These findings provide indirect mechanistic context; whether comparable pathways operate in children with myopia remains an open question.

3.3. Interactions Among Behavior and Lifestyle Factors

Childhood myopia develops within a complex interplay of behavioral and lifestyle factors. A large cross-sectional study in Tianjin, China, identified significant interactions between parental myopia and children's lifestyle patterns [68]. The researchers developed an eye-health lifestyle risk score and found that both a high-risk lifestyle profile and parental myopia were

independently associated with a higher risk of childhood myopia, with the combination of these factors showing the strongest association. A predictive model incorporating both lifestyle risk scores and parental myopia history demonstrated the highest predictive performance. These findings suggest that lifestyle modification may be a particularly important component of myopia prevention for children with a family history of myopia.

A study in Ningxia, China, used a moderated mediation model to examine the dynamic relationships among lifestyle behaviors, physical activity, academic stress, and visual status [69]. Lifestyle behaviors were significantly negatively associated with visual status, and physical activity was found to exert a significant suppression effect on the association between lifestyle behaviors and visual status. This finding suggests that physical activity may partly counteract the adverse association between unfavorable lifestyle patterns and visual outcomes. Academic stress acted as a moderator in this relationship, potentially weakening children's willingness or opportunities to participate in physical activity.

Increasing time spent in physical activity may partly displace sedentary near-work activities, thereby reducing exposure to a behavioral factor associated with myopia. A survey of Korean adults found a higher prevalence of myopia among those using smart devices for more than 4 hours per day (68.0%) than among those using them for less than 1 hour per day (46.2%) [70]. A dose–response meta-analysis found that, compared with the lowest exposure categories, higher levels of near work (OR = 1.71) and screen time (OR = 1.59) were associated with higher odds of myopia, whereas higher physical activity levels were associated with lower odds (OR = 0.77) [71]. These adult and observational findings should not be interpreted as direct evidence of a causal effect in children.

Physical activity may also influence ocular development indirectly through improvements in overall health and neuroendocrine regulation. The school physical activity environment has been significantly associated with the risk of co-occurring overweight/obesity and myopia, with students in less favorable school activity environments exhibiting higher odds of this comorbidity (OR = 1.85) [30]. Adequate sleep has also been identified as a protective factor against myopia (OR = 0.722) [17]. Because regular physical activity can improve sleep quality and duration, it may indirectly support physiological recovery during sleep, potentially creating more favorable conditions for ocular development and homeostasis.

A substantial gap may exist between parental awareness and children's actual behavior. A Korean study evaluating the MyopiaEd digital intervention found that parental knowledge improved significantly, but children's time spent in near-work activities did not change significantly [72]. A large cross-sectional study in China found that lower parental awareness was associated with children not using eye-protective desk lamps (OR = 1.95), unfavorable rest practices (OR = 1.60), and excessive total near-work time (OR = 1.45) [73]. These findings suggest that even when parents recognize the importance of outdoor activity, translating this awareness into behavioral change may be constrained by children's own preferences and broader structural and environmental factors.

4. From Evidence to Application: Monitoring Technologies and Integrated Intervention Strategies

Translating scientific evidence into effective clinical and public health practice is essential to addressing childhood myopia. This process depends on precise monitoring technologies to assess myopia risk and progression, alongside the development and implementation of comprehensive, evidence-based intervention strategies.

4.1. Emerging Monitoring Technologies for Objective Quantification and Precise Assessment

Emerging monitoring technologies are enabling more objective assessment of visual behaviors, axial elongation, and fundus structure in childhood myopia prevention and control. Wearable devices, such as visual-behavior monitors, can record viewing distances and light exposure. One study reported that near-work activities accounted for 49.19% of monitored time among children with progressive myopia, whereas time under high-illuminance conditions accounted for 23.6% [74]. Algorithms based on smartwatch data can also distinguish indoor from outdoor environments and estimate physical activity intensity [75].

Smart wearable devices equipped with multiple sensors and analytical algorithms may support simultaneous monitoring of physical activity and ambient light. In the Shanghai cohort, 4,306 children aged 6–9 years wore smartwatches for one year. The researchers calculated a weighted measure of activity duration and intensity, termed “activity load.” Higher activity loads were associated with less myopic shift in both indoor and outdoor settings, and these associations persisted after adjustment for light intensity [14]. These findings illustrate the potential of wearables to quantify activity and classify environmental context; they do not by themselves establish that activity independently causes reduced myopia progression.

Artificial intelligence (AI) is increasingly being applied to myopia screening, risk stratification, and progression prediction. DeepMyopia, a deep learning-based system, uses routine retinal fundus photographs to predict the risk of myopia onset over the subsequent 1–3 years and classify children into risk groups, potentially supporting targeted prevention [76]. AI-assisted fundus-image analysis has also been used to quantify fundus tessellation in early-onset high myopia, potentially supporting further investigation of ocular structural correlates [77].

Ocular biometric parameters, particularly the axial length-to-corneal radius of curvature ratio (AL/CR), may provide diagnostic and predictive information beyond axial length alone. A study involving more than 500,000 children in Chengdu reported an area under the receiver operating characteristic curve (AUC) of 0.9112 for AL/CR, compared with 0.8923 for axial length alone [78]. Longitudinal evidence indicates that baseline AL/CR predicts subsequent premyopia and myopia, with a reported hazard ratio (HR) of 2.979 for the highest versus lowest quartile [79]. A meta-analysis reported pooled sensitivity of 0.88, pooled specificity of 0.89, and a summary AUC of 0.93 for AL/CR in diagnosing myopia [80].

4.2. Developing Evidence-Based Integrated Intervention Strategies

Effective childhood myopia prevention requires evidence-informed approaches ranging from public health policy to individualized clinical management. China’s Implementation Plan

for the Comprehensive Prevention and Control of Myopia in Children and Adolescents and related reviews recommend increasing time outdoors, reducing prolonged near work, ensuring adequate sleep, performing eye exercises, and improving reading and writing environments [12,18]. The Expert Consensus on Comprehensive Public Health Interventions for Myopia Prevention and Control in Children and Adolescents outlines six measures: establishing visual-health records; assessing and promoting healthy visual behaviors; delivering health education; improving reading and writing environments; ensuring two hours outdoors during daylight each day; and implementing graded myopia management and medical treatment [81].

At the policy and school levels, allocating time outdoors during and outside the school day is a practical implementation approach. Taiwan's "Outdoor Recess" intervention encouraged students to spend recess outdoors and was reported to reduce myopia onset among school-aged children without myopia; among children with premyopia, incidence decreased from 37.8% to 19.6% [11]. A study in Shanghai found that students attending schools with well-implemented recess activity programs had a 20% lower risk of myopia, while schools providing sufficient outdoor time during physical education classes had a lower risk still [25]. Following a prevention program in Yilan County, myopia prevalence among kindergarten children decreased from 15.5% to 8.4%, with the reduction sustained over time [82].

Individualized prevention planning should prioritize sufficient daily outdoor exposure (often around two hours in current guidance) while also promoting age-appropriate physical activity. In the Shanghai cohort, children with an outdoor activity load of at least 1.47 weighted hours/day had 34%–77% higher odds of limited myopia progression than those in the lowest activity-load group [14]. Children aged 6–9 years were included in this cohort, which identified associations between activity load and myopic shift [14]; however, the optimal age and timing for intervention still require further study. For children who already have myopia, established clinical options for controlling progression include appropriately selected concentrations of atropine, orthokeratology lenses, and multifocal lenses [84].

Environmental and behavioral optimization may include improving classroom and home lighting, educating parents about avoiding unnecessary restrictions on time outdoors, and supporting healthier visual habits. Higher classroom illuminance has been associated with slower axial elongation [85]. A three-year study of artificial daylight reported a lower cumulative incidence of myopia, from 26.4% to 21.2% [86]. During the COVID-19 pandemic, reduced time outdoors and increased screen time were associated with accelerated myopic shifts in several populations [52-54]; behavioral-monitoring research also documented changes in children's near-work and outdoor-exposure patterns [87]. These findings support attention to environmental context, but they do not show that any single behavioral factor fully explains pandemic-related changes.

5. Future Research Directions and Challenges

Baseline axial length and the axial length-to-corneal radius of curvature ratio (AL/CR) have been investigated as indicators for predicting premyopia and myopia in preschool children [79, 88]. Future research should integrate baseline refraction, age, parental myopia history, and

lifestyle behaviors into more accurate and individualized prediction models and determine the optimal timing for initiating interventions. Artificial intelligence, particularly machine learning and deep learning, offers potential for risk stratification and progression prediction using large-scale, multimodal datasets [89-90].

Second, optimizing and individualizing intervention strategies is central to improving prevention and control outcomes. Individuals vary in their responses to the same intervention, underscoring the need to investigate the underlying mechanisms and biomarkers associated with treatment response and to develop personalized approaches. Combination therapies, such as low-concentration atropine combined with optical interventions, may offer synergistic benefits. However, their long-term safety, optimal combinations, and potential rebound effects after treatment discontinuation require validation in large-scale, long-term studies [91].

Further mechanistic research is needed to clarify the independent contributions and potential synergistic effects of physical activity intensity and light exposure in myopia prevention, as well as the molecular and cellular pathways underlying these effects. Basic research should investigate how physical activity at different intensities influences the release of neurotransmitters, including retinal dopamine and melatonin, and how these changes may affect downstream processes such as choroidal thickness regulation and scleral remodeling.

High-quality longitudinal evidence is also needed. Multicenter randomized controlled trials and long-term cohort studies are required to evaluate the sustained effects of different physical activity doses, defined by frequency, intensity, duration, and type, and to investigate interactions with genetic susceptibility, nutritional status, and other relevant factors. Childhood myopia is a multifactorial condition, and the effects of physical activity are intertwined with genetic background, nutrition, near-work behaviors, and other determinants. Future research must therefore move beyond single-factor analyses toward more integrated approaches that account for these complex interactions.

Practical challenges include implementing and maintaining physical activity interventions in educational settings with high academic demands. A study in Ningxia reported that academic stress moderated modeled relationships among lifestyle behaviors, physical activity, and visual status [69]. Baseline findings from Israel's iREAD study underscore the importance of considering environmental and device-use patterns alongside refractive status; they do not by themselves establish educational intensity as a causal barrier to outdoor activity [92]. Encouraging students to participate in organized sports during free time may help offset some prolonged near-work exposure [93].

Developing interventions that are engaging, feasible, and affordable is another priority. Potential approaches include school-based physical activity programs and indoor activities that simulate outdoor experiences using virtual reality. Incorporating accommodative training or motor imagery training into physical education classes may improve aspects of visual function [26, 94]. A network meta-analysis identified badminton and table tennis as activities associated with favorable improvements in children's visual-health outcomes [95]. Smartphone-based

vision screening has also shown promise in resource-limited settings [96], suggesting that mobile technologies could support intervention delivery and follow-up.

Interdisciplinary collaboration among ophthalmology, exercise science, public health, and education is important for developing an integrated system linking monitoring, assessment, and intervention. The Wenzhou large-scale childhood myopia survey involving approximately one million children provides a data foundation for population-based epidemiological research and precision prevention [97]. From a socioecological perspective, comprehensive myopia prevention requires coordinated participation by government agencies, schools, healthcare institutions, families, and wider society. This five-sector collaborative network has been proposed as a basis for more coordinated prevention efforts [98].

6. Conclusion

Taken together, the evidence supports increasing time spent outdoors as an important strategy for reducing myopia onset, particularly among children who are not yet myopic. Physical activity, including moderate-to-vigorous activity, is a promising complementary target, but its independent contribution beyond outdoor light exposure remains uncertain. Potential pathways include light-related dopamine signaling and possible influences on ocular hemodynamics, metabolic regulation, scleral remodeling, and central nervous system function. Evidence for several of these mechanisms comes from animal models or studies of other ocular conditions, rather than direct studies of children with myopia. Reducing the benefits of outdoor activity to a form of "light therapy" may therefore overlook the possible contributions of physical activity and related behavioral changes, but synergistic or independent causal effects require direct testing.

A critical appraisal of the evidence calls for balancing the overall promise of physical activity against important unresolved questions. Epidemiological evidence consistently associates longer outdoor exposure with a lower incidence of myopia, especially in children who are not yet myopic. Evidence that increased outdoor time slows progression among children who already have myopia is less consistent. The optimal intensity and dose of physical activity, and its contribution beyond measured light exposure, remain insufficiently understood and require mechanistic studies and high-quality randomized controlled trials. Public health recommendations to increase outdoor time can be implemented while research continues to clarify the biological processes and the specific contribution of physical activity.

Technological advances, particularly the integration of smart wearable devices with machine-learning algorithms, offer promising tools for addressing these challenges. Such technologies enable long-term, objective, and multidimensional monitoring of physical activity and visual behaviors, providing a foundation for individualized risk prediction models and dynamic feedback loops for intervention. These developments may facilitate a transition in childhood myopia prevention and control from broadly applied public health recommendations toward data-driven, precision-oriented health management.

The COVID-19 pandemic highlighted the vulnerability of children's visual health to changes in daily environments and behaviors. Stay-at-home restrictions reduced time outdoors

and increased exposure to prolonged near work, and several studies reported accelerated myopic shifts or changes in myopia prevalence during home confinement [52-54,83,87]. This experience underscores the need for integrated prevention strategies. Continued investment in multidisciplinary clinical and basic research is needed to strengthen the evidence base for physical activity interventions. Research findings should be translated into practical, evidence-informed physical activity and outdoor-time guidance and disseminated through schools, communities, and families. Ultimately, an integrated lifestyle-support system should combine sufficient physical activity, appropriate outdoor light exposure, healthy visual behaviors, and regular eye-health screening. Coordinated research, policy, and practice are needed to create environments that support children's visual health and shift emphasis from treating established disease toward preventing onset.

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