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A Comprehensive Study on Improving Contact Lens Performance Through Various Approaches

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Abstract

Contact lenses improve vision quality by correcting refractive errors and thus provide a convenient alternative to traditional eyeglasses. Apart from vision enhancement, they have multiple applications in cosmetics, drug delivery, and therapeutic use. The performance of these lenses depends on various factors such as material, design, fitting, and interaction between the lens and the eye. The selection of appropriate materials is crucial for maintaining optimal eye health. Properties like oxygen permeability, biocompatibility, and moisture retention improve long-term wear comfort and prevent complications like dryness or irritation. Moreover, proper fitting and precise lens design is essential for enhancing lens performance to achieve a sharp, clear, and undistorted vision. Advances in computational and mathematical modeling such as finite element analysis, eye biomechanics, drug delivery mechanisms, and tear film or lubrication dynamics have significantly improved lens performance. Despite these advancements in lens technology, there is still a limited understanding of effective modeling and analysis to optimize these parameters to improve lens performance. This paper explores the critical aspects of lens design, focusing on material selection and performance parameters, and investigates the multifaceted modeling and analysis approaches to improve lens performance. This offers valuable insights into the development of contact lenses across various applications, from everyday use to specialized medical needs.

Keywords: Contact lens, material, lens performance, modeling, analysis

INTRODUCTION

Contact lenses (CLs) are thin optical devices, placed directly on the outermost layer of eye, called the cornea [1]. They are preferred over eyeglasses for several reasons, including cosmetics, aesthetics, and therapeutic purposes [2]. CLs move along with the eye, and provide a more accurate and consistent focus, leading to a stable and clear vision with few visual distortions [3]. They provide solutions for common refractive errors, including astigmatism, farsightedness, nearsightedness, and presbyopia [4]. Moreover, a few corneal irregularities, such as keratoconus, aniseikonia and aphakia, are usually better treated with CLs than eyeglasses [5].

As a result of the diverse applications of CLs, the design and fitting of these lenses have become increasingly important, particularly for patients with complex visual needs or high prescription requirements. For such individuals, even slight deviations in the lens parameters can significantly impact vision quality. Therefore, precise lens fit and optimal design are essential for enhancing vision by addressing challenges such as lens discomfort, corneal abrasion, redness of eyes, dryness, irritation, and the risk of eye infections [6]. To ensure the accuracy and effectiveness of these lenses, various parameters must be considered,

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including material properties, optical parameters, lens fit and alignment, surface design parameters, friction, wear, and comfort [7]. Additionally, modeling and analysis play a significant role in optimizing lens performance by providing a deeper understanding of the eye-lens interactions and enhancing these dynamics to improve the wearer's comfort. This assists in simulating the interactions between lens and cornea, predicting their performance, and analyzing their long-term effects on eye health to develop more effective and accurate lenses to meet the visual and comfort needs of patients with specialized requirements.

OVERVIEW OF CONTACT LENSES

Contact lenses are usually categorized based on purpose, anatomical placement, material, design, water content, and wearing schedule [8]. They offer diverse applications, including vision correction, aesthetic enhancement, and medical treatment [9]. Like eyeglasses, they help to refract and focus the light for better vision (as illustrated in Figure 1) [10,11]. However, they move naturally with the eye, offering some benefits over eyeglasses. Despite their advantages, many wearers experience discomfort, such as dryness or irritation, particularly after prolonged use. Improper fitting of CLs also leads to severe complications, such as infections or even long-term damage to the eye surface.

Although CLs have been in use for decades, such issues indicate that there are still limitations in their design and material, leading to user discomfort. The scope of CLs has expanded beyond vision corrections to therapeutic uses, driving the need for more advanced materials and innovative approaches for CL technology in the medical field. This highlights the importance of optimizing CL performance to enhance the wearer's comfort.

MATERIALS

The key factors to be considered when selecting contact lenses include the lens material, wettability, oxygen permeability, moisture content, radius of curvature, and refractive properties of both the lens and the surrounding environment [12].

The selection of appropriate material is crucial for enhancing lens performance, improving vision effectiveness, and addressing environmental concerns. An ideal material should possess excellent visual properties, biocompatibility, oxygen permeability, moisture retention, and sustainability. Based on the material and nature of the lens, contact lenses are mainly classified as soft and rigid, with hybrid lenses as an alternative option that combines the features of both soft and rigid CLs.

The most common soft CLs are the hydrogel and silicone hydrogel lenses. They are composed of water-based plastic materials that soften the lens by absorbing moisture when hydrated with water or lens solution [13,14]. Hydrogel lenses are made up of gel-like water-containing polymers that are highly flexible due to their water content, providing better comfort compared to rigid lenses. Therefore, hydrogels are considered most suitable for sensitive eyes due to their biocompatibility with the human eye [15]. However, water in these lenses can evaporate slowly after prolonged hours of wear or in dry environments, causing the material to become drier and less comfortable for the wearer. These lenses also limit oxygen permeability, causing issues like red eyes, corneal swelling, and discomfort.

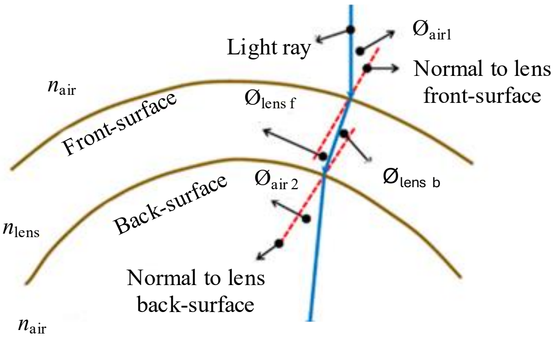

Figure 1. Refraction process through soft contact lens [10].

For this reason, silicone hydrogel lenses developed as an advanced option. They incorporate polydimethylsiloxane (PDMS), a silicon-based material that significantly enhances oxygen permeability, making these lenses more suitable for extended wear by allowing more oxygen to reach the cornea, thus reducing frequent replacements. This reduction in replacement frequency can help address the environmental impact of disposable lenses by minimizing their frequent disposal. However, silicone hydrogels tend to increase the accumulation of protein and lipids compared to hydrogels, reducing the water content in the lens and potentially affecting comfort. Moreover, Silicone breaks down slowly, releasing microplastics into the soil and water, leading to environmental impacts. Currently, PDMS is the most commonly used material in such lenses, while materials like tris (trimethylsiloxy) methacryloxy propyl silane (TRIS) are being explored for further improvements in oxygen permeability and mechanical stability [16].

Another type of contact lenses are the hard or rigid CLs, often known as Rigid Gas Permeable (RGP) lenses, which offer sharper and clearer vision than soft lenses. They are made from less flexible polymer materials and are primarily used for correcting refractive errors and vision-related problems [17]. Conventional hard contact lenses initially used polymethyl methacrylate (PMMA), a rigid plastic material. While PMMA is inert and biocompatible, it acts as a barrier to oxygen, making these lenses less oxygen-permeable. As a result, they are made smaller to cover the lesser eye’s surface. Additionally, a gap is provided between the lens and cornea for tear fluid exchange to supply oxygen. This design makes them less comfortable for wearers [18].

In contrast, modern RGP lenses use a flexible plastic containing fluorocarbonate (fluoromethacrylate siloxy copolymer), which is highly oxygen-permeable. This material not only enables oxygen flow but also enhances the comfort and durability of the lens, making it an ideal choice for addressing complex vision-related issues such as corneal irregularities. These lenses have largely replaced PMMA lenses due to their superior oxygen permeability and lower tendency for tear film deposits. However, they require a longer adjustment period than other lenses [19].

Moreover, the non-biodegradable composition of CLs contributes to significant environmental challenges. Commonly used materials like hydrogel and silicone hydrogel, used in these lenses, led to plastic waste, causing pollution in the ecosystems. Improper disposal further exacerbates this issue by causing accumulation of microplastic waste in the landfills, thereby increasing environmental pollution.

Addressing these issues requires sustainable innovations in lens design to reduce their environmental impact. Researchers are exploring biodegradable alternatives like hydroxypropyl cellulose (HPC), a cellulose derivative-based hydrogel that offers both user comfort and sustainable benefits [20]. However, these lenses face challenges, like optical performance concerns, high production costs, and durability limitations. Another approach involves recycling, processing, and reusing disposable lenses into other products. This significantly assists in reducing waste, providing a more sustainable solution to lens disposal.

Hybrid contact lenses are the latest and most advanced option that combine the technology from both rigid and soft lenses. They provide comfort of wear with sharp and clear vision, making them a suitable option. Currently, these lenses are highly favored for their superior oxygen permeability, ensuring excellent comfort for extended wear that assists in environmental waste reduction by minimizing frequent disposals. This unique combination ensures a perfect balance between the comfort provided by soft lenses and the sharp vision offered by rigid lenses [21].

Advancements in materials have significantly improved the functionality and comfort of CLs. Hydrogel lenses, known for their flexibility, provide enhanced biocompatibility with the eyes. Silicone hydrogel lenses further advance this by incorporating polydimethylsiloxane (PDMS) to ensure more oxygen permeability for cornea [16]. Hybrid lenses provide visual clarity with superior comfort by combining the best features of both soft and rigid lenses. Moreover, biodegradable materials are emerging as a sustainable alternative that helps in addressing the environmental impact of CLs. These advancements not only enhance the wearer's comfort but also provide a way for secure, effective, and sustainable CL technology.

Table 1 represents the lens materials currently in use and for future applications in contact lenses. This provides a comprehensive view of the current and future aspects of CL materials.

CONTACT LENS MODELING

Mathematical and computational models provide a foundation for more effective contact lens solutions, assisting in visual acuity and overall comfort of contact lenses. They play a significant role in simulating lens behavior on the eye, including lens deformation, mechanical interactions, tear exchange, and tear film dynamics, that provide comprehensive insights into the performance of contact lenses. One important factor in lens performance is the ability to allow oxygen to reach the cornea. Oxygen flux models help in accurately estimating the amount of oxygen reaching the eye while wearing CLs. One such study developed a mathematical model to estimate oxygen flux through CLs that provides valuable insights into the physiological effects of lens wear. This model helped to understand how the amount of oxygen delivered to the cornea impacts both comfort and eye health, highlighting the importance of adequate oxygen supply for maintaining optimal ocular conditions [31]. Advanced modeling techniques integrating a spreadsheet model with corneal topography were investigated, which help in predicting lens fit and highlight the role of ocular parameters like corneal radius in the determination of lens tightness [32]. Another study focused on the optical impacts of varying vaults in scleral lenses, using computational simulations to assess image quality across different spatial frequencies. This assists in optimizing lens performance for vision corrections [33].

Table 1. Summary of Lens Material, Characteristics and Usage.

Material	Type	Characteristics	Current usage	References
Poly(methyl methacrylate) [PMMA]	Rigid	poor oxygen permeability rigid, durable, biocompatible	Earlier Used	[22]
Poly(2-hydroxyethylmethacrylate) [PHEMA]	Soft	durable, light-weight, high oxygen permeability	Widely Used	[22,23]
Polydimethylsiloxane [PDMS]	Soft(Silicone-Based)	high flexibility, high oxygen permeability	Commonly Used	[23]
tris (trimethylsiloxy)methacryloxy propyl silane [TRIS]	Soft(Silicone-Based)	biocompatible, lower water content, high oxygen permeability	Under Development	[24]
Fluorocarbonate (fluoromethacrylate siloxy copolymer)	Rigid Gas Permeable (RGP)	oxygen permeable, biocompatible, good wettability	Under Development	[25]
Cellulose acetate butyrate [CAB]	Rigid Gas Permeable (RGP)	less durable, oxygen permeable, improved wettability	Earlier Used	[26]
N-vinylpyrrolidone [NVP]	Soft	limited oxygen permeability, high evaporation rate, increased water content	Commonly Used	[27]
Methacrylic acid [MAA]	Soft	improved wettability, increased water content	Commonly Used	[28]
N,N-dimethylacrylamide[DMA]	Soft	oxygen permeable, biocompatible, improved wettability	Widely Used	[29]
Amphiphilic co-networks [APCNs]	Soft(Silicone-Based)	high flexibility, high oxygen permeability	Under Development	[30]

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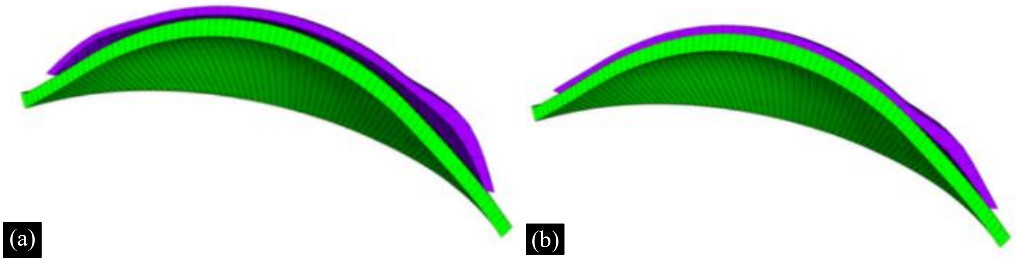

Figure 2. Finite element model of contact lens (purple) and cornea (green) Before (a) and After (b) Fitting [10].

Another study [10] evaluated the variation in optical power during the fitting of soft CLs using different hydrogel materials for both spherical and cylindrical lens designs. Four hydrogel materials were tested under varying loading conditions using uniaxial tensile tests. Additionally, finite element models simulating cornea-lens interactions (as illustrated in Figure 2a and b) were generated for lenses with powers ranging from -10 D to +20 D. The results indicated a strong inverse correlation between the effective power change (EPC) and lens power, particularly at higher powers. Stiffer hydrogels were more resistant to EPC for lower power ranges, while at higher powers, the material's impact was less significant. This highlights the role of material selection in enhancing lens performance across different power ranges.

A viscoelastic corneal model was developed to study the impact of air puff-induced vibrations on corneal health and intraocular pressure [34]. Surface roughness modeling of contact lens polymers under various conditions helped improve the machining accuracy of CLs by providing valuable insights into contact lens interaction with the cornea and eye [35]. This assists in a better understanding of mitigating potential risks that are associated with long-term wear, including corneal damage and discomfort.

CLs with UV-blocking properties provide better protection against harmful ultraviolet (UV) radiations that cause cataracts and other ocular diseases. An in vitro method was developed to analyze the impact of UV radiations on human corneal epithelial (HCE) cells in order to evaluate their protective effects. The study demonstrated that these UV-blocking CLs significantly reduced the production of reactive oxygen species (ROS) and improved cell viability, highlighting their potential to protect the cornea from UV radiation damage [36].

Moreover, drug release through CLs using in vitro models is an emerging field in ocular ophthalmology that plays a significant role in treating eye conditions such as dry eye syndrome. Traditional vial methods using conventional hydrogels released more drugs that highlight the need for more effective drug delivery systems [37]. A study involved developing a microfluidic cell to simulate tear fluid flow, which assists in a more accurate drug release estimation [38]. Mechanistic models were developed to predict drug concentration over time that provide a tool for optimizing ocular drug delivery [39]. This highlights the potential of CLs as drug delivery systems in enhancing drug release consistency, particularly for treating chronic eye conditions and exploring new materials for improved drug retention and release.

LENS PERFORMANCE PARAMETERS

To improve the performance and fit of contact lenses in the user's eyes, various parameters have been introduced such as material properties, lens design, wear, and optical factors. Material properties involve oxygen permeability (Dk), hydrophilicity, and biocompatibility. For improving comfort, clarity, and corneal health these parameters were evaluated on various silicone hydrogels. The results obtained from the testing of one to six parallel-sided lenses revealed that two hydrogel materials met the desired oxygen permeability (Dk) intervals, 162.0 ± 9.8 and 107.4 ± 7.4 [40]. Another study showed, that

Lotrafilcon A, a biphasic block-copolymer combining silicon with a hydrogel water phase, is highly effective in preventing overnight developed corneal swelling [41]. To enhance the wettability of lenses, different artificial tears having varying levels of hyaluronic acid (HA) and tear film surface were investigated using Medmont E300, videokeratoscope, and regression model, which showed that hydrogel lenses have better wettability than silicone [42].

Geometrical features such as overall diameter, base curvature, optic zone diameter, edge configuration, refractive power, thickness, and tint are essential for improving lens performance (as illustrated in Figure 3) [10, 43]. To study their impact, a trial was done on 100 patients, projecting different base curve radii and lens movement. The overall fit was monitored using a slit lamp, and it predicted that lenses having stepper base curve radii (8.4 mm) were more favored by users than flatter lenses (9.0 mm) [44].

The optical coherence tomography (OCT) technique measures the edge shape and base curve radii using an image processing algorithm. A study examined the back optic zone radius of a CL within the tolerance range of ± 0.05 mm [45]. Further investigations analyzed several parameters including, back optic zone radii between 8.2 mm and 9.0 mm, different back surface designs (monocurve, bicurve, and aspheric), edge thickness ranging from 0.12 mm to 0.24 mm, and back vertex power from +1.0 D to −6.0 D. The results showed that edge thickness had minimal impact on comfort. However, lenses with flatter back optic zone radius were less preferred over steeper lenses, and correspondingly monocurve lenses were also rejected in favor of bicurve or aspheric lenses due to poor centration issues. This study showed that geometric considerations investigated using various modeling and OCT techniques, increase the fit of contact lenses when analyzed through careful survey [46].

Moreover, mathematical models using data from 163 subjects investigated the relationship between lens diameter and base curve (BC) radius. The study assessed edge strain from 0% to 6% and horizontal corneal overlap between 0.2 mm and 1.2 mm. The results showed that a success rate of 90.2% was achieved for a medium strain of 3.2% with an 8.6/14.2 mm (BC/diameter) design [47].

An ideal CL fit greatly enhanced wearer comfort, as highlighted by the study investigating the impact of fitting characteristics and 3D topography on Rigid Gas Permeable (RGP) lens comfort [48]. Some studies utilized finite element models to explore the effect of lens parameters, lens diameter and base curve on effective power change (EPC), particularly for extreme prescriptions [49].

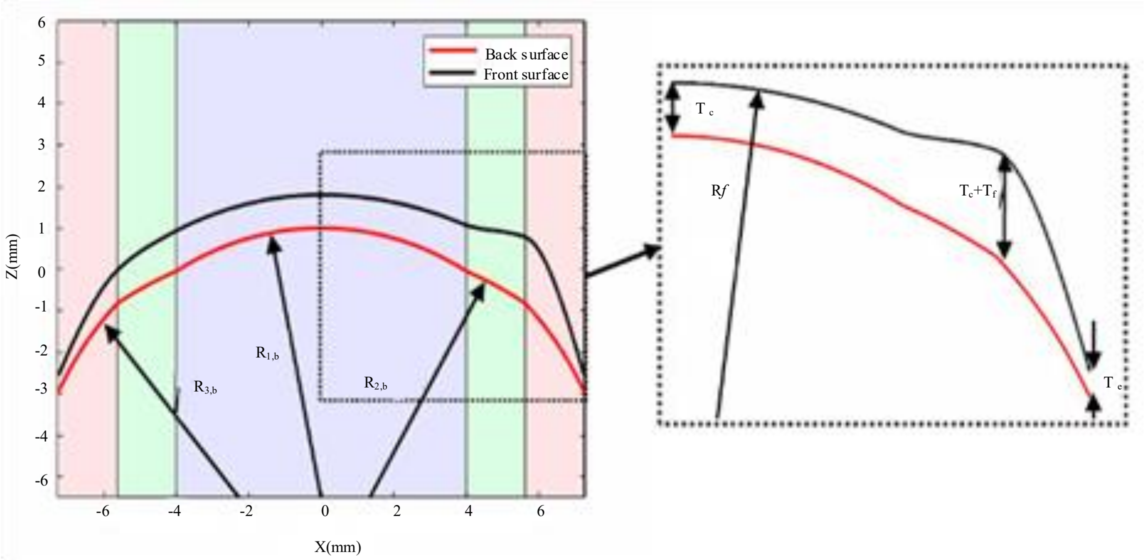

Figure 3. Geometric parameters in contact lens design: optic, transient, and peripheral zones [10].

Centration, movement, and corneal coverage are also considered important factors for reducing discomfort and irritation in the eyes [50]. A study analyzed two categories of soft lenses with significant differences ($p < 0.001$), used by various subjects. The investigations showed that vertical gaze lagged considerably compared to horizontal gaze. The push-up recovery rate during blinking provided additional insights into overall lens dynamics, as silicone hydrogels demonstrated less centration and faster push-up recovery than HEMA for the same $p < 0.05$ [51].

Additionally, the position of the eyelid, blinking patterns, and tear film quality are crucial for RGP lens fitting [52]. These factors should be considered for lens fitting to achieve better results with a more sophisticated fit. The tear film exhibits surface tension and viscosity, allowing the contact lens to adhere to the cornea surface. Furthermore, the mucus on the conjunctival surface interacts with the lens, facilitating tear fluid distribution over the surface and ensuring it remains adhered to the corneal surface [53].

Different lens materials significantly affect the lubricating properties of eye drops in contact with the lens material and thus impact the lubricant’s effectiveness [54]. Based on these findings, different hydrogel materials were examined through tensile testing. The results indicated stiffer hydrogels to be more resilient to EPC for lower-power lenses [10]. Mathematical models were investigated to simulate fitting success rates across different lens design parameters that revealed a substantial variation in theoretical success rates based on factors such as eye shrinkage and selection of lens diameter and base curve (BC) [55].

Therefore, when selecting contact lenses, various factors must be considered, including eye health, usage, materials, design, fit, and geometric specifications. The selection procedure requires careful balancing of these factors to ensure the lens maintains eye health and comfort with effective vision correction. For instance, individuals with refractive errors like astigmatism significantly benefit from toric lenses, as these lenses are particularly designed to correct the curvature of the lens or cornea for better comfort and improved visual clarity [56]. Hence, by considering both general lens requirements and specific conditions, an ideal balance can be achieved to enhance the quality of vision and overall eye health.

Moreover, personalization in the material, curvature, and design of CLs plays a significant role in improving their performance by tailoring them to the specific needs of the wearer. Optimizing curvature reduces discomfort, irritation, and lens movement, improving its fit and alignment with the cornea. For instance, steeper base curve radii are often favored, as they reduce corneal strain and provide better centration [46]. Material selection is equally important, impacting the comfort, safety, and performance of CLs. Different materials provide distinct properties to meet specific requirements, ensuring vision correction with optimal eye health. Materials like silicone hydrogels enhance corneal health and prevent complications like corneal swelling and dryness due to high oxygen permeability [15]. Lotrafilcon A, a biphasic block-copolymer, consisting of silicone for oxygen permeability and a hydrogel phase for moisture retention provides a balance between comfort and performance [41]. Design customization, including curvature, edge configuration, optic zone diameter, and surface profile (monocurve, bicurve, and aspheric), further enhances fit, comfort, and vision clarity. These adjustments contribute to a more personalized experience for wearers, offering superior optical performance with greater comfort [43].

Thus, personalization ensures that CLs meet specific visual and physiological requirements, leading to improved comfort, better eye health, and enhanced optical performance.

FRICTION AND WEAR ANALYSIS

The tribological properties of contact lenses, particularly friction and wear, are crucial for understanding lens interactions with the corneal surface over time. High friction between lens and eye can lead to discomfort and irritation, while increased wear can damage the cornea, increasing the risk of eye infections such as conjunctivitis, swelling, blurred vision, etc. To investigate these effects, various soft CLs were examined using a tribometer and a mass-spring system to measure horizontal vibrations. The results showed that silicone hydrogel lenses provide more comfort as they dissipate less energy and have a lesser coefficient of friction than hydrogel lenses [57]. In another study, the impact of different lubricants' viscosity on lens friction was assessed. Assuming different eye conditions, different sliding velocities and normal loads were applied, and the results showed that even low concentrations of hyaluronic acid can significantly reduce friction and increase comfort. However, there is a need for more research to understand the impact of friction and wear on the ageing of soft contact lenses [58].

The friction behavior of the commercially available Etafilcon A lens was also analyzed under varying contact pressure and speeds using a model (as illustrated in Figure 4) incorporating viscoelastic dissipation and interfacial and viscous shear. This model was calibrated with experimental data for more accuracy (as illustrated in Figure 5). The results indicated that most frictional forces arise from the viscoelastic properties of lens material and interfacial shear. This study provides insights for improving the comfort and safety of CLs by understanding and mitigating friction-related issues [59]. Another study investigating the frictional properties of Senofilcon A lenses confirmed that friction behavior is primarily influenced by solid-solid contact [60]. Modeling lubrication dynamics during blinking further emphasized the importance of fluid film in improving lens comfort highlighting the need for friction and lubrication optimization in lens design [61].

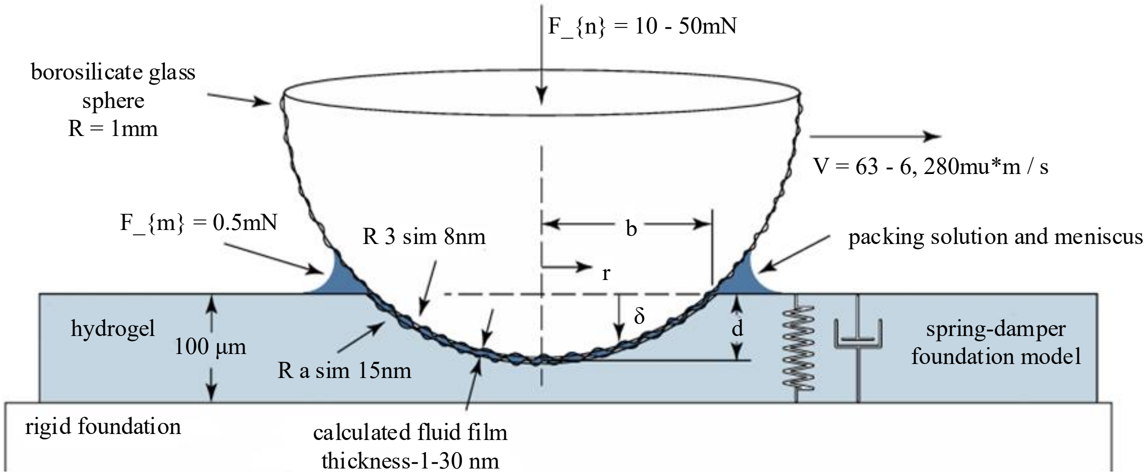

Figure 4. Modified Winkler Foundation Model showing: Meniscus, Lens Thickness, Fluid Film Thickness and Surface Roughness [49].

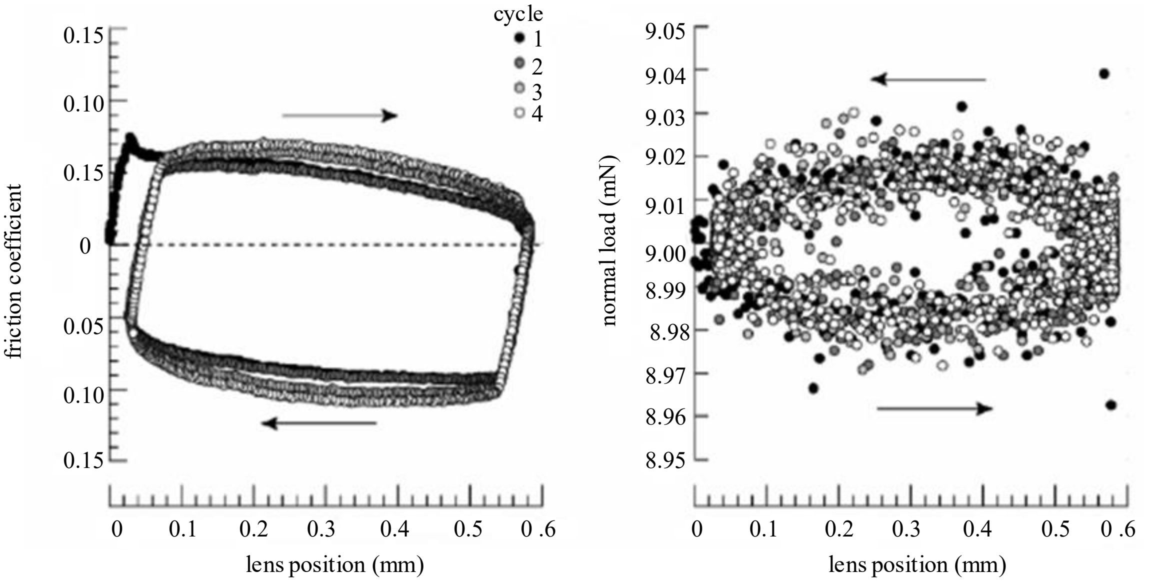

Figure 5. Analysis of friction coefficient and normal load variations in contact lens sliding tests [49].

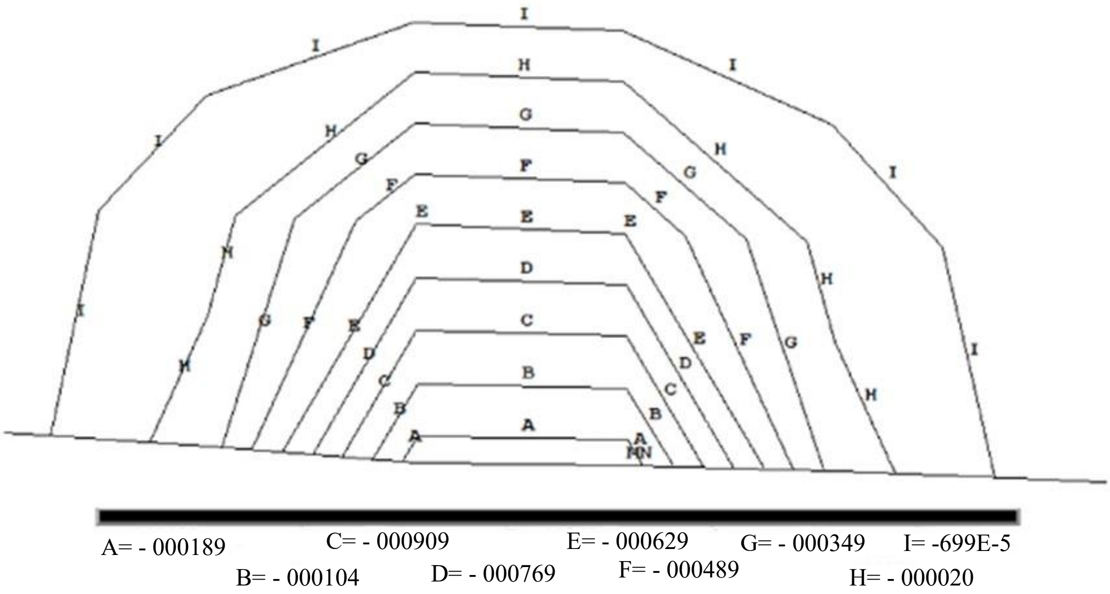

Figure 6. Analysis of wear levels in contact region [52].

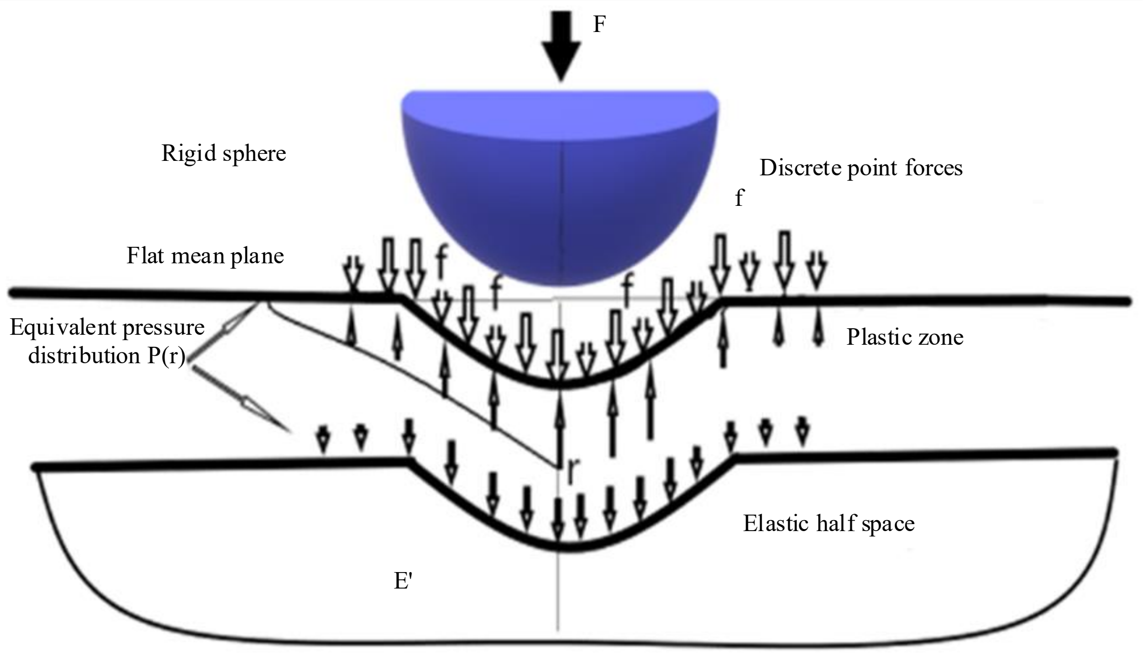

Figure 7. Representation of 3D wear system model [52].

Additionally, FEM was utilized to analyze the biomechanical behavior of the cornea, particularly under conditions like keratoconus. The study investigated the impact of eye rubbing and wear patterns (as illustrated in Figure 6) through simulations on the cornea. The results showed that von Mises stress and contact pressure was maximum at contact points, causing the keratoconus cornea more susceptible to wear (as illustrated in Figure7). This study highlights the effectiveness of FEM in modeling complex structures like the cornea, offering a significant tool for evaluating and understanding corneal disorders, thus providing valuable insights in wear analysis [62].

CONCLUSIONS

A comprehensive investigation of various approaches helps in a deeper understanding of factors affecting contact lens performance and corneal health. These approaches have focused on lens material, design, and physiological impacts to improve the comfort, safety, and performance of contact lenses. Based on these investigations, silicone hydrogel lenses were found more effective in providing comfort and reducing friction compared to hydrogel lenses. Hyaluronic acid has further improved the wearer's comfort by reducing friction. Additionally, computational and mathematical models, including viscoelastic modeling, drug delivery mechanisms, finite element analysis (FEA), and lubrication dynamics, have advanced the understanding of lens parameters under varying conditions of pressure, velocity, and corneal biomechanics. Future research should focus on further refining these models to effectively simulate real-world conditions by incorporating factors like surface roughness and more personalized techniques to address individual wearer's need, particularly for long-term use and specific eye conditions. Advancements in biotechnology, material science, and digital health have shown promising future directions in therapeutic innovations, sustainability, and enhanced functionalities. To address environmental concerns, research should focus on exploring biodegradable materials like plant-based alternatives or biopolymers produced through energy-efficient sustainable methods. Additionally, developing CLs by integrating smart technologies with controlled drug release mechanisms, such as biosensors for real-time monitoring of parameters like intraocular pressure, could significantly improve their functionality for therapeutic applications. Moreover, efforts are required to identify materials that further improve biocompatibility, oxygen permeability, lubrication, and friction reduction, ensuring long-term comfort with reduced risk of corneal damage.

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