Equilibrium modeling increases contact lens comfort

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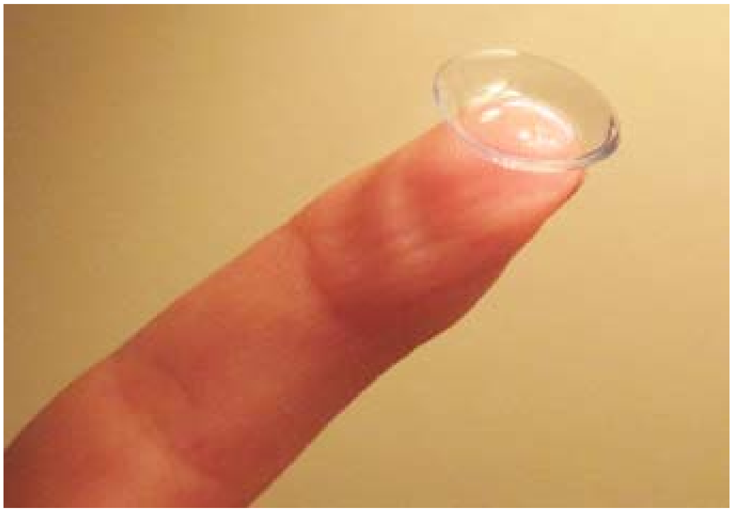

David Ross, Kara Maki, and Emily Holz design an equilibrium model to enhance the design and increase the comfort of contact lenses. Credit: Lina Sorg

According to the Vision Council of America, roughly 75% of adults in the United States require some form of vision correction. Yet only 10% of Americans wear contact lenses. Studies estimate that one in four initial contact-users finds the lenses uncomfortable and stops wearing them. Thus, increasing the comfort level of contact lenses and expanding the market is a continual objective in the vision industry.

In order to understand the factors that contribute to lens comfort, it is important to study the solid and fluid mechanics of a lens' interaction with an eye. In an article publishing this week in the *SIAM Journal on Applied Mathematics*, authors David Ross, Kara Maki, and Emily Holz design an equilibrium model to demonstrate the elastic stresses and suction pressure distribution between a soft hydrogel contact lens and an eye. The model allows arbitrary (radially-symmetric) lens shapes, eye shapes, and thickness profiles, and illustrates the dependence of pressure distribution on lens and eye shape. "The important thing about our model is that it identifies, and expresses mathematically, the essential elements that balance when a contact lens is in equilibrium: radial tension, hoop tension, and suction pressure," says Ross. "We established that other effects—like bending stresses and viscous stresses at the interface of the lens and the tear film—are negligible."

A contact lens acts as a suction cup on the eye. In any suction cup, a thin lubrication layer separates the two solids, at least one of which is deformed by the suction. In this case, the lens distorts its shape when placed on the eye, immersing itself in the naturally-occurring, thin post-lens tear film that acts as the lubrication layer and holds the lens in place. "The post-lens tear film transmits to the eye the normal stresses that deformation establishes in the contact lens," says Maki. This sustains the deformation. When the lens is at equilibrium, the suction pressure—which pushes or pulls the lens towards or away from the eye—integrates to zero and generates no net force on the lens; for the desired equilibrium to occur, pressure must balance with radial and hoop tension.

"The suction pressure is the only mechanical influence of the lens on the eye in equilibrium," says Ross. "So understanding it is essential to understanding how to design for comfort. During and after blinks there's also shear stress exerted by the tear film on the eye; but to understand that, we need to understand suction pressure."

Maki and Ross designed the model in 2014 for practitioners in the field of contact lens design. Now, along with Holz, they introduce a preliminary mathematical analysis of that model. "The model in the form we present in this paper is virtually identical to the model we originally derived by force balance," says Ross. "Good modeling practice in mathematical physics requires that you try to understand problems both from the force balance and the energy-minimization, or variational, perspectives. We wanted to find, apply, and analyze the variational formulation because it enriches the account of the application field problem."

Maki and Ross's first paper on this subject presented computational results. Subsequently, Holz computed numerical solutions of the equations, which helped the authors understand the structure of solutions and their reliance on input data. "We used our code to study the dependence of suction pressure distributions on eye and lens shapes," says Holz. "These studies were the starting point for the theoretical investigations whose results are presented in this paper."

Analysis of the model reveals telling results about lens thickness and pressure distribution, both of which affect comfort. "The biggest takeaway is that mundane-seeming application problems—a hydrogel lens is really just a suction cup—can yield tough math problems," says Maki. "While we're pleased with the crispness of our formulation, the problem is a singular, complicatedly-nonlinear, two-point boundary-value problem." The existence of a solution to this boundary problem depends on lens thickness; in some cases, no solution exists. Ultimately, the varied solutions—or lack thereof—confirm the influence of lens thickness and eye and lens shape in the model.

Ross *et al*. hope to use their model's results to reevaluate contact lens design and comfort, and are already working to put this into action. "We're working with collaborators at Bausch & Lomb to understand how the details of suction pressure profiles correlate with comfort," says

Maki. "Then we can address the inverse problem of designing lens shapes and thickness profiles for optimal comfort." Increased comfort in contacts may also lend itself to novel applications of the lenses themselves, including drug administration (to treat glaucoma, for example), metabolic monitoring, augmented reality techniques, and sensory enhancement.

The authors are trying to generalize their model by eliminating the constraint of radial symmetry in the lens. "With asymmetric lenses suction pressure gradients in the post-lens tear film can drive flows that exert net shear stresses on lenses," says Ross. "We're generalizing our model to capture the motion of a lens over the course of a blink cycle."

Maki and Ross will present further advances in this research during a session on ocular modeling at the SIAM Conference on the Life Sciences in Boston this summer.

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