Research Article

Accommodative Haptics Study Based on Flexible Amplification Mechanism

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ABSTRACT

In this study, we take the effect of the anterior movement of the optic into account and propose a novel haptic based on lever-type and bridge-type flexible amplification mechanisms. Based on the consideration of the offset of the rotation center of the flexible hinge, we have deduced the formula for calculating the amplification ratio of the proposed four-stage amplifier. The geometric parameters and the material property parameters, in terms of the clinical measurement data of the human eye, are assumed to restrain the structural features and motion trajectories for the amplifier. As the ciliary muscle achieves the contraction limit, the output displacement and amplification ratio reach the highest and lowest values, separately, and gradually approach a stable range. The amplification ratio of formula calculation and FEA (Finite Element Analysis) are around 18.86 and 17.79, respectively, with the input displacement ranging from 0.115mm to 0.127mm. The error of the amplification ratio between theoretical method and FEA is less than 5%. The presented haptic acting as a four-stage displacement amplifier, enables an improved lens power of 3.80 diopters to obtain much more focus shift to achieve a better near visual performance for patients.

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Introduction

Many of the neopathy of cataract treatment have been solved through the evolution of surgical technique and intraocular lens (IOL) technology, but the problem of loss of sufficient adjustable lens power in pseudophakic patients remains baffling [1, 2]. Increasing range of accommodation is the ultimate goal of cataract surgery to restore unaided distance and near vision. A variety of methods to recover near vision are available, including contact lenses correction, scleral expansion techniques, and refractive or diffractive multifocal IOLs [3]. Although acceptable to restore near vision, the vision function of multifocal IOLs obtained is subject to deliberate due to the problems of optical aberrations and contrast sensitivity decrease. An alternative approach using the “focus shift” principle is proposed by an enhancement in effective lens power [4]. IOLs have been developed with a modified haptics design that allows the optic to move forward in connection with the haptics on accommodation as a result of the transmission of ciliary muscle contraction to the capsular bag [5].

To date, three IOLs are commercially available: the AT-45 Crystalens (Eyeonics Vision, Aliso Viego, California, USA), the Tetraflex (Lenstec, St. Petersburg, Florida, USA), and the 1CU (Human Optics, Erlangen, Germany). These IOLs differ in their haptics design and material. The movement of such IOLs has been investigated with clinical performance research. Crystalens AT-45 IOL, featuring two hinged haptics with a small 4.5mm diameter silicone optic and an overall diameter of 12.5mm, achieves a mean accommodative amplitude of ~1.25-3.50 diopters [6]. The Tetraflex IOL, with an angle of 5-degree between haptics and optic, obtains an accommodative amplitude of (1.85 ± 0.12) diopters at 3 months [7, 8]. 1CU IOL is a single-piece hydrophilic acrylic IOL with 5.5mm optic and four symmetrical square haptics to allow even anterior movement of the optic. Accommodative amplitude is approximately (1.90 ± 0.80) diopters at 6 months and (0.30 ± 0.20) diopters after second year [9]. The IOLs appear to produce increased near vision, but they do not work well in eyes where there is a distinction between subjective reading performance (at least 3.00 diopters) and the improved accommodative amplitude.

In this study, we take the effect of the anterior movement of the optic into account and propose a novel haptic based on a lever-type flexible amplification mechanism. The proposed haptic acting as a four-stage displacement amplifier enables a higher displacement amplification ratio, improved lens power and better near visual performance for...
patients. In order to accurately describe the amplification ratio, an analytical model in terms of the rotation center deviation of the flexure hinge is established [10, 11]. Moreover, the effectiveness of compliance features of flexure hinges, mechanism dimension and amplification ratio are validated with finite-element analysis (FEA) and experimental studies in the current research.

Materials and Methods

The schematic diagram of the IOLs (Crystalens AT-45, Tetraflex, 1CU, respectively) with accommodative function are depicted in (Figures 1a-1c). The proposed IOLs interact with ciliary muscles, using hinged or angled haptics and at both ends to catch on and move forward. Once driven with an input displacement, the haptics produce an amplified vertical output displacement along the anterior direction for the optic. Thus, the problem of haptic design can be taken as amplifier design, where the contraction of ciliary muscles is employed as driven, and the haptic is the amplifier.

At present, many of the displacement amplifiers using different principles with flexure hinges have been implemented in field stretches from precise servo systems, active isolation, and biological science [12-14]. Lever-type mechanism is the most common one [15-17]. In addition, bridge-type, four-bar linkage and Scott-Russell mechanisms are also frequently used [18, 19]. A diamond micro-displacement amplifier is here shown to achieve both the displacement amplification and two-way outputs [20]. Although the error was reduced, the displacement amplification ratio is only around 2.5, which is not large enough for the requirement of haptic design. A flexure-based amplifier with 3 degrees of freedom is indicated, but it needs much more space to operate [21]. Parallel compliant amplifiers with two-axis linear motion are designed for ultra-precise motion [22]. Pei et al. proposed a large-displacement straight-line flexural mechanism with rotational flexure joints for precision applications [23]. Suitable shape for the capsular bag is of significance besides high amplification ratio, linear and multi-direction motion, as well as limited operating space.

As shown in (Figure 1d), the novel accommodating IOL is put at the center of the capsular bag with ciliary around. Haptic incorporates a

![Image]

Figure 1: Accommodating IOLs: a) Crystalens AT-45 IOL has 2 hinges on each haptic; b) Tetraflex IOL has four symmetrical square haptics to increase stability, c) with a 5-degree angle, 1CU IOL obtains further anterior displacement; d) in the novel accommodating IOL, there is a couple of antisymmetric four-stage amplifiers combined with an optic at each output terminal (i.e. the end of the fourth lever).
couple of antisymmetric four-stage amplifiers, where the optic is settled in the middle. Here, we assume the material of the optic is hard enough to avoid structural deformation. According to practical requirements, a three-stage lever-type amplifier (comprised of three vertical levers named first, second and third lever, and two horizontal connecting links) and a single-stage bridge-type amplifier (the fourth lever with 5-degree angle to the lever-type amplifier) are performed to develop the spatial four-stage amplifier to achieve even higher accommodation ratio. Right-circular hinges are adopted because of the larger linear displacement compared to other types under the same load conditions. In addition, there are four loops at each side of the haptic to receive the driving force from the ciliary body and support as well. The overall size is 12.5mm, where the optic shares 4.5mm.

Assume that each flexure hinge has 1-DOF rotational compliance and an offset that arise from the rotational deformation, and other components are rigid bodies. The lever mechanisms are depicted in (Figure 2b). The axial force $F_i$ and moment $M_i$ on flexure hinge $i$ produce an axial deformation $\Delta_i$ and a rotational angle $\alpha_i$, which obtains the following relations:

$$\Delta_i = F_i \times C_F \quad (i = 1, 2, 3, ..., 12) \quad (1)$$

$$\alpha_i = M_i \times C_M \quad (i = 1, 2, 3, ..., 12) \quad (2)$$

Where $C_F$ donates the tensile compliance coefficient, $C_M$ represents the rotational compliance coefficient.

$$C_F = E h \frac{2(2\times 1+5)}{8P} \sqrt{\frac{\pi}{2} + \frac{1}{4}} \quad (3)$$

$$C_M = \frac{E h}{2} \frac{2x^4(2x^2+4x+1)}{(4x+1)^2} + \frac{12x^2(2x^2+1)}{(4x+1)^2} \arctan \sqrt{\frac{4x}{4x+1}} - \frac{1}{2} \frac{1}{2} \frac{1}{2} \frac{1}{2} \quad (4)$$

Referring to the first lever, the flexure hinge 1 is the rotation center, which is subjected to tension $F_1$, resulting in an axial extension $\Delta_1$. The flexure hinge 2 comes in for pressure $F_2$ because of the contraction of ciliary body, producing an axial compression of $\Delta_2$. The input displacement $x_1$ and the rotation angle $\theta_1$ of the first lever can be described by the squares of equations (3) and (4), i.e.,

$$x_1 = D_{in} = \Delta_2$$

$$\theta_1 = (x_2 - \Delta_2)/L_2 = (D_{in} - \Delta_2 - \Delta_1)/L_1 \quad (6)$$

Where $D_{in}$ is the output displacement of ciliary body, $x_2$ is the output displacement, $l_1$ is the length between the input terminal and the fulcrum, and $l_2$ is the length between the output terminal and the fulcrum.

Considering the force equilibrium and the moment equilibrium along the x-axis, the following relation can be written as:

$$F_2 = F_1 + F_3 \quad (7)$$

$$F_2 \times l_2 + M_2 + M_1 = F_2 \times l_1 + M_3 \quad (8)$$

Owing to the identical equilibrium state in the second lever, the equations become:

Figure 2: Half of the four-stage amplifier and its parameters: a) input ($D_{in}$), output ($D_{out1}$ in the horizontal direction and $D_{out2}$ in the vertical direction), deformation and eight hinges; b) mechanics analysis of the lever mechanisms from first to fourth stage; c) and the middle transition connecting links.
\[
x_3 = D_{in} - \Delta_3 \\
\theta_3 = \frac{(x_3 - \Delta_3)}{l_4} = \frac{(D_{in} - \Delta_2 - \Delta_3)}{l_3} \\
F_5 = F_4 + F_6 \\
F_5 \times l_4 + M_4 + M_5 = F_5 \times l_4 + M_6 \\
\theta_5 = x_2/l_5
\]

Where \(x_4\) is the output displacement, \(l_4\) is the length between the input terminal and the fulcrum, and \(l_5\) is the length between the output terminal and the fulcrum. In view of axial pressure on flexure hinge 3, 4, and 5, 6, one can derive the input displacements \(x_3\) and \(x_6\) on the third lever:
\[
x_3 = x_2 - \Delta_3 - \Delta_4 \\
x_6 = x_4 - \Delta_5
\]

and the equilibrium relationship can be generated:
\[
F_7 = F_6 \\
M_6 = M_5 + F_7 \times l_5
\]

Where \(l_5\) donates the length between the two input terminals on the third lever.

The output displacement \(D_{out3}\) of the third lever can be deduced by:
\[
D_{out3} = \theta_3 \times l_6
\]

and the geometric relation on the third lever gives an expression of rotation angle \(\theta_3\):
\[
\frac{D_{out1}}{D_{in}} = \frac{(C_F^2 + 2C_F \Delta_1 l_2 + C_F \Delta_1 \Delta_3 + C_F (-\Delta_1 \Delta_2 l_3) + (l_2 - l_4 + 4l_6))}{(C_F^2 + 2C_F \Delta_1 l_2 + C_F \Delta_1 \Delta_3 + C_F (-\Delta_1 \Delta_2 l_3) + (l_2 - l_4 + 4l_6))}
\]

From the above relationship, one can observe that the amplification ratio is related to the parameters \(s\) (ratio of cutting radius and minimum thickness), \(E, R, l_4\) to \(l_5, C_F\) and \(C_M\). The architectural parameters of the amplifier (Figure 2b) are tabulated in (Table 1). Hence the horizontal amplification ratio is a constant of 19.6.

**Table 1:** Parameters of the amplifier.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| \(s\)     | 3     | \(l_4\)   | 1.10mm|
| \(E\)     | 3 GPa | \(l_5\)   | 4.90mm|
| \(R\)     | 0.1mm | \(l_6\)   | 2.65mm|
| \(l_1\)   | 1.20mm| \(l_7\)   | 6.30mm|
| \(l_2\)   | 2.35mm| \(l_8\)   | 2.50mm|

Considering the hinges on the fourth lever are much smaller than those on other levers, it is assumed that the fourth lever can be simplified as a rigid lever without flexure hinges. With 5 degree angle to the three-stage lever-type amplifier, it produces an output displacement \(D_{out2}\) straight along the y-axis:
\[
D_{out2} = \frac{l_2}{\sqrt{l_2^2 - (l_2 \times \cos\theta_2 - D_{out2})^2 - l_2 \times \sin\theta_2}} \times \sin\theta_2
\]

Where the \(D_{out2}\) is both the output displacement of the three-stage lever-type amplifier and the input displacement to the single-stage bridge-type amplifier.

As can be seen from (Figure 3), the two curves show the change of the output displacement and amplification ratio of the four-stage amplifier, respectively.

![Figure 3: Changes of output displacement and amplification ratio of the four-stage amplifier.](image)

With the ciliary muscles contract, \(D_{in}\) increases, and \(D_{out2}\) has a tendency of non-linear growth, that is a parabolic relationship between \(D_{out2}\) and \(D_{in}\). However, the amplification ratio shows a non-linear downward trend. \(D_{out2}\) reaches its peak of around 2.273mm when the \(D_{in}\) is 0.127mm, while the amplification ratio gets the minimum value of approximately 17.97. When \(D_{in}\) varies from 0.115mm to 0.127mm, the amplification ratio obtained a relatively stable value range, with an
average of around 18.86. Due to the limited contractility of the residual force, the ciliary muscle returns to its original condition from now on, resulting in a decrease of $D_{out2}$ and a growth of amplification ratio (not shown in Figure 3, because of the symmetry). 0.127mm input displacement can generate 3.80 diopters to obtain much more focus shift, which meets the requirement of subjective reading performance mentioned above. In this section, the established analytical models for the assessment of the amplification ratio is verified by static carried out with the FEA software package ANSYS TM.

A 3D model is created with the 10 node SOLID 187. In the simulation, zero displacements are assigned on the surfaces of the fixing body to immobilize the mechanism, and the input displacements are applied on the two input side surfaces of the amplifier for the static analysis. The corresponding FEA results indicate that an input displacement of 0.10mm and a horizontal output ($D_{out1}$) about 1.1083mm is obtained, as shown in (Figure 4a). In addition, the deformation and critical displacement ($D_{out2}$), which is 2.0170mm of the amplifier, is depicted in (Figure 4b).

In order to verify the reliability and relevance of the mechanism, ($D_{out1}$) and $D_{out2}$ are collected from 0.01mm to 0.12mm once per unit length of 0.01mm, different input displacements were loaded into the above model for finite element analysis (Table 2), respectively. It is straightforward that the proposed analytical model can well predict the amplification capability of the amplifier in the case of different input displacements existing. The displacement amplification ratio of the proposed four-stage amplification mechanism rises gradually, which basically coincides with the theoretical value calculated by the approaches of geometric relations analysis (Section 3). Note that the value obtained by FEA is less than that of the theoretical, although the certain offset and drift of the flexure hinges are considered. This displacement loss is partly due to the reason that the rigid links are not absolute rigid bodies and thus undergo elastic deformation. Moreover, a friction coefficient between the contact

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### Table 2: Amplification ratio at different input.

| Input (mm) | $D_{out1}$ (mm) | $D_{out2}$ (mm) | Ratio (FEA) |
|------------|-----------------|-----------------|-------------|
| 0.01       | 0.1162          | 0.7486          | 74.86       |
| 0.02       | 0.2341          | 1.1016          | 55.08       |
| 0.03       | 0.3475          | 1.3143          | 43.81       |
| 0.04       | 0.4659          | 1.4996          | 37.49       |
| 0.05       | 0.5847          | 1.6585          | 33.17       |
| 0.06       | 0.6973          | 1.7922          | 29.87       |
| 0.07       | 0.7928          | 1.8718          | 26.74       |
| 0.08       | 0.9016          | 1.9496          | 24.37       |
| 0.09       | 0.9824          | 2.0412          | 22.68       |
| 0.10       | 1.1083          | 2.0170          | 20.17       |
| 0.11       | 1.1769          | 2.0856          | 18.96       |
| 0.12       | 1.2524          | 2.1696          | 18.08       |
| 0.13       | 1.3145          | 2.2143          | 17.86       |
| 0.14       | 1.4326          | 2.1021          | 18.44       |
surface and the target surface is developed during FEA simulation. In addition, weight and elastic deformation of the optic are defined as zero during the simplification in this paper and deserve further studies in future research.

Results

According to the lens parameters of the human eyes, the structural parameters, material properties, adjustment space, and adjustment principles of the haptic have been assumed to simulate a series of changes of the ciliary muscle residual force. Compared with the single-stage amplifier applied to Crystalens AT-45, Tetraflex and ICU, the novel haptic acquires a large increase in anterior displacement of the optic lens by using a four-stage amplification mechanism with flexible hinges. As the input displacement increases, the amplification ratio of the proposed four-stage amplifier gradually decreases until it reaches a stable interval from 17.45 to 18.14. These results not only confirm that the defined performances are satisfied by the four-stage amplifier, but also validate the effectiveness of the proposed mechanism. By analysing and comparing the results between the theoretical method and the FEA, there is an error of no more than 5%, and the reasons are discussed as follows. Firstly, each flexure hinge of the amplifier is simplified as a 2-DOF joint and the other elements are considered as rigid bodies. When the flexure hinge moves, there is not only angular deformation but also stretching and compression deformation, which results in the difference between theoretical results and FEA results. Furthermore, actual material parameters may be different from their nominal values. Moreover, the gravity influence is omitted in theoretical analysis.

Discussion

Based on the mechanism of the flexure hinge, the analytical model of a four-stage amplification mechanism is established to evaluate the amplification ratio. Specifically, the offset of the flexure hinge’s rotation is considered to obtain static models to predict the amplification ratio since the theoretical method is based on geometric relations analysis. The model is verified by three-dimensional solid modeling and finite element simulation by ANSYS. It is demonstrated that the relationship between the output and input displacements of the four-stage amplifier is parabolic. However, it has a stable value interval, which fits the contraction range of the ciliary muscle residual force. Besides, the error of the amplification ratio between theoretical method and FEA is less than 5%, confirming the correctness of the theoretical analysis. The output displacement can be adjusted greatly through a small input displacement, thereby achieving greater deformation in a limited operating space. The proposed method offers a new look into the analysis and design of ‘focus shift’ IOL based on flexure hinges.

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Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

Author Contributions

All authors read and approved the final manuscript.

Competing Interests

None.

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