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Simulated zonular tension analysis in the presence of zonular disinsertion

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Abstract

Purpose: To analyze and understand the zonular tension and distribution of forces in the presence of zonular disinsertion in a model simulation with and without a capsular tension ring (CTR).
Methods: This study was conducted at Complejo Hospitalario Universitario Albacete, University of Castilla La Mancha, Spain. Twelve load cells were arranged in a circular fashion to simulate the 360 degrees of zonulae in the eye. An elastic band was pre-stretched in a uniform and radial manner in 12 directions. Force measurements were taken using 12 load cells, uniformly arranged at 30° spacing around the elastic band. Tension was measured at each cell, before and after the simulated zonular disinsertion. Every clock hour of zonular disinsertion was cycled through all 12 load cells. The tension was evaluated for zonular disinsertion ranging from 0 to 5 clock hours (0° to 150°) with and without a CTR.
Results: An increase in zonular tension was recorded in the load cells adjacent to the segments of zonular disinsertion. As the zonular disinsertion progressed, opposing forces could no longer cancel each other out, leading to a displacement of the complex. The use of a CTR redistributed the forces, providing better centration in the presence of zonulolysis.
Conclusion: This study visualizes the distribution of forces and displacement of the capsular bag complex in the presence of zonular disinsertion and demonstrates a significant increase in zonular tension in the areas adjacent to the segment of

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zonular disinsertion. The use of a CTR managed to redistribute the tension over the remaining zonulae, maintaining better centration in the presence of zonulolysis. The knowledge of this behavior can help surgeons tackle clinically significant zonular disinsertion.

Keywords: capsular tension ring, cataract surgery, zonular disinsertion, zonulolysis

1. Introduction

The adult crystalline lens typically measures 9 mm equatorially and 5 mm antero-posteriorly, with a weight of approximately 225 mg. The lens is suspended to the pars plana and pars plicata of the ciliary body by the zonular fibers, which are inserted in a continuous fashion on the lens capsule in the equatorial ring. The fibers are 5–30 µm in diameter and composed of strands 8–10 nm in diameter.[1] The forces acting on these fibers, as well as information about the mechanical properties, number, and geometry of these fibers are unknown. However, several models have estimated the forces acting on the lens during accommodation to be in the magnitude of 0.08 nN.[2]

Zonular weakness can be seen after trauma and iatrogenia, or in association with pseudoexfoliation syndrome, Marfan syndrome, idiopathic ectopia lentis, or Weill-Marchesani syndrome. Forces acting on the zonulae combined with pre-existing pathology can lead to lens instability and lens subluxation.

Tension segments, sutured capsular tension rings (CTR), scleral-sutured intraocular lenses (IOL), and anterior chamber IOLs, can be used to help with the condition, depending on the extent of the zonular weakness. CTRs are typically open-ended rings made of PMMA filament, with eyelets at either end, and are mainly used for capsular bag stabilization during and after cataract surgery.[3-5] Standard CTRs are recommended for cases of mild zonular disinsertion ranging up to 3–4 clock hours.[6] However, prospective studies have also shown capsular stability in more severe cases with zonular dialysis of up to 160°.[7]

However, late dropped IOL-bag complex, despite the use of a CTR, has also been described many years after an uneventful lens surgery.[8] Capsulorrhexis phimosis was described in most of these cases. The capsular phimosis is believed to exert a tractional force on the capsular bag that is transmitted to the zonules, eventually leading to rupture.[9] To the authors' knowledge, no data has been published on the contraction forces acting on the zonulae in the presence of capsular phimosis.

Several other properties have also been attributed to these rings, such as better centration of premium IOLs generating less tilt and induced aberrations, better predictability of refractive outcome, prevention of posterior capsular opacification, and prevention of capsular bag contraction.[10,11] Clinical data to support these properties is limited.[12,13]

Understanding the forces acting on the zonules in the presence of zonular weakness can help understand the pathogenesis of the late dropped IOL-bag complex and provide information for the development of improved CTRs and IOLs.

2. Methods

Twelve straight bar load cells (maximum capacity 1 kg), each representing 1 clock hour of zonulae, were arranged in a circular fashion to simulate the 360° of the eye's zonulae (Fig. 1). Each load cell was hooked up to an HX711 load cell amplifier, connected to a Teensy 3.2 microprocessor which in turn fed data to a database at 10 measurements per second. All 12 load cells were reset to 0.0 N prior to each cycle of measurements.

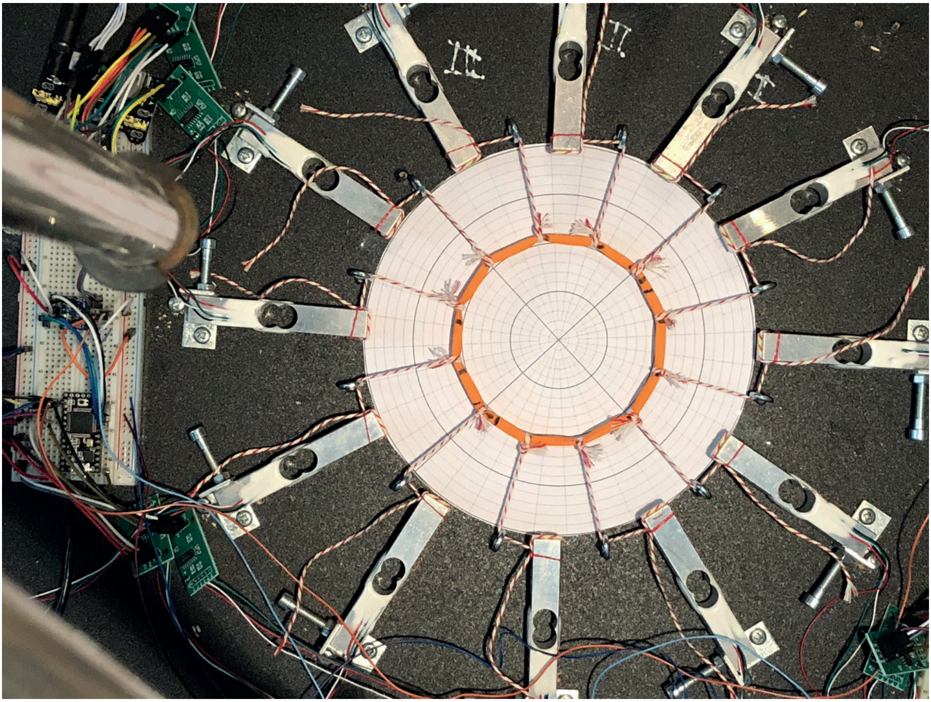

Fig. 1. Setup showing the arrangement of the load cells and the pre-stretched elastic band.

A pre-stretched elastic band was used to simulate the contraction force of a contracting capsular bag. The pre-stretched elastic band was attached though pulleys to the 12 load cells at 30° spacing (Fig. 1). The elastic band was manually stretched, centered, and adjusted to a diameter of 10 cm, generating a radial pulling force of 2.84 N on each load cell at the start of each cycle of measurements. Tension was measured at each cell before and after zonular disinsertion was simulated by releasing the attachment between the elastic band and the corresponding load cells. The same measurements were also performed using a simulated rigid CTR. The CTR was made of polypropylene and had an outer diameter of 11 cm, slightly larger than the capsular bag.

Tension and displacement were evaluated for zonular disinsertion ranging from 0 to 5 clock hours (0° to 150°). Every clock hour of zonular disinsertion was cycled through all 12 load cells, making a total of 122 measuring moments.

3. Results

In the starting case without zonular disinsertion, each of the 12 segments supported the preset 2.84 N (range 2.83–2.80, SD 0.013) of pull, 1/12 (8.3%) of the load. As the zonular disinsertion progressed, the weight distribution changed, placing a higher load on the segments adjacent to the zonular defect (Tables 1 and 2). Capsular bag displacement towards the area opposite the zonular defect was observed once the opposing forces could no longer balance each other out (Fig. 2).

The use of a CTR maintained better centration throughout the study. Although forces were still greatest in the areas adjacent to the zonular defect, the load was more evenly distributed using a CTR (Table 2). Even in the cases of more extensive areas of zonular disinsertion, the use of a CTR managed to keep the capsular complex better centered, balancing out opposing forces (Fig. 3).

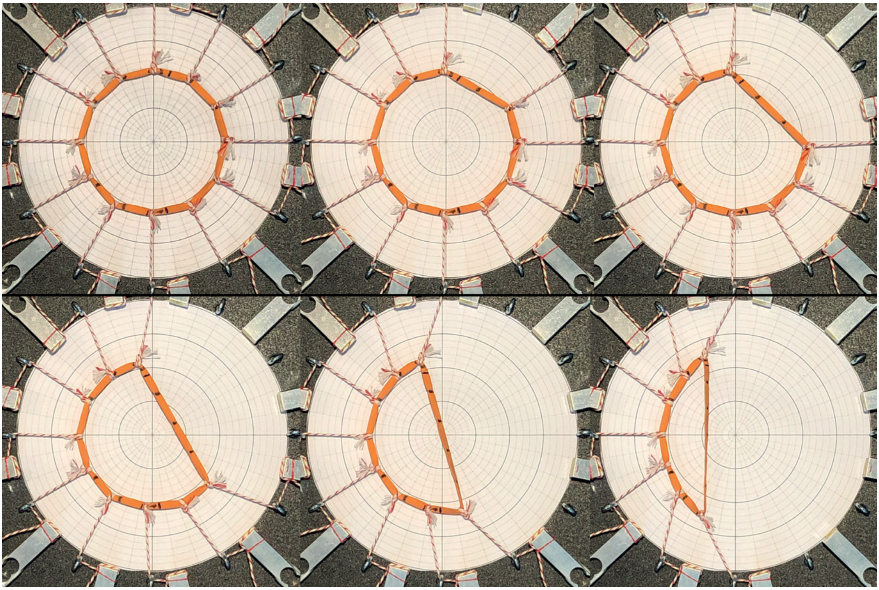

Fig. 2. Simulated capsular bag with varying amounts of zonulolysis, ranging from 0 clock hours up to 5 clock hours.

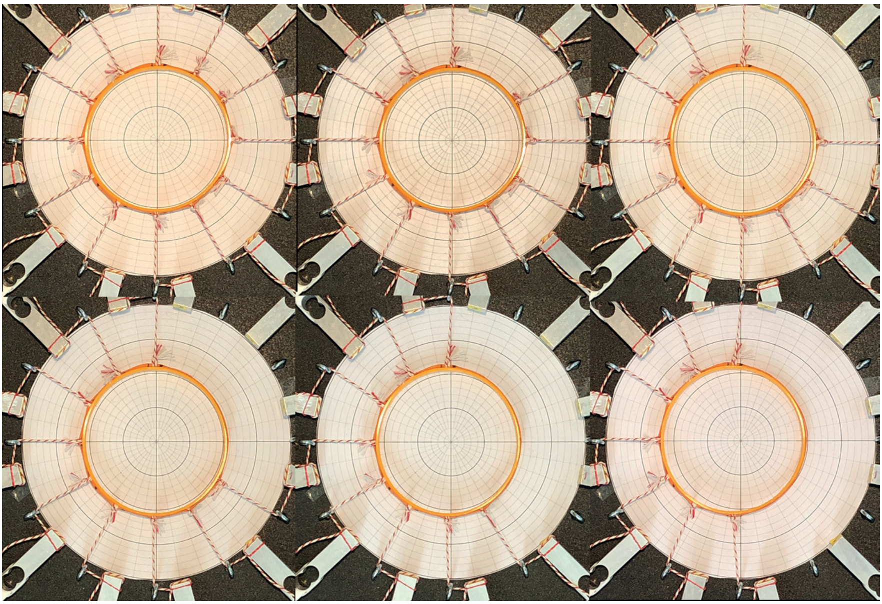

Fig. 3. Simulated capsular bag with varying amounts of zonulolysis, ranging from 0 clock hours up to 5 clock hours, while using a rigid capsular tension ring.

Table 1. Zonulolysis without capsular tension ring

Segment		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Clock hour 0	Force (N)	2.84	2.84	2.84	2.84	2.84	2.84	2.84	2.82	2.80	2.84	2.84	2.85
	(SD)	0.014	0.051	0.028	0.016	0.088	0.072	0.086	0.025	0.080	0.032	0.033	0.040
	Angular deviation	0	0	0	0	0	0	0	0	0	0	0	0
Clock hour 1	Force (N)		4.23	2.67	2.69	2.73	2.75	2.76	2.75	2.67	2.75	2.69	4.32
	(SD)		0.209	0.057	0.040	0.033	0.019	0.018	0.014	0.159	0.065	0.042	0.402
	Angular deviation		-3.1	-0.5	-0.4	-0.7	-0.9	0	0.7	1.8	1	1.4	2.4
Clock hour 2	Force (N)			5.47	2.22	2.37	2.35	2.51	2.51	2.47	2.38	2.25	5.31
	(SD)			0.729	0.056	0.100	0.243	0.028	0.048	0.053	0.096	0.108	0.555
	Angular deviation			-4.1	-3	-2.4	-0.9	-0.3	0.8	1.8	2.2	3.2	4.9
Clock hour 3	Force (N)				5.94	1.60	1.80	1.96	2.05	1.91	1.82	1.47	5.74
	(SD)				0.531	0.258	0.172	0.126	0.077	0.160	0.186	0.336	0.557
	Angular deviation				-10.2	-6.5	-2.9	-2.2	0	3.2	4.4	7	10.8
Clock hour 4	Force (N)					5.97	1.19	1.49	1.76	1.77	1.53	1.22	5.90
	(SD)					0.397	0.347	0.297	0.311	0.243	0.304	0.293	0.563
	Angular deviation					-17.6	-10.7	-6	-2.1	2.4	5.5	10.6	18.6
Clock hour 5	Force (N)						5.04	1.12	1.09	1.24	1.10	1.10	4.93
	(SD)						0.536	0.630	0.634	0.572	0.594	0.696	0.612
	Angular deviation						-27.4	-17.1	-6	0	6.4	16.5	28

Table 2. Zonulolysis with capsular tension ring

Segment		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Clock hour 0	Force (N)	0.70	0.70	0.83	0.82	0.65	0.77	0.72	0.80	0.79	0.85	0.77	0.74
	(SD)	0.080	0.060	0.093	0.048	0.036	0.162	0.047	0.164	0.106	0.237	0.020	0.094
	Angular deviation	0	0	0	0	0	0	0	0	0	0	0	0
Clock hour 1	Force (N)		0.91	0.86	0.73	0.68	0.66	0.70	0.67	0.69	0.74	0.87	0.95
	(SD)		0.022	0.029	0.077	0.046	0.087	0.065	0.033	0.053	0.078	0.117	0.043
	Angular deviation		-0.2	-0.5	-0.8	-0.6	-0.1	-0.3	1.2	0.6	0.9	0.2	0.2
Clock hour 2	Force (N)			1.18	0.93	0.73	0.61	0.59	0.54	0.61	0.74	0.93	1.17
	(SD)			0.044	0.068	0.027	0.053	0.048	0.049	0.111	0.033	0.051	0.051
	Angular deviation			-0.6	-0.8	-1.3	-0.2	-0.2	1.4	0.4	1.3	1	0.2
Clock hour 3	Force (N)				1.55	1.00	0.69	0.42	0.34	0.39	0.65	1.00	1.53
	(SD)				0.091	0.048	0.028	0.038	0.033	0.025	0.045	0.050	0.122
	Angular deviation				-2.1	-2.3	-1	-0.2	1.6	1	1.8	2.1	2
Clock hour 4	Force (N)					2.00	0.86	0.24	0.14	0.13	0.21	0.84	1.96
	(SD)					0.075	0.034	0.049	0.010	0.011	0.052	0.052	0.048
	Angular deviation					-3.6	-2.4	-2	1.5	1	2	2.7	3.9
Clock hour 5	Force (N)						2.07	0.16	0.06	0.00	0.04	0.16	2.15
	(SD)						0.053	0.048	0.046	0.012	0.018	0.051	0.054
	Angular deviation						-4.7	-5	-3.2	1.2	2.9	5	5.7

4. Discussion

This in vitro study visualizes the distribution of forces in the presence of zonular disinsertion. The purpose of this study is to better understand the forces acting on the zonulae in the presence of zonular disinsertion and how zonular disinsertion can eventually lead to a dropped IOL-bag complex. There are still many unknown variables impeding a more realistic replica of a human capsular bag complex, such as but not limited to the size of the capsular bag, forces acting on the zonulae, contraction force of capsular phimosis, the spring force of the CTR, and the exact size of the zonular defect. The setup, therefore, presents many limitations. However, it provides a simple understanding of the consequences of zonular disinsertion.

Twelve straight bar load cells with a maximum capacity of 1 kg were used to perform the measurements. This type of bending beam load cell measures the resulting force pulling in one direction, perpendicular to the load cell. Once the elastic complex is displaced, the direction of the force will be altered. To overcome this misalignment, we opted for the use of pulleys. The pulleys redirect the resulting force into the bending plane of the load cell.

Load cells with a maximum capacity of 1 kg together with an elastic band, pre-stretched to 10 cm, generating 2.84 N of pulling force per load cell, were used to minimize reading errors due to friction or gravity.

Although the diameter of the CTR and pulling force of the simulated capsular bag were arbitrarily chosen, the correct size and spring force of the real CTR during an operation is also just an estimate. Despite published methods,[14] there is still no accurate method for selecting the ideal CTR size or tension. The smaller the CTR in relation to the diameter of the capsular bag, the less effect it will have counteracting the forces. In this model, we opted for a rigid CTR with a size slightly larger than the diameter of the pre-stretched elastic band.

In the case of 5 clock hours of zonular defect with a CTR, the forces opposite the area of zonular defect are close to 0, mirroring the forces in the area of zonular defect, indicating good centration of the capsular bag (Fig. 3.). Therefore, most of the load must be carried by the only 2 segments left, perpendicular to the defect. The same situation without the CTR shows an in-balance of the forces, indicating a decentration of the bag, as visible in Figure 2. The findings of this study are consistent with previously published clinical studies, demonstrating better centration of premium IOLs generating fewer aberrations.[10]

This study focused only on the effects of 30° segments and not on generalized zonular weakness due to pathologies such as pseudoexfoliation. Reducing the size of the segments would increase the precision and probably show an even higher load ratio adjacent to the zonular defects.

To the authors' knowledge, this is the first study to visualize the distribution of forces in the presence of zonular disinsertion and demonstrate a significant increase in zonular tension in the areas adjacent to the segment of zonular disinsertion.

The use of a CTR managed to distribute the tension over the remaining zonulae, achieving better centration. Understanding the forces acting on the zonules in the presence of zonular weakness can help understand the progression of zonular disinsertion and provide information for the development of future CTRs and IOLs.

Declarations

Ethics approval and consent to participate

Not required.

Competing interests

None to declare.

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