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Contact Probe Based Stiffness Sensing of Human Eye

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***Abstract*— The internal eye pressure is an important index for judging whether an eye suffers from glaucoma or not. The conventional eye pressure measurement is valid only under the condition that all subjects have the same structural eye stiffness. This paper challenges stiffness sensing of the human eye by pressing it with a contact probe. The displacement of the eye is captured by a camera with high resolution (see Fig.1). Experimental results show that the stiffness is roughly constant for each subject, while it differs by up to a factor of five between subjects. The method can detect subjects whose eye stiffness is smaller than average for further careful medical examination.**

***Index Terms*—** *Medical Application, Eye Stiffness, Static Sensing.*

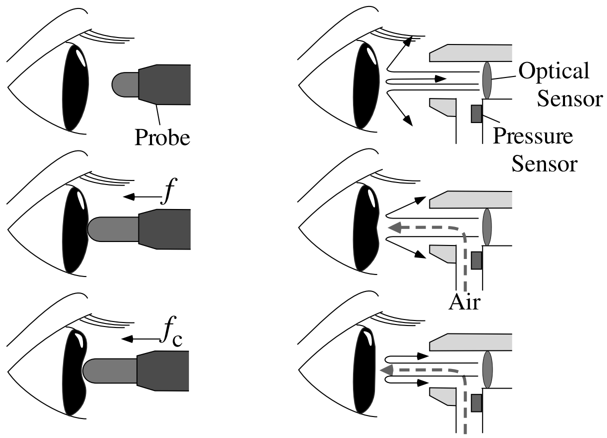
I. Introduction

An increased internal eye pressure may cause a damaging and subsequent partial death of the eye nerve system on the retina and the patients gradually lose their eye sight. At worst, the patients completely lose their eye sight. This disease is called glaucoma. Today, there is no essential medical treatment for recovering from this disease. An effective treatment to avoid a further progress of glaucoma is decreasing the internal eye pressure by either an eye lotion or a medical operation. In addition to the observation of the abnormality of the eye sight or the optic papilla, the measurement of the internal eye pressure is very important to judge whether the eye suffers from glaucoma or not. However, it is hard to measure the internal eye pressure accurately without penetrating the eye ball with a pressure needle. A less accurate, but also less invasive method is estimating the eye pressure by evaluating the deformation of the eye when the external force is applied. Fig. 2 shows the overview and the basic working principle of the eye pressure estimation method. Fig. 2(a) shows a contact method where the eye is deformed by a rigid probe, (b) shows a non-contact method where the eye is deformed by an air jet. The eye pressure (IOP: IntraOcular Pressure) used in the medical field is originally defined by the external pressure causing an applanation of the cornea surface. Note that the true internal eye pressure may be different from the external eye pressure (IOP). In this paper, we purposely discriminate one from the other by using the terms "external pressure" and "internal pressure", respectively.

Fig. 1. Eye pressure measurement by using a contact probe.

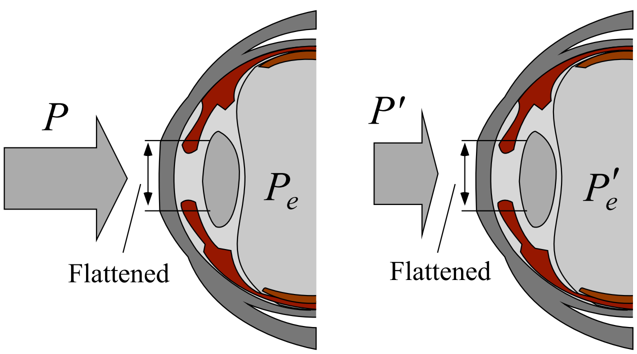
Now, let us consider two eyes as shown in Fig. 3, where the eyes in (a) and (b) have a normal structural stiffness and lower than average stiffness, respectively. Under such a condition, the eye surface in Fig. 3(b) becomes flat with less external pressure than that in Fig. 3(a). This indicates that the eye pressure estimation system always provides smaller external pressure values for patients with compliant eyes than for those with normal eyes. The external eye pressure (IOP) is measured under the assumption that all the patients have the same structural eye stiffness.

The total stiffness of a human eye can be estimated if both the applied force and the displacement are known. Kaneko et al.[1], [2] have captured the dynamic deformation and measured the eye stiffness during a non-contact tonometry. In those papers, it is assumed that the effects coming from both the viscosity and the inertia of the eye are sufficiently small in comparison with the effect of the stiffness. However, since the dynamic behaviors of the eye deformation are clearly observed in the non-contact measurement, the estimated stiffness of the eye includes the dynamic effects and changes depending on the time.



(a) Contact method. (b) Non-Contact method.

Fig. 2. Estimation method of the internal pressure.



(a) Normal eye. (b) Compliant eye.

Fig. 3. Effect of the eye stiffness under the internal pressure $P_e = P'_e$.

In order to eliminate the dynamic effects, we use a contact probe to applanate the cornea surface. The eye stiffness is statically measured based on the deformation captured by a high resolution camera. The experimental results show that the relation between the displacement of the cornea tip and the applied force is linear and the eye stiffness may differ by a factor of five between subjects.

II. Related Work

There are a number of applications for measuring stiffness (or compliance). For stiffness measurement, there are two methods: one is a contact method [3] and the other one is a non-contact method [4], [5]. In the contact method, a force is directly applied to the object by using a solid probe while in the non-contact method a flow of air or water is used instead of a solid probe. If the object is fragile and might be damaged by a solid probe, the non-contact method may be preferred to the contact method.

These two measurement methods also exist in tonometry, a contact type and a non-contact type. The contact type measurement system[6] provides us with a good example of static based sensing, where a medical doctor presses a rigid probe to an anesthetized eye until the cornea deforms to a prescribed value (circle with a diameter of 3.06[mm]). This system provides us with a relatively accurate value due to the direct contact method. The non-contact type measurement system[7] is perhaps the closest one to dynamic sensing, while it is still based on static strategy. It is known that the estimated eye pressure depends on the method[8] used.

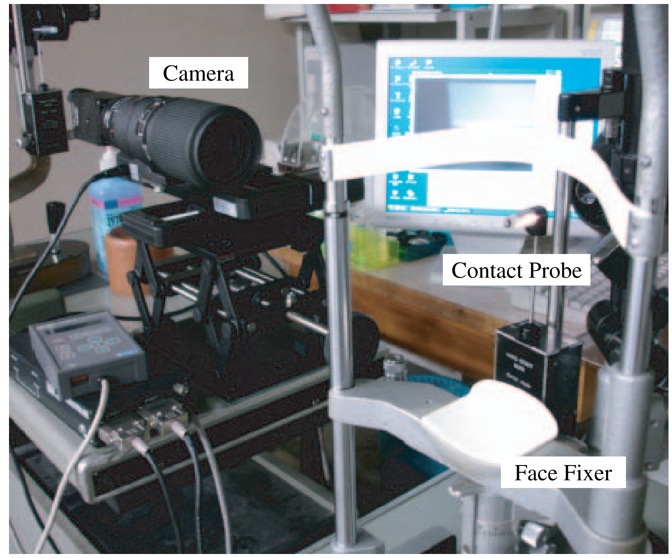


Fig. 4. Overview of the experimental system.

Moreover, the individual difference of the cornea property also affects the estimation of the internal eye pressure. Since the present estimation method of the eye pressure is based on the assumption that all the patients have the same structural properties, the individual difference of the cornea causes an error in the estimation. For example, it is well known that the cornea thickness affects the estimation of the eye pressure[9], [10], [11]. The same applies to the elasticity of the cornea, which was measurement in vitro[12], [13]. Consequently, several papers propose correction methods considering the difference of the cornea properties[14], [15]. An accurate model of a human eye has also been constructed for more precise diagnosis of eye disease by using FEM models[16], [17], [18]. However, the simulation result has not been compared with the experimental result of a real human eye.

There are very few works that investigate the stiffness of human eyes in vivo. In recent years, Pallikaris et al.[19] have measured the cornea rigidity in vivo. Kaneko et al.[1], [2] have also measured the total eye stiffness in vivo. Although they have revealed that the individual difference in the eye stiffness can be observed, their experimental results seem to be affected by the viscosity and the inertia of the eye and the air jet. As far as we know, this is the first work on statically measuring the eye stiffness in living human.

III. Experimental System

A. System Configuration

Fig. 4 shows the constructed experimental system. The system is composed of a Goldmann eye pressure measurement

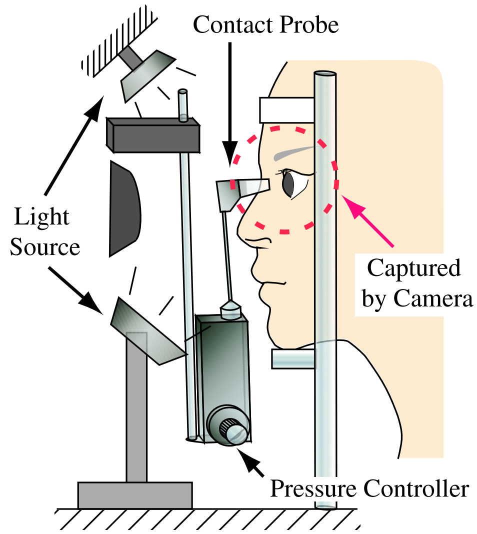


Fig. 5. Side view of the experimental system.

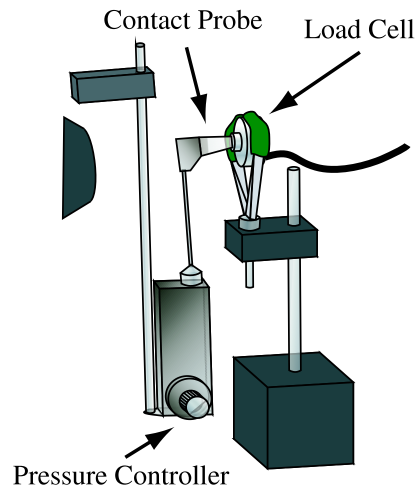


Fig. 6. The calibration method for contact force.

system and a high resolution camera. The Goldmann tonometer is a standard contact type eye pressure measurement system. In the Goldmann method, the internal eye pressure is estimated based on the pressure when the eye surface is applanated in a circle with a diameter of 3.06[mm][6]. The eye is applanated by pressing a rigid probe onto the cornea. We use a Goldmann tonometer as the static force applying system. In order to measure the stiffness, it is also necessary to measure the displacement. In this study, we use a high resolution camera (Flovel co., Ltd.: ADP-210B) to capture the eye deformation during applanation. The camera has the spatial resolution of 5.6[μm/pixel] and the size of 1600×1200[pixels].

Fig. 5 shows the side view of the experimental system where the camera is set up perpendicular to the axial direction of eye and additional light sources are installed to ensure sufficient illumination for the measurement.

B. *Force Calibration*

Since it is hard to measure the pressure during the experiment, the calibrated force is utilized for the calculation of the eye stiffness. The force applied by the contact probe to the cornea surface is measured by a load cell. Fig. 7 shows the overview of the calibration. The pressure value can be changed by rotating the dial connected to the link for applying the force to human eye(cf. Fig. 7). The relation between the pressure value of the Goldmann tonometer and the applied force is shown in Fig. 8 where a highly linear relationship can be observed.

C. *Displacement of the cornea tip*

The deformation of the eye during the probe contact is captured by a camera. Fig. 9 shows a captured image. Because the subject does not stand still during the experiment, the position of the eye differ in each image. Therefore, the distance between a mark on the probe and the fringe of the cornea is used to obtain the displacement. Although the tip of the cornea is deformed by the contact of the probe, the fringe of the cornea is hardly deformed. Since the line on the probe can be clearly observed in the captured images, the displacement of the cornea tip can be measured by utilizing the distance between the line and the fringe edge of the cornea.

Fig. 7. Overview of the force calibration.

IV. Experiment

A. *Subjects*

11 young healthy subjects aged 23$\sim$34 years old (8 males and 3 females) participated in the experiment. The eye deformation was measured by the constructed system during the applanation tonometry by a contact probe. The applanation tonometry was conducted by a medical doctor. In the experiment, the pressure is applied on the cornea in steps of 5[mmHg] from 10 to 30[mmHg]. Fig. 10 gives an overview of the experiment where the forehead and the chin of the subject were supported by a face fixer.

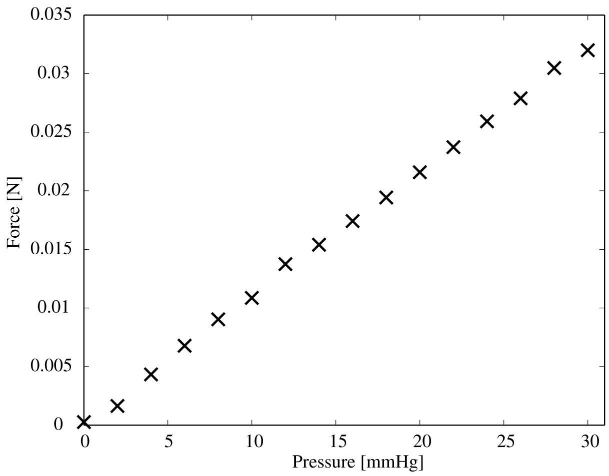


Fig. 8. Relationship between the applied force and the pressure value on the Goldmann tonometer.

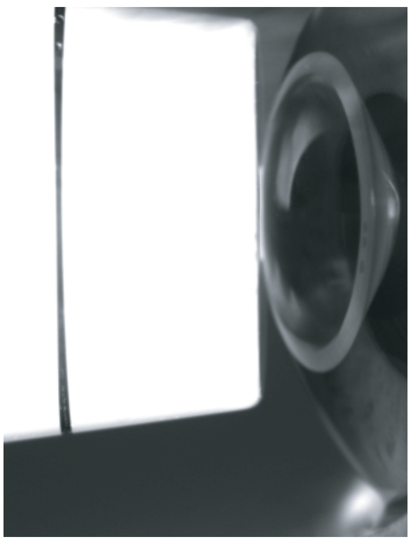


Fig. 9. Captured image.

B. *Behavior of the Eye under the Force Application*

Fig. 11 shows representative pictures of the cornea under the probe contact where Fig. 11 (a)$\sim$(d) are: the probe just contacting the cornea surface (a), a pressure of 10[mmHg] being applied (b), a pressure of 20[mmHg] being applied (c), a pressure of 30[mmHg] being applied (d), respectively.

The shape of the deformation of the cornea caused by the probe contact may be affected by various geometrical parameters, such as the cornea thickness, the cornea curvature, and the length of the eye axis. The deformation may be also affected by material properties of the cornea, the sclera, and the vitreous body.

The displacement of the cornea tip is evaluated for each pressure application in the static measurement of the human eye stiffness. Fig. 12 (a) $\sim$ (k) show the displacement for different pressure values for all the subjects (Subject A $\sim$ K).

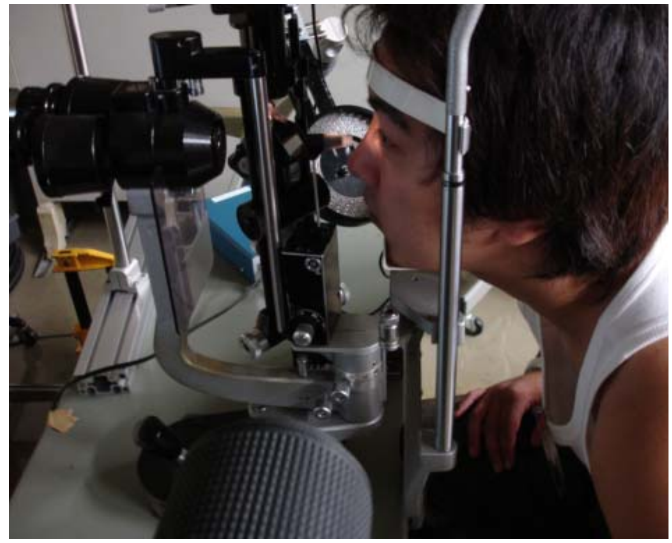


Fig. 10. Overview of the experiment.

TABLE I

MIN, MAX, AVG, AND DEVIATION OF THE EYE STIFFNESS.

Mean	140.36 [N/m]
Standard deviation	82.2 [N/m]
Minimum	67.80 [N/m]
Maximum	344.8 [N/m]

Note that some images (for subjects D, J, and K) where neglected since they were so noisy that the cornea displacement could not be detected. We can clearly observe a linear relation between the applied pressure and the cornea displacement. The approximation lines in the figures are computed based on the minimum mean square error.

C. *Definition of the eye stiffness*

The slope of the approximation line in Fig. 12 is highly correlated with the stiffness of the eye. Now we evaluate the individual stiffness based on the cornea displacement and the applied force. The relation between the pressure value and the applied force is known by the calibration shown in Fig. 8. In this study, the eye stiffness is defined by the relation between the increase of the cornea displacement and the applied force:

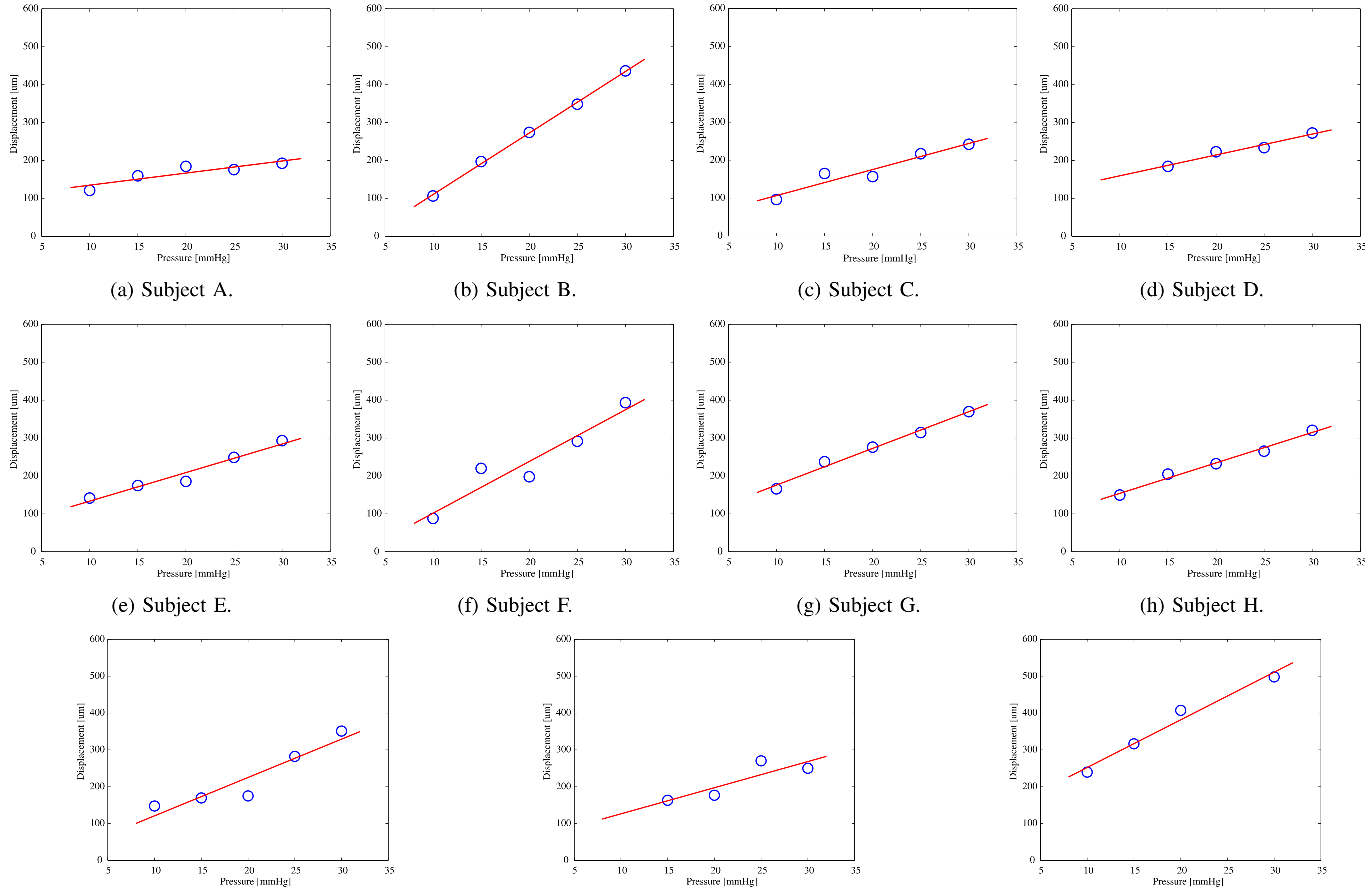
$$k = \boldsymbol{\Delta} f / \boldsymbol{\Delta} d \qquad (1)$$

where k is the eye stiffness, $\boldsymbol{\Delta} f$ is the increase of the applied force and $\boldsymbol{\Delta} d$ is the increase of the cornea displacement. $\boldsymbol{\Delta} f$ and $\boldsymbol{\Delta} d$ are calculated from the approximation line of the relation between the displacement and the force shown in Fig. 12.

Fig. 13 shows the computed eye stiffness for all the subjects. The minimum, the maximum, the mean and the standard deviation of the eye stiffness are shown in Tab. I.

V. DISCUSSION

This is the first work that measures the static stiffness of the human eye. There are a few works that investigate the



(a) Subject A. (b) Subject B. (c) Subject C. (d) Subject D.
(e) Subject E. (f) Subject F. (g) Subject G. (h) Subject H.
(i) Subject I. (j) Subject J. (k) Subject K.

Fig. 12. Cornea displacement by the applanation for eleven subjects. (The displacement under 10[mmHg] application of Subject D, 10[mmHg] of Subject J, and 25[mmHg] of Subject K are not detected because of the noise of the captured image.)

eye stiffness by a non-contact method. Kaneko et al. have estimated the stiffness and the viscosity of the human eye by a dynamic deformation and showed that the estimated stiffness is $104 \sim 160$[N/m][1]. Our results (mean of the eye stiffness is 140[N/m]) agrees with their result. Kurita et al. have also captured the cornea displacement during the dynamic deformation of the human eye and the displacement at the beginning term of the deformation (13.2[ms] after the start of the measurement)[2] and showed that the displacement is $9.86 \sim 56.7[\mu m]$. The applied force at their evaluated time has been 0.0034[N]. In our result, however, the displacement when the force of 0.0033[N](= 30[mmHg]) is applied is $192 \sim 498[\mu m]$. In Kurita's paper, the force is applied by an air jet. As mentioned in their paper, since the applied force by the air jet is dynamic, their experiment may be affected by the viscosity and the inertia parameters of the eye larger than our experiment.

Moreover, when we assume the eye ball as a non-linear elastic material, the contact stiffness changes depending on the deformation[20]:

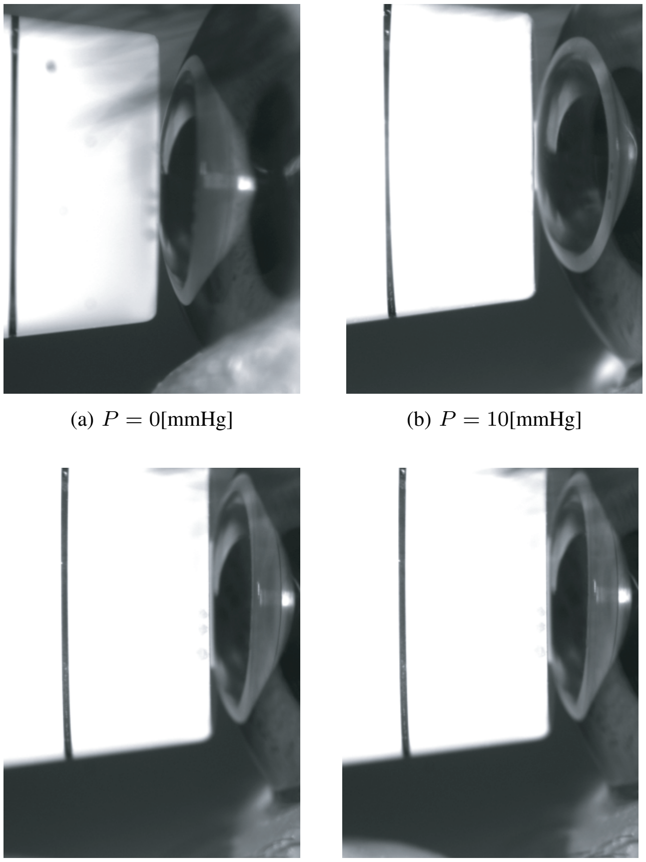
$$k_s = \zeta \left(\frac{f}{d} \right) \quad (2)$$

where $\zeta = 1/2\gamma$, and γ is related to the strain hardening factor, n, by $\gamma = n/(2n-1), 0 \leq n \leq 1$. We need to correct the eye stiffness based on this equation to evaluate the non-linear contact stiffness.

In this study, the individual difference in eye properties can be observed in the cornea displacement and the eye stiffness. We can see 2.5-fold and 5-fold difference in the displacement and the eye stiffness respectively from Tab. I. However, note that this result does not simply indicate that the stiffness of the cornea is individually different because the eye stiffness defined in this study may be affected by both the cornea stiffness and the internal eye pressure. Unfortunately, we can not separate the effects of the cornea and the internal pressure only based on the tip displacement of the cornea. The separation of these two effects will be included in our future work by using other information of the deformation, such as the whole contour of the cornea.

VI. Conclusion

There are some reports that show the stiffness information of the eye. However, these papers have measured the stiffness based on the cornea deformation by a dynamic force appli-



(a) $P = 0$[mmHg] (b) $P = 10$[mmHg]

(c) $P = 20$[mmHg] (d) $P = 30$[mmHg]

Fig. 11. Deformation of the eye by the probe contact.

cation. This study is the first work that measures the static stiffness of the human eye. What we have done in this paper can be summarized as follows:

- The deformation measurement system of the human eye composed of Goldmann tonometer system and a high resolution camera was constructed.
- The static eye stiffness was measured in vivo.
- Linear correlation between the applied force and the displacement of the cornea tip was observed.
- The eye stiffness differs by a factor of five.

For future work, we will conduct the experiment with a large number of subjects for the further investigation.

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REFERENCES

[1] M. Kaneko, K. Tokuda, and T. Kawahara. Dynamic sensing of human eye. In *Proc. of the IEEE Int. Conf. on Robotics and Automation*, pages 2882–2887, 2005.

[2] Y. Kurita, Y. Iida, R. Kempf, M. Kaneko, H. K Mishima, H. Tsukamoto, and E. Sugimoto. Dynamic sensing of human eye using a high speed camera. In *Proc. of the IEEE Int. Conf. on Information Acquisition*, pages 338–343, 2005.

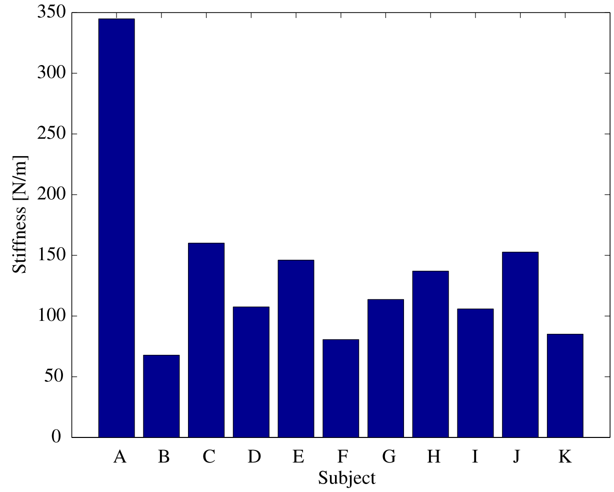

Fig. 13. Stiffness for all the subjects.

[3] H. Oka and T. Irie. Mechanical impedance of layered tissue. *Medical Progress through Technology*, 21:1–4, 1997.

[4] S. Terasaki, N. Wada, N. Sakurai, N. Muramatsu, and D. J. Nevins. Nondestructive measurement of kiwifruit ripeness using a laser doppler vibrometer. *Trans. of ASME*, 44(1):81–88, 2001.

[5] M. Kaneko, T. Kawahara, S. Matsunaga, and S. Tanaka. Non-contact stiffness imager. In *Proc. of the IEEE Int. Conf. on Robotics and Automation*, pages 1562–1567, 2004.

[6] H. Goldmann. Applanation tonometry. In F. W. Newell, editor, *Glaucoma; Transactions of the Second Conference*, pages 167–220. New York: Josiah Macy, Jr, Foundation, 1957.

[7] Topcon corporation. *http://www.topcon.co.jp/*.

[8] P-A. Tonnu, T. Ho, K. Sharma, E. White, C. Bunce, and D. Garway-Heath. A comparison of four methods of tonometry: method agreement and interobserver variablity. *Br. J. Ophthalmol.*, 89:847–850, 2005.

[9] N. Ehlers and F. K. Hansen. Central corneal thickness in low tension glaucoma. *Acta Ophthalmol.*, 54:740–746, 1974.

[10] R. Z. Levene. Low tension glaucoma: a critical review and new material. *Surv. Ophthalmol.*, 24:621–631, 1980.

[11] Y. Morad, E. Sharon, L. Hefetz, and P. Nemet. Corneal thickness and curvature in normal-tension glaucoma. *Am. J. Ophthalmol.*, 125:164–168, 1998.

[12] C. Edmund. Corneal topography and elasticity in normal and keratoconic eyes. *Acta Ophthalmol.*, 44:367–408, 1989.

[13] J. O. Hjortdal. Regional elastic performance of the human cornea. *J. Biomechanics*, 29(7):931–942, 1996.

[14] M. Shimmyo, A. J. Ross, A. Moy, and R. Mostafavi. Intraocular pressure, goldmann applanation tension, corneal thickness and curvature in caucasians, asians, hispanics, and african americans. *Am. J. Ophthalmol.*, 136:603–613, 2003.

[15] G. J. Orssengo and D. C. Pye. Determination of the true intraocular pressure and modulus of elasticity of the human cornea in vivo. *Bull. Math. Biol.*, 61:551–572, 1999.

[16] P. M. Pinsky and D. V. Datye. A microstructurally-based finite element model of the incised human cornea. *J. Biomechanics*, 24:907–922, 1991.

[17] M. R. Bryant and P. J. McDonnell. Constitutive laws for biomechanical modeling of refractive surgery. *J. Biomech. Eng.*, 118:473–481, 1996.

[18] I. A. Sigal, J. G. Flanagan, I. Tertinegg, and C. R. Etbier. Finite element modeling of optic nerve head biomechanics. *Investigative Ophthalmology and Visual Science*, 45(12):4378–4387, 2004.

[19] I. G. Pallikaris, G. D. Kymionis, H. S. Ginis, G. A. Kounis, and M. K. Tsilimbaris. Ocular rigidity in living human eyes. *Investigative Ophthalmology and Visual Science*, 46(2):409–414, 2005.

[20] I. Kao and F. Yang. Stiffness and contact mechanics for soft fingers in grasping and manipulation. *IEEE Trans. on Robotics and Automation*, 20(1):132–135, 2004.