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Comparison of Frictional Characteristic Curves of Human Ocular Surface Determined by Using Hersey Number and Proposed New Number

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Abstract - The purpose of this research is to investigate such appropriate parameters that the frictional characteristic curves of human ocular surfaces can be arranged well. The frictional characteristic curves were determined by using the three methods: the Hersey Number in employing LSM (Least-Squares Method), the proposed new number in employing the BSG (BattleStar Galactica)-Starcraft of PSO (Particle Swarm Optimization) and LSM, and the proposed new number in employing the Genetic Algorithm and LSM. Then the obtained frictional characteristic curves were compared. Consequently, in both the mixed lubrication and the lubrication containing the mixed and fluid ones, the appropriate frictional characteristic curves could be obtained for the three methods. While, in the fluid lubrication, the appropriate frictional characteristic curves could be obtained for the two methods using the proposed new number, but the appropriate ones could not be obtained for the method using the Hersey Number.

***Keywords*:** Frictional Characteristic Curves, Human Ocular Surface, Hersey Number, Dry Eye.

1. Introduction

Dry eye syndrome has been considered to be related to friction on human ocular surfaces. In dry eye, a deficiency of the tear fluid causes continuous friction between the eyelid and the ocular surface during blinking [1]. As the tear fluid is decreased, the friction between the eyelid and the ocular surface is increased. The increase in friction is thought to cause the increase in the severity of LWE (Lid Wiper Epitheliopathy) and LIPCOF (Lid-Parallel Conjunctival Folds) [2]. Then the friction during blinks can damage the ocular surface [3]. In addition, in dry eye, the pressures of the upper and lower eyelids were significantly higher than those in normal ones [4]. Therefore, the eyelid pressure may change the shape of the cornea during blinking [5].

On the other hand, research on frictional characteristics of human ocular surfaces has been increased significantly. It has been reported that during spontaneous blinking in healthy patients, when sliding velocity is high, the friction between the eyelid and the cornea is in the fluid lubrication [6]. In addition, lubrication regimes in contact lens wear during a blink also have been examined by some researchers [7].

Although many researchers have examined the frictional characteristics of human ocular surfaces, there is no research investigating such appropriate parameters that the frictional characteristic curves of human ocular surfaces can be arranged well. Therefore, in this research, three methods were used to obtain the frictional characteristic curves: the Hersey Number in employing LSM (Least-Squares Method), the proposed new number in employing the BSG (BattleStar Galactica)-Starcraft of PSO (Particle

Swarm Optimization) and LSM, and the proposed new number in employing the Genetic Algorithm and LSM. The obtained frictional characteristic curves were compared to find the appropriate method for determining the frictional characteristic curves of human ocular surfaces.

2. Frictional Coefficients of Human Ocular Surface

In mechanical engineering, frictional coefficients on journal bearings can be identified using the Hersey Number. The Hersey Number [8] is shown as (1).

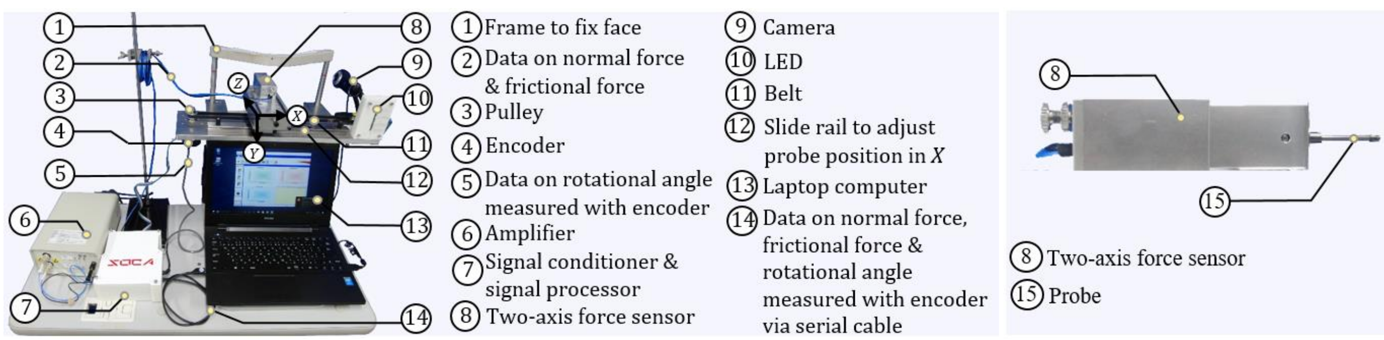
$$H_s = \eta\omega/p \tag{1}$$

Where η, ω, and p are the viscosity of lubricating oil, the rotational speed of a shaft, and the pressure of lubricating oil behind the location of the minimum separation between the bearing and the shaft, respectively.

In this research, frictional coefficient of the human ocular surface is considered related to the viscosity of tear fluid, the velocity of nictation, and the palpebral pressure. The measurements of frictional coefficient of the human ocular surface were conducted by using the ocular surface tribometer that developed in the previous research by authors [9].

2.1. Ocular Surface Tribometer

Figure 1 shows the ocular surface tribometer. The ocular surface tribometer is equipped with a two-axis force sensor (Alpha Tech, Japan). The ocular surface tribometer is used for measuring normal force, N frictional force, F acquired by the probe. Moreover, the ocular surface tribometer is used for measuring displacement, d of the probe. The data on normal forces, frictional forces, and displacements of the probe are sampled synchronously by using a data logger. The data logger consists of a signal conditioner, a signal processor, a laptop computer and a data logger software. The signal conditioner is used for changing the voltages of the normal forces and the frictional forces. The voltages are adjusted to the input voltage range of the signal processor. The signal processor is used for converting the analog data of normal forces and frictional forces to the digital ones. The laptop computer is used for executing data logger software. The data logger software is used for processing the measured data.



(a) Total device (b) Two-axis force sensor and probe

Fig. 1: Ocular surface tribometer.

2.2. Measurement Procedure

In this research, the measurements of frictional coefficient of the human ocular surface were conducted on six healthy subjects (A, B, C, D, E, and F). The frictional coefficients on the cornea and the bulbar conjunctiva near the ear side were measured on the left eye of the subjects.

Figure 2 shows the flowchart of the measurement procedure. The procedure to measure frictional coefficients of human ocular surfaces consists of several steps. The first step, to eliminate the pain during the measurement of the frictional coefficients, an anesthetic solution (0.4% of Benoxyl eye drop, Santen) was dropped to the eye of the subject. The second step, after 15 to 20 seconds since the dropping of the anesthetic solution, the face of the subject was fixed on the frame by adjusting the height of the frame. Then the position of the probe in X direction was adjusted to locate the tip of the probe in front of the left eye as shown in Figure 3 (a). The probe position was adjusted in Z direction until the probe nearly touch the eye of the subject as shown in Figure 3 (b). The slide rail clamper was used to tight the probe position. Next, using a screw, the probe was moved in Z direction until the tip of the probe touch the eye surface. The third step, the eye of the subject was opened to prevent the eyelid from touching the probe. Then the measurement of the frictional coefficient was started. In this step, the applied normal forces in Z direction were controlled in the range below 4.6 [gf] and the probe was moved in X direction in order to obtained frictional forces and displacements of the probe. Finally, after the measurement, an antibacterial ophthalmic solution (0.3% gatifloxacin ophthalmic solution, Senju Pharmaceutical Co., Ltd.) was dropped into the eye of the subject.

Figure 4 shows the examples of measurements frictional coefficients on the cornea and bulbar conjunctiva of healthy subjects. The measurements on the cornea were firstly conducted, then followed by the measurements on the bulbar conjunctiva.

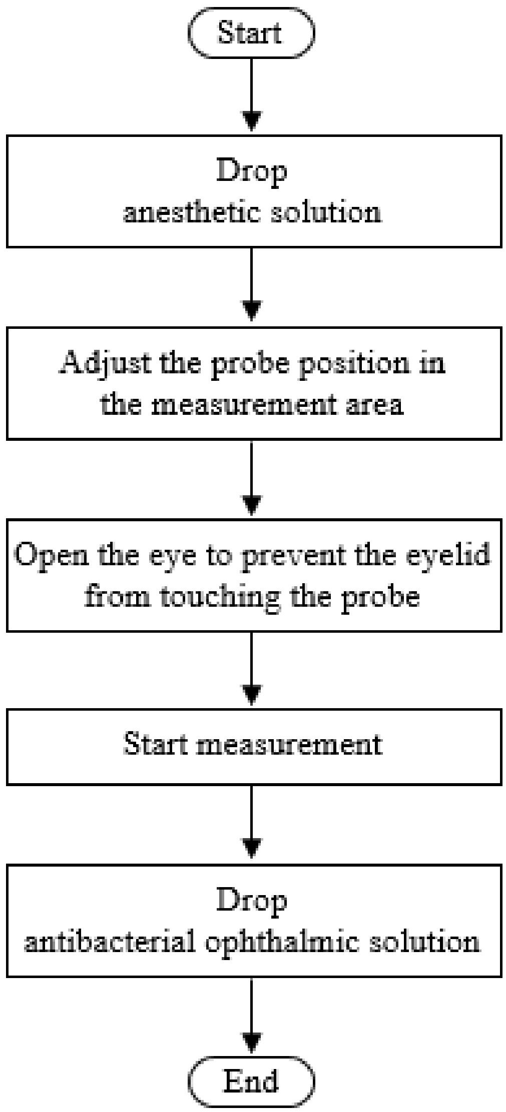
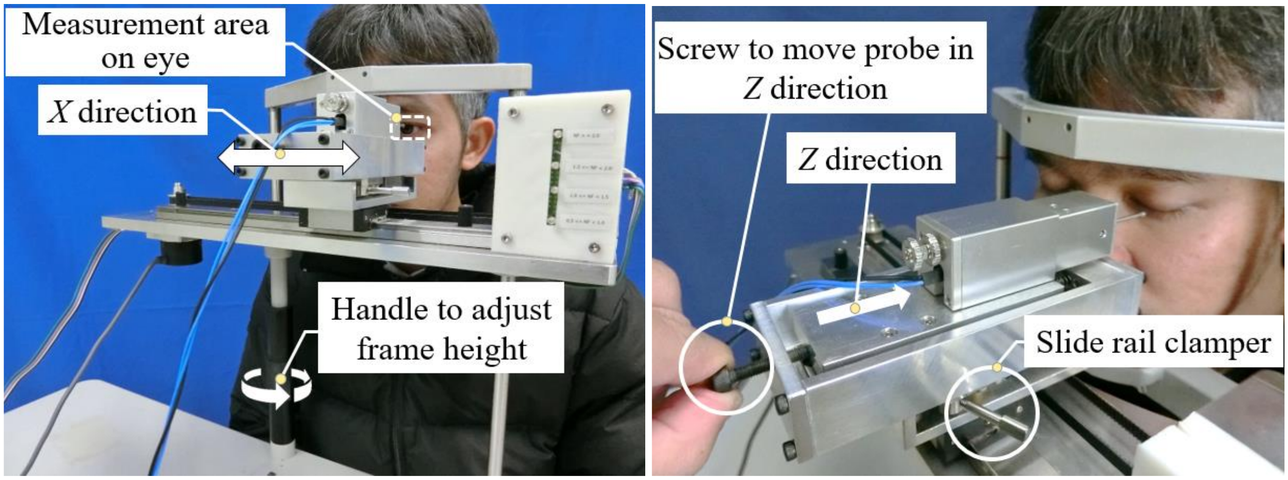
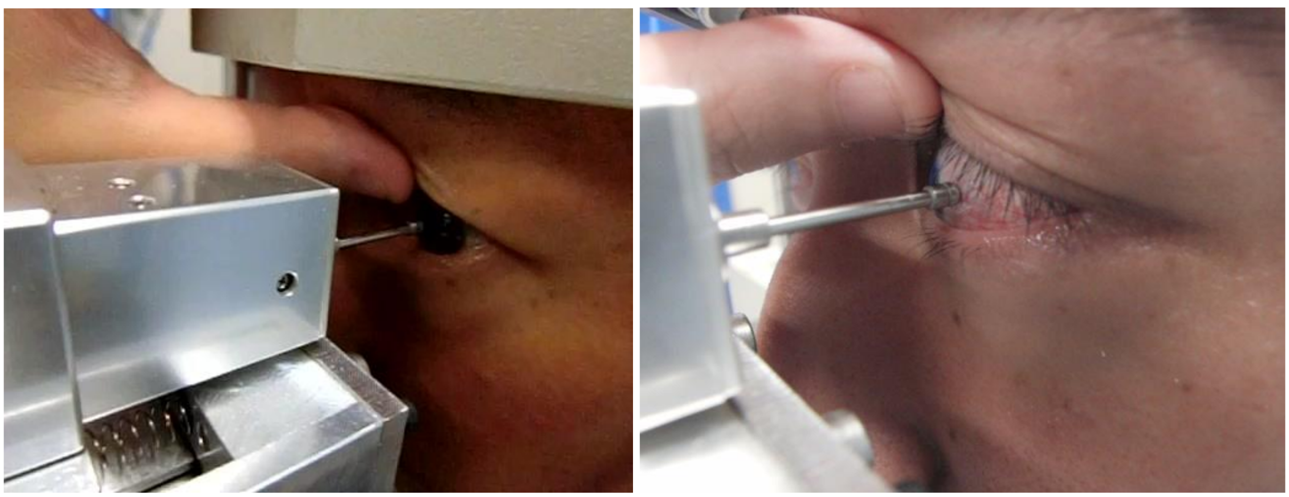


Fig. 2: Flowchart of measurement procedure.



(a) Probe position in X direction (b) Probe position in Z direction

Fig. 3: Adjustment of probe positions



(a) Measurement frictional coefficients on cornea (b) Measurement frictional coefficients on bulbar conjunctiva

Fig. 4: Measurements frictional coefficients on cornea and bulbar conjunctiva of healthy subjects.

3. Determining Frictional Characteristic Curves of Human Ocular Surfaces

3.1. Mathematical Model for Frictional Coefficients

In a normal eye, the eyelid and the ocular surface are separated by a tear layer. However, in a dry eye, some areas of the eyelid and the ocular surface directly contact each other. Thus, when the tear layer fully separates the eyelid and the ocular surface, the frictional coefficient of the human ocular surface is considered to be within the range of fluid lubrication. On the other hand, in the condition of the ocular surface is dry, the frictional coefficient of the human ocular surface is considered to be within the range of mixed lubrication. In this research, a new number, X was proposed to calculate frictional coefficient, μ on the human ocular surface as given in (2).

$$X=\frac{\eta^{p_1}V^{p_2}}{N^{p_3}} \tag{2}$$

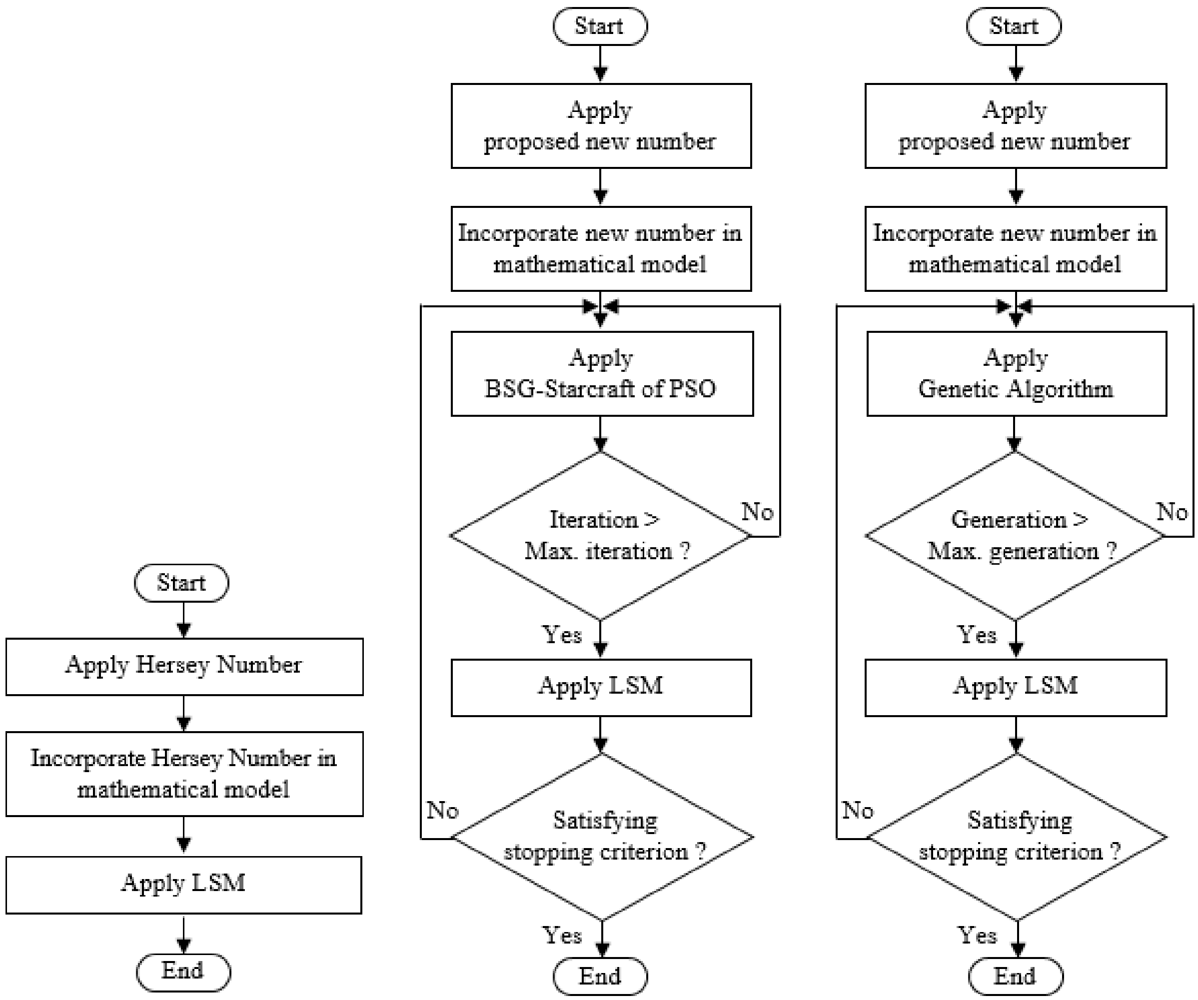
Where parameters, p_1, p_2, and p_3 are arbitrary real numbers. Then by incorporating the proposed number, X, a mathematical model was proposed to describe μ of the human ocular surface as given in (3).

$$\mu = p_4 X^{n-4} + p_5 X^{n-5} + \ldots + p_{n-1} X + p_n \tag{3}$$

Where parameters, p_4, p_5, …, and p_n are arbitrary real numbers. In this paper, it is assumed that η is constant and equal to 1, in other words $p_1 = 0$.

3.2. Procedure for Determining Frictional Characteristic Curves of Human Ocular Surfaces

In this research, the Hersey Number and the proposed new number were used for determining frictional characteristic curves of human ocular surfaces. The procedures for determining frictional characteristic curves of human ocular surfaces are shown in Figure 5.



(a) In using Hersey Number by employing LSM

(b) In using proposed new number by employing BSG-Starcraft of PSO and LSM

(c) In using proposed new number by employing Genetic Algorithm and LSM

Fig. 5: Procedures for determining frictional characteristic curves of human ocular surfaces.

Figure 5 (a) shows the procedure for determining frictional characteristic curves in using Hersey Number by employing LSM. Using the Hersey Number, the parameters p_2, and p_3 in Eq. (2) were set to be constant and equal to 1. Then by incorporating the Hersey Number to the mathematical model in Eq. (3), the parameters p_4, p_5, ..., and p_n were determined by employing the LSM.

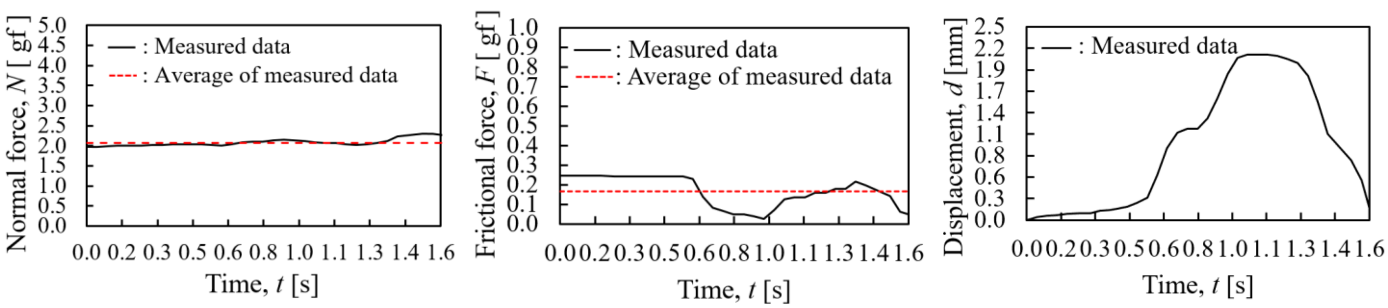
Figure 5 (b) shows the procedure for determining frictional characteristic curves in using proposed new number by employing BSG-Starcraft of PSO and LSM. The BSG-Starcraft of PSO was employed using the computational code that developed by the authors in the previous research [10]. The procedure was started by using the proposed new number, X. Then the proposed new number, X was incorporated in the mathematical model in Eq. (3). The parameters p_2, …, p_n in Eq. (2) and Eq. (3) were determined by employing the BSG-Starcraft of PSO and LSM. The BSG-Starcraft of PSO would terminate when the maximum number of iteration was reached. Then using parameters p_2 and p_3 obtained by the BSG-Starcraft of PSO, the parameters p_4, p_5,…, and p_n were determined by employing the LSM. In this research, the determination of optimal parameters in the mathematical model would terminate when the stopping criterion, namely the $p_4 > 0$ was met.

Figure 5 (c) shows the procedure for determining frictional characteristic curves in using proposed new number by employing Genetic Algorithm and LSM. The Genetic Algorithm was employed using the computational code that developed by the authors in the previous research [11]. The procedure was started by using the proposed new number, X. Then the proposed new number, X was incorporated in the mathematical model in Eq. (3). The parameters p_2, …, p_n in Eq. (2) and Eq. (3) was determined by employing the Genetic Algorithm and LSM. The Genetic Algorithm would terminate when the maximum number of generation was reached. Then using parameters p_2 and p_3 obtained by the Genetic Algorithm, the parameters p_4, p_5,…, and p_n were determined by applying the LSM. In this research, the determination of optimal parameters in the mathematical model would terminate when the stopping criterion, namely the $p_4 > 0$ was met.

4. Results

4.1. Experimental Data Measured by Ocular Surface Tribometer

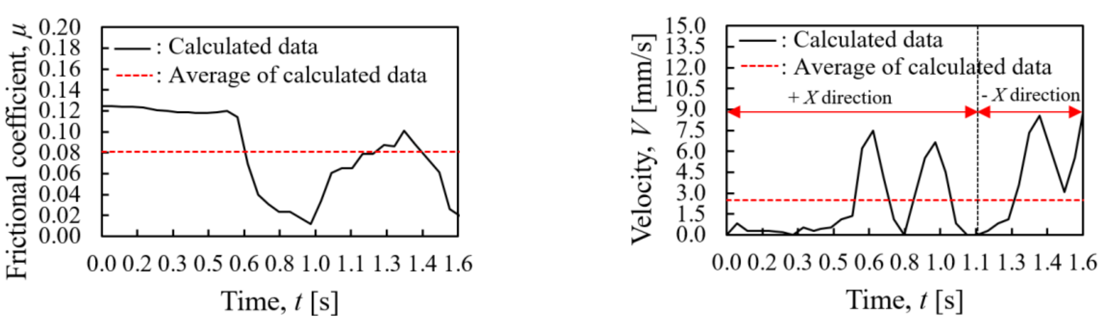
Figure 6 shows the examples of cornea's data measured by the ocular surface tribometer. Time history responses of N, F, and d were measured at the same time using the ocular surface tribometer. In this measurement, normal forces were applied to the cornea within the range of 1.98 [gf] to 2.30 [gf]. Frictional forces were measured in the range of 0.03 [gf] to 0.25 [gf]. The average values of normal forces and frictional forces are 2.08 [gf] and 0.17 [gf], respectively. The displacements of the probe were measured by the encoder and controlled to be within the maximum range of 2.12 [mm].



(a) Normal force (b) Frictional force (c) Displacement

Fig. 6: Examples of cornea's data measured by the ocular surface tribometer.

Figure 7 shows the examples of cornea's results calculated by using the measured data. The frictional coefficient, μ was calculated by using the measured N and F. The velocity of the probe, V was calculated by using the measured d. The average values of μ and V in this calculation are 0.08 and 2.51 [mm/s], respectively. The average values of μ and V were used for determining the frictional characteristics of human ocular surfaces.



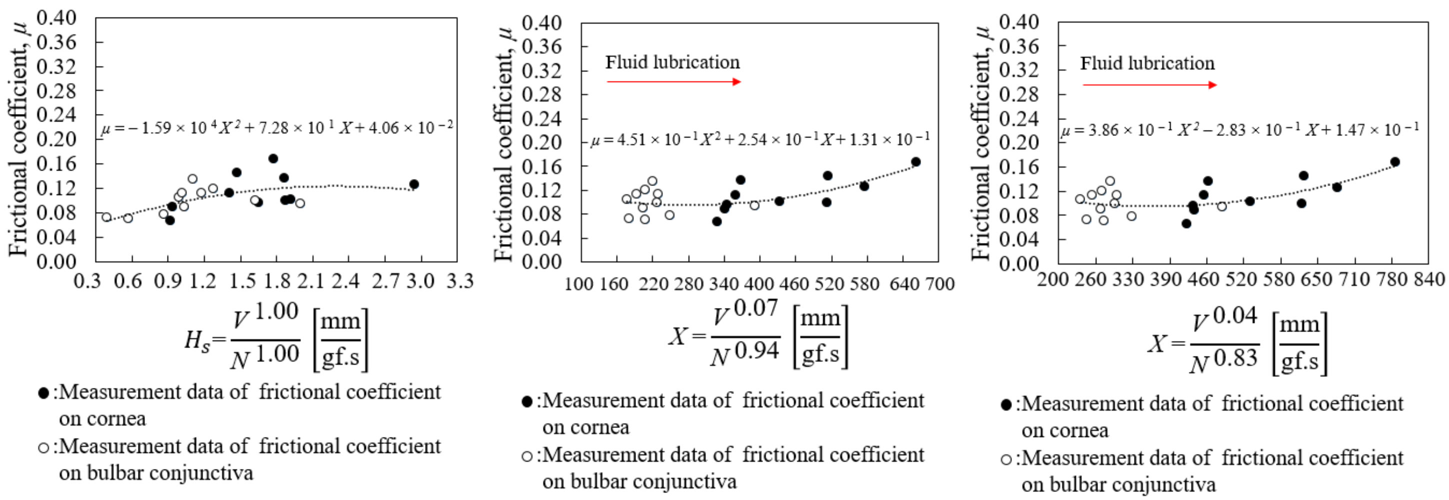
(a) Frictional coefficient (b) Velocity of probe

Fig. 7: Examples of cornea's results calculated by using the measured data.

4.2. Frictional Characteristic Curves of Human Ocular Surface

Figures 8, 9, and 10 show the examples of frictional characteristic curves on the cornea and bulbar conjunctiva of subject A, B, and C, respectively. As for subject A, by using the Hersey Number in employing the LSM, the obtained frictional characteristic curve shows a concave-downward characteristic. Frictional coefficients on both the cornea and bulbar conjunctiva fall outside the fluid lubrication region and the mixed lubrication region. While using the proposed new number in employing the BSG-Starcraft of PSO and LSM, the obtained frictional characteristic curve shows an upward-sloping characteristic. The frictional coefficients on both the cornea and bulbar conjunctiva fall within the fluid lubrication region where the eyelid and ocular surface are fully separated by the tear layer. The frictional characteristic curve determined by using the proposed new number in employing the Genetic Algorithm and LSM is similar to that determined by using the proposed new number in employing the BSG-Starcraft of PSO and LSM.

In this research, similar to the subject A, the frictional characteristic curves on the cornea and bulbar conjunctiva of subjects D, E, and F determined by using the Hersey Number in employing the LSM show the concave-downward characteristic. However, the frictional characteristic curves on the cornea and bulbar conjunctiva of subjects D, E, and F determined by using the proposed new number in employing the BSG-Starcraft of PSO and LSM show the upward-sloping characteristic. The upward-sloping characteristic curves of the frictional coefficients on the cornea and bulbar conjunctiva of subjects D, E, and F also obtained by using the proposed new number in employing the Genetic Algorithm and LSM.



(a) In using Hersey Number by employing LSM

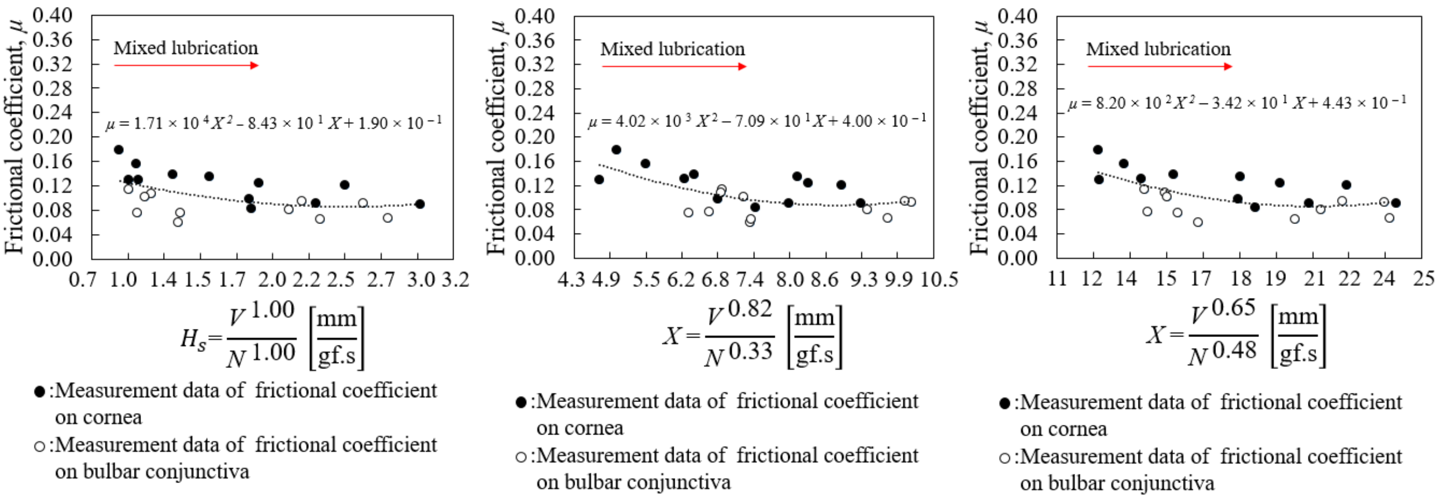
(b) In using proposed new number by employing BSG-Starcraft of PSO and LSM

(c) In using proposed new number by employing Genetic Algorithm and LSM

Fig. 8: Examples of frictional characteristic curves on cornea and bulbar conjunctiva of subject A.

As for subject B, the frictional characteristic curves obtained by the three procedures show a downward-sloping characteristic. The frictional coefficients on both the cornea and bulbar conjunctiva fall within the mixed lubrication where a part of the eyelid and ocular surface is supported by the tear layer, and in the other part, the eyelid surface may be in contact with the ocular surface.

As for subject C, the frictional characteristic curves obtained by the three procedures show a concave-upward characteristic. The frictional coefficients on the cornea fall within the fluid lubrication where the eyelid and the cornea are fully separated by the tear layer. The frictional coefficients on the bulbar conjunctiva fall within the mixed lubrication where a part of the eyelid and ocular surface is supported by the tear layer, and in the other part, the eyelid surface may be in contact with the ocular surface.

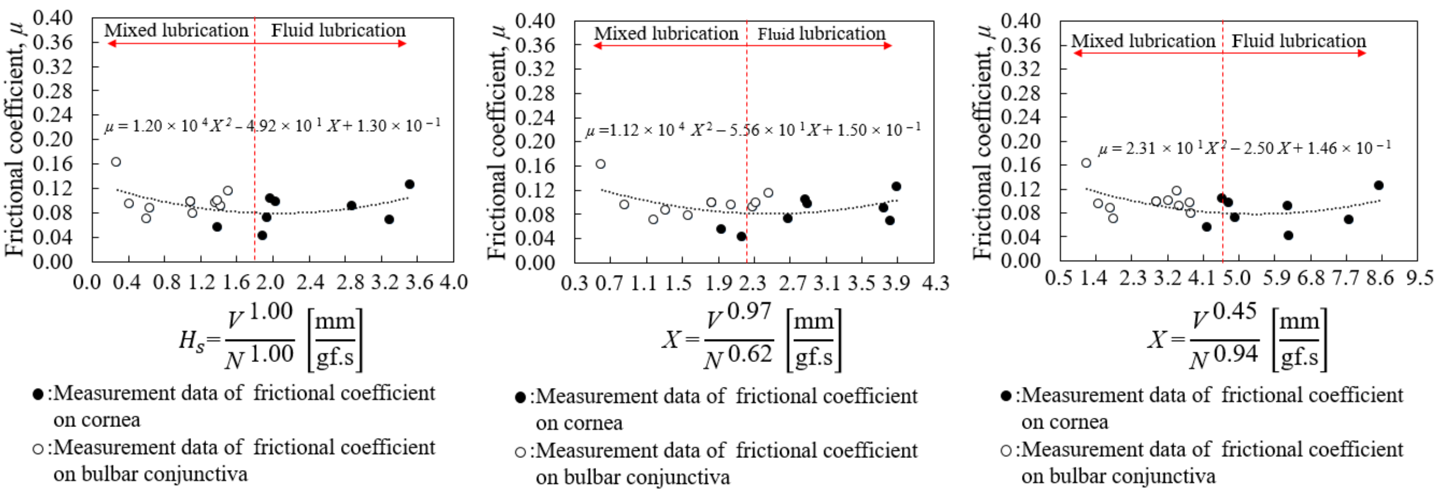


(a) In using Hersey Number by employing LSM

(b) In using proposed new number by employing BSG-Starcraft of PSO and LSM

(c) In using proposed new number by employing Genetic Algorithm and LSM

Fig. 9: Examples of frictional characteristic curves on cornea and bulbar conjunctiva of subject B.



(a) In using Hersey Number by employing LSM

(b) In using proposed new number by employing BSG-Starcraft of PSO and LSM

(c) In using proposed new number by employing Genetic Algorithm and LSM

Fig. 10: Examples of frictional characteristic curves on cornea and bulbar conjunctiva of subject C.

4. Conclusion

The summary of the results is shown below.

(1) The appropriate parameters that the frictional characteristic curves of human ocular surfaces can be arranged well have been obtained.

(2) The frictional characteristic curves have been determined by using three methods: the Hersey Number in employing LSM, the proposed new number in employing the BSG-Starcraft of PSO and LSM, and the proposed new number in employing the Genetic Algorithm and LSM. Then the frictional characteristic curves have been compared.

(3) The frictional characteristic curves obtained by using the three methods on both the mixed lubrication and lubrication containing the mixed and fluid ones have similar patterns, namely a downward-sloping characteristic and a concave-upward characteristic, respectively. However, for the fluid lubrication, the frictional characteristic curves obtained by using the Hersey Number shows a concave-downward characteristic, while those obtained by using the proposed new number shows an upward-sloping characteristic.

(4) In both the mixed lubrication and the lubrication containing the mixed and fluid ones, the appropriate frictional characteristic curves could be obtained for the three methods. While, in the fluid lubrication, the appropriate frictional characteristic curves could be obtained for the two methods using the proposed new number, but the appropriate ones could not be obtained for the method using the Hersey Number.

Acknowledgements

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