Proceedings of the 2012 IEEE
International Conference on Robotics and Biomimetics
December 11-14, 2012, Guangzhou, China

Basic Experiments on Collision of Sharp Mechanical Hazards against Eye for Estimation of Injury Severity

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Abstract— **This study deals with the avoidance/mitigation possibilities in an estimation of severity of injury from a mechanical hazard when a sharp-edged object approaches a human eye. We assume that the sharp end effector of a robot approaches the eye of a human in a human-robot coexistence system. We conduct a static eye collision experiment and dynamic eye collision experiment taking into consideration human avoidance/mitigation actions. Three conditions (collision position, collision angle, and eyelid state—open/closed) are varied in the static collision experiment. Consequently, it is confirmed that differences in severity result from these changes in the experimental conditions. In the dynamic collision experiment, Bell's phenomenon, which is an upward rotation of the eyeball at the time of closing the eyelid, is taken into consideration, and two conditions (collision position and angle) are changed. Through these experiments, we find that Bell's phenomenon plays an important role in the risk estimation. Although the avoidance/mitigation possibilities have not previously been taken into consideration in eye collision experiments, we consider these to be indispensable to the risk estimation.**

I. INTRODUCTION

A. Background

When the eye is injured by a mechanical hazard, the severity of injury is much higher than that for other parts of the human body. Haddadin *et al.* [1] indicated that the injury severity of the soft skin of a swine leg traumatized by the sharp tool of a robot was reduced by limiting the torque of the robot. However, it is necessary to estimate the risk to the eye separately from other parts of the body when considering human safety in the presence of a robot. The eye may easily become seriously injured, especially by a sharp mechanical stimulus, even if the robot is allowed to exert only a weak external force. A robot body can be designed to eliminate mechanical hazards such as stabbing based on the principle of an inherently safe design. However, it might not be possible to apply the inherently safe design principle to an end effector and gripped object. We targeted this case with the goal of estimating the risk in terms of severity.

Specifically, we targeted an upper-body humanoid robot for assembling machine parts and assumed a situation where the robot's sharp end effector impacts a worker's eye. It has been concluded that when a robot poses mechanical hazards, a human has to take safety measures such as wearing protective goggles for safe human-robot coexistence.

This work was supported by KAKENHI 21246041.

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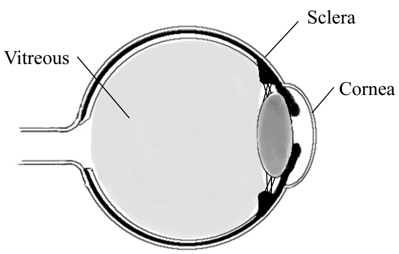


Fig. 1. Structure of eyeball

However, the severity of the injury to the eye depends on the coexistence form, including the positional relationship between the human and robot. That is, an eye collision may not necessarily result in a serious injury such as blindness.

In a study on the eye injuries caused by a collision with an object, Kennedy *et al.* [2] developed an artificial eyeball and orbit for collision experiments by referencing eye collision experiments with human cadavers. Weaver *et al.* [3] conducted simulations of eyeball collisions with various objects such as a plastic bar and BB and investigated the stress applied to the cornea and the pressure applied to the sclera. See Fig. 1 for understanding of the structure of eyeball. However, these studies did not take into consideration the influence of human avoidance/mitigation actions such as closing the eyelid or changing of the collision angle.

B. Purpose

We conducted eye collision experiments by changing the approach angle of a sharp end effector, as well as the collision position.

The collision timing of the end effector could be divided into three categories: an open eyelid, closing eyelid, and closed eyelid. If an end effector moves too fast or a human does not notice its approach, it will collide when the eyelid is open. If a human notices the approach of the end effector and closes his/her eyelid quickly, the end effector will collide during the closing of the eyelid or after it is closed. Moreover, eyelid movement and Bell's phenomenon [4], which is an upward rotation of the eyeball during the closing of the eyelid, should be taken into consideration when the end effector collides during the closing of the eyelid. This is because the movement of the eyelid and eyeball may make a difference in the severity of the injury.

For the three collision timings mentioned above, we only had to conduct a static collision experiment with the eyelid open or closed, without taking into consideration eyeball

978-1-4673-2126-6/12/$31.00

movement during the collision, because the eyeball is not moving in these states. However, we needed to conduct a dynamic collision experiment that took into consideration eyeball movements in a collision where the eyelid was closing, because of the occurrence of Bell's phenomenon. In this study, we conducted static and dynamic eye collision experiments as basic experiments, where a human head was fixed under collision conditions that took into consideration human avoidance/mitigation actions. We here discuss the influence of the collision conditions on the severity of the injury.

C. Risk Assessment

One of the targets of our study was a rational risk assessment in a human-robot coexistence system. In the field of safety of machinery, the risk elements in a risk assessment are the severity of harm and the probability of occurrence of harm, according to the international safety standard ISO 12100:2010 [5]. The probability of occurrence of harm is further divided into three elements: the exposure frequency, occurrence probability of a hazardous event, and human possibilities for avoiding harm. These can be summarized as follows.

- Severity of harm
- Probability of occurrence of harm
  - Exposure frequency
  - Occurrence probability of a hazardous event
  - Human possibilities for avoiding harm

If all of these elements are estimated, we can conduct a risk assessment. In this study, we investigated the severity of harm from the collision of an end effector approaching the eye from various directions. The exposure frequency and occurrence probability of a hazardous event can be calculated statistically under our assumed situation because we deal with a repetitive task. In addition, Hattori *et al.* [6] and Sunada *et al.* [7], who are part of the author's group, have investigated the possibility of avoiding an approaching end effector by conducting psychological experiments and proposed simulation of extrapolating robot movement. Therefore, combining these findings will allow us to estimate the risk under the assumed situation.

D. Study Objective

The event tree for an end effector colliding with a worker's eye is shown in Fig. 2. First, the end effector approaches during "originating accident" (EA: End effector approaches). The worker would try to avoid the end effector by throwing himself/herself backward or turning his/her head. If the worker avoids the end effector or the end effector collides with a different part of his/her body, his/her eye does not get injured (EA·SA: Succeeds in avoiding). Otherwise, the end effector collides with the worker's eye (EA·FA: Fails to avoid), and he/she gets injured. If a body/head movement changes the collision position or collision angle of the end effector or the worker closes his/her eyelid before the end-effector collision, and the collision condition is moderated, the severity will be low (EA·FA·MC: Mitigated condition). Otherwise, the collision condition is severe and the severity would be high (EA·FA·SC: Severe condition). An example of high severity will be a case of severe vision loss that makes it difficult to return to work, while some other injury would be a slight one. The severity is classified in detail in Section II-D. In Fig. 2, while "avoidance of body/head" indicates whether the worker can avoid a collision between the end effector and his/her eye, "collision conditions" affect the severity. Our study objective is to determine how changes in the collision conditions at the eye affects the severity.

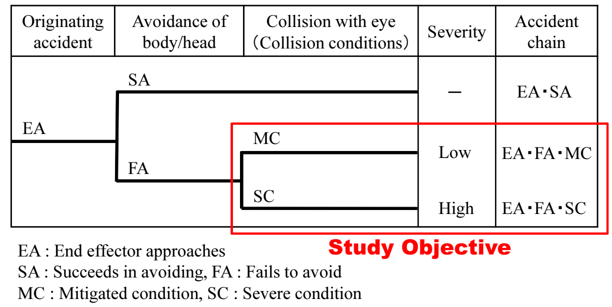


Fig. 2. Event tree for eye collision with end effector

II. Static Eye Collision Experiment

A. Experiment Objective

In this experiment, we investigated the severity by varying three conditions: eyelid state—open/closed, collision position, and collision angle. It was important to compare collisions when the eyelid was open and closed to determine whether it could protect the eyeball from the end effector and mitigate the severity. Furthermore, human avoidance/mitigation actions such as turning the face could change the collision position or collision angle and affect the severity.

B. Experimental Equipment

We used a dummy eye composed of a porcine eyeball, artificial eyelid, and mechanisms to fix the eyeball and eyelid, and to express the elasticity of the soft tissue around the eyeball. The appearance of this dummy eye is shown in Figs. 3 and 4, and its specifications are listed in Table I. A porcine eyeball has often been used as a substitute for a human eyeball because its structure is similar to that of a human's and its availability is comparatively easier [8]. Two springs expressing the elasticity of the soft tissue were placed behind the eyeball. Schutte *et al.* [9] showed that the Young's modulus of soft tissue is 300 Pa. Therefore, we supposed that the spring constant corresponding to this characteristic was 19.9 N/mm.

The impactor was an end effector made of aluminum (YH75), which had the shape of tweezer. Its appearance and dimensions are shown in Figs. 5 and 6, respectively. The shape was the same as that developed for grasping mechanical parts at production sites. This end effector was

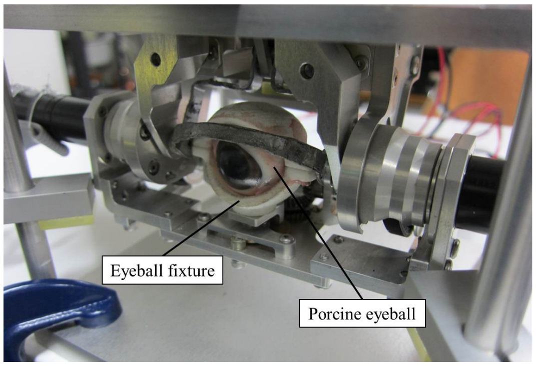


Fig. 3. Dummy eye without eyelid

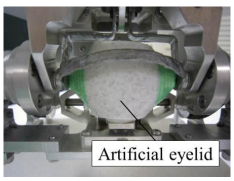


Fig. 4. Dummy eye with eyelid

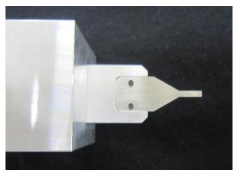


Fig. 5. End effector

TABLE I
SPECIFICATION OF DUMMY EYE

Eyeball	· Porcine eyeball · Elliptical ball · Diameters: 25 mm, 24 mm, 22 mm
Eyelid	· Silicon series rubber material · Thickness: 1 mm · Stab strength: 22.3–31.2 N · Tensile strength: 0–4.9 N/mm^2
Soft tissue	· 1 DOF in the direction of optical axis · Spring constant: 19.9 N/mm

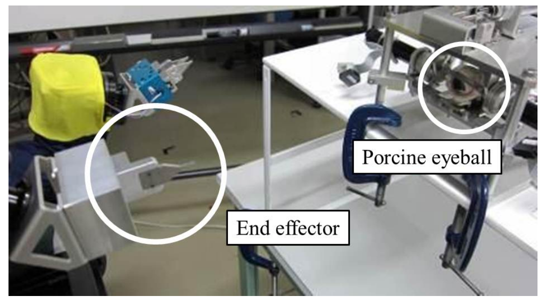


Fig. 7. Eye collision experiments

attached to an upper-body humanoid robot (HIRO, Kawada Industries, Inc.) [10], [11] and operated.

C. Experimental Conditions

The robot and dummy eye were set up to face each other, as shown in Fig. 7. C-clamps were used to mount the dummy eye on a stand. Ideally, human avoidance/mitigation actions by body/head movements should be considered, instead of having the eye clamped in place. However, we did not have detailed knowledge of such human avoidance/mitigation actions. Therefore, we clamped the eye in a fixed position in this experiment as a worst-case scenario where the human body and head do not move. The robot's right arm was operated in a straight line, and the end effector was made to collide with the dummy eye. The end effector was made to stop about 10 mm past the surface of the eyeball when it collided from the normal direction. If the collision depth was greater than 10 mm, the end effector would puncture the eyeball and the vitreous would escape, which would result in a high severity of injury. A depth of 10 mm made it possible to discuss the injury condition. The collision speed of the end effector was about 280 mm/s. This is the speed of the end effector at the eyeball surface when the robot's right arm operates at the maximum speed possible. This speed was set to investigate the most hazardous case in the assumed situation.

While the robot's operation condition was fixed, the three collision conditions were varied for the dummy eye: eyelid state, collision position, and collision angle. There were two eyelid states (open/closed), two collision positions, and three collision angles. These are shown in Fig. 8. When the eyelid was open, the end effector collided directly with the eyeball, and when the eyelid was closed, the artificial eyelid was set in front of the eyeball. The collision positions were the cornea and sclera near the cornea. The sclera was set 45° from the optical axis on the same horizontal surface as the axis. We chose this angle to place the impact to the sclera between the cornea and the corner of the eye. We expected that the severity of injury to the cornea would be different from that to the sclera because their anatomies are different. The collision angles were the normal direction of the eyeball, along with 30° and 45° from the normal direction. The collisions at 30° and 45° from the normal direction were set as being representative of a human avoidance/mitigation

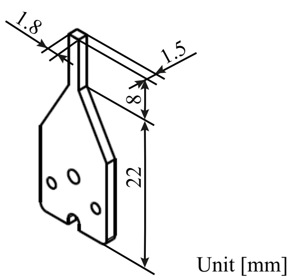
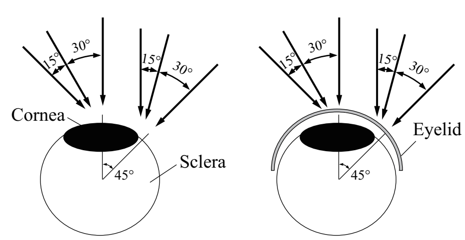


Fig. 6. External dimensions of end effector



(a) Open eyelid (b) Closed eyelid

Fig. 8. Experimental conditions for static collision experiment

TABLE II
CLASSIFIED SEVERITY AND THEIR INJURY CONDITIONS

Severity	Injury condition
4	The eyeball was punctured and the vitreous leaked out
3	The cornea surface was injured
2	The sclera surface was injured
1	No injury was able to be confirmed with the naked eye

action such as turning the face. We set these two angles in addition to the normal direction to confirm the influence of the magnitude of the collision angle on the severity.

D. Experimental Results

We classified the injury conditions and their severity into four categories, as shown in Table II, in imitation of an international standard for safety of machinery [12] . It is hard to consider the influence on eyesight in the case of the severity “1”. The severity “2” and “3” may cause impaired vision. The severity “3” is more severe than the severity “2” in terms of visual function. The severity “4” may cause severely impaired vision. In the worst case, this presents the possibility of losing sight. Based on the above, the experimental results of the collisions with the cornea and sclera are presented in Tables III and IV, respectively.

In the case of a collision with the cornea from the normal direction, the end effector punctured the eyeball in both the open and closed state of the eyelid. Fig. 9(a) shows a photograph of an eyeball that underwent a collision with the eyelid open and was punctured. We confirmed that the cornea was punctured by the end effector. Fig. 9(b) shows a photograph of the punctured eyelid after a collision in the closed state of the eyelid. We confirmed that the eyelid was split where the end effector collided. In the case of a collision with the cornea from an angle, we confirmed a scratch on the surface, but the end effector did not puncture the eyeball, except in the collision at 45° from the normal direction with the closed eyelid.

While we could confirm a scratch on the surface of the eyeball in the case of a collision with the sclera from the normal direction, we could not confirm injury in the other cases of collision with the sclera.

E. Discussion

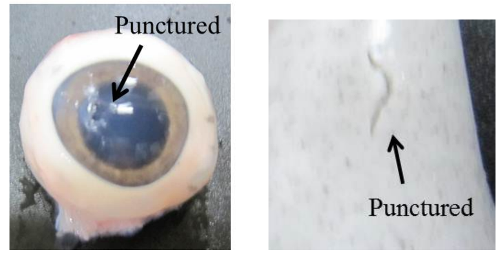
First, we discuss the influence of the collision position. In the case of a collision with the cornea, the eyeball was often

TABLE III
RESULTS OF STATIC COLLISION EXPERIMENT WITH CORNEA

	0°	30°	45°
Open eyelid	4	3	3
Closed eyelid	4	3	1

TABLE IV
RESULTS OF STATIC COLLISION EXPERIMENT WITH SCLERA

	0°	30°	45°
Open eyelid	2	1	1
Closed eyelid	1	1	1



(a) Punctured eyeball (b) Punctured eyelid

Fig. 9. Injured eye

punctured or scratched. In contrast, the severity of injury in the case of a collision with the sclera was lower. Therefore, the severity in the case of a collision with the cornea was estimated to be comparatively high, and in some cases, there was a possibility of blindness.

Second, we discuss the influence of the collision angle. In the case of a collision with the cornea from the normal direction, the eyeball was first dented and then punctured by the end effector. On the other hand, in the case of a collision with the cornea from an angle other than the normal direction, even if the eyeball might have been dented, it did not extend to be punctured. With an increase in the angle from the normal direction, the end effector began to slide across the eyeball and eyelid, or the eyeball began to rotate and divert the end effector. Therefore, if a human exercises an avoidance/mitigation action such as turning his/her face to avoid a collision from the normal direction, the severity is estimated to be lower during the collision of an end effector with human eye.

Third, we discuss the difference in severity of injury between collisions with an open eyelid and closed eyelid. In the case of a collision with the cornea from the normal direction, the eyeball was punctured in both cases (open/closed eyelid). We confirmed that in some cases, the eyelid was injured but the eyeball was not injured with a closed eyelid, while the eyeball surface was injured with an open eyelid in the case of a collision from a direction other than the normal direction. Therefore, it is estimated that closing the eyelid would reduce the severity of injury, except for a collision from the normal direction.

In addition, we confirmed the repeatability of this experiment under one collision condition in which the result was observed to be the severity “3”. The condition was a collision with the cornea at 30° from the normal direction with the open eyelid. The collision experiments were repeated 10 times under the condition. As a result, the severity was “3” in all trials. Although only one condition was dealt with, the high repeatability of this experiment was confirmed. Since the individual differences in the porcine eyeballs we used were small, it is expected that results of repetition experiments will not change greatly, irrespective of collision conditions. Therefore, it is considered that the boundary value of the collision angle at which an eyeball does not get punctured is up to 30° from the normal direction.

However, these results cannot necessarily be applied to

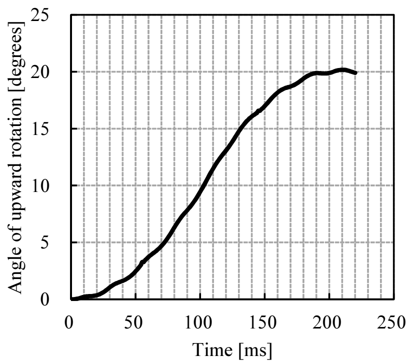


Fig. 10. Upward rotation of eyeball driven by motor

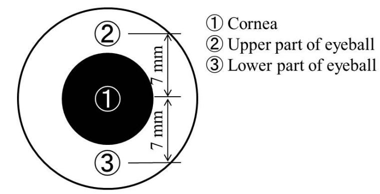


Fig. 11. Collision positions in dynamic collision experiment

TABLE V
RESULTS OF DYNAMIC COLLISION EXPERIMENT

	0°	30°	45°
Cornea	3	3	1
Upper part of eyeball	3	3	1
Lower part of eyeball	1	—	—

other cases. Tweezers are one of the sharpest and most useful tools. It is estimated that the severity would have been lower if the impactor was a rounded tool.

III. DYNAMIC EYE COLLISION EXPERIMENT

A. Experiment Objective

It has been reported that Bell's phenomenon [4], in which the eyeball rotates upward, occurs when a human closes his/her eyelid. Seo *et al.* [13] investigated Bell's phenomenon using the search coil method. In some people, an upward rotation of their eyeball is associated with a slight outward or inward rotation. For simplicity, in this experiment, we took into consideration a simple upward rotation with a closed eyelid. Specifically, the end effector was made to collide with the dummy eye at different collision positions and angles during the upward rotation of the eyeball, with the eyelid closed, and the severity was investigated. The objective of this experiment was to investigate how the upward rotation of the eyeball expressed by closing the eyelid, which is an action to mitigate harm, affects the severity.

B. Experimental Equipment

The experimental devices were primarily the same as those used in the static collision experiment. The difference was the mechanism of eyeball rotation. The eyeball was rotated using motors (RE16, Maxon Motor AG) connected via gears, pulleys, and belts.

C. Experimental Conditions

The operation conditions of the robot were the same as in the static collision experiment. The dummy eye was operated to mimic human eyeball movement, unlike the static collision experiment described in II. Specifically, the initial angle of the eyeball was considered as the primary position, and the eyeball began to rotate upward when the end effector reached the eyeball surface. The eyeball rotated by 20° in 200 ms, which was the speed measured by Seo *et al.* [13]. The eyeball's upward rotation pattern is shown in Fig. 10.

The eyelid of the dummy eye was closed, and three collision positions and three collision angles were set. The collision positions were the cornea in the initial state before the eyeball's upward rotation, the upper part of the eyeball, and the lower part of the eyeball. These collision positions are shown in Fig. 11. The upper and lower parts of the eyeball were about 7 mm above and below the cornea center, respectively. These parameters were set considering that a change in the collision position by eyeball rotation could affect the injury condition. For example, a collision with the upper part of the eyeball could affect the cornea because of the eyeball's upward rotation, while the end effector would collide with the sclera if the eyeball did not move. The collision angles were the normal direction of the eyeball, along with 30° and 45° from the normal direction.

D. Experimental Results

The experimental results are presented in Table V. For the numbers in the table, see Table II. The symbol "—" represents the case that no experiment was conducted.

In the case of a collision with the cornea and upper part of the eyeball, the eyeball was scratched, with the exception of 45° from the normal direction. No injury was able to be confirmed in the case of collision with the cornea at an angle of 45° from the normal direction and collision with the lower part of the eyeball.

E. Discussion

First, we discuss the effect of the collision angle. As can be noted from Table V, the severity decreased with an increase in the angle from the normal direction of the eyeball.

Second, we discuss the effect of the collision position. In the case of a collision with the cornea, only the surface of the eyeball was injured. The deviation from the center of the cornea as a result of the eyeball rotation produced this outcome. The collision condition with the upper part of the eyelid was similar to the collision condition with the sclera from an angle in the static collision experiment, the exception being eyeball rotation that occurred in the former. While no injury was able to be confirmed in the static collision experiment, injury to the cornea was confirmed in the dynamic collision experiment. A slight scratch was also confirmed. The injury condition is shown in Fig. 12. It can be said that the upward rotation of the eyeball influenced the

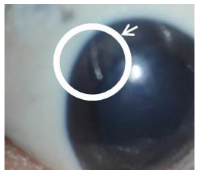


Fig. 12. Slight scratch

injury condition. We believe that no injury was confirmed in the case of a collision with the lower part of the eyeball because the end effector collided with the sclera even when the eyeball rotated upward.

This experiment involved collisions with a closed eyelid. It is considered that the eyeball was not punctured because it was protected by the eyelid. Thus, we found that while a closed eyelid mitigated the severity to some extent, the eyeball movement associated with closing the eyelid also influenced the severity. It is estimated that even if a human could close his/her eyelid before an end-effector collision, the severity would be higher than that of a collision with the sclera if the eyeball rotated in association with this closing and the cornea then returned to a position behind the collision area of the eyelid. While closing of the eyelid against a collision with an object is one of the mitigation actions, the eyeball movement associated with this action would not necessarily mitigate the severity. Therefore, the position of the cornea at the collision is important in an investigation of the severity of injury to an eye.

However, the above discussion might not necessarily be applicable to another end effector with different shape.

IV. Conclusions

In this study, we investigated the impact of a robot's sharp end effector on a human eye in a human-robot coexistence system. We conducted basic eye collision experiments under various collision conditions, taking into consideration human avoidance/mitigation actions. And we examined how differences in the collision conditions influenced the severity of injury. Three collision conditions (collision angle, collision position, and eyelid state—open/closed) were varied in a static eye collision experiment. The results showed that all of the conditions had some influences on the severity. Specifically, the eyelid served as a safeguard. In regard to the collision position, the severity of injury to the sclera was estimated to be lower than that to the cornea. In regard to the collision angle, the severity decreased with an increase in the angle from the normal direction of the eyeball. This was a very interesting result. If the probability that a human can avoid the end effector is the same against approach from any direction, the risk of collision from the side is estimated to be lower than that from the front. In this instance, it is desirable to locate the robot so that its motion range is beside the human. In the dynamic eye collision experiment, the collision position and collision angle were varied taking into consideration Bell's phenomenon, in which an eyeball rotates upward in association with a closing eyelid. As a result, we found that eyeball movement was an important factor influencing the severity. Although avoidance/mitigation actions have not been taken into consideration in previous eye collision experiments, we consider these to be indispensable to the risk estimation.

We need to increase the number of collision conditions and trials to statistically assess the probability of occurrence of injury corresponding to the severity under each collision condition.

V. Acknowledgment

We are indebted to Associate Professor Yasuki Ito of Nagoya University for his insightful advice. We are also indebted to Tsuyoshi Mizuno of Mizuno Technical Institute for his assistance in designing and manufacturing the experimental equipment. We are grateful to graduate student Koji Sunada at Nagoya University for his cooperation.

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