2012 IEEE RO-MAN: The 21st IEEE International Symposium on
Robot and Human Interactive Communication.
September 9-13, 2012. Paris, France.

Extrapolation Simulation for Estimating Human Avoidability in Human-Robot Coexistence Systems

Koji Sunada, Yoji Yamada, Takamasa Hattori, Shogo Okamoto, and Susumu Hara

Abstract— **In the design of human-robot coexistence environments, human avoidance actions are not taken into consideration. We conduct a psychological experiment to observe human avoidance actions where a mechanical harm approached his or her eyes. Using the observed motions, we carry out "extrapolation simulation" of human avoidance actions in collision situations. As simulation results, first, we express collision probability using the motion range of the end effector of a robot as a variable. Second, we identify the motion conditions, which ensure the safety, of the end effector in our setup. Finally, we quantitatively compare the safety conditions between taking and not taking avoidance actions into consideration. This study contributes to providing a tool for conducting a practical risk assessment aimed at realizing a safe human-robot coexistence system.**

I. Introduction

Humans, by nature, take harm-avoidance actions when they perceive a threat from an approaching object. Hence, the possibility of avoiding or limiting harm (hereafter referred to as "avoidability"), which is one element of risk [1], should be taken into consideration when designing human-robot coexistence systems. Nonetheless, avoidability currently tends to be either neglected or discretely estimated in two or three levels by assessor's intuition because human avoidance action is an unexplored human factor.

Previous research into the safety of human-robot interactions has focused mainly on the end result of a harmful interaction. Oberer and Schraft [2] investigated injury indices using finite element models to simulate the collision of a robot with the head, chest, and pelvis of a dummy, and Haddadin *et al.* [3] followed this up with head and chest collision experiments. Park *et al.* [4] proposed a model for the collision between a human head and a robot, and showed that the optimal elastic modulus and thickness of the robot's covering could be determined so as to prevent skin injuries. However, harm-avoidance action, which humans are most likely to engage in, was not taken into consideration in these studies.

Human reactions have been considered in some studies. Ikeura *et al.* [5] measured the galvanic skin reflex of a subject when a robot was projected straight toward the subject's face to investigate which robot motions the human regarded as threatening. In order to identify robot motion conditions that aroused human fear, Yamada *et al.* [6] measured the pupillary diameter of a subject when a robot end-tip accelerated towards the subject's face. Again, however, the effects of human actions to avoid harm were not studied.

The second author of this paper previously proposed and developed a next-generation cell production system, in which a human and a robot work cooperatively [7], [8]. There is a strong desire to remove the light curtains from production sites because they cause a reduction in available space that tends to decrease productivity. The light curtains can be removed if the coexistent robot is basically designed as being inherently safe, yet there is always the fundamental problem that a power-limited robot grasping a sharp-edged object could cause more harm to a human eye than to another part of the body (e.g., a shoulder).

We conducted psychological experiments to observe human avoidance actions in a particular situation where human eyes were under threat in a human-robot coexistence system [9].[1] In our experiments, the robot's motions were controlled so as not to touch the participants to ensure their safety.

Using the data from the psychological experiment, we propose to simulate collisions between the human eye and robot's end effectors, taking human avoidance actions into account. We termed this an "extrapolation simulation." Human avoidance actions have not been taken into consideration in previous robot safety simulations. Collision probability involving avoidability can be estimated by carrying out extrapolation simulations under various conditions. This paper presents a method to estimate safety conditions under our experimental setup. We can identify the difference between safety conditions when avoidance actions are taken and when they are not. This study contributes to the development of a tool for conducting practical risk assessments in order to realize a safe human-robot coexistence system.

II. Psychological Experiment

A. Experimental Design

We consider a general situation in which a gripper or an object grasped by a next-generation robot, which should coexist with humans, becomes a hazard. In reference to a practical study [7], we assume a situation where a sharp end-effector tip of a production site robot is suddenly projected towards the eyes of a worker sitting opposite.

In the assumed situation, the worker naturally takes some avoidance actions based on visual and auditory information. Nevertheless, workers may not necessarily hear the motors

This work was supported by KAKENHI 21246041.

K. Sunada, Y. Yamada, T. Hattori, S. Okamoto, and S. Hara are with the Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan. http://www.mech.nagoya-u.ac.jp/asi/en/

[1]The present studies were approved by the local ethical committee.

installed in the robots while in an actual working environment. For this reason, we focus on the more hazardous situation in which visual information alone is provided to the worker.

An upper-body humanoid robot (HIRO, Kawada Industries, Inc.), designed to operate collaboratively with a human [7], [8], was used in the experiments. The participant wore protective glasses and was separated from the robot by a working table. To minimize any hazard to the participant, the original end effectors for picking up and placing mechanical parts were replaced with pyramid-shaped flexible polyurethane foams.

B. Experimental Conditions

1) Participants: Nine people, five males and four females between the ages of 18 and 28, participated in the experiment. Every participant was healthy with good eyesight; no one reported suffering from belonephobia.[2]

2) Experimental Setup: Each participant sat on a stool in front of the robot. The participants wore noise-canceling earphones (NW-A845, Sony Corp.) to block any external auditory information; they instead listened to sounds recorded in a factory. They were exposed to the working area of the robot and performed the task of inserting two mechanical parts, rollers and retainers, between bearing rings using tweezers. While they were performing the task, one end effector at the tip of the robot arms would suddenly approach their eyes. The end-effector tip arrived at a point approximately 50 mm forward of the participant's initial eye position at the end of the robot motion. It was because we ensured the participant's safety. The contact between the end effector and the participant might cause some damage to the participant.

The probability distribution of the foreperiod (i.e., the period of the task before the robot arm is projected towards the participant) is often modeled using an exponential distribution [10]. In this manner, statistically random foreperiods were taken as the sum of 10 s and exponential random values with a mean of 15 s, excluding those longer than 60 s.

Fig. 1 shows a schematic diagram of the relevant locations and distances in the experimental setup. The location of the bearing rings is indicated by the cross. Three initial positions (far, middle, and near) were set for the end effectors. The initial distance between the participant's eyes and an end-effector tip was set to be approximately 470, 370, and 270 mm for far, middle, and near patterns, respectively. For all patterns, each participant was asked to confirm that the end-effector tips, located at a viewing angle of approximately 30°, were in their peripheral vision when the task position was in the center of the visual field.

Fig. 2 shows the speed patterns of the end-effector tip.The maximum speed and initial acceleration of the tip were based on the runaway assumption.[3]

[2]For safety reasons, initial experiments had to be conducted with young people in good health who seemed to have reasonably good reactions.

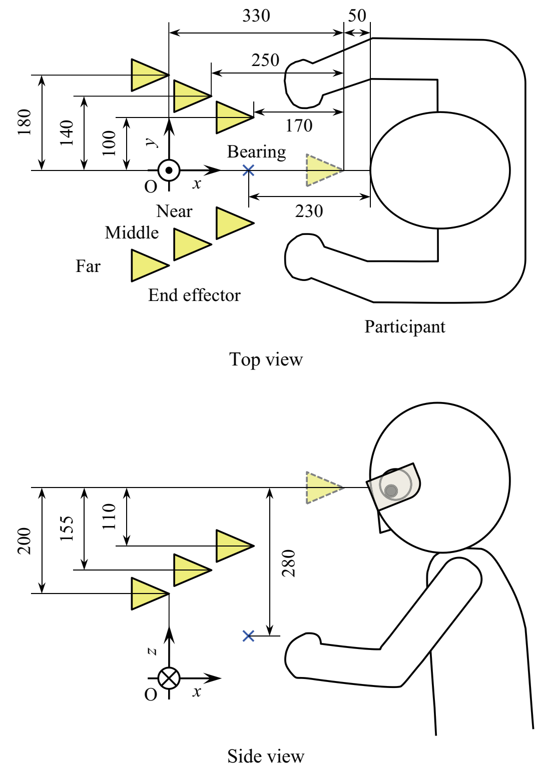

Fig. 1. Schematic diagram of the human-robot interactive locations in psychological experiment (unit: mm)

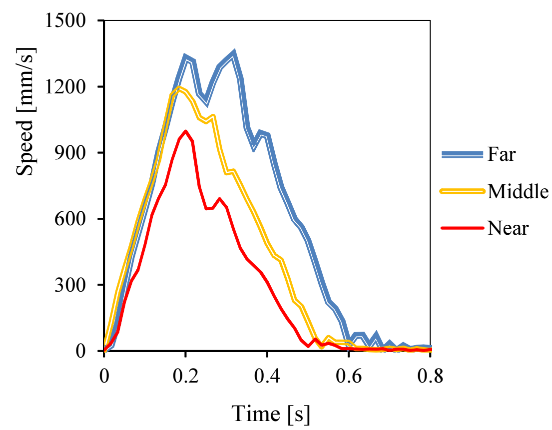

Fig. 2. Speed patterns (far, middle, near) of the end effector in psychological experiment

C. Experimental Procedure

Each participant performed 60 trials. Either the right or left end effector approaching humans and its initial position were randomly chosen for each trial.

[3]We set the robot to output the same highest possible speed percentage for each pattern. The maximum speed and initial acceleration inevitably decreased in the order pattern far, middle, near due to differences in the travel distance.

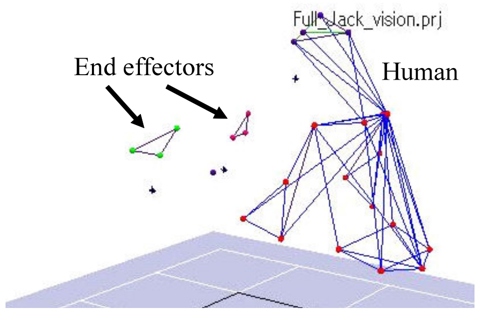

Fig. 3. Observed marker positions with motion capture system

D. Observed Data

The movements of the participants, as well as those of the robot, were captured by motion capture cameras. Each participant wore a cap and a suit with motion capture markers attached. Fig. 3 shows the observed data of the markers. Four markers were attached to the participant's head and 15 markers were attached to the upper body. Three markers were attached to each end effector, and the positions of the end-effector tip were estimated.

III. EXTRAPOLATION SIMULATION

A. Method

In the extrapolation simulations, we made an end effector collide with the eye of a human model on a computer, while the human model performed according to the motion observed in the psychological experiment. Fig. 4 shows three pictures of the extrapolation simulation. In the left picture, the end effectors are still not moving, and the human model was performing the task. In the middle picture, the end effector is approaching the human model, and the human model is avoiding from it. In the right picture, the end effector collides with the eye of the human model.

The system of extrapolation simulations was constructed by the motion capture system and a human modeling software (Jack, Siemens AG). The motion capture system and the human modeling software shared marker-position data, and the human-motion data was generated from the series of marker-position data from the participant's body. The human model was created tailoring to each participant's physical size.

B. Simulation Rules

It has not been discussed how a collision involves human avoidance action in the pre-impact phase [2], [3]. In the extrapolation simulations, we used the motion data observed in the psychological experiment as the human model's motion, while we modified the end-effector motion to be more hazardous. We established two rules for the modification of the end-effector motion to ensure that the extrapolation simulations were reasonable.

The first rule is not to modify the initial relative location of the end effector to the participants. Hattori *et al.* [9] reported the psychological experimental results which suggested that a shorter initial distance between the eyes and the end-effector tip is associated with a shorter avoidance reaction time. The initial distance between the eyes and the end effector significantly influence the avoidance reaction time. Therefore, the initial distance should be remained as it was in the psychological experiment.

The second rule is not to modify the end-effector motion during the short time after the end effector started approaching. The end effectors were in participant's peripheral vision before one of them started moving. We considered that the participants reacted to the end effector approaching when it first started moving towards them. Hence, it is considered that the end-effector motion immediately after it started moving particularly related to the human avoidance actions. Therefore, the end-effector motion during the short time after it started moving should be remained as it was in the psychological experiment.

On the basis of these rules, we have to modify the end-effector motion a short time after it starts moving and simulate a collision between the eye and the end effector. When the end effector approached closer to the participants, they might take some additional avoidance actions. These actions may possibly increase the avoidability. However, we could not observe such actions in the psychological experiment owing to our setup to ensure participant's safety as was described in II-B.2. Under the current experimental condition, it is not possible to take into account the additional human avoidance actions. We estimate the avoidability based on the observed data in the psychological experiment, while the additional avoidance actions are not taken into account.

C. Simulation Condition of End-effector Motion

We set the end-effector motion in the extrapolation simulation according to the above simulation rules. The end effector starts moving and accelerates with the same timing and motion as in the psychological experiment. After the end effector reaches the pre-set maximum approach speed, the end-effector motion is modified from the experimental motion to a uniform linear motion. The end effector maintains the maximum approach speed and the direction until it collides with a human eye. The maximum approach speed is assumed to be the limiting speed of an end effector in actual production site robots. The linear trajectory of the end effector is adjusted to collide with the human model's eye at near-side eye. That is, a right end effector collides with a left eye and a left end effector collides with a right eye.

We set five levels for the maximum approach speed for each initial-position condition, based on our experimental setup. Fig. 5 shows the speed for velocity levels I–V under the far condition. In velocity level I, the maximum approach speed is set to the approximate maximum speeds observed in the psychological experiment, which were 1300 mm/s under the far condition, 1200 mm/s under the middle condition, and 1000 mm/s under the near condition. The maximum approach speeds for velocity levels II, III, IV, and V were

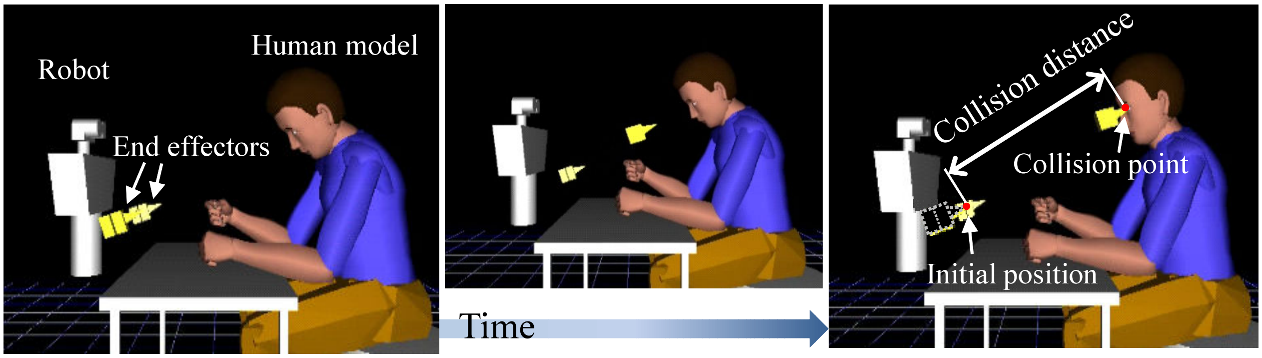

Fig. 4. A series of screen images in extrapolation simulation

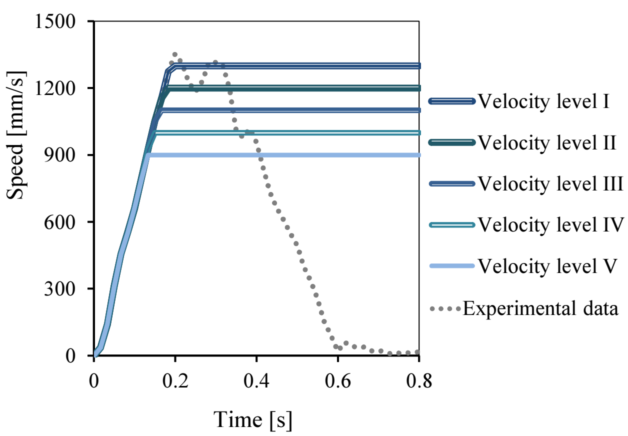

Fig. 5. Velocity levels I–V under far condition

TABLE I
MAXIMUM APPROACH SPEED IN EXTRAPOLATION SIMULATION [mm/s]

	Velocity level				
	I	II	III	IV	V
Far	1300	1200	1100	1000	900
Middle	1200	1100	1000	900	800
Near	1000	900	800	700	600

each set 100 mm/s slower than in the previous velocity level (see Table I).

D. Simulation Procedure

For the simulations, we picked out 60 trials from one participant, who did not behave peculiarly in the psychological experiment. This gave a total of 300 trials, owing to the five simulation patterns.

E. Simulation Results

1) Definition of Collision Distance: We measured the distance of the end-effector tip from its initial position until collision for each trial, as shown in the right picture of Fig. 4. We termed the distance as "collision distance." We regarded the movable distance of the end effector from its initial position as the motion range of the end effector. If the motion range of the end effector is longer than the collision distance, the end effector may collide with a human eye. The collision distance becomes an important criterion for estimating the safe motion range.

2) Collision Probability Curve: In the field of mechanical safety, risk analysis often involves the construction of a risk curve. The risk curve indicates the relationship between the frequency (probability) and the effect (severity) of a risk. We would like to draw a risk curve using our simulation results, but we cannot estimate the severity of harm in this study. As a preliminary stage for drawing of the risk curve, we present the collision probability under the variable conditions of the end-effector motion.

An end effector collides with a human eye when the collision distance is shorter than the motion range of the end effector. Hence, once the motion range has been defined, all trials can be divided into collision trials and non-collision trials. We expressed the collision probability as the rate of collision trials in each simulation pattern, using the motion range as a variable.

Fig. 6 shows the collision probability curve for three initial-position conditions when the maximum approach speed was set at 1000 mm/s. For example, when the initial distance between the eyes and the end effector is middle, approximately 370 mm apart, the collision probability is shown by yellow squares. The probability is zero when the motion ranges of the end effector is smaller than 400 mm. The probability then increases with the motion range. It reaches 1.0 when the motion range is 515 mm.

As these curves show, our simulation method is a practical tool to provide the collision probability curves involving human avoidance actions. However, we should note that in the simulations, the end effector goes directly towards the human model and collides with the eye; but this scenario is rare in real situations. Therefore, our collision probability tends to be higher than the real probability of an end effector colliding with a human eye.

3) Minimum Collision Distance as Safe Motion Range: We estimate the safe motion range of the end effector from the collision probability curves. Fig. 7 shows the conceptual diagram of a collision probability curve and a safe motion

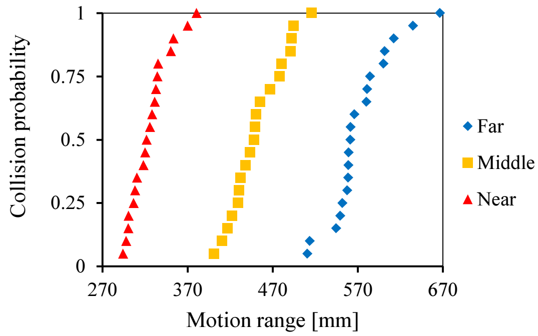

Fig. 6. Collision probability curve for three conditions (far, middle, near) with maximum approach speed set to 1000 mm/s

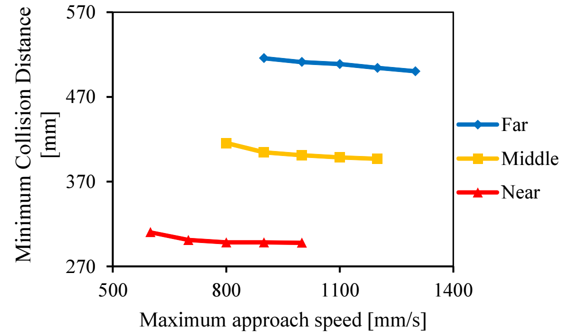

Fig. 8. Relationship between minimum collision distance and maximum approach speed for three conditions (far, middle, near)

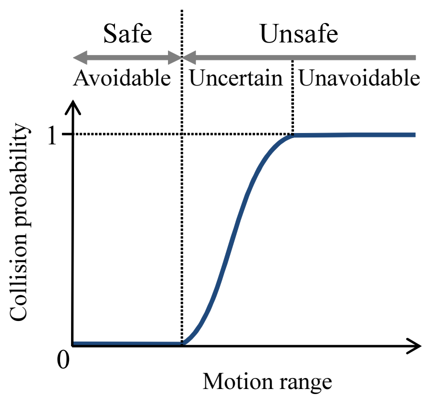

Fig. 7. Safety condition according to collision probability curve

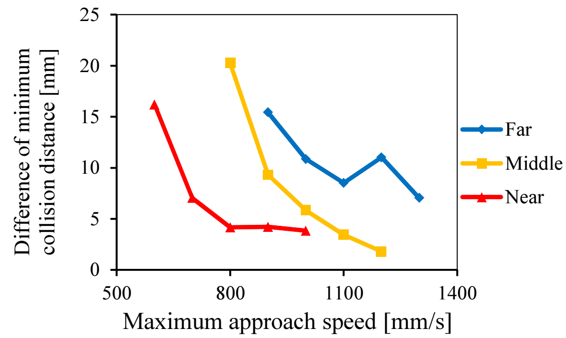

Fig. 9. Effect of avoidance actions: Differences of the minimum collision distances on taking and not taking human avoidance into consideration

range. It is sure that the participant is able to avoid collision in the motion range where the collision probability is zero. Such a motion range is regarded as a safe motion range. On the other hand, in the motion range where the collision probability is above zero, it is unclear whether the participant is able to avoid collision. Therefore, a minimum collision distance is a critical value between the safe and unsafe motion range. We regard the minimum collision distance as the maximum safe motion range.

Fig. 8 shows the minimum collision distances. They depend on the maximum approach speed of the end effector and the initial distances between the eyes and the end effector. In general, the minimum collision distances decrease as the maximum approach speed of the end effector increases. This is simply because it becomes more difficult to avoid a more quickly approaching harm for humans. We are able to estimate the safety conditions according to Fig. 8. For example, when the initial distance between the eyes and the end effector is middle, approximately 370 mm apart, and the maximum approach speed is 800 mm/s, the motion range of the end effector should be limited shorter than the minimum collision distance of 415 mm. We should note that if human avoidance actions are not concerned then the minimum collision distances are flat unlike those in Fig. 8. Hence, the extrapolation simulations provided us with estimated parameters important for risk analysis.

4) Effects of Human Avoidance Actions: In order to quantify the effects of human avoidance actions on the minimum collision distances that is the safe motion range of the end effector, we calculated their differences on taking and not taking avoidance actions into consideration. If a human does not take avoidance actions, minimum collision distances are equal to the initial distances between the human and the end effector.

Fig. 9 shows the differences of the minimum collision distances between taking and not taking human avoidance actions into consideration. Again, in general, the effects of human avoidance actions vary by the maximum approach speed of the end effector and the initial-position conditions. The effects are most significant when the maximum approach speed is slow. For all of the three initial positions, the effects reach approximately 15 mm when the maximum approach speed is slowest. This means that the participants could avoid the harm by approximately 15 mm in the setup. The effects of avoidance actions tend to decrease as the end effector becomes quicker and are least significant when the end effector is quick; they are around 5 mm or less.

These data quantitatively indicate the effects of human avoidance actions. These effects for avoidability have never been considered thus far in risk assessment.

IV. Discussion

A. Effects of Human Avoidance Actions

We quantified the effects of human avoidance actions on the extension of the safe motion range in our setup. These effects were at most 20 mm. Some may consider that they are not important in risk assessment. However, we consider that they affect significantly to the mitigation of the severity of harm as well as the extension of safe motion range. We assumed harm to an eye of which the severity becomes particularly high. Ito *et al.* [11] reported the experimental results which suggested that an eyelid contributed to the mitigation of the severity of harm to the eye from a mechanical hazard approaching. In the psychological experiment, we observed that some participants closed their eyelid when an end effector approached to the eye. In Fig. 9, for example, at 600 mm/s under near condition, the difference of minimum collision distances was around 15 mm. The 15 mm extended distance to collision makes the 25 ms extension of time to collision. The experimental results by Evinger *et al.* [12] suggested that the time from applying stimulus to closing eyelid was around 90 ms. The extended time by consideration of the human avoidance actions corresponds to time between one-fourth to one-third of time required for closing eyelid. The human avoidance actions could make closing eyelid in time and mitigate the severity of harm. Therefore, we consider that the quantified effects of avoidance actions are important in practical risk assessment.

B. Remark about Extrapolation Simulation

We proposed the extrapolation simulation while we did not consider the additional avoidance actions which could have been caused by closer approaches of the end effector. We consider that it is more accountable to estimate the avoidability lower in the practical risk assessment, which is reflected by choosing subjects who likely to take slower avoidance actions for establishing the standard data.

V. Conclusions and Future Work

This study aimed to take human avoidance actions into consideration when designing a human-robot coexistence environment. We have conducted a psychological experiment to obtain data on human avoidance actions. Using the obtained data, we carried out extrapolation simulations of human avoidance actions in collision situations. As the simulation results, first, we expressed the collision probability as the rate of collision trials in each simulation pattern, using the motion range as a variable. Second, we estimated some safety conditions for the end-effector motions in our simulation setup. Finally, we quantified the effects of the avoidance actions as the difference between taking and not taking avoidance actions. The motion ranges of the end effector, that ensures safety, increased by approximately 20 mm at most when human actions were involved. This paper contributes to our ability to take human avoidance actions into reasonable consideration when designing industrial environments.

We will focus on situations in which human avoidance actions affect most efficient. We consider a situation in which a robot attacks from side of a human. Because the trajectory at which the human avoids collision would be different to that at which the end effector approaches. We plan to conduct a new psychological experiment.

VI. Acknowledgments

We are indebted to Professor Shuji Mori of Kyushu University and Professor Kazunori Hase of Tokyo Metropolitan University for their insightful advice. We are also grateful to graduate student Soichiro Ito at Nagoya University for his cooperation.

References

[1] *Safety of Machinery — General Principles for Design — Risk Assessment and Risk Reduction*, ISO 12100:2010, 2010.

[2] S. Oberer and R. D. Schraft, "Robot-dummy crash tests for robot safety assessment," in *Proc. 2007 IEEE International Conference on Robotics and Automation*, Roma, Italy, Apr. 2007, pp. 2934–2939.

[3] S. Haddadin, A. Albu-Schäffer, M. Frommberger, J. Rossmann, and G. Hirzinger, "The "DLR crash report": Towards a standard crash-testing protocol for robot safety - Part I: Results," in *Proc. 2009 IEEE International Conference on Robotics and Automation*, Kobe, Japan, May 2009, pp. 272–279.

[4] J.-J. Park, S. Haddadin, J.-B. Song, and A. Albu-Schäffer, "Designing optimally safe robot surface properties for minimizing the stress characteristics of human-robot collisions," in *Proc. 2011 IEEE International Conference on Robotics and Automation*, Shanghai, China, May 2011, pp. 5413–5420.

[5] R. Ikeura, H. Otsuka, and H. Inooka, "Study on emotional evaluation of robot motions based on galvanic skin reflex," *The Japanese Journal of Ergonomics*, vol. 31, no. 5, pp. 355–358, Oct. 1995, (in Japanese).

[6] Y. Yamada, Y. Umetani, and Y. Hirasawa, "Proposal of a psychophysiological experiment system applying the reaction of human pupillary dilation to frightening robot motions," in *Proc. 1999 IEEE International Conference on Systems, Man, and Cybernetics*, vol. 2, Tokyo, Japan, Oct. 1999, pp. 1052–1057.

[7] New Energy and Industrial Technology Development Organization, "Project for strategic development of advanced robotics elemental technologies, Human-robot cooperative cell production and assembly systems (Field of next-generation industrial robots), Safe upper-body humanoid equipped with compact handling systems, Accomplishment Report in Fiscal 2006–2008," May 2009, (in Japanese).

[8] T. Ogure, Y. Nakabo, S. Jeong, and Y. Yamada, "Hazard analysis of an industrial upper-body humanoid," *Industrial Robot: An International Journal*, vol. 36, no. 5, pp. 469–476, Sep. 2009.

[9] T. Hattori, Y. Yamada, S. Mori, S. Okamoto, and S. Hara, "Psychological experiments on avoidance action characteristics for estimating avoidability of harm to eyes from robots," in *Proc. 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Vilamoura, Portugal, Oct. 2012, (accepted).

[10] R. D. Luce, *Response Times: Their Role in Inferring Elementary Mental Organization*. New York, NY: Oxford University Press, 1986.

[11] S. Ito, Y. Yamada, T. Hattori, S. Okamoto, and S. Hara, "Investigation into the severity of eyes attacked by a sharp object in collision experiments taking human avoidance/mitigation actions into consideration," in *Proc. 29th Annual Conference of the RSJ*, Tokyo, Japan, Sep. 2011, pp. 1N1-7, (in Japanese).

[12] C. Evinger, K. A. Manning, and P. A. Sibony, "Eyelid movements mechanisms and normal data," *Investigative Ophthalmology & Visual Science*, vol. 32, no. 2, pp. 387–399, Feb. 1991.