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Estimating Child Collision Injury Based on Automotive Accident Data for Risk Assessment of Mobile Robots*

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Abstract— **Risk assessment considering child injury risks in collisions should be performed before introducing mobile robots into human-robot collaborative environments. This paper provides data for estimating the injury level and the injury probability for risk assessment using information from automotive-accident research. Experiments representing collisions between six-year-old children and mobile robots were conducted using an automotive crash-test dummy. Mechanical data on the head, neck, and chest of the dummy were measured. The results indicate that robot manufacturers should consider head injuries in collisions before introducing their mobile robots into environments with children.**

I. Introduction

In Japan, New Energy and Industrial Technology Development Organization conducts the "Project for Practical Applications of Service Robots" in an effort to introduce service robots, including mobile robots, into human-robot collaborative environments. Human injury risks in collisions should be assessed before introducing these robots. However, not enough injury data has been reported to make risk assessment possible. The lack of child injury data is especially serious when introducing robots into household environments where the probability of exposing children to hazards by robot movement is sometimes high. The probability of injury is higher for children than for adults, according to automotive-accident research [1]. This study seeks to provide data for estimating the injury level and the injury probability of children for risk assessment. To this end, we use information from automotive-accident research. Experiments representing collisions between six-year-old children and mobile robots were conducted using an automotive crash-test dummy. Mechanical data on the dummy's head, neck, and chest were measured. From these data, the injury level and probability under several conditions were predicted based on automotive-accident data.

As hazards introduced by robot movement, we should consider collision between a human and a robot body or robot parts (e.g., manipulator), being crushed by a falling robot, and being run-over by a robot. We should also consider collision between a rider of a person carrier robot and an obstacle or the floor. Haddadin et al. conducted collision tests between a manipulator and a automotive crash-test dummy [2, 3]. They also conducted drop-testing experiments with a pig abdominal wall [4] to evaluate the effects of mass and velocity of the manipulator on human injury. Echávarri et al. proposed a formula to estimate head injury risk from the mass and stiffness of a manipulator based on automotive-accident research [5]. Laffranchi et al. [6] measured the kinetic energy and the potential energy of a manipulator in order to evaluate the risk of collision with a human head. Measurement of head acceleration and chest deflection during a wheelchair fall by Ishikawa et al. [7] provides information on the injury of a rider caused by a falling person carrier robot. This study deals with collision between a human and a robot's main body, focusing on the effects of robot mass and velocity on the injury of a child's head, neck and chest.

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II. Experiment

A. *Test Dummy*

The experiment requires a test dummy that represents human body responses (e.g., acceleration and deflection) in collisions. Automotive crash-test dummy "Q6" was used, since it is being standardized to represent typical responses of a six-year-old human child and is equipped with detectors for measuring responses during collisions [8]. At this stage of our study, we focused on six-year-old children who are anticipated to contact robots without proper adult supervision.

B. *Representation of Robot*

This study deals with mobile robots with sizes comparable to six-year-old children, which may cause serious risk when a collision occurs. To represent a robot, we used a moving object that had a steel structure covered with polystyrene panels (Fig. 1). The moving object had no driving mechanism but was driven by the electric power of the crash-test equipment. The robot mass was adjusted to specified levels by changing weights fixed on the steel structure.

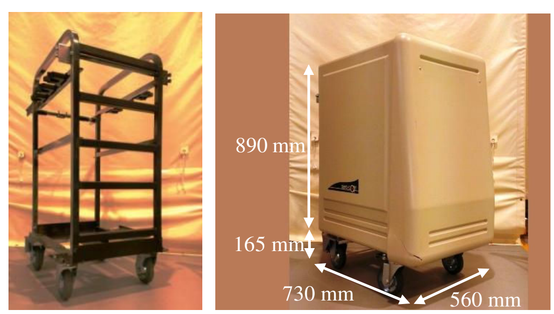

Figure 1. Object that represents a mobile robot with a polystyrene panel. Left: steel structure. Right: polystyrene panel.

C. Procedures

We developed test procedures based on automotive crash-test procedures. First, a dummy is placed in the robot path facing a mobile robot. Second, the robot tested is fixed to a wire of the crash-test equipment. The wire is driven by an electric motor to accelerate the robot. The robot is released from the wire after it reaches the test velocity. Mechanical signals from sensors installed in the dummy and hi-speed video data are recorded during the collision between the robot and the dummy. The signals are filtered according to automotive crash-test procedures [9]. Fig. 2 depicts the test set-up, which represents a collision between a child standing in front of a wall and a mobile robot.

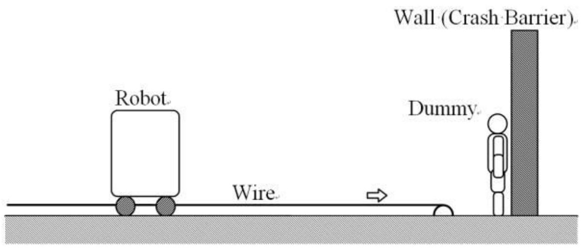

Figure 2. Set-up of the test.

III. DATA PROCESSING

We used data obtained in the automotive field to estimate injury levels in collisions with mobile robots. The severity of injury is expressed by the Abbreviated Injury Scale (AIS). "AIS 1" indicates minor injuries (e.g., superficial laceration, neck sprain, and single rib fracture). "AIS 2" indicates moderate injuries (e.g., moderate skull fracture, neck fracture, and multiple rib fractures). "AIS 3" indicates serious injuries.

At this stage of our study, we are focusing on three body parts: the head, the neck, and the chest. In the automotive field, the injury levels of these body parts are related to three mechanical parameters: Head Injury Criterion, Neck Injury Criterion, and Maximum Chest Deflection. We calculated these parameters from the measured data as follows.

A. Mechanical parameters for head injury

Head Injury Criterion HIC_{15} is defined [1] as

$$HIC_{15} = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} (t_2 - t_1) \cdot \quad (1)$$

Here, a(t) is head acceleration in acceleration of gravity (g), and t_1 and t_2 are times during the acceleration pulse with 15 ms intervals.

B. Mechanical parameters for neck injury

Neck Injury Criterion Nij is defined [1] as

$$Nij = F_z / F_{zc} + M_{ocy} / M_{yc} \ . \quad (2)$$

Here, F_z is the axial force in tension or compression, F_{zc} is the critical intercept value of the load used for normalization (F_{zc} = 3096 N in tension and 2800 N in compression for a six-year-old child), M_{ocy} is the occipital condyle bending moment in flexion or extension, and M_{yc} is the critical intercept value for moment used for normalization (M_{yc} = 93 Nm in flexion and 42 Nm in extension for a six-year-old child).

C. Mechanical parameters for chest injury

Maximum Chest Deflection is the peak value of longitudinal rib deflection of the dummy.

IV. INJURY PREDICTION

Although automotive safety regulations focus mainly on injuries with higher severity (AIS 3) than we consider in robotic fields (AIS 1 or 2), automobile accident researchers have reported data of AIS 1 or 2. The following data on injuries of children applies for introducing mobile robots into non-industrial environments.

The National Highway Traffic Safety Administration [1] reported on formulas for injury probabilities as functions of mechanical parameters that are applied to the bodies of one-year-old, three-year-old, and six-year-old children as well as adults. They derived these formulas based on accumulated injury data and techniques for analysis reported in previous research. They introduced the effects of age variation into the formulas using a scaling ratio determined by the size and mechanical properties of body parts. They derived formulas for head injury probability at AIS 2+ and AIS 3+. The head injury probability formulas for six-year-old children [1] are

$$P_{Head2+} = [1/\{1 + \exp(2.49 + 140/HIC_{15} - 0.00690 * HIC_{15})\}] \quad (3)$$

$$P_{Head3+} = [1/\{1 + \exp(3.39 + 140/HIC_{15} - 0.00531 * HIC_{15})\}] . \quad (4)$$

Here, P_{Head2+} is the probability of head injury at severity level AIS 2 or greater, and P_{Head3+} is that at AIS 3 or greater.

They also provided probability values for specific levels of HIC_{15} for AIS 1, although they did not present a formula (Fig. 3).

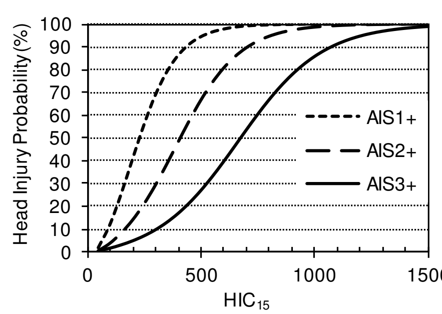

Figure 3. Head injury probability of a six-year-old child [1].

The formulas for neck injury probability at AIS 2+ and AIS 3+ for six-year-old children are [1]

$$P_{Neck2+} = [1/\{1 + \exp(2.0536 - 1.1955 * Nij)\}] \quad (5)$$

$$P_{Neck3+} = [1/\{1 + \exp(3.2270 - 1.9690 * Nij)\}]. \quad (6)$$

Here, P_{Neck2+} is the probability of neck injury of AIS 2 or greater, and P_{Neck3+} is that of AIS 3 or greater.

The probabilities expressed by formulas (5) and (6) somehow contradict each other, as plotted in Fig. 4. Where *Nij* exceeds 1.7, the probability of AIS 2+ is lower than that of AIS 3+, although it should be higher. Formulas for injury probability sometimes exhibit such contradictions, since they are obtained by statistical processes. We need to further analyze the original data from which formulas (5) and (6) are derived.

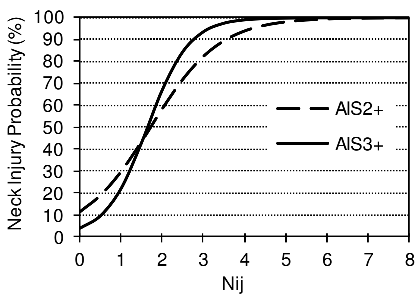

Figure 4. Neck injury probability of a six-year-old child [1].

The formulas for chest injury probability at AIS 2+ and AIS 3+ for six-year-old children are [1]

$$P_{Chest2+} = [1/\{1 + \exp(1.8706 - 0.06991 * d)\}] \quad (7)$$

$$P_{Chest3+} = [1/\{1 + \exp(3.7124 - 0.07481 * d)\}]. \quad (8)$$

Here, $P_{Chest2+}$ is the probability of chest injury of AIS 2 or greater, $P_{Chest3+}$ is that of AIS 3 or greater, and *d* is Maximum Chest Deflection (mm). The probabilities expressed by the formulas are plotted in Fig. 5.

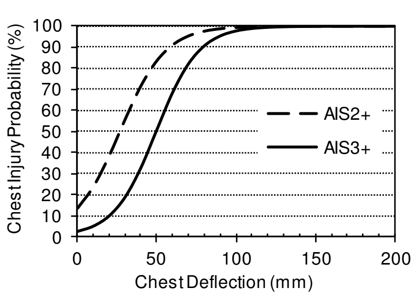

Figure 5. Chest injury probability of a six-year-old child [1].

V. Results

Haddadin et al. reported that manipulator mass and collision velocity are important parameters for injury evaluation [2, 3]. Fig. 6 presents HIC_{15} obtained in a collision between a six-year-old dummy in front of a wall and a mobile robot with a polystyrene panel at two collision velocities and four robot masses. The collision with a robot mass of 200 kg at a velocity of 6 km/h resulted in $HIC_{15} = 217$. This corresponds to 45% probability of AIS 1+ injury, 16% probability of AIS 2+ injury, and 5% probability of AIS3+ injury, based on Fig. 3. Fig. 7 illustrates that the head and the chest of the dummy were crushed by the robot body and the wall during a collision with a robot mass of 200 kg at a velocity of 6 km/h.

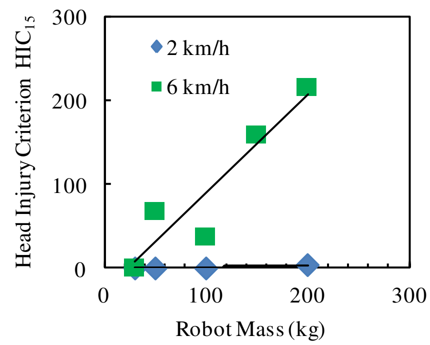

Figure 6. Head Injury Criterion obtained in collision between a six-year-old dummy in front of a wall and a mobile robot with a polystyrene panel. Robot velocity, 2 km/h and 6 km/h.

Fig. 6 also indicates that HIC_{15} with a robot mass of less than 100 kg at a velocity of 6 km/h decreased remarkably, corresponding to less than 10% probability of AIS 1+ based on Fig. 3. Here, HIC_{15} was less than 3 in all cases at a velocity of 2 km/h; therefore, the probability of AIS 1+ head injury is almost negligible. These results indicate that robot manufacturers should consider head injuries in collisions when introducing their mobile robots into environments with children, and that lighter mass and lower velocity remarkably decrease the risk.

Figure 7. Collision between a six-year-old dummy in front of a wall and a mobile robot with a polystyrene panel. Robot mass, 200 kg; velocity, 6 km/h.

Fig. 8 plots *Nij*. Here, *Nij* was less than 0.32 at all levels of robot mass and collision velocity, corresponding to less than 20% probability of AIS 2+, based on Fig. 4. Neck injury probability does not decrease to zero at *Nij* = 0, since Fig. 4 is a result of statistical analysis. Palisson et al., however, reported that no neck injury occurred below 730 N of shearing force, below 1450 N of tension force, or below 13 Nm of flexion moment in three-year-old children, according to their review of 40 accidents [10]. According to the definition of *Nij*, these values of force and moment correspond to $Nij < 0.34$ for six-year-old children. This result indicates that the probability of neck injury is low in collisions of the robot tested in this study, with a mass of 200 kg or less at velocities of 6 km/h or less.

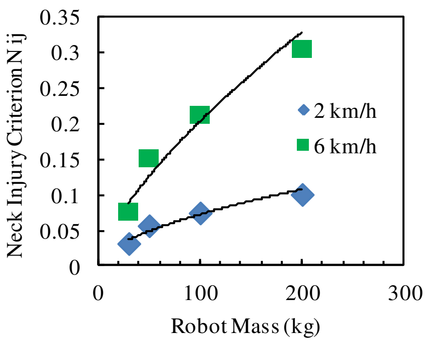

Figure 8. Neck Injury Criterion obtained in collision between a six-year-old dummy in front of a wall and a mobile robot with a polystyrene panel. Robot velocity, 2 km/h and 6 km/h.

Fig. 9 plots Maximum Chest Deflection. The Maximum Chest Deflection was less than 9.0 at all levels of robot mass and collision velocity, corresponding to less than 20% probability of AIS 2+, based on Fig. 5. Chest injury probability does not decrease to zero at deflection = 0, since Fig. 5 is a result of statistical analysis. Palisson et al., however, reported that no chest injury occurred below 20 mm of chest deflection, according to their review of 24 accidents [10]. This indicates that the probability of chest injury is low in collisions of a robot tested in this study with a mass of 200 kg or less at velocities of 6 km/h or less.

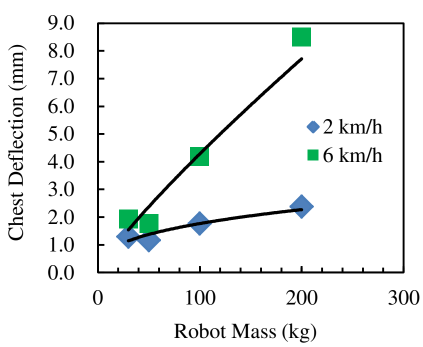

Figure 9. Maximum Chest Deflection obtained in collision between a six-year-old dummy in front of a wall and a mobile robot with a polystyrene panel. Robot velocity, 2 km/h and 6 km/h.

VI. Discussions

A. *Modes of Head Collision*

High-speed video data recorded during the tests indicate three modes of head collision: head/robot contact, head/wall contact, and crushing (Fig. 10). HIC_{15} used in this study estimates injuries caused by dynamic impact in these three modes. However, it is not yet possible to evaluate injuries caused by crushing force. Here, we discuss details of impact injury, though force measurements and analysis of crush injury criterion should be performed in the future.

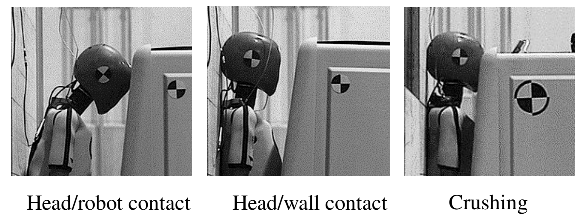

Figure 10. Modes of head collision.

Our close inspection of head acceleration data indicates that head/wall contact dominates the head injury risk, and that acceleration caused by head/robot contact is negligible compared with that caused by head/wall contact. An example of a set of video and acceleration data is depicted in Fig. 11. Posteroanterior acceleration, which governs head acceleration in this experiment, has a small negative value at the first head/robot contact at time = 0 s. Head/wall contact at time = 0.09 s causes the largest acceleration, which rules HIC_{15} of this experiment, since equation (1) deals with only the highest peak of acceleration. The video data shows that head/wall contact and crushing occur simultaneously, since robot velocity after the first head/robot contact is greater than the head response to the first contact. After that, the dummy head and the robot exhibit vibratory movements. The head moves in the anterior direction, causing negative acceleration at time = 0.1 s, and is crushed to the wall again, causing the second largest peak of acceleration at time = 0.11 s; however, this second peak does not affect HIC_{15}.

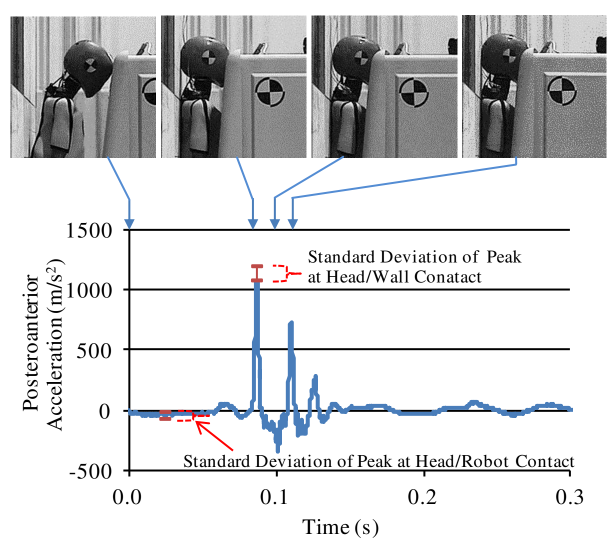

Figure 11. Head acceleration measured in collision between a six-year-old dummy in front of a wall and a mobile robot with a polystyrene panel. Robot mass, 200 kg; velocity, 6 km/h.

B. *Head Injury and Kinetic Energy of Robot*

Acceleration caused by head/wall contact is ruled mainly by head/wall contact velocity, which is governed by robot velocity v_r before a collision, robot mass m_r, and dummy head mass m_h. Assuming that dummy neck stiffness is negligible, head velocity v_h after head/robot contact is expressed as follows, in terms of the law of conservation of momentum.

$$v_h = v_r(\mathrm{e} + 1) / \{(m_h/m_r) + 1\}. \quad (9)$$

Here, e is the coefficient of restitution, which has a value between 0 and 1 that decreases with increased dispersing kinetic energy during contact. The energy disperses mainly as heat energy when the robot material has hysteresis loss.

Equation (9) indicates that smaller v_r and/or smaller m_r reduce head velocity. Thus, lower momentum or lower kinetic energy may reduce the head injury level. Although the equation becomes more complicated when head/wall contact and crushing occur simultaneously (Fig. 11), momentum and kinetic energy are thought to be important parameters. In Fig. 12, the data of HIC_{15} obtained by the tests are plotted against robot kinetic energy $m_r v_r^2/2$ before collision. The result indicates that robot kinetic energy is an important factor for head injury. According to Fig. 3, the probability of AIS 1+ head injury is less than 10% when HIC_{15} is less than 90. This corresponds to the kinetic energy less than 120 J in Fig. 12.

This study does not consider the driving force that acts on a robot during collision. The increased momentum that originates in the driving force causes the impulse. If the impulse is not negligible compared to the momentum of the robot before collision, it affects the injury risk. In such a case, we should take this effect into account.

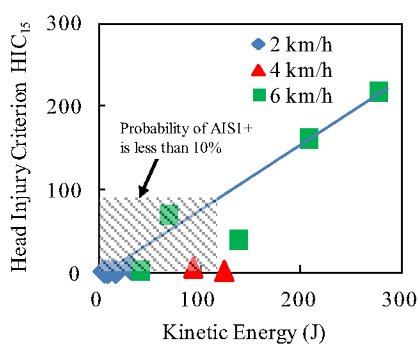

Figure 12. Head Injury Criterion and kinetic energy of the robot. Collision between a six-year-old dummy in front of a wall and a mobile robot with a polystyrene panel. Robot velocity, 2 km/h, 4 km/h and 6km/h.

C. *Effects of the Robot's Outer Material*

To investigate the effects of the robot's outer material on head injury, a moving object with a steel structure without polystyrene panels (left of Fig. 1) was tested. Fig. 13 compares the results of the tests repeated three times for each material (steel and polystyrene). Head Injury Criterion is low at a collision velocity of 2 km/h and high at 6 km/h for both materials. This result indicates that the elastic polystyrene panels used in this study do not have a major effect on head injury level, though the standard deviation of HIC_{15} is remarkably large for the steel structure, since contact conditions between the dummy and the steel structure fluctuate, depending on a small variation of dummy posture.

It is clearly demonstrated that the first negative peak of head acceleration at head/robot contact which is shown in Fig. 14 diminishes for the case with the polystyrene panel in Fig. 11. This result indicates that a less stiff outer material helps decrease injury risk in head/robot contact. However, the highest peak of head acceleration at head/wall contact, which dominates the head injury in these experiments, indicates no clear difference between the two materials. Kinetic energy that disperses in the polystyrene panel during head/robot contact is not thought to be large enough to lower the coefficient of restitution e in equation (9). To reduce the injury level, materials with greater hysteresis should be used. Since only two types of material are examined in the present study, we plan further examination of materials and structures.

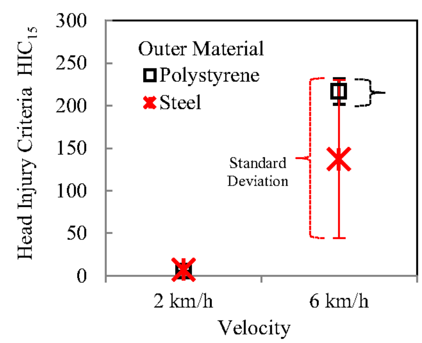

Figure 13. Effects of the robot's outer material on Head Injury Criterion obtained in collision between a six-year-old dummy in front of a wall and a mobile robot with a mass of 200 kg.

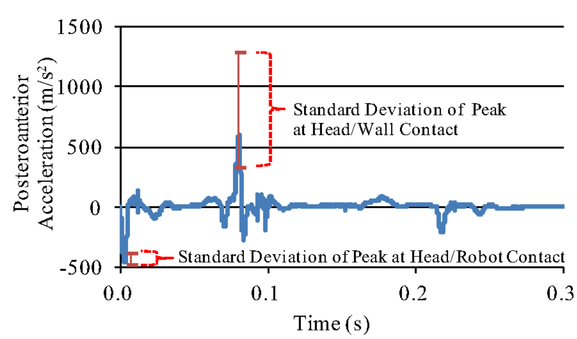

Figure 14. Head acceleration measured in collision between a six-year-old dummy in front of a wall and a mobile robot with a steel structure. Robot mass, 200 kg; velocity, 6 km/h.

D. *Ongoing Work*

This paper provides data on only one type of robot. However, injury in collisions varies, depending on the robot design. We are planning to obtain injury data on other robot designs.

This study used the injury data of automobile accidents, which deal with injuries more severe than AIS 1 and AIS 2. Additional study is needed to obtain information on less severe injuries suitable for risk estimation in the robotic field. For example, such cutaneous damage as wounds caused by collision are thought to have mechanisms differing from those of the injuries discussed in this study.

This paper does not address injuries of the extremities because of lack of information. Arm injury was not the focus in automotive accidents until side-impact tests were introduced. Studies should be performed to summarize information on arm injuries by referring to data on side impacts. Leg injuries of automobile passengers differ from those of people who collide with mobile robots. The former have a compression mode caused by steep deceleration during accidents, whereas the latter have a bending mode caused by contact with part of the robot, which is similar to pedestrian accidents. Studies should be conducted using data from pedestrian accidents.

VII. CONCLUSIONS

Experiments representing collisions between six-year-old children and mobile robots were conducted to provide data for estimating injury levels and probabilities. The results indicate the following.

(1) Robot manufacturers should consider head injuries in collisions when introducing their mobile robots into environments with children. Head/wall contact is especially important.

(2) The kinetic energy of a robot is an important factor for head injury. Lighter robot mass and lower velocity remarkably decrease head injury risk.

(3) Injury probability of the neck and chest is low in collisions examined in this study (collisions of a robot with a mass of 200kg or less at velocities of 6km/h or less).

(4) Additional studies are needed to determine the effects of robot design on injury, crush injury, less severe injuries including skin damage, and injuries of the extremities.

ACKNOWLEDGMENT

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