

# Collision Analysis and Evaluation of Collision Safety for Service Robots Working in Human Environments

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**Abstract**— Collision safety between humans and robots has drawn much attention because service robots are increasingly being used in human environments. The design of a service robot usually requires reliable collision analysis based on appropriate safety criterion. Previous safety criteria are too restrictive or generous with respect to collision injury. This paper proposes a new safety criterion for physical human-robot interaction. Injury tolerance related to the fracture force of the thyroid and cricoid cartilage in the neck is more suitable to measure injury to humans from robots than criteria representing serious injury in car crash tests. To accurately evaluate robot collision safety, a novel collision model between a human and a robot is established which include the stiffness of the neck and covering, and the input torque of the robot. The injury criteria suggested in this paper were verified to estimate the safety of service robots. Various collision analyses based on this criterion are conducted, and thus the design parameters of robot arms can be adjusted to enhance safety.

## I. INTRODUCTION

In recent years, service robots have received considerable attention. Because these robots work in human environments, safety issues related to physical human-robot interaction has become increasingly important. Therefore, several types of safe robot arms have been proposed for collision safety between a human and a robot.

First, when collision can be predicted using non-contact sensors, the robot can avoid the collision using a collision-free path planning algorithm [1]. Second, if collision is detected by contact sensors, the robot reacts to this collision by stopping itself, or by generating a reflexive motion so as to minimize the collision force delivered to humans [2]. Third, when a relatively large collision occurs, the collision force can be absorbed by several passive compliance mechanisms [3], [4]. Since the robot arm directly contacts humans in the case of the second and third approaches, collision analysis and estimation of the injury level caused by the physical interaction between a human and a robot are very important.

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Several safety criteria have been suggested to estimate injury level from human-robot collision. ISO-10218 provides safety requirement for interaction with industrial robots [5]. Human pain tolerance, which determines an individual's safeguarding space, was evaluated through experiments in [6]. The head injury criterion (HIC) introduced in automobile crash tests has also been used to verify the collision safety of robots [3], [4], [7]. The fracture force of the head bone and the compression and viscous criterion of the chest have been suggested to help define relevant injury mechanisms [8], [9]. However, ISO-10218 and the pain tolerance criteria are too restrictive, even for robots conducting ordinary tasks. The HIC and fracture force tolerances of the cranial bone are not appropriate injury indicators for service robots having relatively low inertia and low speed because these criteria were introduced for life-threatening injury in a car crash test. Thus, in this research, the fracture forces of the thyroid/cricoid cartilage in the neck is suggested as the most appropriate safety criterion with which to measure a serious injury due to human-robot collision.

To evaluate the safety of a robot arm based on the proposed injury criterion, an accurate collision model and reliable collision analysis are required. Therefore, we present more accurate collision models that consider joint torque, the covering stiffness of a robot arm, and the human head-neck mechanism. Various analyses of dynamic collisions were conducted using accurate collision mechanism models, which verified the validity of our proposed injury criteria. In our proposed collision analysis based on novel safety criterion, a human-robot collision can be accurately estimated without the expense involved in real collision tests.

The paper is organized as follows. Safety criteria for physical human-robot interaction are discussed in Section II. Section III describes our collision model and collision analysis for the robot arm. Various evaluations of collision safety with a constrained human are provided in Section IV. Finally, Section V presents our conclusions and future work.

## II. SAFETY CRITERIA FOR SERVICE ROBOTS

Several types of safety criteria for physical human-robot interaction have been suggested. ISO 10218-1: 2006, which is the only international standard protocol related to industrial robots, describes safety requirements of collaborative operation with humans [5]. ISO 10218-1 states that the velocity and maximum static force of the flange/TCP should be less than 0.25 m/s and 150 N, respectively, and the maximum power of a robot must be less than 80 W. In [6], human pain tolerance is used as a main safety criterion, based on the observation that humans usually suffer if contact force exceeds 50 N in the case of static collision (i.e., collision speed below 0.6 m/s). However, these safety requirements are too restrictive for robots to efficiently perform their given tasks.

To cope with the limitations of such safety requirements, the injury criteria used in automobile crash tests were often borrowed to estimate collision safety between humans and robots. Among the injury criteria used in car tests, the head injury criterion (HIC) is the most widely used index in the robotics community [3], [4], [7]. The HIC can be defined as:

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

where  $a(t)$  is the head acceleration expressed in terms of gravitational acceleration  $g$  ( $9.8 \text{ m/s}^2$ ) during the time interval  $(t_2 - t_1)$ . An HIC value of 1,000 or greater indicates severe head injury [10]. The HIC is often converted to injury severity based on the abbreviated injury scale (AIS). In this case, an HIC value below 650 represents a very low possibility of injury, which means the probability of serious injury (AIS > 3) is less than 5%.

Since the collision speed of a robot is usually much less than that of a car, the HIC values of most robot collisions are typically very low numbers. Moreover, it was recently claimed that the HIC value does not increase much even for heavy robots compared to light robots. According to the HIC, no robots moving at 2 m/s can inflict injury on humans, which is quite unrealistic. Therefore, other injury mechanisms, such as fracture of a cranial bone, were introduced in [8], [9].

Table I represents the tolerances of injuries which might occur while humans coexist with robots. As shown in Table I, injuries of various body parts can occur below the tolerance level of a cranial bone. In this research, the neck injury tolerance is mainly considered because it is much lower than the others.

Neck injuries can occur by indirect or direct impact. Indirect impact means that the collision force acting on the head affects the spinal column of the neck. The bending moment associated with the extension of the neck results in a much more severe injury when the angular displacement of the head relative to the body reaches a maximum value ( $73^\circ$  rearward). For this reason, the extension angle of the neck

TABLE I  
INJURY TOLERANCE OF BODY PARTS

Cranial bone [11]	Fracture tolerance
Frontal	4.0 kN
Temporal	3.12 kN
Occipital	6.41 kN
Neck	Injury tolerance
Extension [12]	47.4 Nm
Max. extension angle [13]	$73^\circ$
Thyroid & cricoid [14]	0.34 kN
Other body parts	Fracture tolerance
Lower abdomen [15]	3.76 kN
Tibia of leg [16]	5.4 kN
Ulna of arm [17]	1.37 kN

and the bending moment due to hyperextension can be used as injury indicators for service robots.

In the case of the direct impact to the neck, the robot hits the anterior portion of the neck containing two stiff tissues: the thyroid and cricoid. Those cartilages are delicate and vital because their collapse can obstruct the airflow of a human. When an impact is applied to the thyroid and cricoid simultaneously, the dynamic fracture load is 0.34 kN as listed in Table I.

In this research, the neck injury criteria including the extension angle and the collapse of cartilage are used to investigate the collision safety of service robots.

## III. COLLISION MODELING BETWEEN HUMAN AND ROBOT

Consideration of collision safety at the robot design stage is desirable because the time and cost involved in real collision tests can be saved. Although several collision safety analyses have been conducted on humans and robots [4], [18], [19], only simplified collision models were suggested for the convenience of analysis. In this research, the stiffness of the human neck, the robot covering, and the joint torque of the robot were all considered to build a more accurate collision model. Furthermore, a fixed wall was considered to accurately simulate constrained impact, which corresponds to a much more severe condition than the case in which the head can move freely after head collision.

A collision model is usually divided into two parts: a robot arm model composed of rotary joints and links, and a human model having a head, body, and neck. The robot arm and human can be modeled as a mass-damper-spring system as shown in Fig. 1. Note that the proposed model also includes the compliance of the robot covering between the endpoint of the robot link and the human head, and the stiffness of the wall.

To investigate various collision situations, four types of collision models, depending on the contact region and the constraint condition, were established as shown in Fig. 2. The robot arm was modeled as a one degree-of-freedom (DOF) planar manipulator which is not affected by gravity. The input

torque applied to the robot joint makes the robot link follow the desired position. It is assumed that the joint stiffness of a robot arm is sufficiently high that the input torque can be fully transmitted to the robot link. The human neck and body was modeled as a two DOF mass-damper-spring system sliding only in the direction of  $x$ -axis. Therefore, neck extension is regarded as the compression of a spring-damper system.

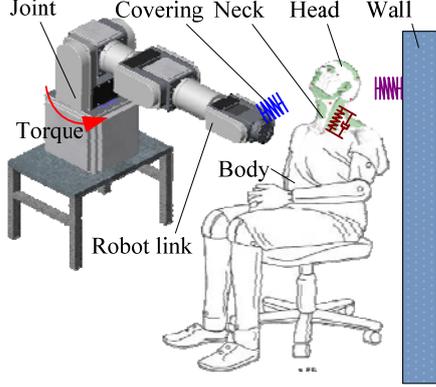


Fig. 1. Concept of collision model between human and robot.

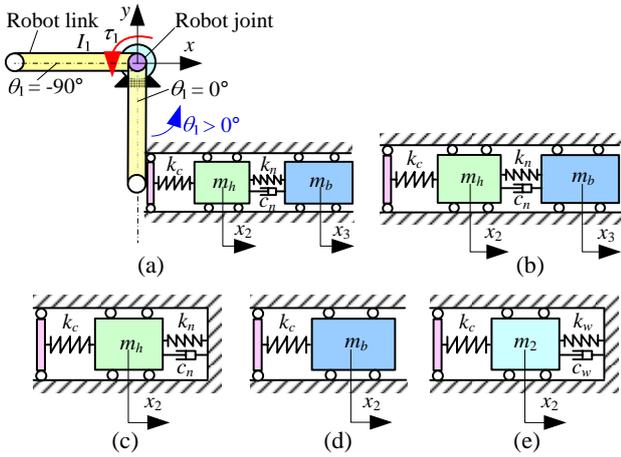


Fig. 2. Collision models between human and robot arm: (a) initial position of each part and onset of collision, (b) unconstrained head-body, (c) partially constrained head-body, (d) unconstrained body, and (e) constrained impact.

The general equation of motion is given by

$$M\ddot{X} + C\dot{X} + KX + R = F \quad (2)$$

where  $M$ ,  $C$ ,  $K$ ,  $R$ ,  $X$ , and  $F$  are the inertia matrix, damping matrix, stiffness matrix, the matrix describing the configuration of the robot link and human, displacement vector, and force vector, respectively.

First, consider the case of the unclamped head and body as shown in Fig. 2(b). The inertia and damping matrices of Eq. (2) are given by

$$M = \begin{bmatrix} I_1 & 0 & 0 \\ 0 & m_h & 0 \\ 0 & 0 & m_b \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & 0 \\ 0 & c_n & -c_n \\ 0 & -c_n & c_n \end{bmatrix} \quad (3a)$$

where  $I_1$  is the moment of inertia of the robot link,  $m_h$  and  $m_b$  are the mass of the human head and human body, respectively, and  $c_n$  is the damping of the neck. The stiffness matrix and the matrix related to the configuration of the robot link is obtained as

$$K = \begin{bmatrix} 0 & -k_c l_1 \cos \theta_1 & 0 \\ 0 & k_c + k_n & -k_n \\ 0 & -k_n & k_n \end{bmatrix}, \quad R = \begin{bmatrix} k_c l_1 \sin \theta_1 \cos \theta_1 \\ -k_c l_1 \sin \theta_1 \\ 0 \end{bmatrix} \quad (3b)$$

where  $k_c$  and  $k_n$  are the stiffness of the covering and the neck, respectively,  $\theta_1$  is the angular displacement of the robot arm, and  $l_1$  is the length of the robot link. The displacement and force vectors are given by

$$X = [\theta_1 \quad x_2 \quad x_3]^T, \quad F = [\tau_1 \quad 0 \quad 0]^T \quad (3c)$$

where  $x_2$  and  $x_3$  is the displacement of the human head and the body, respectively, and  $\tau_1$  is the joint torque of the robot. The joint torque can be obtained using  $\tau_1 = k_p(\theta_d - \theta_1) - k_v\dot{\theta}_1$

where  $\theta_d$  is the desired angle, and  $k_p$  and  $k_v$  are the PD gains for position control of the robot arm. If the human body is partially constrained by the wall but the head can rotate on the fixed body, it can be modeled as shown in Fig. 2(c). The matrices and vectors of Eq. (2) can be described by

$$M = \begin{bmatrix} I_1 & 0 \\ 0 & m_h \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 \\ 0 & c_n \end{bmatrix} \quad (4a)$$

$$K = \begin{bmatrix} 0 & -k_c l_1 \cos \theta_1 \\ 0 & k_c + k_n \end{bmatrix}, \quad R = \begin{bmatrix} k_c l_1 \sin \theta_1 \cos \theta_1 \\ -k_c l_1 \sin \theta_1 \end{bmatrix} \quad (4b)$$

$$X = [\theta_1 \quad x_2]^T, \quad F = [k_p(\theta_d - \theta_1) - k_v\dot{\theta}_1 \quad 0]^T \quad (4c)$$

Next, consider an impact which acts directly on the neck of the unconstrained body as shown in Fig. 2(d). The inertia and stiffness matrices of Eq. (2) can be expressed as

$$M = \begin{bmatrix} I_1 & 0 \\ 0 & m_b \end{bmatrix} \quad (5a)$$

$$K = \begin{bmatrix} 0 & -k_c l_1 \cos \theta_1 \\ 0 & k_c \end{bmatrix} \quad (5b)$$

The matrix  $R$  and the vectors  $X$  and  $F$  are the same as in Eqs. (4b) and (4c).

Finally, when a collision force is directly applied to a human head or a body fixed at the wall, the collision model

shown in Fig. 2(e) is considered. The inertia matrix, damping matrix, and stiffness matrix in Eq. (2) can be described by

$$M = \begin{bmatrix} I_1 & 0 \\ 0 & m_2 \end{bmatrix}, C = \begin{bmatrix} 0 & 0 \\ 0 & c_w \end{bmatrix} \quad (6a)$$

$$K = \begin{bmatrix} 0 & -k_c l_1 \cos \theta_1 \\ 0 & k_c + k_w \end{bmatrix} \quad (6b)$$

where  $k_w$  is the wall stiffness, and  $m_2$  should be selected as either  $m_h$  or  $m_b$  depending on the contact point: head or neck. Also, in this case, the matrix  $R$  and the vectors  $X$  and  $F$  are the same as in Eqs. (4b) and (4c).

#### IV. ANALYSIS RESULTS ON COLLISION SAFETY

Collision analyses between humans and robots were conducted using the equations of motion introduced in Section III. Furthermore, based on the injury criteria discussed in Section II, the collision safety for both unconstrained and constrained body parts were evaluated.

##### A. Impacts for unconstrained human

We conducted a collision analysis of the impact to an unconstrained human head as shown in Fig. 2(b). The joint angle of the robot arm was  $-90^\circ$  at the initial configuration and the desired angle  $\theta_d$  was set to  $15^\circ$ . The robot link, rotating at an angular velocity of  $230^\circ/\text{s}$  (which is equivalent to an end-point velocity of 2 m/s), was forced to collide with the human head or neck which was located at a joint angle of  $0^\circ$ , as shown in Fig. 2(a). The mass of the human head and body were set to 4.8 kg and 65 kg, respectively, and the length of the robot arm was set to 0.5 m.

If the human-robot collision does not occur, the covering stiffness in Eq. (3b) is zero because it does not affect the motion of the human and robot arm as follows:

$$k_c = \begin{cases} 0, & x_2 > l_1 \sin \theta_1 \\ 300 \text{ kN/m}, & x_2 \leq l_1 \sin \theta_1 \end{cases} \quad (7)$$

where it was assumed that the covering of the robot arm is made of high density polyethylene (HDPE).

When the human neck is bent by a contact force acting on the head, the neck behaves like a spring-damper system. However, if the contact force acting on the head is removed and no more extension of the neck occurs, the neck has only the damping effect. To realize this neck property in the collision model, the stiffness and damping of a human neck according to the velocities of the head and body are described as follows:

$$k_n = \begin{cases} 5 \text{ kN/m}, & \dot{x}_2 \geq \dot{x}_3 \\ 0, & \dot{x}_2 < \dot{x}_3 \end{cases} \quad (8)$$

$$c_n = 2\zeta_n \sqrt{m_h k_n} \quad (9)$$

where the neck stiffness of 5 kN/m is a mean value of an adult male [20]. When the damping ratio of a human neck  $\zeta_n$  is set to 0.42 [21], the damping value is computed as 133 Ns/m.

Since Eq. (2) is a coupled second-order nonlinear differential equation in the displacement vector  $X$ , it must be solved numerically for this analysis. From Eq. (2), the differential equation of motion of the collision model is expressed as

$$\ddot{X} = M^{-1}(F - C\dot{X} - KX - R) \quad (10)$$

Figure 3 shows a block diagram for the simulation obtained from Eq. (10). In this analysis, simulations were conducted using the 4<sup>th</sup> and 5<sup>th</sup> order Runge-Kutta ordinary differential equation solver offered in the Matlab/Simulink package.

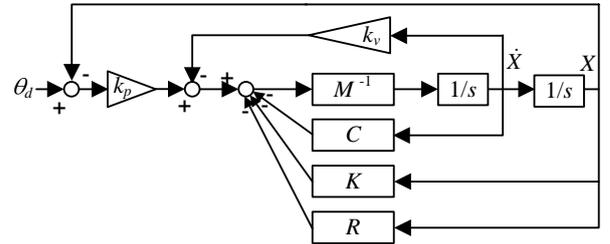


Fig. 3. Block diagram for collision model.

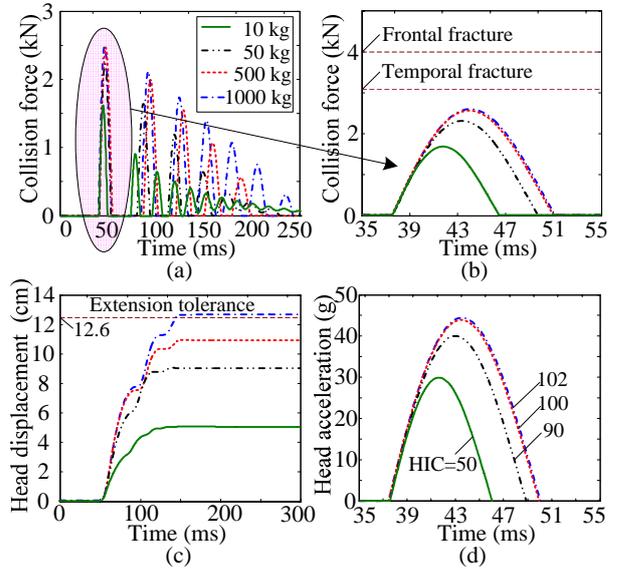


Fig. 4. Analysis results of impacts to unconstrained human head: (a) collision force versus time, (b) enlarged view of (a), (c) head displacement relative to body, and (d) head acceleration.

Figure 4 shows the collision force, head displacement, and acceleration according to the mass of the robot link. Although the mass of the robot link increased from 10 kg up to 1000 kg, the peak values of collision forces were saturated at about 2.5

kN which was below the fracture tolerance of the cranial bone listed in Table I. Moreover, the HIC values calculated from Eq. (1) were also saturated at around 100 with the increase in the mass of the robot link. These analysis results agreed with real collision tests in which the maximum impact force of KR6 (link mass of 67 kg) moving at 2 m/s was measured to be about 2.5 kN [8].

Consider the extension angle tolerance of a neck. Since the bending motion of a neck is converted into the translation of a head as mentioned in Section III, the displacement tolerance of a head relative to a body can be set to 12.6 cm, which corresponds to the maximum extension angle of  $73^\circ$  in which the conversion ratio of  $5.8^\circ/\text{cm}$  is used [20]. As shown in Fig. 4(c), when the mass of the robot link is 1000 kg, the relative displacement of the head is 13 cm which is greater than the tolerance level. In the case of the 1000 kg robot arm moving at 2 m/s, the hyperextension injury of the neck can occur, although the cranial bone does not fracture. Therefore, for unconstrained head impacts, the neck injury criteria related to the extension angle is more conservative than the fracture tolerance of the head bone.

Next, we conducted collision analyses of direct impact to the human neck with the body unconstrained (Fig. 2(d)). The analysis conditions, including the collision velocity and position, the mass of the body, and the length of the robot arm, were set to the same values as those of the impacts to the head.

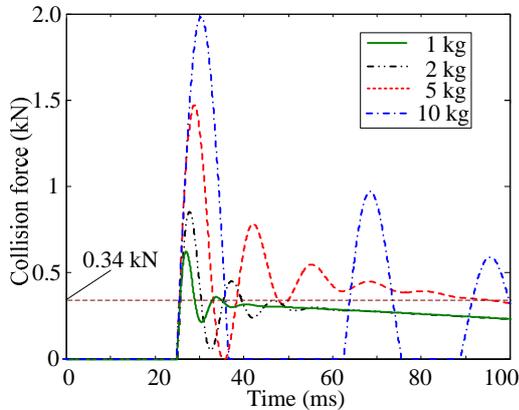


Fig. 5. Analysis results on direct impacts to human neck without clamping body.

As shown in Fig. 5, the robot arm with a link mass of 1 kg delivered a collision force, which increased up to 0.6 kN, to the human neck, which is above the fracture tolerance of the thyroid and cricoid cartilage. Compared to head impacts, direct impact to the neck is more dangerous, and this injury criterion for the neck is much more conservative. For example, when a robot arm with a link mass of 10 kg rotates at an end-point velocity of 2 m/s, this impact does not cause cranial bone fracture and the hyperextension of the neck. However, it can collapse the thyroid and cricoid cartilage of the neck. Moreover, the maximum collision force acting on

the neck is 2 kN, which is larger than the 1.8 kN maximum collision force of the head.

### B. Impacts for constrained human

For collision between the constrained human and the robot, the worst case condition was considered: the head and neck were initially clamped with the fixed wall as shown in Fig. 2(e). The analysis conditions were set to the same values as those of the unconstrained impacts. The stiffness  $k_w$  and damping  $c_w$  of the fixed wall were set to 1000 kN/m and 650 Ns/m, respectively.

The analysis results on the impacts to the clamped head are shown in Fig. 6(a). Using a link mass of more than 50 kg, the collision force acting on the head exceeded the fracture tolerance of the frontal bone.

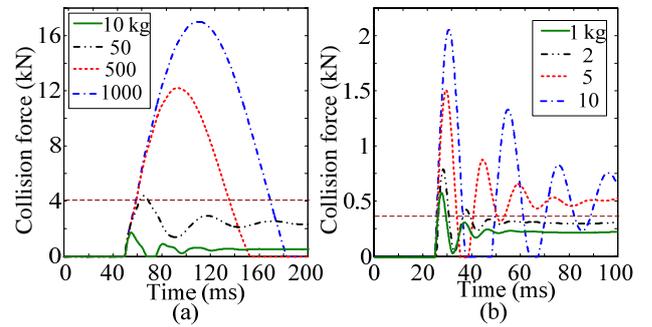


Fig. 6. Analysis results on impacts to constrained human: (a) human head, and (b) human neck.

Figure 6(b) shows the analysis results for the collision impacts to the neck with clamping. The collision force of the robot arm with a link mass of 1 kg reached a peak value which was higher than the fracture tolerance of the thyroid and cricoid cartilage. Since the neck injury criterion is more conservative than other criteria in all cases, the fracture tolerance of the thyroid and cricoid cartilage can be regarded as the most appropriate indicators for service robots.

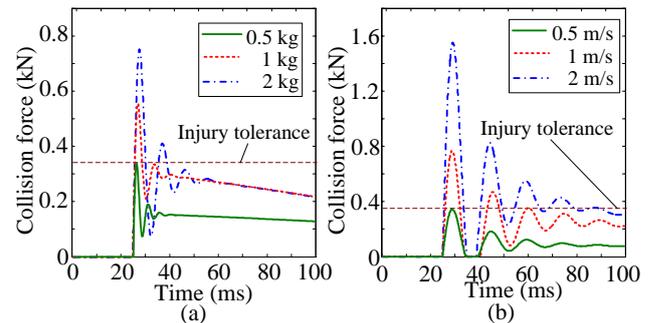


Fig. 7. Analysis results on impacts to neck with constrained human: (a) effects of mass of robot link, and (b) effects of collision velocity.

For service robots working in human environments, several requirements may coexist such as a payload of more than 2 kg (the corresponding mass of the robot link is 5 kg), an operational velocity of 1.5 m/s, and so on. Therefore, such

requirements can be evaluated by conducting the proposed analysis based on the neck injury criterion. If a velocity of 1.5 m/s is the most important design parameter, the mass of the robot link should be less than 0.5 kg to guarantee collision safety, as shown in Fig. 7(a). If the mass of the robot link is fixed at 5 kg to carry a payload of 2 kg, the end-point velocity should not exceed 0.5 m/s for safe human-robot interaction, as shown in Fig. 7(b).

To simultaneously achieve performance and safety requirements of a robot, a safety control algorithm and/or mechanical safety mechanism should be installed on robot arms. Furthermore, the collision analysis and safety criterion proposed in this paper can be also applied in developing safe robot arms.

## V. CONCLUSION

In this research, more accurate collision analysis and an appropriate injury criterion for service robots were proposed. The collision analysis and safety criterion suggested in this paper can be easily applied to estimate the collision safety level of a service robot. From this research, the following conclusions are drawn:

- 1) More reliable analysis results for human-robot collisions can be obtained using the proposed accurate models. Therefore, evaluation of collision safety is possible at the design phase of a robot, which can save time and cost associated with real collision tests.
- 2) Various analysis results verified that the neck injury criterion related to the fracture of thyroid and cricoid cartilage is the most appropriate safety indicator for service robots.

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