Study on Verifying Thresholds for Mechanical Pain Caused by Human-Robot Transient Collision

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***Abstract*— With the recent rise of the 4th Industrial Revolution, industrial fields are pursuing more efficient and flexible production. As part of achieving this goal, many companies are introducing collaborative robots in their production processes. Because collaborative robots share workspace with workers, collaborative robots need to ensure collision safety. As a basic study of verifying important collision safety in the use of collaborative robots, this study conducted clinical test to identify threshold of mechanical pain initiation caused by dynamic collisions.**

I. Introduction

Robots have been used steadily in industrial production processes. In the production process, robots can move heavy objects that cannot be lifted by humans and make it possible to repeat tasks faster and more accurately than humans [1]. For these reasons, manipulators are often used in industrial fields. Most of the existing industrial manipulators are very dangerous when they collide with humans, so the workspace of the robot is separated from that of the human by a fence.

But recently, with the development of robotics, several collaborative robots that have countermeasures against collision with humans have emerged. Since collaborative robots share a workspace with workers, it is very important to ensure collision safety. A previous study related to collision safety of robots that was conducted by Y. Yamada used a pressure cylinder to put a load on the subject's body and measure the force that initiates unbearable pain [2]. In the experiment conducted by R. Behrens, transient contact to the subject was generated by using collider that moves like a pendulum and the force and pressure that initiates the mechanical pain were measured [3].

However, since previous studies on transient contact have been conducted with a small number of subject, it is also difficult to clearly identify the quantitative threshold of mechanical pain onset by transient contact. In this paper, we present a clinical test of 38 subjects and statistical analysis of a threshold for the onset of mechanical pain.

II. Experimental Design

A. Ethics and Subjects

In order to conduct an ethically appropriate and safe clinical test, the clinical test presented in this paper has been approved by the Kyung Hee University Institutional Review Board (IRB No. KHUH 2018-11-023). Because the goal of the test is to identify the threshold of pain onset, the experiment was designed for the subjects to feel only minimal pain. If the subject felt pain during the experiment, the experiment was stopped, and the force and pressure exerted on the subject in the corresponding collision case were recorded.

Based on the results of the quasi-static experiments (IRB No. KHUH 2016-10-022) performed previously in Kyung Hee University [4], the body parts where the distribution of the measured individual threshold was not wide were selected to be tested for the transient collision. However, the points where the internal skin is weak so that damage to the skin could easily appear were excluded. Thus, the forehead, deltoid (shoulder) and thigh area were selected as test sites. Participants were recruited from healthy adult males in their 20s and 30s, and a total number of 37 subjects were recruited (age 25 ± 2.34, weight (70.1 ± 4.82) kg, height (1.736 ± 0.048) m, BMI (Body Mass Index) (23.2 ± 2.8)

B. Pain Threshold Assessment Equipment

The experimental system is illustrated in Fig. 1. An impactor made in the form of a pendulum on the experimental equipment collides with the participants. Three types of shapes were applied to the impactor, and the impact velocity was adjusted by changing the retraction angle of the lifted impactor. The following equation was used to calculate the retraction angle of the impactor to achieve the target impact velocity.

$$v_{target} = \sqrt{2gL(1-\cos\theta)} \tag{1}$$

where v_{target} is the target velocity of the impactor, g is the gravitational acceleration, L is the length of the pendulum arm

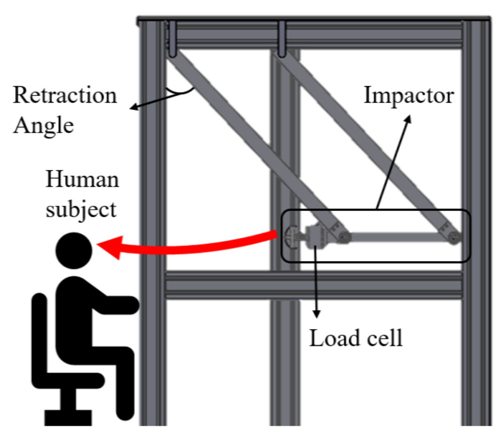

Fig. 1: Schematic of experiment system for measuring the threshold of mechanical pain caused by transient contact

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Fig. 2: Three shapes of impactor with pressure measuring film (left: 40 mm radius hemisphere, center: cylinder edge of 5mm radius, right: cylinder edge of 40 mm radius)

and θ represents the retraction angle of the impactor. The force generated by the transient contact was measured by the load cell attached to the impactor. The pressure was measured using a pressure-measuring films (Tekscan Inc., MA, USA) attached to the surface of the impactor as shown in Fig. 2. The hemispherical impactor was used for the forehead collision test, and the two cylinder-edge shaped impactors were used for the collision test with deltoid and thigh. This difference in collision shape is intended to implement the contacts identified in the Hertzian theory, and these contact characteristics will be used in collision analysis.

C. *Experimental Methods*

The experiment was designed to let subjects to be impacted with three different shapes of impactors. The experiment on each body part begins with a low contact velocity and progressively the impact speed was increased until the pain to the subject was reported. In order to reflect the actual collision situation, the effective inertia of the robot under normal driving condition is applied to the impactor mass. When the experiment was completed in one body site, the next experiment of other body sites was conducted after enough time to prevent confusion in pain sensation that could be caused by the residual sensation from the previous test.

III. RESULTS

A. *Statistical Analysis*

The data of 37 subjects for each collision case obtained through the experiments were statistically analyzed. As shown in Fig. 3, Maximum likelihood method was applied on the 37 sample data. The normal distribution estimated by the maximum likelihood method can be interpreted as the result that we would get if we continue the same test infinite number of trials [5]. The solid red line in Fig. 3 represents the estimated normal distribution and the mean of these distributions can be expected to be the threshold of mechanical pain with the highest probability.

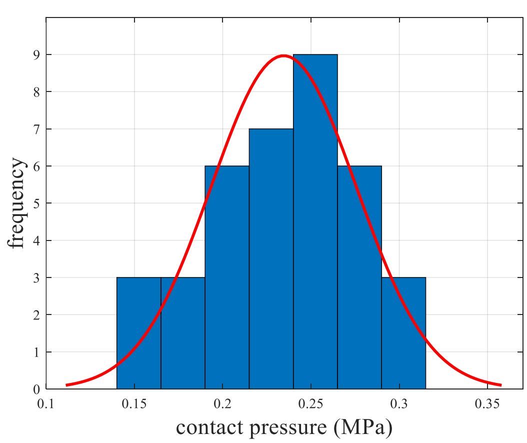

Fig. 3: Normal distribution of the pressure pain threshold (red solid line) estimated by using the maximum likelihood method based on the result of the case that thigh collision with a cylinder edge shape with a radius of 40 mm (blue histogram)

B. *Pain Thresholds*

The mean of the estimated normal distributions described above was used to calculate the threshold for mechanical pain. A sufficiently predictable correlation is that in the case of a collision with the cylinder edge shape, the pain threshold of the force and pressure become smaller as the radius of the cylinder becomes smaller. However, unexpectedly, the pressure threshold is observed much smaller than those of the quasi-static contact experiments. Also, even though the deltoid and thighs have similar tissue composition, the difference of the pain thresholds corresponding to two impactor shapes for deltoid is much bigger than the difference of the pain thresholds for thigh. There is a plan to study the causes of these results and further research will be conducted to develop an integrated solution to the risk of human-robot collision.

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