人共存ロボットの安全性に対する表面痛と深部痛の違いを識別するためのヒューマンライクな痛覚センシングシステム
A Human-inspired Pain Sensing System to Recognize Difference between Superficial and Deep Pain for Personal Care Robot Safety

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Abstract
In this paper, we introduce the concept of a human-inspired pain sensing system, imitating the sensing location of mechanical nociceptors in human skin (superficial somatic pain) and skeletal muscle (deep somatic pain) for personal care robot safety application. We expect that the system will not only measure the pain for personal care robot safety evaluation, but also show the difference between these two kinds of pain due to various contact conditions. In this study, we developed the arm prototype which imitates human nociceptor mechanism, and verified our pain sensing concept by conducting experiment with various contact situations.

Keywords — Pain, Dummy, Robot Safety, Pain Recognition

1 Introduction
As the development of personal care robot is getting more advanced, it is now possible to use it interactively with human. Ensuring safety during physical human-robot interaction (pHRI) has become a fundamental concern and many researches were conducted to address this matter refer to [7], [26], [15].

With high possibility of contact between human and robot, in order to minimize the risk of human injury, safety evaluation is required. In automobile industries, crash test dummy [8] is commonly used for safety evaluation, which involves high level of impact that leads to bone fracture or death.

Abbreviated Injury Scale (AIS) which is an anatomical scoring system where injuries are ranked from 1 to 6, with 1 means minor, 5 means critical, and 6 means nonsurvivable injury. To ensure the safety of personal care robot, robot safety design factors such as mass, speed, cover material, and surface shape are concerned by applying low level of impact evaluation such as pain and discomfort level. Even though AIS 1 concerned as the minimum injury indicator in this case, but it also includes closed fractured nose and one broken rib [9], [1]. Therefore, AIS criteria might not be appropriate to be used for personal care robot safety evaluation.

Studies related with determination of pain sensitivity in human-machine-interface for collaborative robots used in industrial field [15] which use pain onset level to determine safety level of physical contact between human and collaborative robot have been conducted and applied to ISO/TS 15066.

There is also commercial force/pressure test system for collaborative robots from GTE Industrieelektronik GmbH which is used in ISO/TS 15066, ISO 10218-1, ISO 10218-2 and EN 415-10 focusing on the main biomechanical body features, but with no anthropometric shape for convenience measurement.

Based on the facts mentioned above, currently there is no equipment that simulates the biomechanical properties and shape of human body to measure lower level of impact that leads to pain which is required for personal care robot safety measurement.

Our research tries to address this matter by focusing on pain-free interaction of personal care robot and human such as in airport, hospital, and shopping center, which have high possibility of contact with human. In order to tackle this requirement, human pain receptors locations are used for design our dummy model. For this, it is worthwhile to take a closer look at human pain receptor location and pressure-pain threshold since they are generally regarded of vital importance to this development.

1.1 Human Pain Receptor Location
Pain usually occurs after most types of noxious stimuli to protect and prevent tissues or nerves from over damaging [24].

It plays an important role in body normal defense mechanisms, warning of contact with possibility of damage, initiating behavioral and reflex avoidance strategies.
Somatic pain, the most common pain occurs when nociceptors in tissue such as skin, muscles, skeleton and joints are activated. This paper will focus on this type of pain.

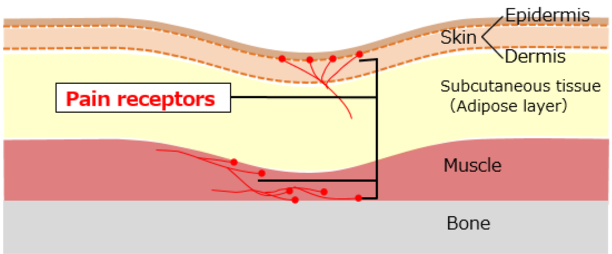

Fig.1. Mechanism of pain sensation detection in human arm

Somatic pain can be classified into 2 types, which are superficial pain and deep pain [20]. Superficial somatic pain occurs when cutaneous nociceptor which lies near blood vessels in the upper regions of epidermis [14], [17] in the skin is stimulated. Deep somatic pain occurs in connective tissue of muscle, between muscle fibers, adventitia, in tendon, periosteum of bone, or joint [21], [22].

1.2 Pressure-Pain Threshold

Pressure-pain threshold (PPT) and pressure-pain tolerance methods have been widely used in pain measurement studies [23, 2], which measure the pressure from external probe that gets in contact with human skin. However, these studies did not put into consideration about human body structure in relation with pain mechanism.
We suspect that the pain caused by pressure from the probe affects not only the skin but also the muscle layer, as suggested in [16], [4], [3], [11] studies, which stated about pressing using cuff algometry effect the muscle pain more than cutaneous pain.
In order to confirm this hypothesis, we developed a human arm prototype with flexible pressure array sensors placed under the artificial skin layer and muscle layers to measure both superficial and deep somatic pain clarifying the pain mechanism algorithm during compression with various types of probe.

2 Human-inspired pain sensing system structures

2.1 Artificial upper arm structure

Human arm structure consists of 3 layers: skin, adipose tissue combined with muscle, and bone in subsequent order from the top. Nociceptors (pain receptors), which lie in the skin layer caused superficial pain and the one which lie in the muscle and bone caused deep pain (refer to Fig.1).

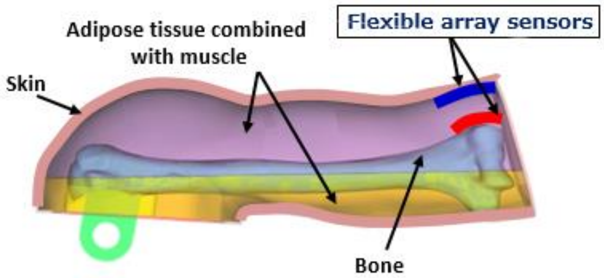

Fig.2. Upper arm human-inspired pain sensing dummy structure

We produced the artificial skin, adipose tissue combined with muscle, and bone according to the solid model of 50th percentile male developed by Zygote with skin thickness of 2 mm [6], [10]. As for the mechanical characteristic of each part, based on the previous studies of human arm, we defined the Young's modulus of the skin and muscle to be around 100kPa [13] and 40kPa [12], [25], [5] respectively and defined the compressive loading of bone to be around 160MPa [18].
The function of nociceptors was simulated by placing two flexible pressure array sensors under each layer excluding the bone (refer to Fig.2).

2.2 Flexible pressure array sensors

For the pressure sensors placed in between the layers, we confirmed the sampling rate and spatial resolution which are possible to effectively measure the impact force by conducting experiment with various settings [27]. Therefore, in this arm prototype, we adopted the sampling rate and spatial resolution for the sensors to 500Hz or above and 14.06mm^2 or smaller respectively.

3 Methods

3.1 Purpose

In order to reveal the difference between superficial pain and deep pain due to various contact conditions, as the first step of our study, the experiment was carried out by pressing two shapes, six types of contact probe which are different in radius and area to pain sensing system as mentioned above. We performed the experiment using indentation system, contact probes, and procedure as followed:

3.2 Indentation system

The experiment was conducted with an indentation system (refer to Fig.3), which is able to produce force up to 500 N, probe displacement up to 35 mm, and maximum speed of 100 mm/s.

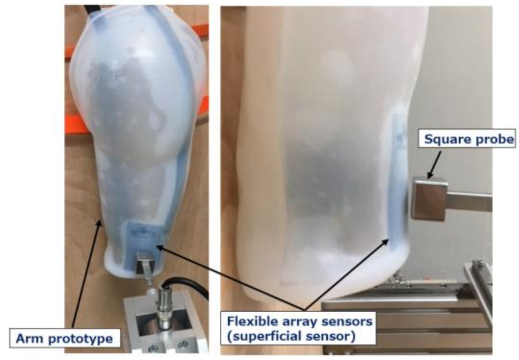

Fig.3. Indentation system with 1st prototype dummy

In order to measure samples from any direction, it was designed by using joint that can be rotated ±45 degrees in horizontal and vertical direction. Furthermore, it is possible to adjust the initial position in both horizontal and vertical direction also using the linear slide attached within this system.

3.3 Contact probes

It is predictable that the difference in shape and size of probe affect the results in pressure pain threshold in human, so we also assume that it probably shows those results in the pressure sensors we placed under skin layer to measure the superficial pain and under muscle layer to measure the deep pain.

Fig.4. Tested 2 types, 6 tip-end shapes of contact probe

In order to investigate the effect of probe shape, the experiment was conducted using six probes with different shape and size. We used three spherical probes with radius of 5 mm (R5), 10 mm (R10), and 15 mm (R15), three square probes with dimension of 14 mm x 14 mm (S14), 19 mm x 19 mm (S19), and 24 mm x 24 mm (S24) (refer to Fig.4). For the square probes, we rounded the corners and edges with radius of 2 mm to reduce the sharp edge [15]. We designed the shape of the spherical and square probes according to previous studies [19, 15]. The reason we used spherical probe because we want to observe the result while the radius of probe is changed and used square probe because we want to observe the result while the area of probe is changed.

3.4 Procedure

We attached each probe on the indentation system then pressed the human artificial arm, perpendicularly with the skin at a constant speed of 2 mm/s, to simulate quasi-static clamping situation of robot, and pressed with probe displacement of 33±1 mm from contact position based on our indentation system limitation. Points of compression were specified at upper arm bone on the dorsal aspect around lateral epicondyle of the upper arm (refer to Fig. 2 and Fig.3) according to previous study [15]. After each compression, 1 second was held at final position before the indentation system moved the tip back to the initial position.

According to ISO/TS 15066 and previous study [15] which use the maximum pressure as the threshold for collaborative robot safety, in this paper, we analyze data by averaging maximum pressure data from flexible array superficial and deep sensor while the probe displacement was in final position.

4 Results

The maximum pressure obtained from superficial and deep sensor using three spherical probes which are different in radius and three square probes which are different in area are plotted in Fig.5 and Fig.6 respectively.

Experiment result revealed that when pressure was generated with R5 spherical probe, deep layer sensor showed less maximum pressure than superficial layer sensor (refer to Fig.5). On the other hand, when pressure was generated with R10 and R15 spherical probe, S14, S19, and S24 square probe, superficial layer sensor showed less maximum pressure than deep layer sensor (refer to Fig.5).

Furthermore, results from the experiment with spherical and square probes (refer to Fig.5 and Fig.6), showed that when the radius of probe (spherical probe) and area of probe (square probe) are larger, the maximum pressure in deep and superficial sensor are higher and lower respectively.

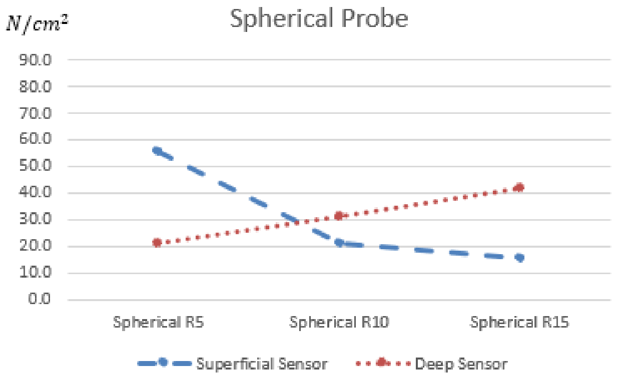

Fig.5. Maximum pressure in superficial sensor and deep sensor during compression with spherical probes with radius of 5mm, 10 mm, and 15 mm.

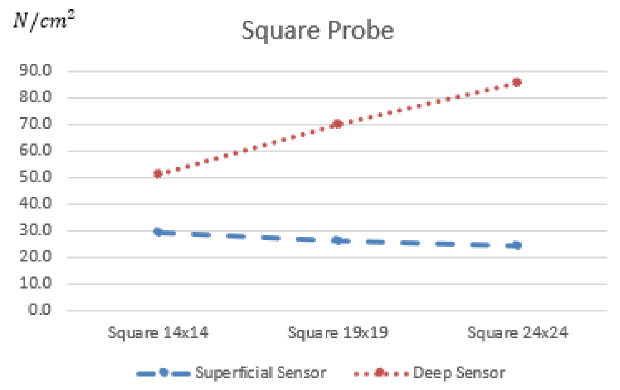

Fig.6. Maximum pressure in superficial sensor and deep sensor during compression with square probes with dimension of 14 mm x 14 mm, 19 mm x 19 mm, and 24 mm x 24 mm.

5 Discussion

Based on the results mentioned above, it can be concluded that superficial pain are more likely to occur when spherical probe with the radius of 5 mm was used. On the other hand, deep pain are more likely to occur when spherical probe with the radius of 10 mm, 15 mm, and square probe with dimension of 14 mm x 14 mm, 19 mm x 19 mm, and 24 mm x 24 mm were used.

Moreover, it also can be concluded that superficial pain is more likely to occur when smaller radius and area of probe are used, and deep pain are more likely to occur when larger radius and area of probe are used.

Therefore we predicted that when probe with smaller surface area such as spherical probe with radius of 5 mm is used, more pain in the superficial layer will occur, and when probe with larger surface area is used, more pain in the deep layer will occur, which is according to the experiment results.

This paper is our first step in superficial and deep pain measurement to ensure the mechanical safety of personal care robot. We developed a human-inspired pain sensing system, which imitates the sensing location of mechanical nociceptors in human skin and skeletal muscle. Furthermore, pain measurement with the system showed that it is possible to distinguish and measure the superficial pain and deep pain using our proposed method.

In the future, we are planning to investigate human pain threshold in various actual contacts. In order to validate the result presented in this paper, we will correlate the pressure in proposed method with the pain recognized by human using pain threshold measurement system. Our main goal is to obtain the satisfying accuracy of the system so that it can be used for predicting mechanical pain incident supporting safety design in personal care robot industries.

6 Acknowledgement

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