Comparison of Tactile Discriminations to Verify the Undetectable Region of SUS Foil Thickness

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***Abstract*—Understanding human capability in performing critical tasks is key to enhancing sensor performance, especially in robotics. In this study, our objective is to analyze human tactile mechanism behavior in recognizing extremely thin foils using a psychophysics method. Seven pairs of stainless foils ranging in thickness from 20 ~ 150 µm were used in the experiment. We applied the method of constant stimuli to define the difference threshold. In order to increase the detection rate, contact between human tactile function and the metal foils was maintained. As a result, we managed to achieve a similar trend to our previous experimentation. The Weber fraction *c* reduces as thickness increases and becomes constant with *c* ≈ 0.4 from *t* = 120 µm onwards. We also validated the behavior of the undetected regions up to 150-µm thickness. Although duplex theory properties could not be observed, the achievement was quite significant considering the higher thickness test ratio.**

***Index Terms*—Cutaneous Function; Difference Threshold (DL); Psychophysics; Weber Fraction.**

I. Introduction

A major focus in the tactile sensing field is the study of the delicate human detection process. A significant challenge is how to adapt this concept effectively to robotics. For example, differentiating the properties of two extremely thin foils is natural for most people when using their fingertips, yet it is an extremely difficult task for robots equipped with tactile sensors. Despite this fact, there are products on the market capable of conducting a similar task, such as the automatic page turning device or bank note counter; however, the majority are non-versatile and limited to their specific task and function. For this reason, the development of a dexterous mechanical hand capable of handling delicate functions is needed, especially for daily use. To create a device able to perform such critical tasks, the best option is to study the complexity of the human tactile mechanism (please refer to our graphical abstract). Through this study, we will be able to improve and optimize the performance of tactile sensors, especially in robotics.

Psychophysics remains the most suitable method for describing the relationship between a person's physical sensations and psychological judgement [1]. It is astonishing how the cutaneous function of human tactile sensation is capable of distinguishing ultra-thin foil thicknesses up to several 10 µms, yet is unable to be monitored by kinesthetic or joint sensory organs [2]. This motivates us to further study this mechanism with a goal towards robotics application. Since tactile sensations play a major role in the thickness discrimination of ultra-thin foils, elucidating this mechanism is the aim of this psychophysics experiment.

Previous psychophysics studies have shown the existence of an undetected region when analyzing materials of 70 to 350 µm in thickness [2, 3]. For humans, the process of thickness discrimination is influenced by two major sensing systems: the cutaneous function (related to delicate contact or touch) and the kinesthetic function (influenced by muscle joint motion) [4, 5]. One hypothesis is that both systems are functioning simultaneously and the transition state occurs somewhere within this region. For the cutaneous function, such critical skill could be activated by mechanoreceptors that are sensitive to constant pressure, constant velocity, or acceleration-type information, such as SA-I, SA-II, FA-I, and FA-II. As in discriminating extremely thin materials, it could be possible that plastic deformation may also influence the result [2].

In robotics, we can relate all of these ideas to the sensor fusion technique to enhance the performance of available sensors. We will monitor this phenomenon during the current psychophysics experiment using a group of extremely thin stainless steel (SUS) foils. The evaluation process is more detailed with a higher thickness test ratio (by focusing on a single thickness group with seven samples) as compared to previous experiments that conducted piecewise examination using four groups of material thicknesses, but with fewer samples [3].

Our objective is to study the behavior of the human tactile mechanism during the evaluation of extremely thin foils and to bridge the gap between the undetected regions, especially below 150-µm thickness. In order to do so, we will compare the Weber fraction between the current and previous psychophysics experiments. The number of thickness samples was increased to monitor the detection, especially between the cutaneous function and the undetected region.

II. Psychophysics

In this section, we shall review the basic psychophysics information and discuss the previous experiment results that are related to this research. In general, psychophysics can be defined as the study of the relationship between the physical properties of a stimulus and perception ability. During the early 1800s, E. H. Weber questioned such differences and suggested that it could be possible to judge and measure human perception even though it may not equal actual physical measurement. Later, G. T. Fechner analyzed this concept and proposed what is known as Weber's Law or the Weber fraction [1, 6, 7]. Theoretically, the Weber fraction shows the ability of a subject to detect distortion of stimuli and discriminate stimuli thicknesses from the amount of distortion. The ratio between the change of stimulus intensity that is just noticeable ($\Delta\Phi$) and the actual value of stimulus Φ could be described using the constant value c, resulting in Eq. (1) below.

$$c = (\Delta\emptyset)/\emptyset \tag{1}$$

Fechner further expanded this law, resulting in Fechner's Law. The main difference is that Weber defines the psychophysics relation using a linear function, whereas Fechner's Law postulated the relation using a logarithmic function, which fits most psychophysics experimentation phenomena. This results in Eq. (2), where S and k represent the sensation magnitude and a constant value, respectively [6].

$$S = k\log(\emptyset) \tag{2}$$

In theory, the classical psychophysics method can be divided into three main categories: the Method of Limits, the Method of Adjustment, and the Method of Constant Stimuli. Each method can be used to measure the Absolute Threshold, *RL* (*Reiz Limen*), and the Difference Threshold, *DL* (*Differenz Limen*; also equal to $\Delta\Phi$). Either selection depends on the merits and weaknesses of each. For this experiment, we will be using the Method of Constant Stimuli and focusing on the *DL* output (where comparison and judgement shall be made by the test subjects between a standard stimulus and comparison stimulus). Although this method is considered one of the most accurate in psychophysics, it is also known as the most time consuming [1].

Next, we discuss related psychophysics studies. The research done by John et al. [8] in discriminating the thickness of thin copper plates shows that the test subjects were capable of discriminating thicknesses from t = 200 ~ 500 µm (within a 75-µm range). John et al. also discussed the influence of the gripping angle between the fingers, as there were no differences when discriminating between the foil's edge and the surface. Miyaoka and Ohka [2, 3] performed similar experimentation, but with thinner SUS and Cu foils, proposing that humans are capable of discriminating until t = 8 ~ 50-µm thickness (which normally cannot be detected by the angular sensory organs of the human finger). Their hypothesis is that evaluations of material of less than 70-µm thickness must be performed using the cutaneous function (of SA-I mechanoreceptor units) and, for thicknesses above 350 µm, the kinesthetic function. There is an undetected region between 70- and 350-µm thicknesses that marks the transition state from one system to another, suggesting the inter-function state between both systems that we described in the earlier section.

Finally, our previous simulation work demonstrates the importance of finite element analysis towards indirect monitoring of human tactile behavior [9, 10]. We also highlighted the impact of angular load on the result and the need to maintain contact between human tactile function and the metal foils to improve the detection rate.

III. METHODOLOGY

Our main objective is to verify the range of tactile sensation between the undetected region (previously determined as within t = 70 ~ 350-µm thickness) in which the inter-function between the sensory mechanism of the cutaneous and kinesthetic functions can occur. Below, we highlight the improvements made to the psychophysics experiment:

(a) The main objective is to monitor performance during the lower range of thickness using a t = 20 ~ 150-µm range of SUS material.
(b) The material handling method has been standardized to reduce unnecessary finger movement through a specific gripping method. The test subject is required to maintain contact with the foil at all times. Gripping motion should follow the vertical versus angular loading method, which is similar to the previous simulation study [10].
(c) The thickness discrimination process shall be performed by the index finger and thumb using both hands simultaneously. Each hand shall separately hold the comparison stimulus and standard stimulus material.

The main intention is to ensure that the psychophysics experimentation process matches closely with the previous finite element analysis simulation setting, especially during various loading angles. These key points shall be monitored closely in order to observe the psychophysics behavior of the test subject during contact analysis. Details shall be discussed in the Results and Discussion section.

The main purpose of the experimentation procedure is to measure the thickness difference thresholds using a pair of SUS foils. Six males aged in their twenties participated in this experiment as our test subjects, all with zero experience in psychophysics experiments, particularly in regard to the thickness differentiating process. Based on a simple interview, all test subjects were determined to be right handed.

Seven pairs of stainless steel foils (SUS 304) were used as stimuli with thicknesses of 20, 40, 60, 80, 100, 120, and 150 µm. Each foil was clamped between aluminum jigs with a 60-mm diameter exposed opening (Figure 1). The temperature of the jig was controlled using two hot plates (AS ONE, EHP-250N), as shown in Figure 2, each positioned beside the test subject's hand.

Figure 1: Gripping method of SUS material.

Figure 2: Arrangements of test materials on hot plate.

First, each test subject was seated and required to wear an eye mask to prevent viewing any of the test materials. They were also required to wear earphones inputting white noise sounds to neutralize any external noise that could influence their judgement. Next, the tester randomly selected a pair of foils from each comparison stimulus and standard stimulus group, and placed the pair near the test subject's hands. After receiving a tap signal from the tester, the test subject gripped each foil simultaneously using the index fingers and thumbs of both hands. This was to determine which foil was perceived to be thicker using the two-alternative, forced-choice technique. The test subject was allowed to move their fingers with five times gripping motion only, maintaining contact with the metal foil throughout the whole process. Finally, each test subject signaled which material was perceived to be thicker by raising the hand which perceived the thicker feeling.

The maximum time to give their feedback was 20 sec (including 15 sec of the gripping process) for each combination of stimulus. The inter-stimulus interval is important for the tester to record data and to exchange material for the next combination of stimulus. Basically, pair-wise combinations of seven distinct stimuli (plus self-combinations) produces 28 steps, with comparison between same thicknesses done twice. As it was necessary to counterbalance the right and left positions of stimuli, the total number of combinations doubles up to 56 steps. Overall, each subject performed around ten trials for each combination of stimuli, resulting in a total of 560 steps each. The total simulation time per trial was about 30 minutes (including 10 minutes resting time during each interval). In order to maintain the decision-making quality, the maximum experiment time was kept below two hours, which limits the number of trials to a maximum of four per day.

The temperature of the hot plate needs to be kept within 35 ± 1 °C in order for the foil to be around 32 ± 4 °C (which is close to normal body temperature). Although the heat dispersion factor could probably increase or reduce the temperature of each foil depending on thickness, it will not influence the tactile decision if the temperature is kept within range.

The main reference for the current psychophysics experiment was based on the research of Miyaoka and Ohka [2, 3], especially when comparing the tactile behavior between different thicknesses. As stated previously, our objective is to verify the existence of two information processing systems in discriminating the thicknesses between the undetected regions. For this reason, we focused on a single group of materials with thicknesses between 20 to 150 μm. This differs from the previous experiment, which used four different groups of material thickness.

IV. Results and Discussions

A. The Psychometric Functions

We analyzed the results of the psychophysics experiment accordingly using the psychometric function graph, as shown in Figure 3. The ordinate represents the probability of the comparison stimulus to be judged as thicker than the standard stimulus and the abscissa represents the thickness of the comparison stimulus. Higher slope values demonstrate the ability of the test subject to differentiate between thicknesses better. Each line represents the probability trend of the base material or standard material. For example, the data at the upper left corner (which represents the trend line for the SUS standard material of t = 20 μm) shows a probability of 0.7 for the t = 40-μm comparison material to be judged as thicker when compared to the 20-μm standard material.

In general, value p = 0.5 marks the threshold point where the probability of judging both types of material thicknesses is similar. As long as the overall slope value is positive and not centered along this region, the ability to discriminate between materials is available.

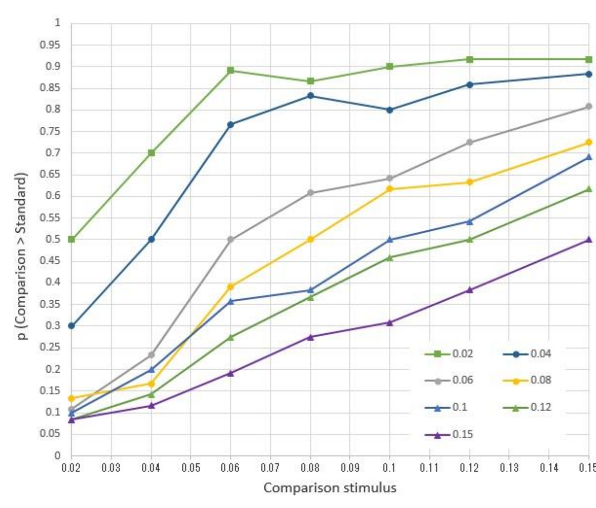

Figure 3: Psychometric function of *p* values vs. thickness

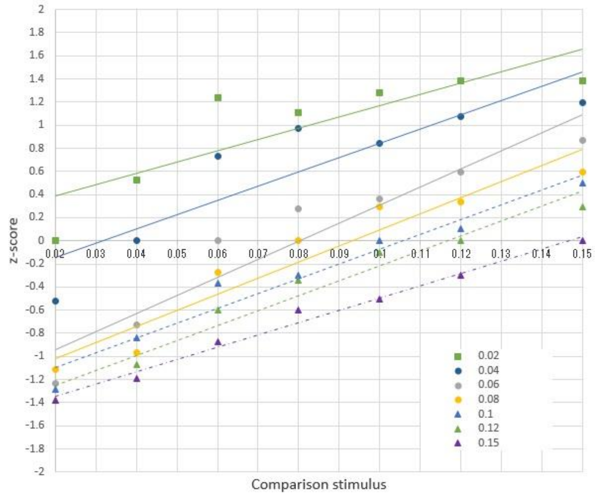

Figure 4: Psychometric function of *z*-score vs. thickness.

B. *The Weber Fraction*

In this experiment, the properties of the duplex theory could not be observed, as there was no increment of fraction values during the undetected region. Although some individual results were able to produce such progress, especially during *t* = 120 µm and onwards, the increment value was still minimal. Furthermore, the current Weber fraction is still high compared to our previous result. Such differences could occur due to the nature of this experiment, where we specifically instruct the test subject to analyze the thicknesses using both hands simultaneously along with other restrictions, whereas, in the previous experiment, the observation was done only with a single dominant hand.

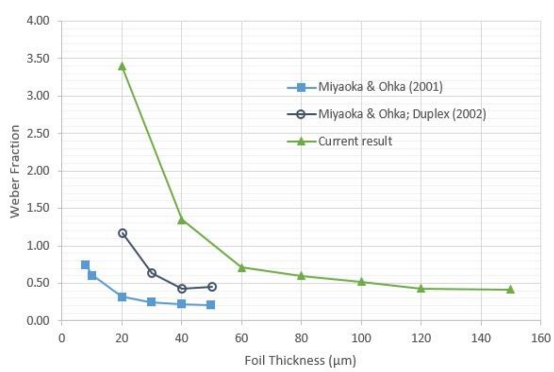

Figure 5: Comparison between Weber fractions.

Referring to the previous duplex theory [3], the undetectable region was defined as relatively wide at a range of 70- to 350-µm thickness, whereas currently the result shows that the undetectable region does not appear until 150-µm thickness. From the current result, we can conclude that the undetectable region exists between 150 and 350 µm of thickness.

V. CONCLUSION

In this psychophysics experiment, we employed a specific procedure to maintain contact between the human finger and SUS foils throughout the experiment. The test subject was required to grip the material between the index finger and thumb without releasing contact with the foils in order to ensure that the only mechanism that activates during contact is the cutaneous stimuli (or mechanoreceptor), especially in detecting distortion. This also shows that the test subject is capable of detecting the thickness of stimuli through this gripping method.

In conclusion, we verified the ability of the human tactile function to detect an extremely thin object from the psychophysics result. Through specific control of the current experiment procedure, we managed to achieve a similar trend. Although the Weber fraction value differed compared to the previous experimental result, we managed to validate the behavior of the undetected regions up to 150-µm thickness. This is a great achievement considering the increased number of the thickness test ratio (between a minimum and maximum thickness range) in a single test group compared to the previous experiment. Further study on the behavior of the undetected regions, especially between the 150 ~ 350-µm thickness range, will be undertaken in the near future.

ACKNOWLEDGEMENT

The main author would like to thank Universiti Teknologi MARA (UiTM) & Kementerian Pendidikan Malaysia (KPM) for the financial support of his doctorate study; also JSPS KAKENHI Grant No. 15K13855 for funding this research.

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