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Tactile texture and friction of soft sponge surfaces

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ABSTRACT

We evaluated the tactile texture and frictional properties of five soft sponges with various cell sizes. The frictional forces were measured by a friction meter containing a contact probe with human-finger-like geometry and mechanical properties. When the subjects touched these sponges with their fingers, hard-textured sponges were deemed unpleasant. This tactile feeling changed with friction factors including friction coefficients, their temporal patterns, as well as mechanical and shape factors. These findings provide useful information on how to control the tactile textures of various sponges.

1. Introduction

Information about the physical origin of tactile textures when humans touch objects is useful in designing of many products and systems, such as clothes, cosmetics, automobile materials, information terminals, virtual reality systems, and robots [1]. Based on various models proposed by psychologists and engineers, there is little doubt that frictional stimulus on the surface of the skin is one of the most important factors for tactile textures [2–4]. To date, we have elucidated the relationships between tactile texture and friction phenomena on skin surfaces using a tactile evaluation system consisting of a high-speed camera and a friction evaluation unit [5–8]. Many objects with characteristic tactile textures are made of soft materials, such as polymers, rubbers, and gels. Making small holes inside these materials can be effective for controlling tactile textures because the size and distribution of the pores drastically change the mechanical and thermal properties of the materials [9,10]. Therefore, soft sponges containing small cells have been used in many fields, including the cosmetic, fabric, and furniture industries. The pleasant texture of soft materials, such as fiber, resin and leather, has been studied [11–13]. Conversely, there are few studies about the texture of soft sponges. Chen et al. classified tactile vocabularies when subjects touched various materials including sponges [14]. Etzi et al. statistically analyzed tactile textures and pleasantness when subjects touched sponge or other materials, and showed that the material with a smooth texture is preferred [15].

In this study, we evaluate the tactile textures and frictional properties of five soft sponges containing various cell sizes. First, the pleasant level was evaluated when twenty subjects touched these soft sponges. Second, the friction between the soft sponges and a contact probe that embodies the geometric and mechanical properties of human fingers was systematically evaluated (Figs. 1 and S1). The polyurethane contact probe, which consists of a surface covered with imitation fingerprints, reflects the elastic modulus and surface properties of actual human fingers [16,17]. Some researchers have suggested that fingerprints perform the spectral selection and amplification of tactile information [18,19]. To confirm the effects of the fingerprints, we evaluated the friction between soft sponges and a contact probe with a flat surface (Fig. S1b). Finally, the relationships between tactile feel and physical and shape factors were statistically analyzed.

2. Experimental

2.1. Materials

We evaluated the frictional properties of five soft sponges (**1**–**5**) made by INOAC Corporation (Nagoya, Japan). The sponges were composed of polyester urethane foams prepared by the additive polymerization of diisocyanate and adipate. The cells in the soft sponges were isotropic. Table S1 and Fig. 2 show the physical properties and scanning electron microscopy (SEM) images of the materials, respectively. As the material number increased from **1**

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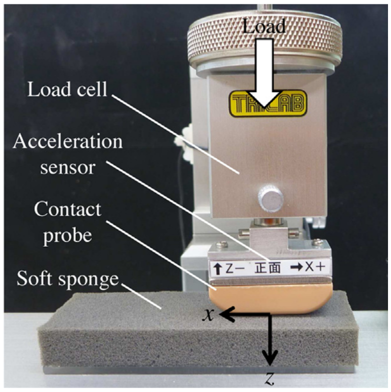

Fig. 1. Friction evaluation system.

to **5**, the density decreased from 75 kg m^{-3} to 30 kg m^{-3} (from 70 to 8 cells per 25 mm) while the ten-point average roughness (R_{Zjis}) increased from 0.62 mm to 2.67 mm. Tensile strength, elongation, and Young's modulus also decreased with increasing material number. The shape and physical factors other than R_{Zjis} were taken from the technical data of INOAC Co., while R_{Zjis} was measured from SEM images according to JISB0601. The R_{Zjis}, which was defined as the average of the differences between the five maximum and minimum surface heights in the reference length (l), was calculated from the following formula (1):

$$R_{Zjis} = \frac{|Y_{p1} + Y_{p2} + \cdots + Y_{p5}| + |Y_{v1} + Y_{v2} + \cdots + Y_{v5}|}{5}, \quad (1)$$

where Y_{pn} (Y_{vn}) represents the height of the n-th from the highest (deepest) peak. In this study, the reference length l was 14.8 mm. We chose five polyester urethane sponges with a variety of cell sizes. Although the size changed systematically, it was impossible to change the cell number independently; with increasing cell number, the density of sponge increased while surface roughness R_{Zjis} decreased. Therefore, we analyzed the effects of these geometrical parameters using multiple correlation analysis.

2.2. Tactile evaluation

Tactile evaluations were performed on twenty subjects: ten male students and ten female students with ages ranging from 18 to 24 years. The evaluations were performed in a quiet room at 25 ± 3 °C after the subjects washed both hands with a commercial liquid hand soap. The relative humidity was 50 ± 2%. The subjects held the contact with the sponge surface with their forefinger for 10 s. After touching, they rubbed the sponges from side to side for 30 s. The subjects were not given any instructions on how to touch and rub the sponges; rather, they were allowed to use the level of force they deemed necessary to evaluate the tactile texture of the sponges. After they rubbed the sponges, the subjects completed questionnaires about the tactile sensations. The first and second questions were "Is the tactile texture of this sample pleasant?" and "Why did you think so?" respectively. The tactile evaluations were based on a seven-point scale (1: unpleasant; 7: pleasant). In the present study, the subjects rated only pleasantness because pleasantness is the most important feeling for the application of the soft sponges in many products, including clothes, cosmetics, and automobile materials. The samples were evaluated in a random order to eliminate order effects, and the subjects touched the samples through a blackout curtain. The purpose of the tests was revealed to the subjects before the evaluations, and the subjects made the decision on whether or not to join the evaluation. Each subject participated in one tactile evaluation trial. All evaluations were conducted according to the principles expressed in the Declaration of Helsinki. The responsible party at Yamagata University confirmed that the ethics and safety of the present test were acceptable.

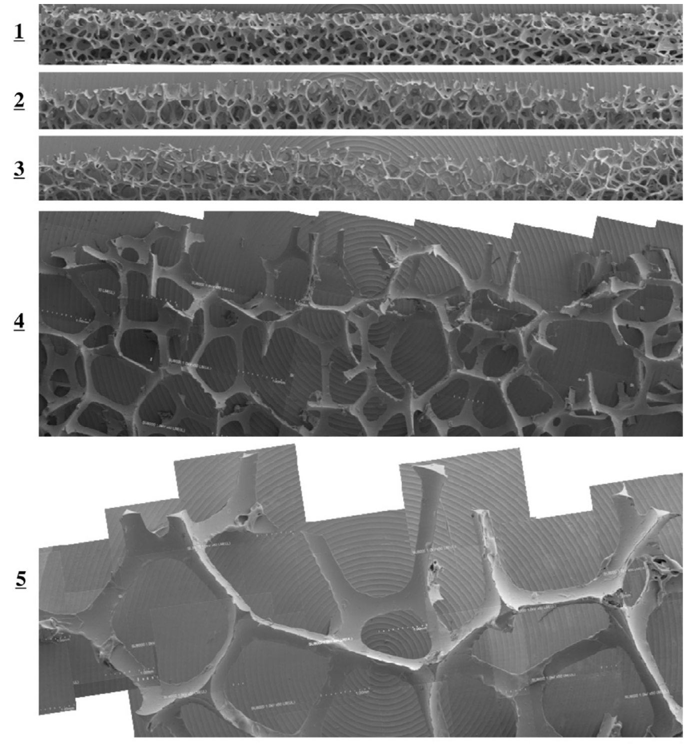

Fig. 2. SEM images of the soft sponges. Scale bar = 1 mm.

2.3. Friction evaluation

Friction measurements were performed using a Tribo master TL201Ts friction evaluation meter (Trinity Lab INC, Tokyo, Japan). The specifications of the apparatus were as follows: measurement range = 0.098–19.6 N; vertical force = 0.098–4.9 N; sliding speed = 0.1–100 mm s^{-1}; sliding distance = 1–100 mm; and an AC servomotor driving motor. Frictional force was evaluated by rubbing soft sponges with dimensions of 80 mm × 30 mm × 10 mm with the polyurethane contact probe, which reflected the geometry and mechanical properties of real human fingers [16]. The probe surface contained 29 grooves with depths of 0.15 mm carved at 0.5-mm intervals (Fig. S1a and c). This geometry is similar to human epidermal ridges, which have depths and widths of 0.11 ± 0.03 mm and 0.46 ± 0.15 mm, respectively [20]. The Young's modulus of the contact probe, which was measured using a ZTA20 N force gauge with an EMX-1000 N test stand (Imada, Aichi, Japan), was 0.64 ± 0.02 MPa. Some solid materials (glass, copper, acrylic acid, velvet, cypress, paper and silk) were rubbed by the contact probe to determine the similarity of the friction properties in the contact probe and the real human finger. The kinetic friction coefficients may be comparable between the actual human finger and the probe in a dry condition. However, the dynamics of friction between the probe and sponges, which is determined by the static and kinetic coefficients, are unclear now. In addition, under wet conditions, it was difficult to mimic the friction phenomena on finger surfaces of the contact probe, because the elasticity and friction properties of human skin change drastically by swelling [21]. Further evaluations are required to determine the final judgment for the similarity.

Friction was also evaluated when soft sponges **1**, **3**, and **5** were rubbed by the contact probe with a flat surface made of polyurethane (Fig. S1b); the friction conditions were as follows: width of sliding = 30 mm; the number of reciprocates = 3; sliding