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Softness Evaluation of Silicone Elastomers

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We evaluated the softness of various silicone elastomers installed on a tactile evaluation system. The softness of the elastomers was reflected by the vertical force when subjects pushed the elastomers with their fingers. The moving behavior depended on the elastic properties of the contacted objects; namely, a pushing pattern and a sliding pattern were observed for the soft and hard elastomers, respectively.

Many industrial products are made of soft elastomers because softness improves safety, usability, and familiarity of the products. Considering the many types of soft elastomers, silicone elastomers show the advantages of thermostability, light stability, and solvent resistance.[1–4] Softness is one of the most important tactile sensations because it is correlated with human preferences or emotions.[5,6] Human subjects evaluate softness on the basis of the relationship between pushing distance and force in the recognition process.[7] Bicchi et al. focused on the importance of the rate of spread of the contact area between the finger and the specimen.[8] We have studied the effects of frictional stimuli on tactile sensations to determine the identification mechanism of some materials by touch.[9–13] During the evaluation process, the friction force on the fingertips and movement velocity were evaluated by a friction meter and a high-speed camera, respectively (Figure 1). To illustrate the mechanisms of tactile recognition, not only forces on the skin but also tactile behavior or movement velocity must be evaluated because tactile sense depends on both these factors.[13] In this study, we evaluated and observed the tactile feel, applied forces on human skin, and moving behaviors when 30 subjects touched four silicone elastomers installed on the tactile evaluation system.[14–17]

Figure 2 shows the sensory score of the four materials. The softness was rated on a seven-point scale in which a score of 1 meant "very soft," whereas a score of 7 meant "very hard." The score of the elastomer with an elastic modulus of 288 N mm^{-2} was 2.5 ± 1.0, which was the lowest, whereas that with 10500 N mm^{-2} was 5.9 ± 1.0, which was the highest. Confidence intervals of >95% were found between the scores of the four elastomers in t-tests. These results show that the subjects can discriminate between the different elastomers on the basis of their softness.

We evaluated the vertical force on the finger pad when subjects touched the silicone elastomers. A typical profile of the force is shown in an inset of Figure 3. In Figure 3, the force is the average of all local maximum values (F_v) when the thirty subjects touched four elastomers for 30 s each. The force was 1.6 ± 1.1 N for the elastomer with 288 N mm^{-2}, and it was 2.5 ± 1.8 N for the one with 10500 N mm^{-2}. Confidence intervals between the scores of the four elastomers were

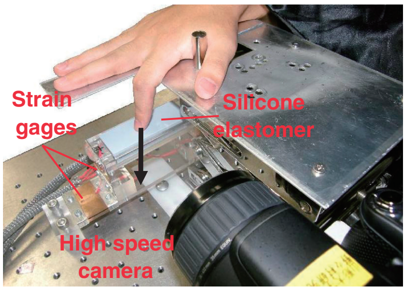

Figure 1. A photograph of the tactile evaluation system.

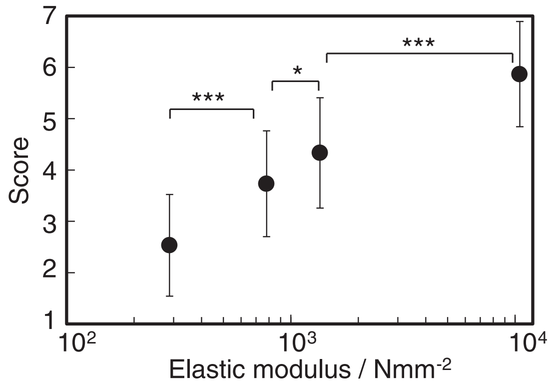

Figure 2. Relationship between elastic modulus of substrates and score of soft/hard feels. ***: significant in 1% level, *: significant on 5% level.

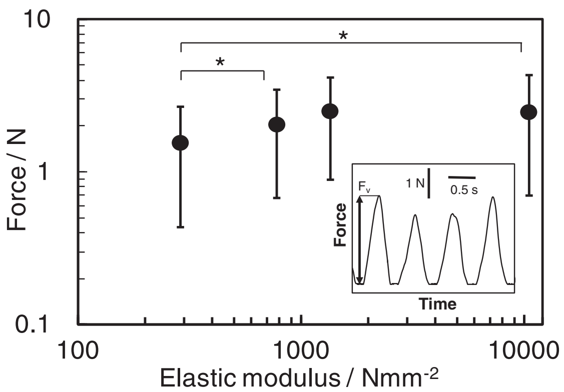

Figure 3. Relationship between elastic modulus of substrates and vertical forces. *: significant in 5% level. An inset is vertical force as a function of time.

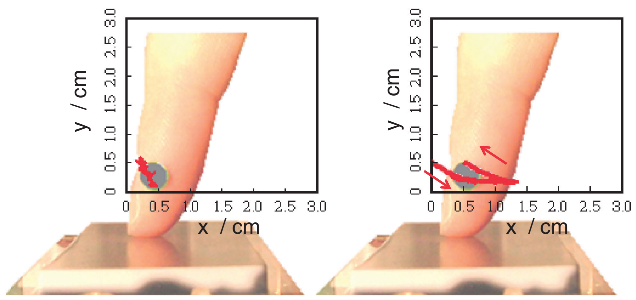

Figure 4. Movement of a finger when a subject contacts with a soft elastomer (a) and a hard elastomer (b).

determined in t-tests. These results indicate that the subjects push strongly when the elastomers are hard. On the other hand, the horizontal force did not change with the elastic modulus: 0.6 ± 0.3 N for the elastomer with 288 N mm^{-2} and 0.6 ± 0.2 N for the one with 10500 N mm^{-2}. These results are consistent with some previous studies. For example, Friedman et al. reported that subjects pushed with weaker force when the objects were softer.[18]

Video images of subjects touching silicone elastomers were obtained with a high-speed camera. The subjects moved their fingers up and down. The number of contacts was about 0.7 s^{-1}, which was independent of the degree of elasticity of the four elastomers. As shown in Figure 4, the moving profiles when the subjects touched soft elastomers were different from those when they touched hard ones. The pushing pattern in which the fingers simply moved up and down was observed for soft elastomers, whereas the sliding pattern in which the fingers slid across the elastomer surface was found for hard elastomers. Furthermore, the rate of the sliding pattern was larger when the elastomer was harder: 40%, 37%, 55%, and 80% for elastomers with 288, 780, 1350, and 10500 N mm^{-2}, respectively. These results suggest that the moving behavior in contact processes depends on the elastic properties of the elastomers. The surface of hard silicone elastomers is slippery owing to their low surface energy. On the other hand, with the soft materials, the sliding behavior is inhibited because the finger is arrested by the projections induced by the deformation of the elastic materials. These moving behaviors can change tactile sensations when touching solid materials because not only mechanical stimuli on human skin but also motion stimuli on muscles are the essential factors contributing to the overall feel.[19] A quantitative analysis of the relationships between these factors will be studied in the near future. These findings will be useful for the design of silicone elastomers for industrial materials.

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14 *Materials*. Tactile evaluations were achieved for four silicone elastomers. Their composition and elasticity are as follows: No. 1: VP7550/SLJ3266/CATALYST 4T (100:7:3, Shin-Etsu Chemical Co., Ltd., Tokyo, Japan), elastic modulus = 288 N mm^{-2}; No. 2: X-32-2428-4/CX-32-2428-4 (100:5, Wacker Asahikasei Silicone Co., Tokyo, Japan), 780 N mm^{-2}; No. 3: KE-1308/CAT-1300L-4 (100:6, Wacker Asahikasei Silicone Co., Tokyo, Japan), 1350 N mm^{-2}; No. 4: KE-26/CAT-RM/CAT-24 (100:1:4.5100:6, Wacker Asahikasei Silicone Co., Tokyo, Japan), 10500 N mm^{-2}. The dimensions of the materials were 30 mm × 80 mm.
15 *Tactile evaluations*. The experiment was approved by the Ethics Committee of the Faculty of Engineering, Yamagata University. All evaluations were conducted according to the principles expressed in the Declaration of Helsinki. The subjects touched silicone elastomers installed on a tactile evaluation system, and the hands of the subjects were fixed as shown in Figure 1. The height of the table on which the hands rested above the elastomer surface was fixed at 3 mm shorter than the length from the fingertip to the second joint. After a 30 s time period allotted for touching the materials, the subjects completed questionnaires about the softness of each object. The softness was rated on a seven-point scale, where a score of 1 meant "very soft," and a score of 7 meant "very hard." All evaluations were carried out by a blind method; that is, the subjects did not know the composition of the materials. The subjects included 30 students, 18–24 years of age. Half of the students were male and half female. They all touched the materials using the forefingers of the dominant hand. The evaluations were carried out in a quiet room at 298 K after the subjects had washed both hands with 6 mL of liquid hand soap and running water. Before the evaluations, their hands were wiped using dry paper towels. The order of the materials was random to eliminate order effects. The contents of the tests were announced previously. The subjects decided for themselves whether they would join our evaluation test.
16 *Fingertip movement analysis*. The high-speed images were taken using an EX-F1 high-speed video camera (Casio, Tokyo, Japan) with a frame rate of 600 frames per second. A black dot, 5 mm in diameter, was put at the side of the nail of the forefinger to follow the movement. The skin surfaces were illuminated with a video light VL-G151 (lamp: halogen 150 W, color temperature: 3075 K, LPL Co., Tokyo, Japan). Finger movements were analyzed using the two-dimensional-movement-analysis software, Move-tr/2D 7.0 (Library Co., Tokyo, Japan), by the center of gravity method.
17 *Mechanical evaluation*. We used a system that simultaneously evaluated tactile sensations and mechanical stimuli. This device measured frictional and vertical forces using strain gauges on two plate springs, as shown in Figure 1. The device's time resolution was 1 ms. The strain gauges on the two plate springs showed linearity and reproducibility with an error under 0.20 or 0.08 N for the friction force and vertical force, respectively. The maximum measurable load of the device was 5 N.
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