Anisotropy in Normal Force and Friction during Active Tracing

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Abstract. This paper investigates differences in normal force for different tracing directions on the basis of friction, taking into account individual differences. The normal force and friction coefficient were measured when sixteen participants naturally traced samples with different friction coefficients in the backward and lateral directions. The results showed that participants applied significantly larger force in the backward direction than in the lateral direction. The coefficient of friction was also significantly higher in the backward direction. In addition, both the normal force and the coefficient of friction varied among individuals. Those with higher coefficients of friction used relatively small normal force, whereas those with lower coefficients of friction tended to have large variance in the normal force.

Keywords: Haptic perception · Friction coefficient · Normal force · Trace direction · Individual difference.

1 Introduction

Haptic perception includes active touch. People adapt their motion spontaneously or consciously according to the information that they derive from the stimuli to improve their performance. For example, people adjust their forces according to the softness of the stimuli [1], and their movement direction according to texture orientation [2]. The characteristics of active touch are useful for the design of objects involving touch and the development of tactile displays. The exerting force is one of the important factors as it influences both tactile perception and performance.

Katircilar et al. [3] reported that participants used higher velocities and greater forces in the anteroposterior orientation than in the lateral orientation. Their samples were rectangular ridge-groove textures, which were always traced orthogonal to the texture. They speculated participants applied more force in the anteroposterior direction to improve their performance. Tanaka et al. [4] reported that humans use smaller forces for rough textures than smooth textures when touching without any perceptual objective.

When investigating exploratory movements, fricton is also important. It has been reported that the friction coefficient is relevant to roughness perceptions as well as surface geometry [5]. However, when the surface geometry changes, the friction coefficient also changes. Because of this complexity there have been only few studies on surface geometry and friction independently. The coefficient of skin friction varies with the normal force. Previous studies have shown that the coefficient of friction decreases with increasing normal force for friction between skin and glasses [6]. Also, the friction coefficient of the fingertip differs depending on the direction in which the fingertip is moved [7].

Moreover, there are individual differences in tactile perceptions and movements. Natsume et al. [8] demonstrated individual differences in skin vibration and contact force when tracing various textures. Thus, in this paper, we will investigate the characteristics of motion in the tracing direction including the perspective of individual differences. We will use glasses as samples with very similar roughness but different frictions.

2 Methods

2.1 Participants

Sixteen healthy adult persons (14 male and 2 female, age range 18–66 years) participated in the experiment. 15 of them were strongly righthanded and one was strongly left-handed according to Coren's test [9]. They used the index finger of their dominant hand in the experiment and were naive about the purpose of the experiment. All participants gave their written informed consent before participating in the experiment and they were paid for their time. The experiment was approved by the Ethics Committee of Nagoya Institute of Technology.

2.2 Stimuli

This study focuses on the effects of friction on motion characteristics. However, different materials differ not only in friction, but also in roughness. We used four smooth glasses, which have very small roughness and different friction. Fig. 1. shows the photograph of the four samples along with the coefficient of friction and the arithmetic mean roughness measured with a commercially available tribometer and roughness meter, respectively. A pilot experiment demonstrated that skin vibration, which was measured with an accelerometer worn on the fingertip when tracing the sample, was so small that it was difficult to be used to discriminate the samples.

2.3 Experimental setup and procedure

Fig. 2. shows the experimental setup. Each sample was placed on an acrylic plate on top of an 6-axis force sensor (ATI Gamma). We measured horizontal and normal forces with this sensor. To prevent the presented sample from slipping, a non-slip leather sheet was attached to the plate.

Participants were instructed to stroke in two different directions (backward and lateral), as shown in Fig. 2. They only traced once in each trial. In order to trace the same length in each direction, the glass was rotated before a trial if the length of samples differed from the others. Participants were not given any specific objectives.

Two directions in each glass were set as one block. Both scanning directions were mixed and tested five times within a block in randomized order and the order of four blocks was randomized over all participants. The four stimuli were tested in separate blocks. Participants performed 40 trials in total (2 directions, 5 repetitions, 4 stimuli). At the beginning of each block, the participant's hand and the glass were wiped with clean papers. During the experiment, the participants wore a headphone so that they could not hear the sound of touching the stimuli.

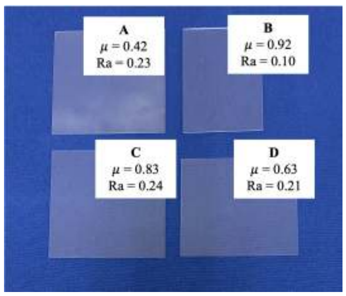

Fig. 1. Stimuli used in the experiment. μ means coefficient of friction. Ra [μm] means arithmetic mean roughness.

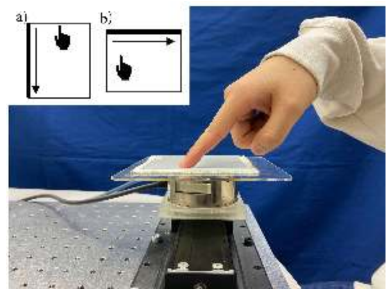

Fig. 2. Experimental setup and illustration of the stroke directions. a) Backward configuration. b) Lateral configuration.

2.4 Analysis

A 10 Hz low-pass filter was applied to the output of the 6-axis force sensor for smoothing. The center 0.3 s of each trace was extracted, and the normal force and friction coefficient were obtained from the force components of the three axes. The friction coefficient f_{rc} was calculated by dividing the average friction force that was calculated from the horizontal forces F_x and F_y ($F_r = \sqrt{F_x{}^2 + F_y{}^2}$) by the average normal force F_z ($f_{rc} = \bar{F}_r / \bar{F}_z$). The force and coefficient of friction for each participant were calculated for each trace and then averaged over the five traces. A two-way repeated measures ANOVA was conducted to compare the normal forces on the four samples and on the backward and lateral tracing directions. A similar analysis was conducted for the coefficients of friction. Since both parameters did not follow a normal distribution, we used the aligned rank transform [10] for non-parametric factorial analyses before the ANOVA. If there was a significant difference, a Wilcoxon signed-rank sum test was conducted with Bonferroni correction for multiple comparisons. In this paper, the significance level was set to $\alpha = 0.05$.

3 Results

Fig. 3. shows the experimental results. Box plots with the data of each participant are shown for the normal force and the friction coefficient. The ANOVA showed a significant difference between the force in the backward and lateral directions ($F_{1,15} = 6.57$, $p = 2.17 \times 10^{-2}$), indicating that the force was larger in the backward direction than

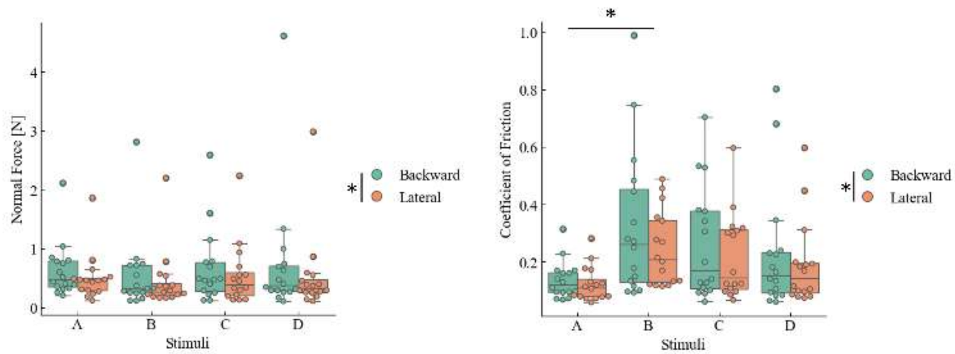

Fig. 3. Results of normal force and friction coefficient. Box plots for all participants are shown on each stimulus. The points show the values for each participant. * denotes $p < 0.05$.

in the lateral direction. There were no significant differences between the samples. The ANOVA showed a significant difference between the coefficient of friction in the backward and lateral directions ($F_{1,15} = 5.48$, $p = 3.36 \times 10^{-2}$), indicating that the coefficient of friction was larger in the backward direction than in the lateral direction. The ANOVA also showed a significant difference between samples ($F_{3,45} = 14.3$, $p = 1.10 \times 10^{-6}$) and, the Wilcoxon signed-rank sum test showed that there was a significant difference between Samples A and B ($w = 58$, $p = 1.20 \times 10^{-2}$).

The coefficient of friction varies with the sample while the normal force does not vary significantly among the samples.

Fig. 4. shows the mean of normal forces and coefficient of friction averaged over the four samples for all participants in different directions. The tracing direction influenced both the normal force and the friction coefficient. Additionally, participants exhibited varying friction coefficients and utilize different normal forces.

4 Discussion

Different coefficients of friction and normal forces were observed for each individual. Participants using small normal forces had large friction coefficients; moreover, their results showed large differences between the friction coefficients in backward and lateral directions. In contrast, those participants using relatively large normal forces had small friction coefficients and they showed large individual differences in the normal force.

The general understanding on adhesive friction is that the friction coefficient of a human finger is proportional to the normal force to the $-1/3$ power [6]. An important finding of this study is that for individuals the dependence on motion direction is inconsistent with the theoretical analysis. The results showed that backward tracing induced significantly higher normal force than lateral tracing when using natural touch. According to the model, the coefficient of friction ought to be lower in the backward direction than in the lateral direction. However, the coefficient of friction remained significantly higher for backward tracing than lateral tracing. The initial state at the beginning of the tracing was the same in the backward and the lateral directions. Therefore, this result indicates that during active tracing, there is a difference in the physical characteristics

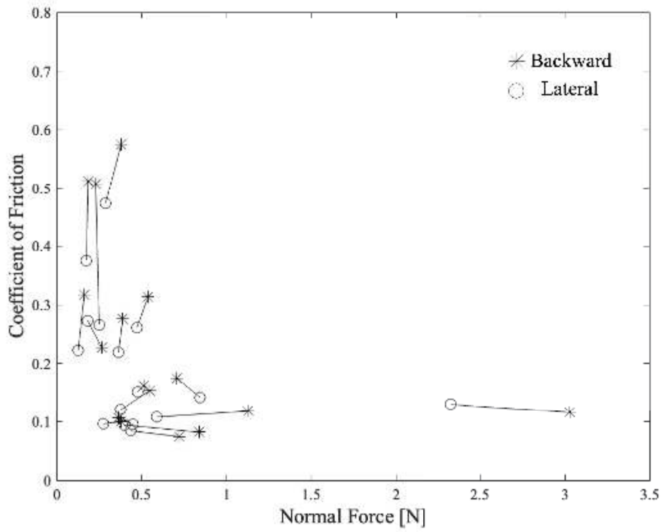

Fig. 4. Distribution of coefficient of friction and normal forces for all participants in lateral and backward directions.

relevant to motion between the backward and the lateral directions. Differences in shear force stiffness were reported between the backward and the lateral direction [7]. Also, the dynamic contact area changes during active touch [11].

Several factors may have caused the difference in normal forces. From a strategic aspect, we speculate that participants attempted to trace more easily. One possibility is the influence of muscle activity. Muscle stiffness might differ between backward and lateral directions, thus causing differences in movement parameters. Another possibility is biomechanical asymmetry between backward and lateral movements of bent finger.

The results demonstrated that participants subconsciously use different normal forces depending on the tracing direction, causing differences in the friction coefficient according to the tracing direction. Additionally it was found that while participants with low friction coefficients use diverse forces, participants with high friction coefficients use relatively small normal forces. In our future work, we will investigate the relationship between normal force and fiction coefficient in more detail.

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References

1. Kaim, L., Drewing, K.: Exploratory strategies in haptic softness discrimination are tuned to achieve high levels of task performance. IEEE Transactions on Haptics, **4**(4), 242–252, (2011).
2. Lezkan, A., Drewing, K.: Interdependences between finger movement direction and haptic perception of oriented textures. PLoS ONE, **13**(12), e0208988, (2018).

3. Katircilar, D., Drewing, K.: The Effects of Movement Direction and Glove on Spatial Frequency Discrimination in Oriented Textures. In: Proceedings of 2023 IEEE World Haptics Conference, pp.313–318, Netherlands (2023).
4. Tanaka, Y., Bergmann Tiest, W. M., Kappers, A. M. L., Sano, A.: Contact force and scanning velocity during active roughness perception. PLoS ONE, **9**(3), e93363, (2014).
5. Smith, A. M., Chapman, C. E., Deslandes, M., Langlais, J. S., Thibodeau, M.P.: Role of friction and tangential force variation in the subjective scaling of tactile roughness. Experimental brain research, **144**(2), 211–223, (2002).
6. Koudine, A. A., Barquins, M., Anthoine, P., Aubert,L., Leveque, J. L.: Frictional properties of skin: proposal of a new approach. International Journal of Cosmetic Science, **22**(1), 11–20, (2000).
7. Nakazawa, N., Ikeura, R., Inooka, H.: Characteristics of human fingertips in the shearing direction. Biological Cybernetics, **82**(3), 207–214, (2000).
8. Natsume, M., Tanaka, Y., Bergmann Tiest, W. M., Kappers, A. M. L.: Skin Vibration and Contact Force in Active Perception for Roughness Ratings. In: Proceedings of IEEE International Symposium on Robot and Human Interactive Communication, pp.1479–1484, Lisbon (2017).
9. Coren, S.: The left-hander syndrome. Vintage Books, New York (1993).
10. Wobbrock, J. O., Findlater, L., Gergle, D., Higgins J.: The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only ANOVA Procedures. In: Proceedings of the International Conference on Human Factors in Computing Systems, pp.143–146, CHI (2011).
11. Liu, X., Carre, M. J., Zhang, Q., Lu, Z., Matcher, S. J., Lewis, R.: Measuring contact area in a sliding human finger pad contact, Skin Research and Technology, **24**(1), 31–44, (2018).