2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Haptic Cue of Forces on Tools: Investigation of Multi-point Cutaneous Activity on Skin using Suction Pressure Stimuli

Lope Ben Porquis, Daiki Maemori, Naohisa Nagaya, Masashi Konyo, and Satoshi Tadokoro

Abstract— **This paper presents an initial data that could show a possible contribution of mechanoreceptor activity to the perception of forces applied on grasped objects. Here, we obtained detailed psychophysical characteristics of perceived force-magnitude in multiple degrees of freedom (MDOF) using multi–point suction pressure stimuli. To obtain such data, we developed a multi–point stimulation method that can represent MDOF perceived force on a tool. We characterized the perceived force response of human subjects to suction pressure stimuli through psychophysical experiments. Moreover, we analyzed the strain energy density (SED) on the finger pads considering the force applied through finite element simulation. The results of the psychophysical experiments showed that multi-point stimulation method is effective for evoking MDOF perceived force on a tool. Interestingly, we found that the results of the finite element analysis agree with those of the psychophysical data. Therefore, we have verified that it is possible to use multi-point suction pressure stimulation for representing perceived force on objects held in a hand. In addition, a preliminary insight into the role of SED for perceiving force on tools is provided.**

I. INTRODUCTION

Humans have the unique skill of perceiving forces applied on grasped objects. We can intuitively recognize the magnitude and direction of the forces applied on objects we hold. For example, if someone gently pushes the tip of a pen we are holding, we can easily recognize the direction of this force even when blindfolded. Another interesting phenomenon is that when using tools to manipulate objects, we occasionally feel those forces interacting with the tool as if they were acting directly on our fingers. It seems that we transparently perceive these indirect forces through our haptic sense. Although we inherently benefit from this ability, there is more for us to learn on the mechanisms underlying this skill.

One of the main challenges in the aforementioned concepts is the multi–contact nature of grasping. On a grasped object, we can physically observe that not all surfaces of the glabrous skin are in contact with the object. There are several discrete contact patterns depending on the type of grasp [1], [2]. Intuitively, these contact patterns or contact areas should be the main source of haptic sensory information for perceiving the force applied on the object. Furthermore, we suspect that this is true of not only forces but, perhaps, other quantities as well. We expect that the skin at these contact areas deforms intricately as forces interact with the grasped object. Measuring these deformations in vivo is very challenging. Data from typical pressure or force-sensor measurements at these contact areas will not suffice for understanding the mechanisms of such deformation and its contribution to perception.

The authors are with the Graduate School of Information Sciences, Tohoku University, 6-6-1, Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi, 980-8579, Japan.{lopeben, maemori, nagaya, konyo, tadokoro}@rm.is.tohoku.ac.jp

In literature, there are basic studies that have served as important foundations of this work. For example, it was already known that our cutaneous senses could contribute to force perception [3], [4]. This encouraged us to further investigate the contribution of the cutaneous sense in perceiving the forces acting on grasped objects. An improved aspect of this study is that we considered the contribution of multiple skin contacts to force perception. Earlier studies had established that the Slowly Adapting Type I cutaneous receptors, i.e., Merkel Disks, respond with strain energy density (SED) [5], [6], [7]. We are interested in this response because SED is produced during skin deformation. This would hopefully lead to the relationship between SED and the forces perceived on grasped objects. Furthermore, SED is easily induced in the skin by tactile stimuli such as suction pressure [8]. Suction pressure is an effective way of producing high SED on the skin without the use of complex mechanical systems in the tactile interface. Our preliminary studies, [9] and [10], have initially shown that suction pressure stimuli can be used for representing the forces applied on grasped objects. However, a detailed relationship between perceived force and suction pressure was not elucidated in those studies.

In this study, we carried out the preliminary steps necessary for confirming the relation of SED to the perception of forces on grasped objects. We elucidated the connection between perceived external forces and suction pressure stimuli through psychophysical experiments. Likewise, we performed a follow-up analysis using finite element simulation to obtain the connection between SED and force applied on a grasped object. The psychophysical experiments were carried out for measuring the effect of suction pressure on force perception. Given with the psychophysical data, we can then compare it with the physical quantities, such as SED, in the skin. Herein, we propose that cutaneous receptor activity is a contributing factor in the perception of forces acting on grasped objects. However, providing actual evidence to support the proposal may seem too difficult to achieve. Thus, we carried out a mechanical analysis to approximate a solution for supporting the proposal.

Included in this paper is a method for representing perceived external forces in multiple degrees of freedom (DOF) by suction stimulation. We developed this method as an alternative to conventional force feedback stimulation. Currently, we studied force perception in three translational DOFs (F_z, F_y, F_x). Although it is possible to display representations for rotational DOFs, we intentional left these as a continuation for this study. In addition, we explore human performance in distinguishing the magnitudes and directions of simultaneously presented suction pressure stimuli for representing external force. The current approach differs from our previous studies, [9] and [10], where only the magnitude of the perceived force was characterized along one

978-1-4673-6357-0/13/$31.00 ©2013 IEEE

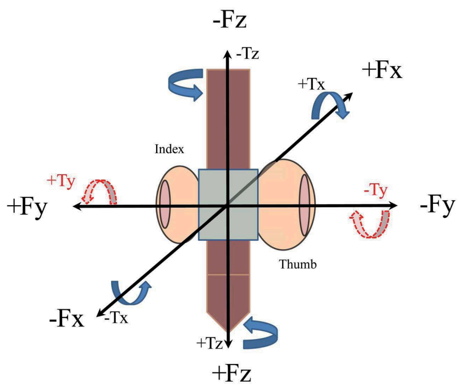


Fig. 1. Hypothetical representations of external force by suction pressure stimuli.

translational direction and one rotational direction. Through this setup, we could provide additional support to the concept of multi-point suction pressure stimulation for representing perceived forces in multiple DOF.

We obtained significant psychophysical data from five subjects verified by common statistical tests. From the way we conducted our experiments, we found that the tendency of perceived force-magnitude depends on the direction in which a force is exerted on the object. In particular, the perceived force-magnitude for laterally exerted forces follows a non-linear tendency, while that for normally exerted forces follows a linear tendency. Interestingly, the simulated data from the finite element analysis (FEA) follows with the experimental data. This leads us to speculate that cutaneous receptor activity, thus SED, possibly contributes to the perception of forces applied on grasped objects.

The following section describes the hypothesis of stimuli presentation for representing multiple DOF external forces. The hypothesis was based on an intuitive model, which has been used in previous studies. The section is followed by a brief description of the tactile interface that was used in the experiments. The design and implementation of the device is described in the same section. Next, the sections describing the psychophysical experiments and the mechanical analysis are presented. The associated results are included within the respective sections. Then, a general discussion is presented. The paper ends with a section presenting the conclusion of this study.

II. HYPOTHESIS OF MDOF PSEUDO-FORCE FEEDBACK

The hypothesis for representing MDOF pseudo-force feedback is based on a simple grasp model. In a precision grip, two finger pads are confronting each other with an object in between them, as shown in Fig. 1. When external forces are exerted on the object, the contact pads are subjected to deformation which affects the strain distribution and strain energy density on the skin. Hypothetically, changes of strain distribution and amount of strain energy density are possible cues for perceiving force magnitude and direction on the grasped object. To establish a reference for discussion, we consider the space between confronting fingers as the origin of a 3D–coordinate system. As an initial consideration, we treated that the external forces are acting only at the translational axis of the 3D–coordinate system.

A. Representing perceived force F_z along the z–axis

Granting an external force (F_z) is exerted along the z–axis (Fig. 1), the skin on the finger pads are subjected to drag because of friction on the contacts. For instance, if an upward force is exerted at the tip of the tool, the finger pads are dragged upwards. The effect of drag stretches the skin on the lower half of the finger pads while inducing compression on the upper half. Apparently, it seems easier to perceived the strain on the stretched regions compared to the compressed regions. This a simple subjective confirmation was observed by applying the conditions mentioned above. Assuming that the subjective inference is correct, the stimuli is reproduced by orienting the gradient on both fingers in–phase. To produce an upward external force, high suction pressure is presented on the lower half of the finger pads while low suction pressure is presented at the upper half. The opposite direction can be achieved by reversing the corresponding positions of the stimuli. The perceptual effect of this method is to be confirmed in this paper.

B. Representing perceived force F_y along the y–axis

When an external force (F_y) is applied on the tool along the y–axis in such way that moments are prevented. For example an external force directed toward the $+F_y$ and passing through the origin. In this case the index finger will experience greater strain than the thumb. To reconstruct an equivalent tactile stimuli for this scenario, we can apply equal pressure initially at the finger pads and then slowly increase the pressure at the index finger while simultaneously decreasing the pressure at the thumb. This is the principle behind differential tactile stimulation that we had studied earlier [10]. Intuitively, either force directions along the y–axis can be represented by changing the order of differential stimuli. This is the easiest among the methods for representing an external force.

C. Representing perceived force F_x along the x–axis

The remaining DOF (F_x) is basically an innovation from (F_z). Obviously, the method in presenting (F_z) requires the upper and lower halves of the finger pad, that is the stimuli is oriented vertically. This means that the contact area was divided at the horizontal. If the contact areas are divided vertically, then we can obtain a distal and proximal halves. Using this horizontal orientation, the stimuli for representing F_x can be reconstructed similarly to what we did for the z–axis. Implementing this method is easily done by providing the interface with several chambers.

III. TACTILE INTERFACE DESIGN

A. Display Components and Internal Structure

The tactile display is composed of three plastic components, illustrated in Fig. 2. The *cap* is used to plug one opening of the chamber. The middle section is the *main chamber*. Its internal structure contains eight hollow quadrants that was carved from a solid block of chemical wood. Each quadrant holds an air capacity of about 400 mm^3. The walls of these chambers are drilled with holes to vent suction pressure on the fingers. The last component is the *base* that serves as a rigid support for the hoses. The hoses are connected to each chamber, in which suction pressure can be controlled independently. These parts are sealed permanently once assembled.

B. Contact Pads and Suction Holes

The grip area of the tactile interface has a contact padding made of silicone rubber material to prevent air leak. This material has a tensile modulus of about 1.44 MPa. The size of the contact pads are different for each finger as shown in Fig. 3. This is to maintain the natural order of contact sizes. The thumb pad was made larger by a factor of 1.1 in diameter. It has a size of about 14 mm in diameter. For this diameter, the average size of the thumb is enough to occupy the contact pad, leanly covering all the holes .

The suction holes has no particular uniformity in terms of size and spacing, but some aspects were adopted from earlier studies. For example, the recommended hole size according to the study of Makino *et al.* was about 1 – 2 mm in diameter. At 1 mm diameter it was shown that contact sensation can be perceived 90% of the time. At 2 mm diameter, they found that it was the optimal value to induce positive pressure sensation [8]. For the hole spacing, the adopted criterion was to follow the two–point discrimination threshold at the fingertips [11], [12], which is about 2 – 3 mm. However, strictly adhering to uniformity would result to a fewer holes installed in the constrained contact space. Thus, the adopted method is to allocate the holes within the range suggested from the previous studies.

The result is that the hole pattern and the total number of holes are different for each contact (Fig. 3). The important issue here is not on the details of hole arrangement, but the perceptual effects induced by this configuration. For this configuration, enough skin strain is produced without inducing pain sensation.

IV. PSYCHOPHYSICAL EXPERIMENT

The relationship between suction pressure and perceived force is an important reference for developing algorithms that controls the amount of stimuli to be presented on the skin. From the relationship, we can reproduce a representation of perceived force by controlling the amount of suction pressure delivered to the skin.

This experiment provides the mapping between perceived force and suction pressure. We used the method of adjustment for measuring the exerted force based from the perceived magnitude of suction pressure.

A. Method

1) Subjects: Five university students participated in this study. They are all naive to the purpose of the experiment. All of them are right–handed by an online handedness test [13]. None of them were known to have medical conditions that would affect the outcome of the experiment.

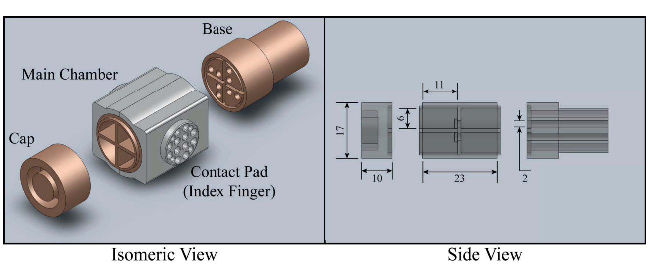


Fig. 2. The sections (*left*) and the internal structure (*right*) of the tactile display. All dimensions in the figure are in millimeters.

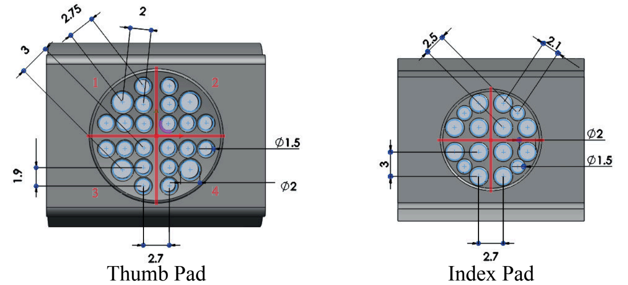


Fig. 3. The sizes and distribution of holes on the silicone rubber pads. All dimensions in the figure are in millimeters.

2) Experiment Apparatus: The developed tactile display was installed on a plastic frame. The frame serves as a constraint to restrict the movement of the display. A 6-axis force and torque sensor (TH0004, Bl AutoTec, Japan) was coupled to the frame and then attached to a rigid wall. The apparatus, shown in Fig. 4, can be configured in three modes. Each configuration corresponds to the DOF under evaluation.

3) Experiment Conditions: Suction pressure magnitude and its location on the contact pads are used as the stimuli for the experiment. The magnitude was used to induce stimulation on the subject at varying amounts to explore the psychophysics of this stimuli in more detail. While the location of the pressure stimuli was used for representing force direction, this is a necessary component for completing the representation of force. Both conditions are presented simultaneously to examine the overall effect of the perceived magnitude and direction of the stimuli on the subject.

Five magnitudes of suction pressure stimuli are used in this experiment. These pressure levels are based from the difference between maximum pressure that is perceivable as push and the minimum detectable suction pressure threshold. The difference is the range of operational pressure level. The range was divided into five levels resulting to these magnitudes; 2, 16, 30, 44, and 58 kPa.

The suction pressure stimuli are applied on the interface in a manner described in Section II. The configurations of stimuli locations are illustrated in Fig. 5. These configurations represent the forces on the x, y, and z–axis. The arrows in the figure represent the direction of perceived external force. Notice in the figure that the stimuli are presented partially on the contact area rather than the gradient or differential presentation. This is to observe if subjects can localize the position of the stimuli and evaluate if they are able to perceive these local stimulations as force directions.

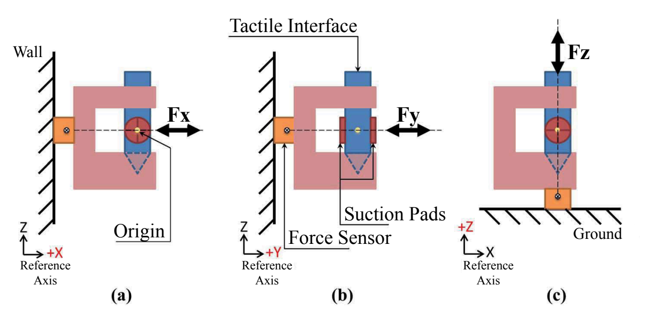


Fig. 4. Configurations of the experiment apparatus; (a) F_x, (b) F_y, and (c) F_z.

During the experiments the grip force was regulated to about 3 N for detecting and perceiving the magnitude and direction of the stimuli. This is necessary not only to prevent pressure leak but gripping force was suspected to affect the perceived magnitude of the stimuli. It is because grip force could affect the stiffness of the skin, making it more difficult for suction pressure stimuli to deform. This could result to lesser differential activity of mechanoreceptors by suction pressure. The value 3 N was a preliminary estimate, but in a follow up experiment [14], it was found that the perception of suction pressure magnitude is not affected by gripping forces between 2 – 4 N.

4) Task and Procedure: The main task of the subject was to sense and register the magnitude of suction pressure stimuli from the experiment apparatus. Then use the perceived stimulus magnitude for representing force. The represented force is conveyed by exerting an equivalent force magnitude on the experiment apparatus. The force is exerted using the right hand of the subject. The subjects' were also instructed to maintain a constant grip during the detection of the stimuli, as well as during exerting the equivalent force on the apparatus.

The subject sat on a chair and grasped the interface with a pinch grip. The subject's arm was rested on an armrest for convenience. The subject was instructed to carefully observe the magnitude and location of suction stimuli on the interface when it is presented. The stimuli is to be presented for three seconds then it is withdrawn. Next, the subject was instructed to exert an equivalent force on the interface based from what was previously perceived. The subject can freely adjust the exerted force by themselves. When the subject considers that the exerted force is the perceived equivalent of suction pressure, he should press a key in the keyboard to log the data. This records the exerted force for 2 seconds. They are told that several stimuli are to be presented in random order and the experiment would last for about 15 to 20 minutes for each DOF. Before starting the experiment, the subject was fitted with visual and aural masks to regulate the contribution of these sensory modalities. After every 10 stimuli presentations, the subject was instructed recalibrate his gripping force on the force sensor. This was conducted because the experiment was lengthy and there is no real time monitoring of grip force. It might be possible that the griping force would drift, which could introduce potential bias.

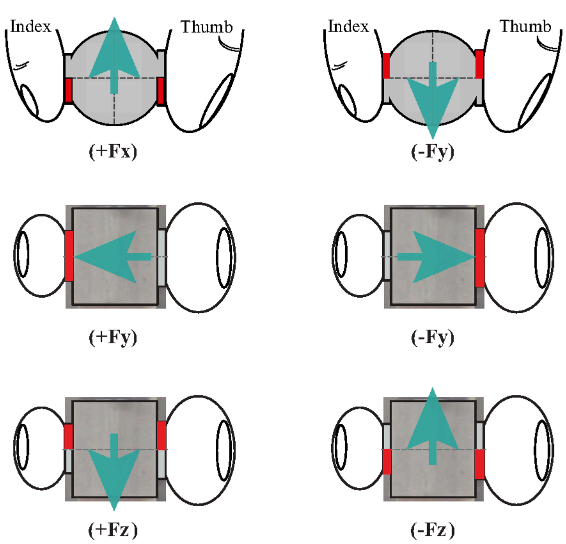


Fig. 5. Representation of force directions by suction pressure stimuli shown in red. These stimuli configurations are expected to evoke its respective representation of external force illustrated by the arrows.

Fifty random stimuli were presented for each force DOF described in the stimuli conditions. Three force DOFs are performed one at a time by the subject. In each DOF, there are two directions of the stimuli, thus there are also two directional response of exerted force. The order of stimuli direction was randomly presented. Five repetitions are assigned for one force direction. This makes ten trials on each force DOF. Also, in each DOF there are five suction pressure magnitudes to be presented. In total, there are 150 trials (2 directions $\times$ 5 repetitions $\times$ 5 pressure magnitudes $\times$ 3 DOFs) executed by each participant.

B. Results

The averaged response of five participants are presented in the following figures, Fig. 6, Fig. 7, Fig. 8. The figures show the averaged exerted force measured on each subject with respect to the level of suction pressure. Each figure represents the relationship between suction pressure and perceived external force. In all three cases, the exerted force–responses appears to increase relative to the perceived magnitude of suction pressure. It was shown that there are two types of correlations between exerted force and suction pressure. For the x and z–axes, the relationship appears to be non–linear. The force exerted on these axes are laterally directed against the interface. The obtained relationship for the y–axis seems to be linear. For this axis, the exerted force was normal against the interface. The curves in the figure were approximated based on the best R^2 quantity.

The horizontal and vertical error bars in the figures represent the variations of suction pressure stimuli and the exerted force of the subjects, respectively. These error bars are based on the standard error of the mean. The results are validated by single factor (exterted force) repeated measure analysis of variance (ANOVA). ANOVA was used to test the means of the exerted force evoked from perceived magnitude of suction pressure. In the z–axis, the ANOVA test showed significant result for Fz+ ($F_{4,20}$=17.01, p<0.00001) and Fz- ($F_{4,20}$=17, p<0.00001). The same ANOVA test showed significant result for forces exerted on the y–axis, Fy+ ($F_{4,20}$=2.88, p<0.05) and Fy- ($F_{4,20}$=3.5, p<0.05). Results are also found to be significant for forces exerted on the

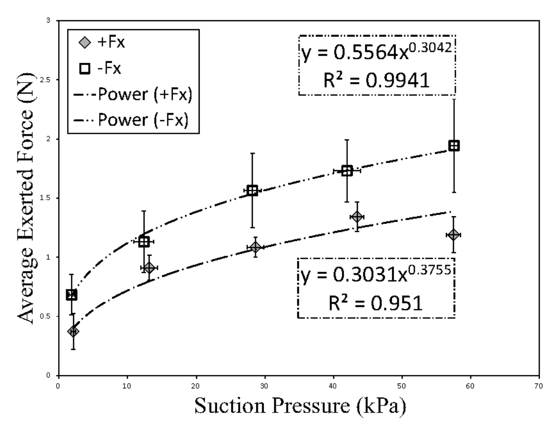


Fig. 6. Estimated tendency of exerted force in the x–axis (n=5).

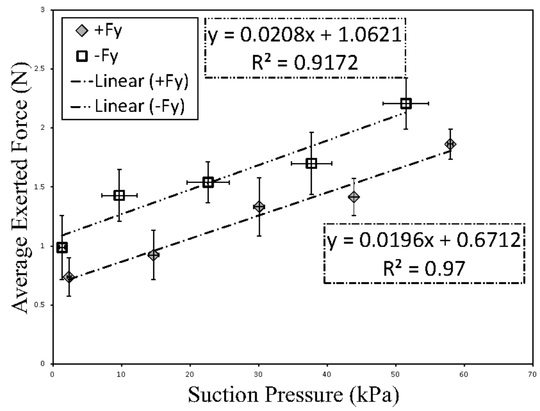


Fig. 7. Estimated tendency of exerted force in the y–axis (n=5).

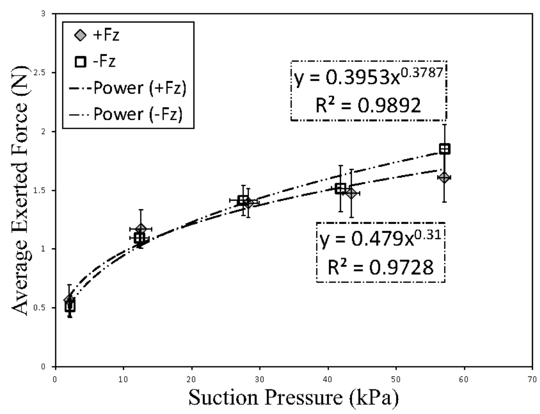


Fig. 8. Estimated tendency of exerted force in the z–axis (n=5).

x–axis; Fx+ ($F_{4,20}$=8.12, p<0.001) and Fx- ($F_{4,20}$=14.1, p<0.001). These data suggests that subjects are able to exert force relative to the perceived magnitude of suction pressure stimuli.

In analyzing the raw answers of each subject, it was observed that some exerted forces did not match to their intended direction. These are falsely recognized stimuli locations which are frequent at low pressure level. Normally at 2 kPa, the pressure is very low such that its magnitude could be perceived insufficiently. This perhaps one of the reasons why perceived force direction is falsely identified. In addition, the device ergonomics could affect the gripping comfort of some participants. The participants could have adjusted their grip posture during the experiments to reduce grip fatigue. Such cases may possibly lead to pressure leak that reduces the effectiveness of the stimuli.

Overall, the false recognitions are minimal. It is about 2% on the average from the total answers. It is maximally observed for subject S1 and S4 with about 3% false recognition from 150 randomly presented stimuli. It was the followed by S2 and S6 which is about 2.6%, then about 1.3% for S5, and 0% for S3.

V. MECHANICAL ANALYSIS ON FINGER DEFORMATION

In the previous section, the experimental results showed that the exerted force on each direction had different correlation tendencies against the perceived magntiude of suction pressure. To investigate the reason where these differences come from, we compare the finger deformation excited by an external force on the grasped pen for each force direction. We focused on the SED inside the finger at the mechanoreceptor layer. We target the layer where Merkel Disks are located because these receptors were known to detect static deformation. It was assumed that suction pressure could generate an equivalent amount of SED similarly for push and pull at this layer [8].

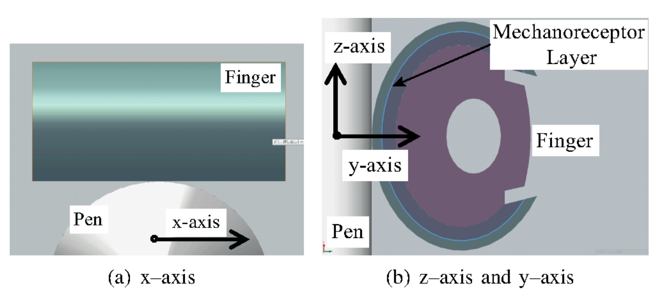
A. Finite Element Model

To compare the differences in SED as stated above, a finite element analysis of the finger pad deformed with a grasped pen is conducted. There are several studies on FEA that uses a precise finger pad model in 2D. Such models have multi-layer structure and uses different material properties that assumes the human skin [6], [7]. On the contrary, we need to evaluate the deformation excited by the external force in three DOFs. In such case, the deformation is strongly affected by the 3D structure of the finger pad. The bone inside the skin also affects the deformation. Individual differences between humans are also known to contribute to the deformation. In this paper, to simplify the finger structure and to discuss the general tendency, we employ the finite element (FE) model for the finger pad as a uniform elastic body with the depressed cylindrical shape restricted from the bone and the nail part as shown in Fig. 9. The grasped pen is modeled as a stiff cylinder in contact with the finger model. The allocation of the finger and pen model is shown in Fig. 10(b) assuming the actual holding posture in Fig.10(a).

The FE model of the finger pad has an ellipse shape, it has the same section structure in the the x–z plane along the x–axis as shown in Fig. 9. The size of the section is 13.2×11 mm. The length of the finger in the x–axis is 25 mm, which is large enough compared to the contact area on the pen. The pen has a cylindrical structure having a diameter of 22 mm. The finger FE model is composed with a hexahedron element with 20 nodes and a hexahedron element with 10 nodes, which consists of 64937 nodes and 14790 elements in total. The FE code is implemented with ANSYS R.14 (ANSYS Corp.).

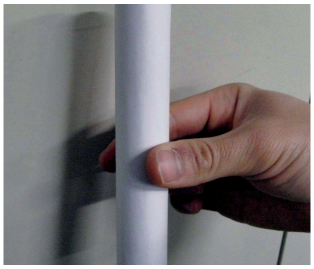
B. Model Parameters

The finger pad was assumed as a uniform linear elastic body. Model parameters are referred from the literature [15], in which the parameters of the uniform linear elastic model of the finger were determined by a three-dimensional deformation analysis constructed from CT images. The Young's Modulus is 65 kPa and the Poisson ratio is 0.48. Although the human finger has a multi–layer structure and it has nonlinear elastic nature, the effects of these characteristics are omitted and will be discussed in future investigation. The model of the pen was treated as a rigid body because it has sufficient stiffness relative to the skin.

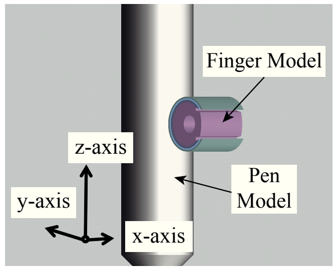


(a) x–axis (b) z–axis and y–axis

Fig. 9. Finite element model of the finger pad.



(a) Assumed posture



(b) FE analysis condition

Fig. 10. Contact allocation between the finger and the pen.

C. Boundary Conditions

Initially, the pen model was pressed to the finger model in the normal direction along the y–axis. This initial pressing applies 2.0 N contact force, we can consider this as the grip force on the pen. Next, the pen model was moved to one of these directions; x–axis, y–axis, and z–axis. This movement produced a reaction force up to 0.65 N, which induces strain on the finger model. The deformation analysis was conducted in a quasi-static manner.

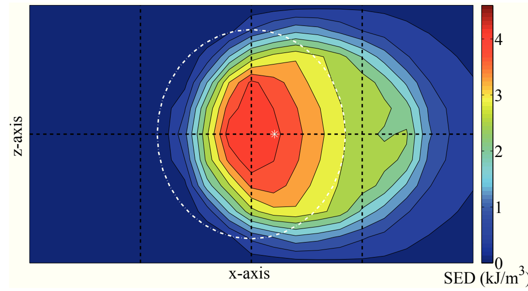
As for the boundary conditions, the finger body was constrained in all directions from the bone and the nail parts. The pen model was also constrained in all the rotational directions, including the two translational directions that are not involved in the analysis. A contact analysis between the finger and the pen was included in the friction model, the static friction coefficient was set at 1.0 and the kinetic friction coefficient was set at 0.2. The selected value for the static friction coefficient is based from the average contact phenomena between the finger and various objects.

D. Results

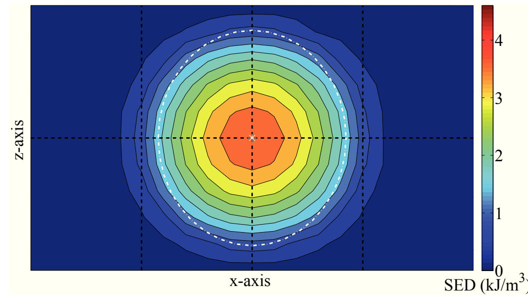
The calculated SED distributions on the mechanoreceptor layer for each direction are shown in Fig. 11(a) — Fig. 11(c). These figures show the differences on the SED distribution when the applied force was 0.65 N in each direction. The scale range of all graphs are 10 mm in the x–axis and 5 mm in the z–axis. The white broken line at the center of each figure represents the initial contact boundary between the finger and the pen. When the force was applied to the normal direction of the skin (Fig. 11(b) y–axis), the SED peaked the center of the SED distribution and remained there for the duration of the applied force. On the contrary, when the forces are applied along the lateral directions of the skin (Fig. 11(a) x–axis, and Fig. 11(c) z–axis), the peak level of SED moved opposite to the direction of applied force. We observed that these tendencies of the SED peak movement agree with our suction pressure generation method explained in Fig. 5.

To compare the increasing tendency of the amount of SED against the applied force on each direction, the total sum of SED from 805 nodes was calculated after the initial contact step. The nodes are located at the contact area including the vicinity near the contact boundary. All these nodes are in the mechanoreceptor layer.

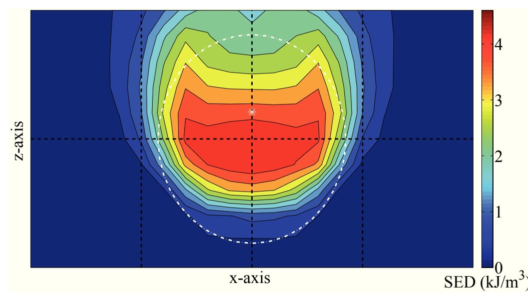
Fig. 12 shows the total calculated SED on each applied force direction. It was confirmed that the normal direction (y–axis) has a linear relationship and the lateral directions (x–axis and z–axis) have nonlinear relationships. Note that the observed variation of the total SED around the highest



(a) x–axis



(b) y–axis



(c) z–axis

Fig. 11. SED distribution when the external force of 0.65 N is applied to the three directions

levels on the x–axis and z–axis is possibly due to the instability of the FE analysis. The analysis would diverge when force is further applied. This means that the magnitude of force reported on the figures are maximum limit for this simulation.

VI. DISCUSSIONS

We obtained two types of correlation between perceived force magnitude and suction pressure stimuli. There is a linear correlation and a non–linear correlation. The linear correlation of perceived force magnitude and suction pressure is obtained when force was exerted normal against the tactile interface. While the non–linear correlation is obtained by exerting force laterally on the interface.

An interesting constituent in the results is that it has linear and non–linear tendencies of exerted force responses. Non–linear tendency in the results are consistent in two DOFs, where force is exerted laterally. Contrary to this, when force is exerted normal to the interface, the response showed linear relationship. We provide preliminary explanation to why these responses occurred based on strain energy density characteristic obtained in the finite element analysis.

The nature in which the experiment was conducted was to perceptually retain the magnitude of suction pressure and perform an equivalent exerted force that matched to the

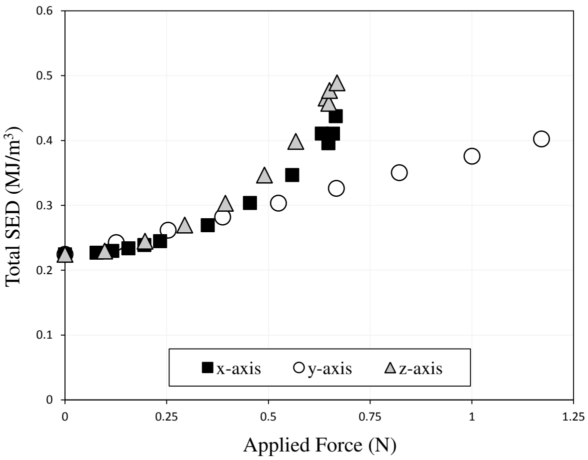


Fig. 12. Relationship between the total SED and the applied force.

stimuli magnitude. If SED has been used as the common factor in the adjustment task, it might be possible that the said quantity may influence our perception of force. This is based from, the results of the finite element simulation that showed similar pattern with the experimental data.

In the simulation, the normal force which is applied on the interface is similar to the exerted force along the F_y axis of the psychophysical experiment. This external force creates normal stress on the finger pads, in which the FEA simulation indicated linear growth of SED. Assuming that SED is an involved factor in the adjustment task, the subjects were able to perform linear adjustments of exerted force in response to stimuli magnitude. This was probably the process that resulted to the linear growth of exerted force obtained in the psychophysical experiment.

In simulating lateral forces applied on the grasped object, FEA data showed non–linear relations of SED and external force. In particular, the SED has an exponential growth over the applied lateral force and it is consistent for lateral forces applied in F_x and F_z. This indicates that lateral skin stress produces rapid increase of SED.

Assuming that the mechanoreceptor activity in the adjustment task is cognitively compared to the mechanoreceptor activity produced from suction pressure stimuli. The rapid growth of SED limits the exertion of lateral force dramatically, greatly reducing the exerted magnitude in order to match to the reference SED. The result of this reaction possibly contributed to the logarithmic growth of exerted lateral force on the interface.

The psychophysical data was originally intended to refine the rendering of suction pressure to evoke perceived force. However, our attention was caught when the simulation showed interesting results. This motivates us to explore further on the role of strain energy density to the perception of forces exerted on grasped objects.

VII. CONCLUSIONS

In this study, we had confirmed that multi–contact suction pressure stimulation can be a viable solution for representing external force on grasped object. The multi-degree of freedom tactile–based force feedback is initially confirmed in this study. This sensory representation method may be used in haptic interfaces for simplifying force display. In detail, we obtained the relationship between suction pressure stimuli and exerted force and analyzed the correlation between strain energy density and applied force on a grasped object. We had found a preliminary indication that suggest possible association between cutaneous activity and perceived force. In the future we will investigate further the possible role of strain energy density in the perception of force on grasped objects.

Further work is in progress for the determining the characteristics of torque on grasped objects. This is more meaningful study because in most case torque is often perceived rather than translational forces on most objects held in the hand. In addition, the pen–type interface we developed often exerts torque rather than translational force when interacting with objects. Obtaining the torque–suction pressure response characteristic is expected to further enhance the performance of the device. Furthermore, the elucidating the relations between SED, suction pressure, and perceived force are the future goal of this work.

ACKNOWLEDGMENT

This research was partially supported by the Cabinet Office, Government of Japan through its "Funding Program for Next Generation World–Leading Researchers." We would like to acknowledge the participants of this study.

REFERENCES

[1] M. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," *Robotics and Automation, IEEE Transactions on*, vol. 5, no. 3, pp. 269 –279, 1989.

[2] N. Kamakura, M. Matsuo, H. Ishii, F. Mitsuboshi, and Y. Miura, "Patterns of static prehension in normal hands," *Amercan Journal of Occupational Theraphy*, vol. 34, no. 7, pp. 437–445, 1980.

[3] C. Giachritsis, R. Wright, and A. Wing, "The contribution of proprioceptive and cutaneous cues in weight perception: Early evidence for maximum-likelihood integration," in *Haptics: Generating and Perceiving Tangible Sensations*, ser. Lecture Notes in Computer Science, A. Kappers, J. Erp, W. Bergmann Tiest, and F. Helm, Eds. Springer Berlin Heidelberg, 2010, vol. 6191, pp. 11–16.

[4] L. Jones and E. Piateski, "Contribution of tactile feedback from the hand to the perception of force," *Experimental Brain Research*, vol. 168, pp. 298–302, 2006.

[5] K. O. Johnson, "The roles and functions of cutaneous mechanoreceptors," *Current Opinion in Neurobiology*, vol. 11, no. 4, pp. 455–461, 2001.

[6] T. Maeno, K. Kobayashi, and N. Yamazaki, "Relationship between the structure of human finger tissue and the location of tactile receptors," *Bulletin of JSME International Journal*, vol. 41, pp. 94–100, 1998.

[7] M. A. Srinivasan and K. Dandekar, "An investigation of the mechanics of tactile sense using two-dimensional models of the primate fingertip," *Journal of Biomechanical Engineering*, vol. 118, no. 1, pp. 48–55, 1996.

[8] Y. Makino and H. Shinoda, "A method to produce tactile sensation using suction pressure," *Transactions of the Virtual Reality Society of Japan*, vol. 11, no. 1, pp. 123–2, 2006, (*In Japanese*).

[9] L. Porquis, M. Konyo, and S. Tadokoro, "Tactile-based torque illusion controlled by strain distributions on multi-finger contact," in *Haptics Symposium (HAPTICS), 2012 IEEE*, mar. 2012, pp. 393 –398.

[10] ——, "Enhancement of human force perception by multi-point tactile stimulation," in *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*, sep. 2011, pp. 3488 –3493.

[11] R. Periyasamy, M. Manivannan, and V. B. Narayanamurthy, "Changes in two point discrimination and the law of mobility in diabetes mellitus patients," *J Brachial Plex Peripher Nerve Inj*, vol. 3, p. 3, 2008.

[12] S. Weinstein, "Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterality," *The First Int' l Symp. on the Skin Senses*, 1968.

[13] M. S. Cohen. (2012, aug) Handedness questionnaire. [Online]. Available: http://www.brainmapping.org/shared/Edinburgh.php

[14] L. B. Porquis, "Haptic representation of force and softness produced by skin stimulation," PhD. Thesis.

[15] S. Shimawaki and N. Sakai, "Quasi-static deformation analysis of a human finger using a three-dimensional finite element model constructed from ct images," *Journal of Environment and Engineering*, vol. 2, no. 1, pp. 56–63, 2007.