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研究課題名（和文）Study of human's slip perception based on the mechanics of localized slippage

研究課題名（英文）Study of human's slip perception based on the mechanics of localized slippage

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研究成果の概要（和文）：局所滑り現象に基づいた滑り提示装置を開発した。そして、提示装置のピンとヒトの指先との接触をダイナミックなモデルの構築を用いてシミュレーションした。また、人間を対象とした実験も行って、被験者に滑り感覚を起こす提示装置を評価した。今後、手術ロボット等遠隔操作システムに滑り提示による制御を提案することを期待します。

研究成果の概要（英文）：We present the concept of a novel haptic display device that could generate lateral localized displacement on a human fingertip, thus enhancing human perception of partial slip phenomenon. The proposed device is characterized by a bundle of pins whose ends gently make contact with a human fingertip. These pins are arranged on a supporting base that can displace endings of the pins to a different extent simultaneously with a single actuation, thus successfully generating localized slippage on a human fingertip. There are no relative movements between pins and the finger pad, resulting different skin stretch instead of moving across the skin surface. We proposed a dynamic model of interaction between haptic pins and finger for investigation of mechanical response of stress or strain on human fingertip under operation of the proposed haptic device. The results presented in this paper may help assess human slip perception for the development of haptic display devices.

研究分野：Robotics

キーワード：触覚提示　局所滑り　滑り検出　滑り提示　ビーム束モデル　ウエアラブル装置　遠隔操作　心理物理実験

１．研究開始当初の背景

Slippage and skin stretching of human fingertips have been researched in humans (psychophysics, neuroscience) and robotics. Slip perception caused by skin stretching is mediated through Meissner corpuscles and Ruffini endings, which correspond to FA-I and SA-II afferent nerves, respectively. In robotics, the use of human-in-the-loop control devices result in haptically controlled devices requiring a rich feedback of tactile sensations through slippage and skin stretching to achieve better and more seamless control of remote robots. Recent developments in material technology have resulted in the introduction of novel actuators that display tactile perceptions; these include SMA (shape memory alloy), piezo material, and active dielectric elastomers. Nonetheless, they require a high-voltage source and complicated driving systems for the matrix of actuators, resulting in a high operating cost and raising questions about their safety for users.

２．研究の目的

Soft object based sliding phenomena are highly nonlinear and dependent on both contact area and relative contact force. These phenomena also involve complicated micro stick/slip on the contact surface, due to the distribution of localized adhering forces. To date, much experimental research has assessed partial movements on the contact area during the pre-slide (i.e. stick) phase of soft robotic fingertips. This phenomenon also likely occurs on human fingertips, due to their soft dermis and curved shape. We previously proposed a Beam Bundle Model (BBM) [1] for modeling the inhomogeneous sliding of a human fingertip on a rigid surface, focusing on the pre- slide phase. BBM is a hybrid of a finite element model and a discrete model, in which the deformation of a fingertip is represented by discrete virtual visco-elastic beams, and the stick/slip phenomenon at the contact surface is modelled by finite element analysis.

In this research, we hypothesized that, if the LDP is *externally* created by a haptic device on a fingertip, humans could perceive localized slippage, enhancing slip perception, especially incipient slippage of soft objects in remote area. In a tele-operated system, in which a user controls a remote robotic hand holding a soft object (*e.g.*, organ tissue in robotic surgery), the ability of the user to feel initial slippage can result in a suit- able gripping force preventing slippage, as well as not harming the object.

３．研究の方法

3.1 Design Proposal

We proposed a method for generation of different displacements on haptic pins using a single actuator. This device used a multiple-pin design, in which one end of each pin was in contact with the skin on a human fingertip and the other end was actuated. By placing pins of various lengths on a specially-designed supporting base, it was possible to generate different patterns of pins movements. The displacement pattern of this device obeyed the propagation of an LDP (Localized Displacement Phenomenon), in which pins distributed at the boundary translate more than more centrally located pins. Thus, movements of the pins contribute to skin stretching on human fingertips, allowing humans to assess a sense of localized slippage. Fig. 1 briefly describes the idea utilized for development of this device. If the movement of one haptic pin is indicated by s1, with its first, actuating end A moving on a surface α, a constrained point B located l1 from A ($l1 < l$), and the other end C free to move along the surface β, the distance between B and C would be $l2 = l - l1$.

If C is chosen to stretch the skin on the fingertip, and if pin design (length and constraint position) were optimized, it would be possible to generate various movements of multiple pins with a minimum number of actuation.

We attempted to display the sliding motion in any planar directions on the human finger pad, thus a two degree-of- freedom (DOF) movement of the base was considered. There are several methods for implementation of this translational 2- DOF movement, for example using linear motors, pneumatic pistons, and so on. In this research, we designed a mechanism that transforms the rotational movement of servo motors into planar translational movement of the base by utilization of crank-shaft mechanism.

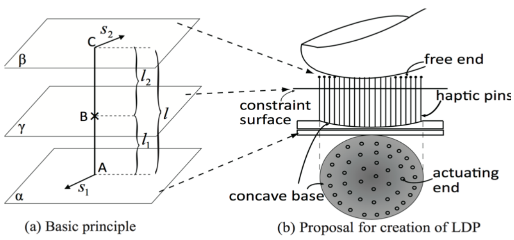

Fig.1: Illustration of principle for generation of localized displacements on human fingertip

3.2 Modeling

We have built a dynamic model describing interaction between haptic pins and fingerpad, which allows numerical simulation of interactions between haptic pins and human fingertips. This model permits analysis of mechanical characteristics during physical contact, such as applied force and lateral skin stretching generated by the movement of haptic pins on a human fingertip.

The model is an extension of our previous Beam Bundle Model (BBM), which simulated soft contact between human or robotic fingertips and grasped objects, focusing on the incipient slip phenomenon. This study also considered interactions between haptic pins and the contact nodes of a human fingertip. Specifically, each pin's free end was assigned a node on the meshed contact surface, as well as to the corresponding end of a virtual beam. This model assumed that the bond between the pin's end and the contact's surface node would not be broken during lateral displacement, thus corresponding to a pure skin stretching phenomenon. As a result, the lateral movement/force of the pins' ends caused by the haptic device was considered a geometric constraint/external force to the BBM. Fig. 2 illustrates the scenario of this simulation and the interactive force acting on a single haptic pin during contact and displacement on a human fingertip.

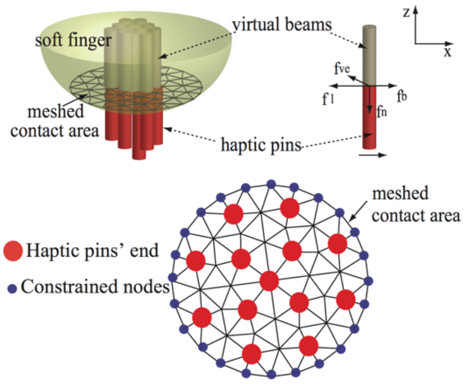

Fig. 2: Dynamic model of haptic pins making contact with virtual beams of the fingertip.

4. 研究成果

4.1 Dynamic Simulation

We introduced the partial displacements of haptic pins that conform to the LDP as mentioned in Section 2. In this simulation the magnitude of force generated when a bundle of haptic pins cause localized skin stretch on a human fingertip is assessed and shown in Fig. 3(a). Using haptic pins with different movements, with the outer pins being displaced more than the inner pins, we were able to calculate generated lateral force distribution over the contact area. Fig. 3(b) shows the distributions of generated lateral force resulting from increased displacement of haptic pins over time. We can assess that this distribution is also identical to LDP, in which the boundary area generated higher lateral force than the inner one, resulting the possibility that human may also feel the localized skin stretch. Moreover, our proposed model not only can estimate lateral force under localized displacements of pins, but also can solve the inverse problem in which generated displacements subjected to given force profile can be obtained. In this simulation, we assigned nodes (red ones in Fig. 2) with forces increased from inner nodes to the outer nodes obeying Fibonacci rule. Fig. 3(b) illustrates dynamic change of lateral displacement distribution on the fingerpad's contact area under the given force profile. It can be seen that the lateral displacement is totally conforming to the idea of the LDP. As a result, ones can utilize this simulation to investigate the effectiveness of generated partial traction on human fingertip under various condition of given force profile, especially to clarify the role of skin's visco-elasticity in traction generation.

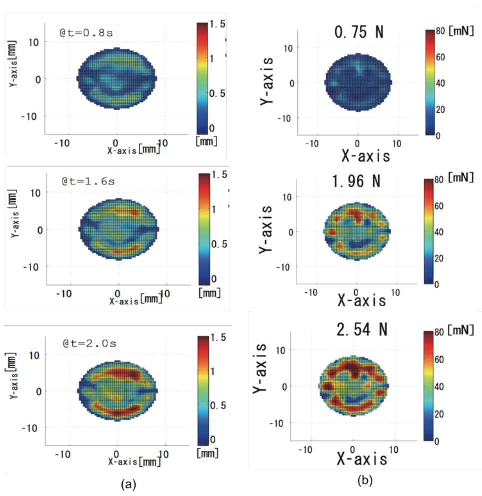

Fig. 3: Dynamic change of distribution of lateral force and traction over time under operation of the multiple haptic pins. (a) All pins are given with pre-determined lateral displacement that conforms to LDP: inner node with 1 mm, middle nodes with 1.5 mm, outer nodes with 2.0 mm. (b) All pins are given with pre-determined force profile that conforms to Fibonacci rule: inner node with 0.2 N, middle nodes with 0.3 N, outer nodes with 0.5 N and so on.

4.2 Design of a portable Haptic Display

We attempted to develop a wearable design that is light-weight, compact, and possible to be attached to off-the-shelf haptic devices. Fig. 4 shows the details of this design. The adapter can be justified to fit to specific kinesthetic haptic displays (in this design, the adapter is fixed onto the stylus of the Geomagic Touch). A hinge is designed so that subject could rest and grip the entire device. Haptic pins are put through holes on a constraint plane, and loosely fixed onto a supporting base. The design of the supporting base is similar to that mentioned in section 1. In order to generate localized displacements on different directions, the supporting base is located onto a planar mobile mechanism. This mechanism has two main orthogonal sliders, each slider is controlled by one servo motor (XL-320, ROBOTIS) through a crank shaft. Two servos are controlled by a compact driving board (CM9.04, ROBOTIS). In order to feedback the gripping force, a thin 3-dof loadcell (USL06-H5, Tek-gihan) is attached under the main frame, accompanied with a base for supporting the subject's thumb. All parts (except haptic pins, sliders) are made by a 3D printer. Total size is 75 mm×75 mm×50 mm, and weight is 183 gr. To use this device, subject's index finger is set between the adapter and the hinge, so that the finger pad makes contact with haptic pins. A thumb's support (if necessary) is attached onto a thin loadcell under the main frame for measuring the gripping force between the thumb and the index finger. The sense of localized slippage is converted by the movements of supporting base, and the subject would adjust the gripping force (measured by the loadcell) through the thumb and index finger.

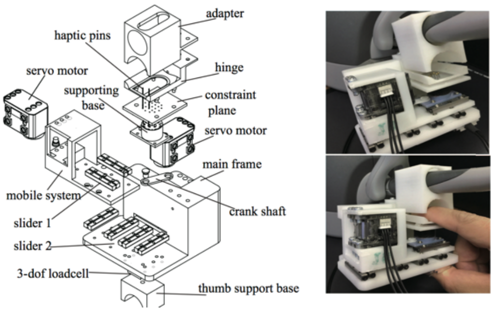

Fig. 4: Experimental setup.

4.3 Phychophysical test

Psychophysical tests were performed on male six volun- teers. All were students of our institution, were aged 21 to 25 years, and had no history of tactile disorder/disease using the proposed device. All subjects were informed about the methodology and purpose of this experiment and provided informed written consent. The study protocol and methods were approved by the Ryukoku University Committee Board. We exploited VAS (Visual Analog Scale 0-100) for evaluation of localized slip perception. Subjects received an explanation about the relation between the sense of localized slippage and the corresponding score of VAS. Scores of 0-20, 20-40, 40-60, 60-80 and 80-100 were regarded as complete lack of localized slippage perception, little perception, clear perception, very clear perception, and strong perception, respectively. The perfect sense of the localized slippage (VAS=100) could be assigned if the subject felt the exact sequence of slippage on the finger pad as stated in section 2, i.e. the slippage occurs first at the boundary then propagated into the inner area. The VAS was 0 if the subject could not assess at all the existence of the order of slippage sequence on the finger pad.

4.3.1 Effect of contact force

Subjects were asked to apply three levels of constant force during each trial, 0.8 N. 1.5 N, and 2 N, while controlling the linear stage to displace 2.5mm at a speed of 1.5mm/s in the four directions, D (distal), P (proximal), R (radial), and U (ulnar). VAS scores increased when subjects applied more force on the haptic pins, with the VAS being highest in the P-direction at 2 N (Fig. 5). The increased VAS may be due to the relationship between higher load on haptic pins and fingertip pad stiffness. Thus, greater displacement of haptic pins can generate a higher value of lateral force, which can react with mechanoreceptors, especially the Ruffini endings, which are both sensitive to skin stretching and located deep within the dermis. This may result in an enhanced feeling of localized displacement on subjects' fingertip pads.

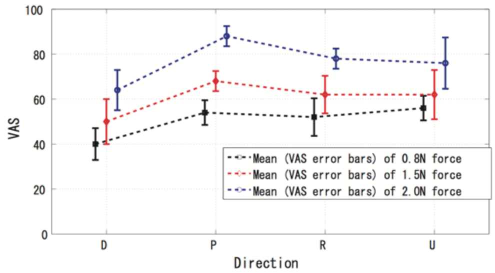

Fig. 5: Effect of contact force on VAS.

4.3.2 Effect of Sliding velocity

Subjects were asked to apply a constant force of 1.0N while controlling the linear stage to displace a distance of 2.5 mm at three different velocities: 1.0 mm/s, 2.0 mm/s, and 3.0mm/s along the four above mentioned directions. Each subject performed five trials at each of the three velocities, in each of the four directions, for a total of 180 trials for the three subjects. Results of obtained VAS are illustrated in Fig. 6. From these plots, we could assess that the VAS does not change significantly when the velocities increases. In this experiment, we found that the VAS at four directions of sliding tend to decrease when the velocity is over 5mm/s. Especially, VAS decreases significantly at extremely high speed of movement (> 7 mm/s).

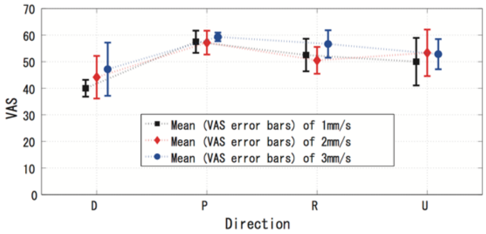

Fig. 6: Effect of velocity on VAS.

Consequently, localized slippage sensation by study subjects was therefore perceptually characterized at different operating conditions of the haptic display device. The results are not only applicable to the proposed device, but can be used to study localized slippage perception for the development of similar devices.

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５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

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〔産業財産権〕

○出願状況（計　２　件）
名称：触覚提示装置
発明者：ホ　アンヴァン
権利者：ホ　アンヴァン
種類：発明
番号：２０１５−２１３５００
出願年月日：２０１５年１０月２７日
国内外の別：　国内

名称：触覚提示装置
発明者：ホ　アンヴァン
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種類：発明
番号：２０１６−１６３２４７
出願年月日：２０１６年０８月２４日
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