Beam Bundle Model of Human Fingertip during Pre-Slide Phase

Van Anh Ho, Zhongkui Wang, and Shinichi Hirai

I. Introduction

Among many senses, tactile perception is considered to as one of the most important factors for both human and robots, which permits acquisition of the outside world information, especially the grasped object's characteristics for stable/dexterous manipulation. Research on tactile perception in robotics has been conducted for over 30 years, mainly focusing on mimicking human's fingertip ranging from shape, function, and distribution of mechanoreceptors. As a result, it is indispensable for robotics researchers to understand functions and characteristics of human fingertip. Among multiple modalities that human finger can sense; including temperature, force, vibration, *etc.*; deformation of skin has played an important role in touch sensation. It stimulates four types of mechanoreceptor cells lying right beneath the skin, then stimulated cells send signal to brain for processing. Thus, recently, there has been many researches utilized skin stretch in haptic devices. Minamizawa [1] has developed haptic device for displaying grasping and weight sensations based on cutaneous stimuli, in which two motors's motion creates controlled skin stretch on the fingertip depending on tele-operative objects. Nakatani and Kawasoe [2] developed a device for studying hatic behaviors via skin deformation of human fingertip. Thus, there is also an increasing need for modeling skin deformation of human fingertip during contact with object, especially during pre-slide or sliding phases. Konyo and Okamoto [3] has attempted to model human fingertip with simple model of mass-spring-damper to investigate stick-slip events. Nonetheless, it is not a sufficient model since the structure of human fingertip is far different.

In this research, we attempted to employ our proposed Beam Bundle Model (see [4], [5]) into modeling human fingertip. In order to implement this, we utilized Magnetic Resonant Images (MRI) of one subject's fingertip to construct mathematical model of fingertip's structure. We also succeeded in representation of localized displacements (also referred to as skin local stretch) during pre-slide phase of the fingertip, which is considered crucial to assess stick/slip events on the contact surface during contact with outside world. This work can be utilized in haptic sensation, and development of sensors for detection of slippage.

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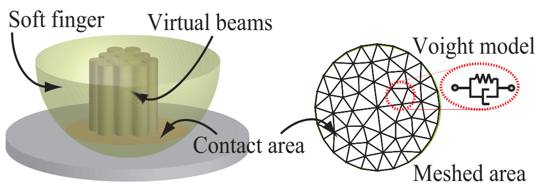


Fig. 1. Beam Bundle Model.

II. Beam Bundle Model

Previously, we proposed Beam Bundle Model (BBM) for modeling sliding motion of cylindrical and hemispherical soft fingertips. In this model, the soft fingertip is necessarily elastic and homogeneous with pre-determined geometrical shape. This model is a hybrid of discrete model and finite element model (FEM) as illustrated in Fig. 1. First, in order to model the deformation of the fingertip under normal and tangential loads, we filled in the volume of the fingertip with *virtual* elastic beams which can be compressible and bendable. As a result, the deformation of the fingertip was calculated based on deformations of all beams. Second, the contact area was meshed with Kevin-Voight model according to finite element theory. Free ends of beams are placed at nodes on the contact area, thus mutual interaction of beams are considered to be solely on the contact surface. Detailed derivation of motion equations can be refereed to [4][5][6]. Using this model, we were able to simulate sliding motion under given speed, and observe responses of normal force and friction force. Moreover, simulation also produced localized displacement phenomenon during pre-slide phase, helping us to assess how and when the slippage occurred on the contact surface. This is considered important to understand slip of soft object, as well as crucial to tactile sensation. Having this tool in hand, we will introduce how to apply it to model human fingertip in the following sections.

III. Beam Bundle Model of Human Fingertip

A. Construction of Human Fingertip Using MR Images

In order to accurately measure the 3D internal and external geometries of human fingertip, a 3 Tesla (3T) MRI system, SIGNA HDXT (GE Healthcare,Waukesha,WI), is used in our experiments. Cross-sectional MR images of an index finger were collected with a 25-year-old adult male, having no history of finger disease. A set of 32 images with size of 512 x 512 pixels were obtained representing volume of the fingertip in term of consecutive cross-sectional layers. For

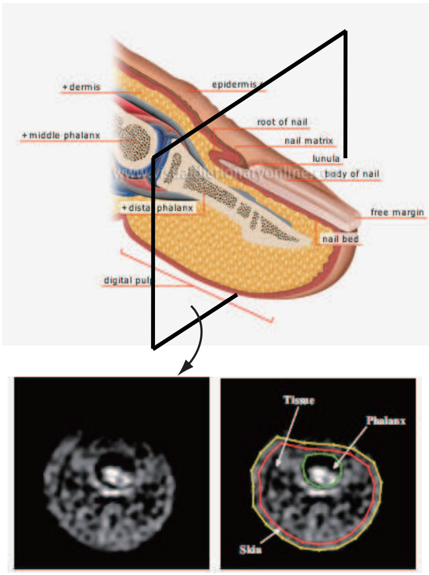
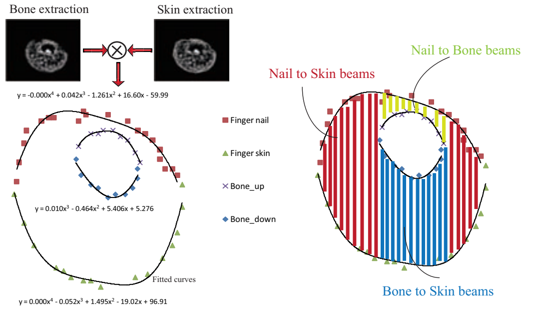
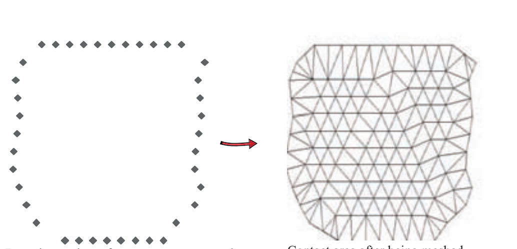


Fig. 2. Slip sensor with piles shaping the surface.



(a) Fingertip structure extraction (b) Groups of virtual beams inside the fingertip

Fig. 3. Structure of human fingertip from MRI.



Boundary points of contact area extracted from all images

Contact area after being meshed

Fig. 4. Meshed contact area.

each image, we can observe the distribution of layers such as skin, tissue, bone, and nail position as illustrated in Fig. 2.

To introduce the BBM to human fingertip, it is necessary to assess the exact distribution of inner layers in order to fill in virtual beams properly. We utilized image processing function in OpenCV to extract boundaries of skin, bone, and position of nail. Each boundary was formed by a group of points which were afterward interpolated into a curve (see Fig. 3(a)). As a result, for each image, we were able to collect four fitted curves, including skin, lower bone, upper bone, and nail as illustrated in Fig. 3(b). By repeating this process on all images, three dimensional geometrical shape of the fingertip could be formed for introduction of BBM.

B. Derivation of BBM for Human Fingertip

As mentioned in Section II, we had to fill in the volume of the fingertip with virtual beams considering distribution of inner constructions (tissue, bone, etc.). For each layer, with fitted curves mentioned above, we were able to attach virtual elastic beams into the tissue volume so that fixed ends of beams were pinned into rigid volumes, such as nail and bone; the other ends of beams resided on skin. Each virtual beam possess cylindrical shape with geometrical property predetermined based on known fitted curves of nail, bone, and skin. As illustrated in Fig. 3(b), there are three groups of beams, including beams attach to nail and skin (N-S), beams attach to bone and skin (B-S), and beams attach to nail and bone (N-B). In this model, we assumed that during sliding motion, which includes pushing and sliding actions, nail and bone are not deformed. As a result, group N-B are considered no deformation during action of the fingertip model, only group N-S and B-S contribute to the deformation of the fingertip volume. Supposed that the fingertip was pushed onto a rigid flat surface, causing a set of contact boundary points on skin. We then meshed the contact area utilizing finite element analysis (FEA) with Kelvin-Voight element that includes a spring and a damper connected in parallel (see Fig. 4), so that each node attached to one free-end of one beam that belongs to either N-S or B-S group. As a result, beams are constrained on the contact area on the skin; and the movement of beams's free-ends would be helpful to assess stick/slip events on the contact area during sliding motion. Derivation of motion equations of whole fingertip are similar to the hemispherical phase, which can be referred in [4].

IV. Simulation

In this simulation, the fingertip was given a vertical push with a pre-determined contact depth, and a tangential movement with constant velocity. Parameters used for simulation are summarized in Tables I and II.

A. Force-Related Results

Fig. 5 shows the normal force distribution when the fingertip was pushed with contact depth of 2 mm. We can observe that maximum force area is around the tip that is close to the nail. This result is similar to the calculation of Tada [7] with finite element analysis model. As a result, it is noticeable that although outer shape of human fingertip is likely symmetrical and even, the force distribution is not produced nicely as hemispherical fingertip case (see [4]). It thanks to inner distribution of distal phalanx that causes non-uniform deformations of beams over the contact area.

Fig. 6 plots response of friction force during stick to slip phase under constant speed. Two phases are easily observed.

TABLE I
PHYSICAL PARAMETER FOR THE HUMAN FINGERTIP

	Tissue	Skin	Bone
E[Pa]	$3.4\text{x}10^4$	$1.36\text{x}10^5$	$1.5\text{x}10^9$
c[Pa.s]	Not used	10	Not used

TABLE II
SIMULATION PARAMETERS

Sliding speed [mm/s]	Friction coefficient	Direction of slide
2-5	0.6-2.0	X+, X-, Y+, Y-

Stick phase represents pre-slide phase, when the fingertip moves but the contact area still sticks to the surface, in which the friction force increases remarkably. Slide phase indicates the total movement of the contact area, and the friction force goes to unchanged value. This phenomenon is similar to hemispherical soft fingertip in [4]. The friction force changes drastically when we varied some parameters, such as sliding speed, contact depth.

B. Localized Displacement Phenomenon during Pre-Slide Phase

One of noticeable results is the success of representation of localized displacements on the contact area during pre-slide phase in simulation. There are several research on experimental detection of micro movements on the contact area of human fingertip during slide action ([8]), however, none of them could explain underlying theoretical background for this phenomenon. By exploiting BBM for hemispherical soft fingertip, we had been able to simulate this process. In this research, for human fingertip model, similar result of the phenomenon was assessed clearly. Fig. 7 illustrates distribution of localized movements of contacting nodes on the contact area over moments of time during pre-slide phase. Bright and hot color zones indicate larger movement than cold and dark color ones. These distribution were taken from the simulation of a sliding trial with sliding speed of 2 mm/s, friction coefficient of 0.7 and contact depth of 2 mm. We can observe that displacement first occurs near the boundary of the contact area, then, along the direction of slide this movements propagates gradually. Moreover, it also spreads from outer area to inner area. As a result, this propagation of displacement relies on the normal force distribution, which indicates small forces are distributed mainly near the boundary than the middle part (see Fig. 5). Finally, the last area to move right before the total slippage of the fingertip happens is circled at time of 1.6 s in Fig. 7, is coincident to the moment in which the friction starts to be constant in Fig. 6(a) (which indicates the start of gross slide phase of the fingertip). Comparing experimental work of Tada *et al.* [8], authors also pointed out that the localized slippage occurs first near the boundary area, then spreads into inner zone, and the last area to move is near the tip, which is similar to our simulation result. We also changed simulation parameters and assessed that

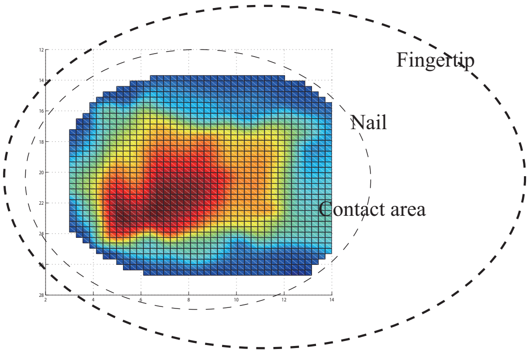


Fig. 5. Normal force distribution on the contact surface in context of fingertip.

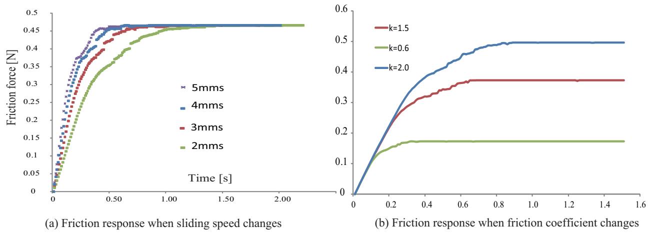


Fig. 6. Friction force during stick-to-slide phase.

the localized displacement occurs differently depending on friction coefficient, speed, especially direction of slide. This partly explains why human feels differently when its fingertip slides on different direction on surfaces.

V. CONCLUSION

We have investigated theoretically sliding motion of a human fingertip model, focusing on pre-slide phase, utilizing previously proposed beam bundle model and MR images. Simulation results help us to assess the change of force, and especially localized displacement phenomenon on the contact area during pre-slide phase. Knowledge about this phenomenon will assist us to understand role of skin in recognition of slippage, as well as to develop sensing system to detect incipient slip of human fingertip that is crucial in stable manipulation.

In the future, we attempt to validate theoretical results with experimental setup. This experiment design will be able to capture not only normal force distribution, but also track partial movements of contacting points on the contact area in order to assess localized displacement phenomenon. Moreover, sensitive sensors, such as slip sensors, will be researched to detect human fingertip slip efficiently. Finally, a complete haptic device which enhancing detection and display of slippage on human will be addressed.

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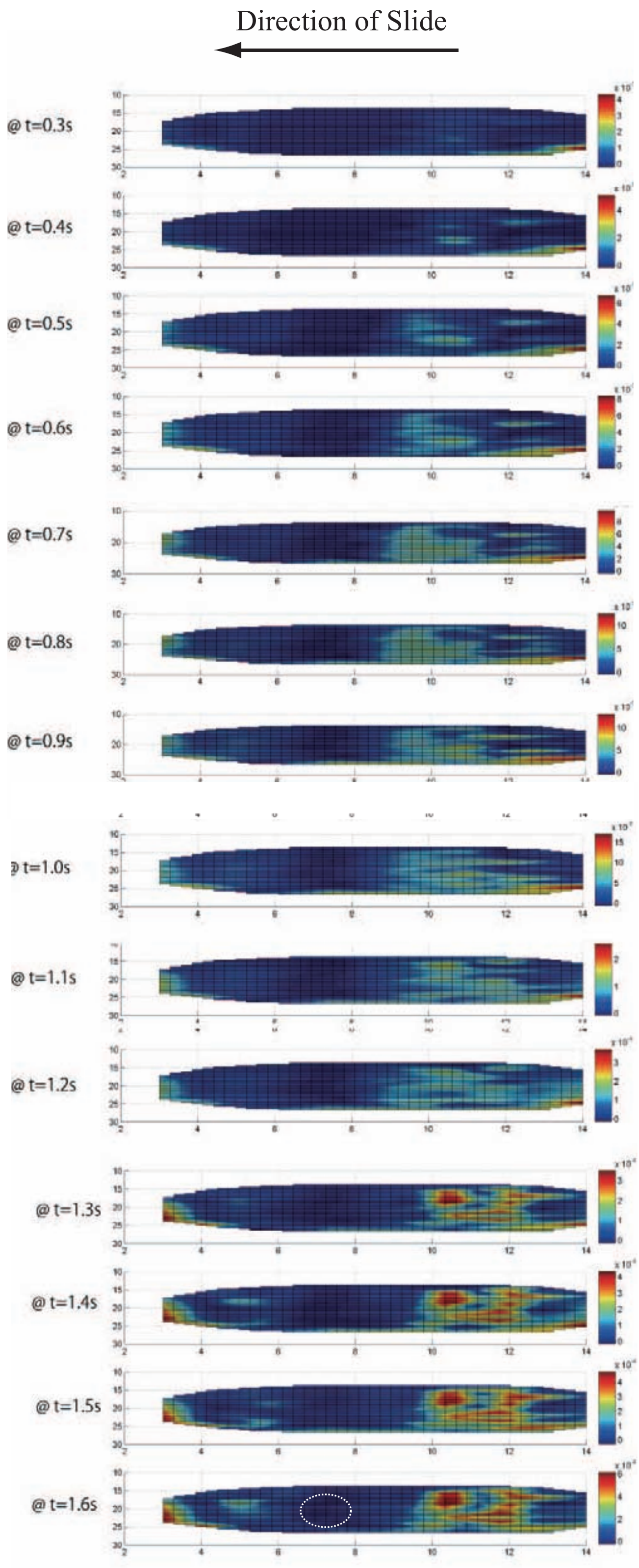

Fig. 7. Localized displacement distribution on the contact area over time during pre-slide phase.