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Simulation of contact deformation property of Digital Hand skin and its experimental verifications

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Abstract. The contact deformation of human skin is a significant factor in the virtual ergonomic assessment of handheld products, but previous works have neglected it or dealt with it in a simple way. In this paper, we propose a physical model of the contact deformation of human skin and, based on this model, present an efficient contact solving method to simulate the physical contact of the Digital Hand with product surfaces. The realistic contact deformation effect was realized, and we experimentally verified the estimated contact area, contact force and pressure distribution, and found the estimation results by the proposed model and the contact solving method well fit with the experimental data and the past data from the literature.

1. Introduction

Background. Ergonomic-conscious design of handheld products, such as digital handheld appliances, handy tools and containers, brings better user experience to customers, and contributes to their market competitiveness. However, conventional ergonomic assessment of these products, such as comfort or fatigue estimation, still greatly depend on sensory tests by real human subjects. Moreover, the preparation of expensive physical mockups and questionnaire-like user surveys are high in cost and time consuming, and only subjective and qualitative evaluation results can be obtained. To solve these problems, our research group has proposed the Digital Hand [1,2], a virtual human hand, where 3D triangular mesh models of the bones and a skin surface are represented based on MRI measured data. Nevertheless, the Digital Hand does not simulate the hand skin deformation caused by physical contact with product surfaces, and instead approximates it in a simple way where the interpenetration between the skin and the surfaces within a specific threshold is allowed.

It is well known that the biomechanical properties of hand skin plays a fundamental role in the tactile sense of humans [3,4]. Humans utilize physical contact with objects to feel their geometrical properties as well as material properties. While grasping the objects, contact condition gives us much information, such as contact force, contact area with the objects, and whether the distribution of contact force is reasonable enough to maintain a stable as well as comfortable grasp.

The purpose of this paper was to propose an efficient simulation method which can physically model contact deformation of hand skin, and solve the contact of hand skin with product surfaces for virtual ergonomic assessment based on the Digital Hand.

We propose a new physical model of the deformation based on modified Boussinesq approximation, which considers compressing-swelling effect to aptly approximate the deformation of hand skin. During contact solving, point force-based discretization is used to solve the irregularity problem of the triangular irregular mesh of the Digital Hand. Finally, collision detecting and solving LCP are used to deal with the contact of the skin with the product surfaces.

Related Works and Our Contributions. Besides the works [1,2] mentioned above, FEM-based methods have been used to simulate finger contact deformation [3,5]. Although they realize higher simulation accuracy, when involving computation efficiency, this method is not suitable for practical virtual ergonomic assessment. Pauly et al. [6] did a pioneering work for efficient simulating contact deformation which modeled deformable objects as quasi-rigid objects, but the biomechanical meaning of human hand skin was not taken into account, and the simulation was not validated.

The contributions of our research are summarized as follows: 1) a new physical model which adopts the biomechanical parameters of real hand skin can estimate the contact deformation of skin with compressing-swelling effect within an acceptable range for ergonomic assessment of handheld products; 2) the contact solving method can guarantee contact without interpenetration efficiently. Thanks to these points, the realistic contact deformation simulation effect was realized, and the estimated contact area, contact force and pressure distribution, which were verified experimentally, are going to be significant measures for virtual ergonomic assessment.

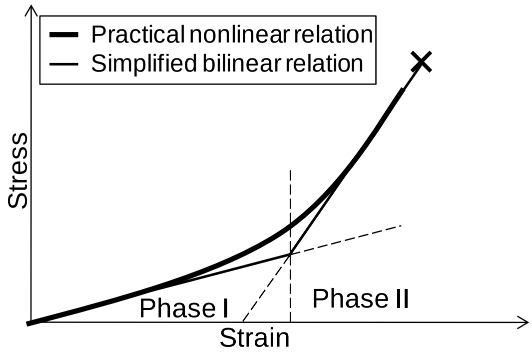

Fig.1 Nolinear ealsticity of human skin [8]

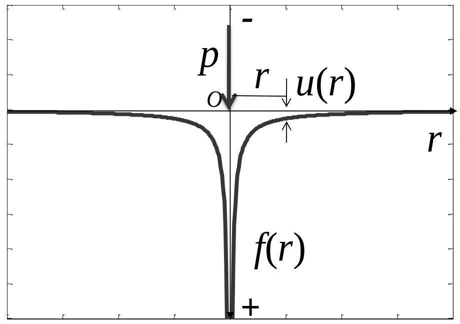

Fig.2 Boussinesq approximation [9]

2. Physical Model of Contact Deformation

Linear Elasticity Assumption. The structure, as well as the material behavior of human skin, exhibits nonlinear viscoelastic, anisotropic and quasi-incompressible mechanical properties [3,4]. For ergonomic assessment, we have to consider the external geometry of the hand, and therefore we can treat hand skin as a bulk material [7].

Human skin presents nonlinear elasticity in the stress-strain relation, owing to the different structures of the elastin and the collagen fibres which are the main components of dermis in different stressing or straightening states [4,8] as the thick curve shows in Fig.1. Delalleau et al. [4] proposed a simplified bilinear elastic model as the thin curve shown in Fig.1. Considering that the rapid increment of the stress in the second phase of the thin curve in Fig.1, where a very tight grip happens and goes beyond ergonomic-conscious product design requirements, we anticipated hand skin deformation which occurs in a natural grasping posture to be small, i.e. within the first phase of the thin curve. In this phase, the anisotropy and the viscoelasticity of skin can be neglected [4]. Therefore, we assumed that the hand skin deformation caused by physical contact with handheld products is of approximately isotropy and linear elasticity.

Boussinesq Approximation. In order to model the linear elasticity in small skin deformation, we adopted a widely used method in contact mechanics, Boussinesq approximation, which approximates the surface deformation around a contact point in an elastic half space [9], and can be expressed by Eq.1:

$$u(r) = (1-\upsilon)p/(2G\pi r) = f(r)p, \quad f(r) = (1-\upsilon)/(2G\pi r) \tag{1}$$

where, as shown in Fig.2, r is the distance between a point and the origin, $u(r)$ the displacement at r due to a normal concentrated force p at the origin, υ Possion's ratio, G shear modulus, and $f(r)$ system response function.

Possion's ratio must be identical to the ones of human skin which varies from 0.45 to 0.50 [10]. Because in our assumption the skin is isotropic, 0.5 was chosen as the Possion's ratio. Young's modulus of hand skin ranges from 0.12 to 0.24 MPa [4].

Compressing-swelling Effect. Human skin is a quasi-incompressible material. In fact, the compressibility of the in vivo fingertip measured by Srinivasan [7] was less than 1%. In realistic simulation, the *compressing-swelling effect*, which means compressive force causes not only regional volume compressing in the force acting region, but also regional volume swelling right outside the force acting region due to a finite volume, needs to be considered. However, the volume after deformation obviously is reduced in the original Boussinesq approximation, behaving like the physical behaviors of a sponge-like material. The compressing-swelling effect can be achieved by ensuring that

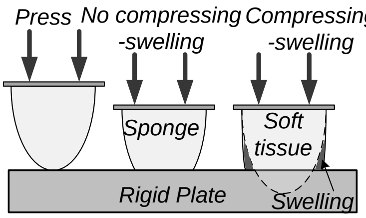

Fig.3 Compressing-swelling effect

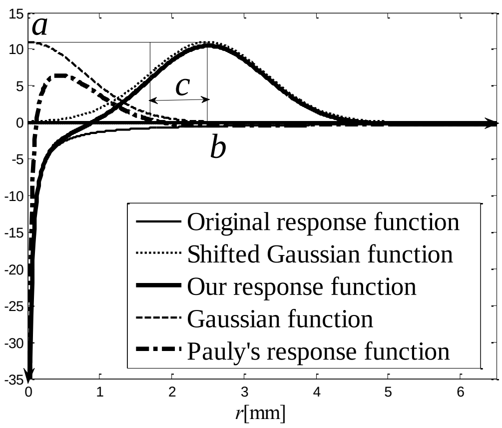

Fig.4 Modefied response function

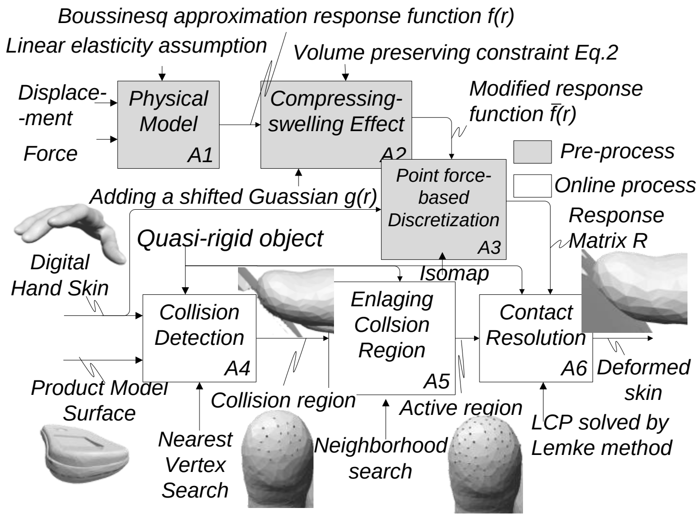

Fig.5 Overview of the contact solving method

the deformation caused by a point force does not lead to a volume change. This constraint can be expressed as Eq.2:

$$\int_0^{\infty} f(r)\,\mathrm{d}r = 0 \quad (2)$$

The compressing-swelling effect of an incompressible material, such as a soft material, as shown in Fig.3, can cause more realistic deformation and give a larger contact area. Moreover, it effects the biomechanical properties of human skin significantly. During physical contact of the soft tissue with objects, a larger force is needed to press the bulges caused by the point forces. That is why it is more difficult to press soft tissue than a sponge-like material.

Modified Boussinesq Approximation. Pauly et al. [6] proposed a plausible analytical response function, represented by the green curve shown in Fig.4, which adds a Gaussian function(the dash curve) to the original Boussinesq's response function (the thin curve) in order to preserve the volume, but the swelling part of this function, theoretically, is very near to the concentrated compressive force, and is not obvious. Therefore, we modulated the original Boussinesq approximation, as the thick curve shown in Fig.4, by adding a shifted Gaussian function(the dot curve) in the opposite direction, as Eq.3:

$$\bar{f}(r) = f(r) + (-g(r)) = f(r) + (-a\exp(-(r-b)^2/2c^2)) \quad (3)$$

where $\bar{f}(r)$ is our modified response function and $g(r)$ the shifted Gaussian function. The shape of the response function is most sensitive to a which controls the swelling height; c which controls the swelling width follows a; and b determines the position of the swelling. The setting of parameters(a=11.0mm, b=2.5mm and c=0.8mm) was chosen based on Eq.2 and by trial and error manner by comparing them with the experiments described in Section.4.

3. Contact Solving Method

An overview of our proposed contact solving method, which includes pre-process and online process, is shown in Fig.5.

Point Force-based Discretization. The discretized contact forces acting at the vertices in contact region can, in general, be presented as the form of pressure distribution. However, the form of the pressure distribution causes much computation and inconvenience in an efficient simulation, especially to our Digital Hand in which an irregular triangular mesh is used. The irregular mesh results in the irregularity problem of force effect, no matter what kind of pressure distribution is used. Therefore, in order to weaken such irregularity, we assumed that point forces replace the pressure distribution, concentratedly acting at vertices. The simplification is reasonable, because the estimation of spatial acuity of human hand skin tested by "two-point touch" is approximately 2-3 mm on fingertips and 10 mm on the palm [11]. On the other hand, for our Digital Hand model, which is based on MRI

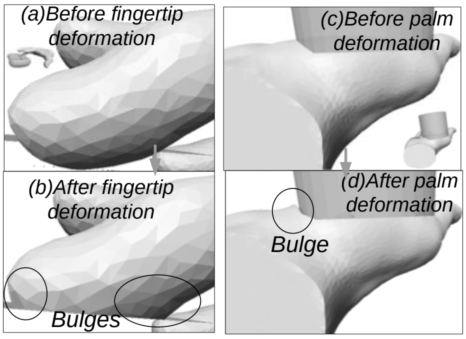

Fig.6 Simulation of fingerpad deformation and palm deformation

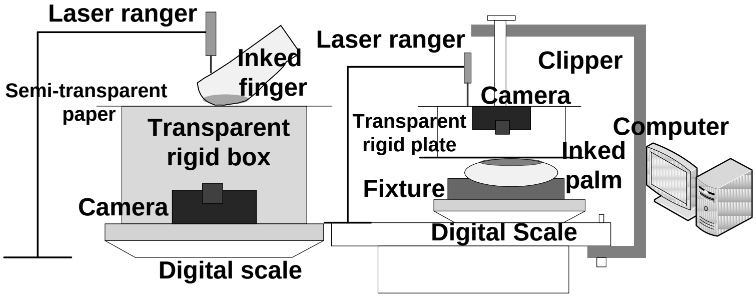

Fig.7 The experiment setting

measurements, its high vertex density (1-3mm among vertices, about 60 vertices/cm^2) can ensure the intensive coverage of point force. Therefore, the assumption does not integrate two separated pressure distributions which humans are able to feel into one concentrated point force. Moreover, such simplification brings efficient simulation performance, because p in Eq.1 can be considered as a constant, and can avoid being numerically integrated for a specific pressure distribution, which is time-consuming.

Isomap. For the 3D Digital Hand, because r must be a geodesic distance of a mesh between two vertices, Isometric Mapping(Isomap) which projects 3D vertices to a 2D plane and preserves geodesic distance was introduced to map r from 3D space to a 2D plane.

Response Matrix. The response relation, R_{ij}, between the displacement, u_i, that the vertex, q_i, experiences, and the force, p_j, acting on the vertex, q_j, can be expressed in the matrix form in Eq.4:

$$\mathbf{u} = \mathbf{Rp}. \tag{4}$$

where $\mathbf{u} = [u_1 \dots u_N]$ is a displacement vector, $\mathbf{p} = [p_1 \dots p_N]$ a corresponding normal force vector, and $\mathbf{R} = \{R_{ij} = \bar{f}(r_{ij})\}$ a system response matrix. r_{ij} is the geodesic distance between q_i and q_j.

For the same Digital Hand, we can pre-compute all the entries of **R** in the pre-process, which enables a relatively fast execution speed in the following online process.

Modeling the Human Hand as a Quasi-rigid Object. In practical simulation, involving all of the vertices lacks efficiency; hence we modeled the human hand as a quasi-rigid object. *Quasi-rigid* [6] indicates that, when objects' surfaces undergo small deformation within the vicinity of contact, called the active region, the remaining shape of the objects still keep. In fact, hand tissue that appears rigid visually is actually deformable, can be modeled in this way. The local deformation in the contact region enables faster simulation.

Collision Detection and the Active Region. A collision detection algorithm [1] was used. Once a collision region is found, by a neighborhood query based on the mesh model, the active region can be defined. In our simulation, the union of the local five ring neighboring vertices for a collided point (radius is about 7-10mm) is used as the active region.

Contact Resolution using LCP. The goal of this step is to realize the deformed surfaces caused by contact without interpenetration. In fact, the forces and their states (intersection, separation or contact) are linearily complementary, i.e., a Linear Complementarity Problem (LCP). By solving the LCP using Lemke's method, the displacement and the force at each vertex can be found to realize skin deformation without intersection.

4. Simulation and Experimental Verifications

Illustrations for the contact solving simulations of a middle fingerpad (penetration depth: 2.98mm) and a palm (6.10mm) are given in Fig.6. The pre-process time for the middle fingerpad (436 vertices) was about 57s, and for the palm (1915 vertices) was about 700s (Intel Core i7, 6GB main memory). As for the online process, our simulation was efficient enough (fingerpad: almost real-time, palm: in deepest depth: 8.5mm, about 31s) for a practical simulation. As shown in Fig.6, the fingerpad and the palm touched the product surfaces without any interpenetration, and obvious bulges resulting from our proposed compressing-swelling effect could be observed.

Experiments which verified the simulation of the fingerpad (subjects: male, 23-26, right middle finger) and palm (subjects: male, 24-51, right hand palm) were conducted. The experimental settings are shown in Fig.7: a laser ranger (KEYENCE IL-030,) was used to measure the penetration depth; a scale (AND EW-12Ki) was used to measure the contact force; a camera (Logitech HD Pro Webcam C910) was used to measure the contact area. The computer was used for image processing (OpenCV) and for synchronous data acquisition. The fixture made of a foam material was used to support and fix the palms. In the fingerpad measurement, the subjects were asked to press the tanspanrent rigid plate coverd by a semi transparent paper using their inked fingerpads. In the palm measurement, the inked palms of subjects were pressed by a transparent rigid plate covered by a semi transparnt paper. At the same time, the measured data were synchronously collected.

Fig.8(a) and (b) and Fig.8 (c) and (d) show the relations among maximum penetration depth, contact area (the sum of area of each triangle in the contact region) and contact force (the sum of point force at each vertex in the contact region) of fingerpad and palm contact deformation, respectively. Our simulation, based on the proposed physical model, generated a larger contact force and contact area than the ones based on Pauly's and the original Boussinesq's functions in the same parameters setting. Our simulation method could effectively match different experimentally measured contact forces of the different subjects by adjusting shear modulus which controls the degree of skin softness (in order fully cover experimental data, we extended the original range of G form 0.040 ~ 0.080MPa [4] to 0.040 ~ 0.120MPa), while the ones based on Pauly's and original Boussinesq's model only covered small portion of the range of the experimental data.

In [7], the volume compressibility of fingerpads was measured experimentally (2 male and 2 female subjects, diameter 6mm indentor). We simulated the experiments using a circle indentor (diameter: 6mm). Our simulation realizes more obvious compressing-swelling effect whose volume compressibility is closer to the experimental ones, and therefore obtains a larger contact area than the simulations based on Pauly's and the original physical model of Boussinesq approximation.

We also verified the pressure distribution (subjects: male, 27, right middle finger, right palm,). The experimental setting is shown in Table 1. Fig.9 shows that the pressure distributions in the fingerpad and the palm estimated by our Digital Hand are similar to the measured ones, even though the dimensions of the Digital Hand is different from those of the subjects' hands.

5. Conclusion and Future Work

We have proposed a new physical model based on modified Boussinesq approximation to model the contact deformation of the human skin within an acceptable range for ergonomic assessment of handheld products, and presented an efficient method for solving the contact. We adopted the biomechanical parameters of in vivo human hand. The realistic contact deformation effect was realized, and the simulation results well approximated the experimental values and data from literatures. Our simulation can provide information, such as contact area, contact force and pressure distribution, as essential measures for the following virtual ergonomic assessment, such as grasping stability and grasping fitness. We are going to integrate our skin deformation simulation with the grasping hand posture for products in the Digital Hand for further evaluation.

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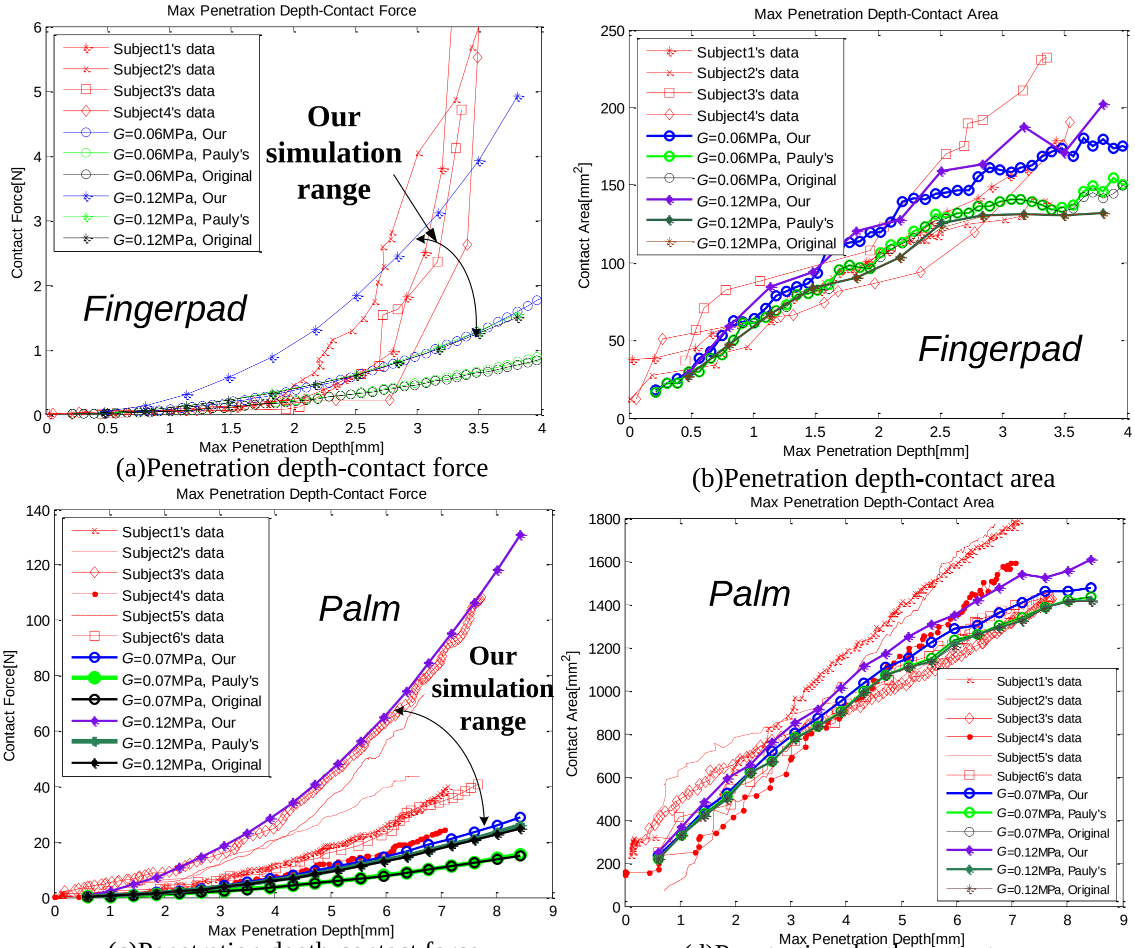
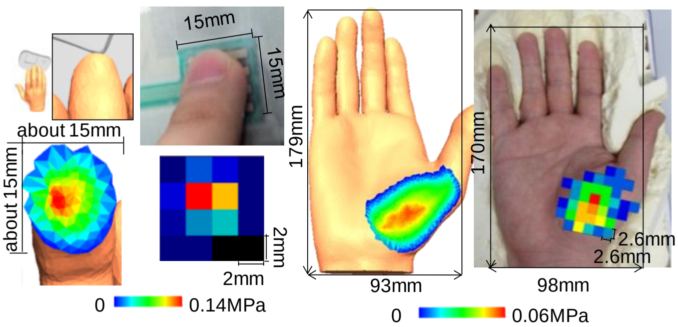


(a)Penetration depth-contact force (b)Penetration depth-contact area

(c)Penetration depth-contact force (d)Penetration depth-contact area

Fig.8 Simulation and experimental verifications



(a)Fingerpad (b)Palm

Fig.9 Pressure distribution verifications

Table 1 Pressure measurements

	Fingerpad	Palm
Measurement device	NITTA GSCAN	NITTA FSCAN
Penetration depth[mm]	3.8	7.6
Sensor size [mm]	2.0*2.0	2.6*2.6
Space between sensors[mm]	2.3	2.5

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