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**PLAUSIBLE 3D HUMAN HAND MODELING FOR
VIRTUAL ERGONOMIC ASSESSMENTS OF
HANDHELD PRODUCT: CONSTRUCTION,
CONTACT SIMULATION AND VARIATIONAL
MODELING**

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Abstract

Handheld products, such as portable digital appliances, have been widely used in daily life and production activities. For their customers, an ergonomic design is always desired for better user experience and high productivity. Therefore, during the development process of handheld products, many grasp factors need to be assessed, for instance, grasp stability, grasp comfort, and grasp safety. 3D human hand modeling and simulation provide significant advantages for ergonomic assessments when incorporated into the early stage of the design process of handheld products. They can, especially, reduce the need for sensory tests on human subjects and also for expensive prototypes, thus reducing costs and time to market. However, current 3D human hand modeling technique that mainly aims to provide visual simulation for game or movie industry (e.g. in famous movie Avatar(2009), CG technique was used to make one lifelike character including hand models) cannot provide a plausible hand model for virtual ergonomic assessment.

Therefore the purpose of this research is to model the human hand for virtual ergonomic assessments of handheld products with an acceptable accuracy. First, the main properties of human hand including surface skin, joint-link structure, and skin contact deformation property need to be modeled to generate a fine template hand model. Moreover, based on a fine template hand model owning the main properties mentioned above, hand model instances, with individual hand size or with specific people's anthropometric statistical characteristics, need to be generated by hand variational modeling method.

This thesis mainly includes the following four topics:

- (1) Based on MRI measurements of human hand, 3D precise human hand modeling for product ergonomic assessments was proposed. The surface skin, the joint-link structure, and the skin deformation caused by joint motion were modeled and experimentally verified.

- (2) The skin deformation caused by contact was efficiently simulated for virtual ergonomic assessment of handheld products. The main properties of human hand skin, nonlinear elasticity and compressing-swelling effect, were realized for precise simulation. The results including estimated contact force, contact area, contact pressure distributions in grasping posture were experimentally verified.
- (3) Variational hand modeling based on image-based 3D model reconstruction was proposed for modeling a hand of a particular person. Experimental verification indicated that the modeling method could model individual hands including hand surface and joint-link structure in a relatively shorter period and with acceptable accuracy for virtual ergonomic assessments of handheld products.
- (4) Based on correlation analysis between anthropometric dimensions from subjects, two major dimensions, hand length and circumference, which can be sampled from a Japanese hand database, are used to predict other hand dimensions for generating hand model instances. By grasping products using these instances in our Digital Hand software, the statistical grasping evaluation indices such as contact area and contact pressure distribution are given.

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Chapter 1

Introduction

1.1 Background

Recently, ergonomic design of hand-held products such as mobile phones, cameras, PC mouse, handy tool, and even beverage containers is seizing the attention of consumers, because they can bring about more comfortable control feeling, more reliable safety and higher working efficiency[1-3]. Therefore, ergonomic assessments play a vital role in the design of handheld product.

Conventional ergonomic assessments are carried out in the form of user-tests which need human subjects and the physical mockups. However, fabricating physical mockups and ensuring sufficient number of subjects costs much, and subjective evaluations are only obtained from the tests which are insufficient for quantitative and objective evaluation of ergonomics and for their redesign.

In addition, in order to decrease the development period, ergonomic assessment are desirable even in the early design stage where product redesign can quickly and easily responses to the ergonomic assessment results, rather than assessing the design after the fabrication of physical mockups. Fortunately, with the wide spread of many 3D CAD system in the design process of handheld products, there is a strong possibility to realize virtual ergonomic assessment by integrating “*digital hand*” models with digital mockups of the handheld products. An example is shown in **Fig. 1-1** where a hand model grasps a digital mockup of a bicycle handle bar with estimated contact pressure distribution.

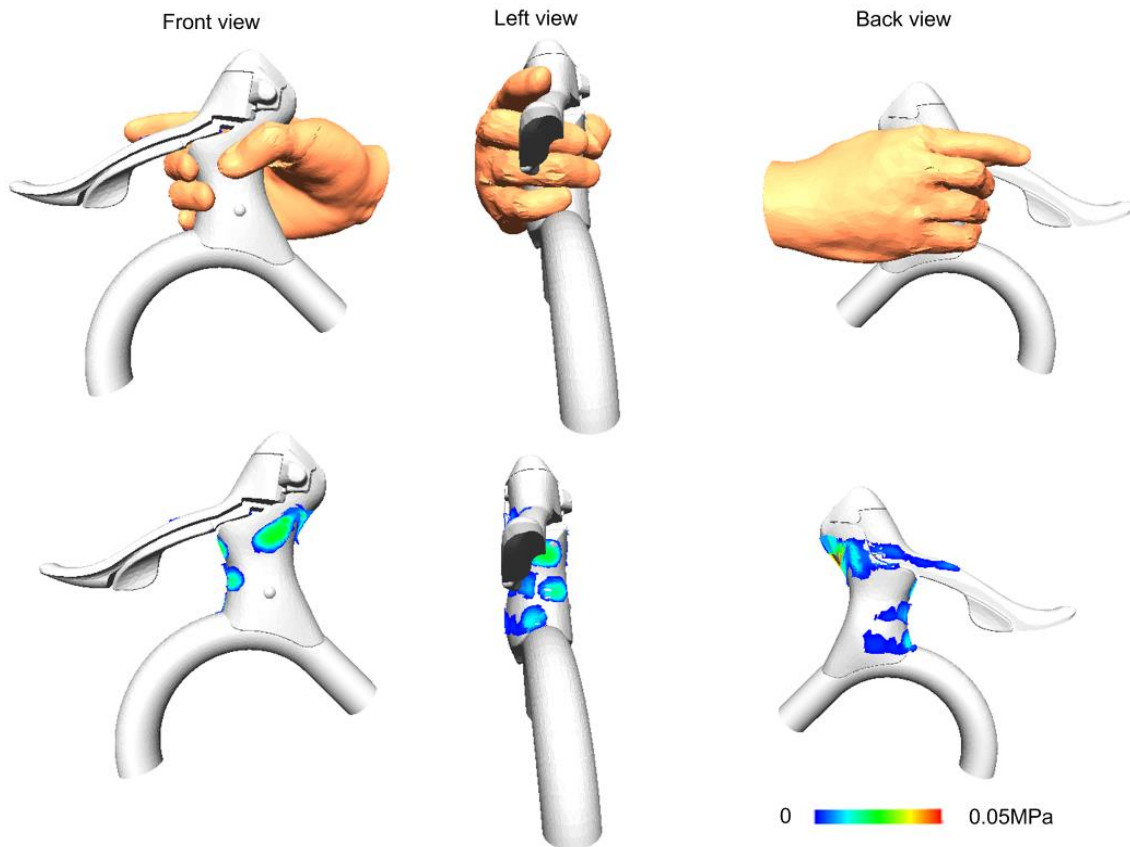


Fig. 1-1 An example of virtual ergonomic assessment by integrating the digital hand model with a bicycle handle bar

Some simulation software using digital human models have been commercialized [4-6] and are being used in the design of automobiles and airplanes. However, the digital hand model included in these human models of such software do not necessarily comply with desired simulation accuracy and efficiency, functionalities and size variation of human hands when evaluating the relevance of grasping and operating the handheld products. Therefore, the requirement of developing a virtual ergonomic assessment system for designing handheld products by integrating the digital hand model with 3-D product model has been increasing.

A typical virtual ergonomic assessment system is shown in **Fig. 1-2**. In a virtual environment (i.e. a computer), hand models and product models are integrated to generate grasp postures, and then they are evaluated to obtain evaluations of grasp. Finally, redesign can quickly and easily responses to the evaluation results. The process can be iteratively executed until the product design satisfying the requirements to the product.

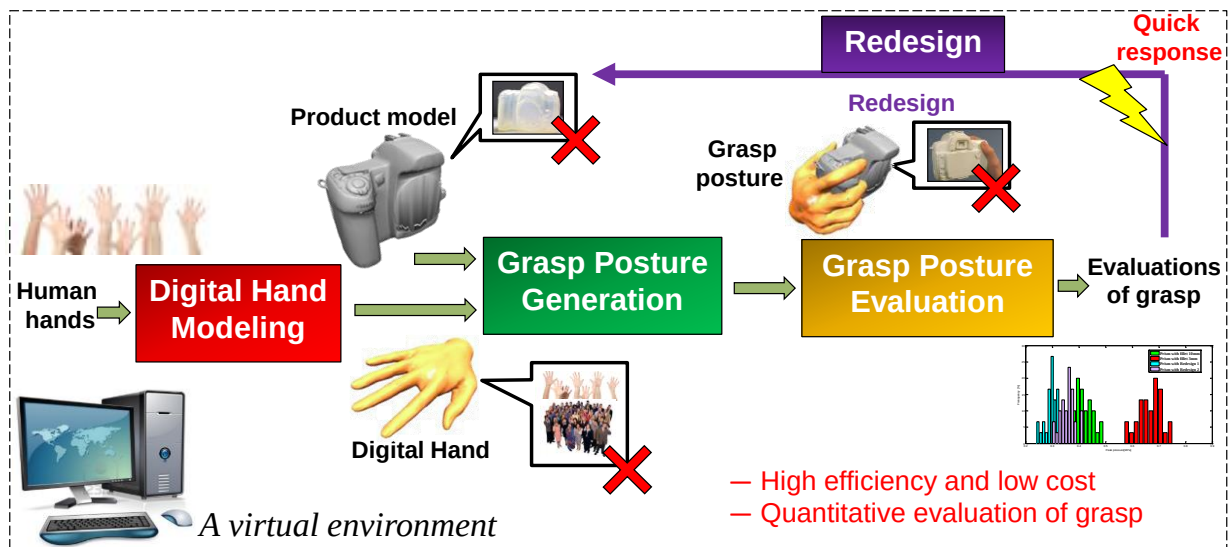


Fig. 1-2 A typical virtual ergonomic assessment system for handheld products

A virtual ergonomic assessment system needs a *Digital Hand* or Digital Hand instances. What is a Digital Hand? Digital Hand is a virtual hand model with hand-like functionalities. In other words, it is a simulation of human hand. For the purpose of virtual ergonomic assessments of handheld products, the simulation must have an acceptable simulation accuracy and efficiency.

For handheld products, grasp posture is the most important when they are used. Therefore, in order to simulate a grasp situation, as shown in **Fig. 1-3**, the following structures and according requirements for virtual ergonomic assessments are necessary:

- Bone-link model
 - Accurate bone length
 - Accurate joint axis
 - Joint range of motion
- Surface skin model
 - Deformation with joint motion
 - Deformation with object contact
- Muscle skeletal model
 - Muscle tendon force distribution
- Size variation model
 - Individual hand model
 - Anthropometric statistical distribution based model

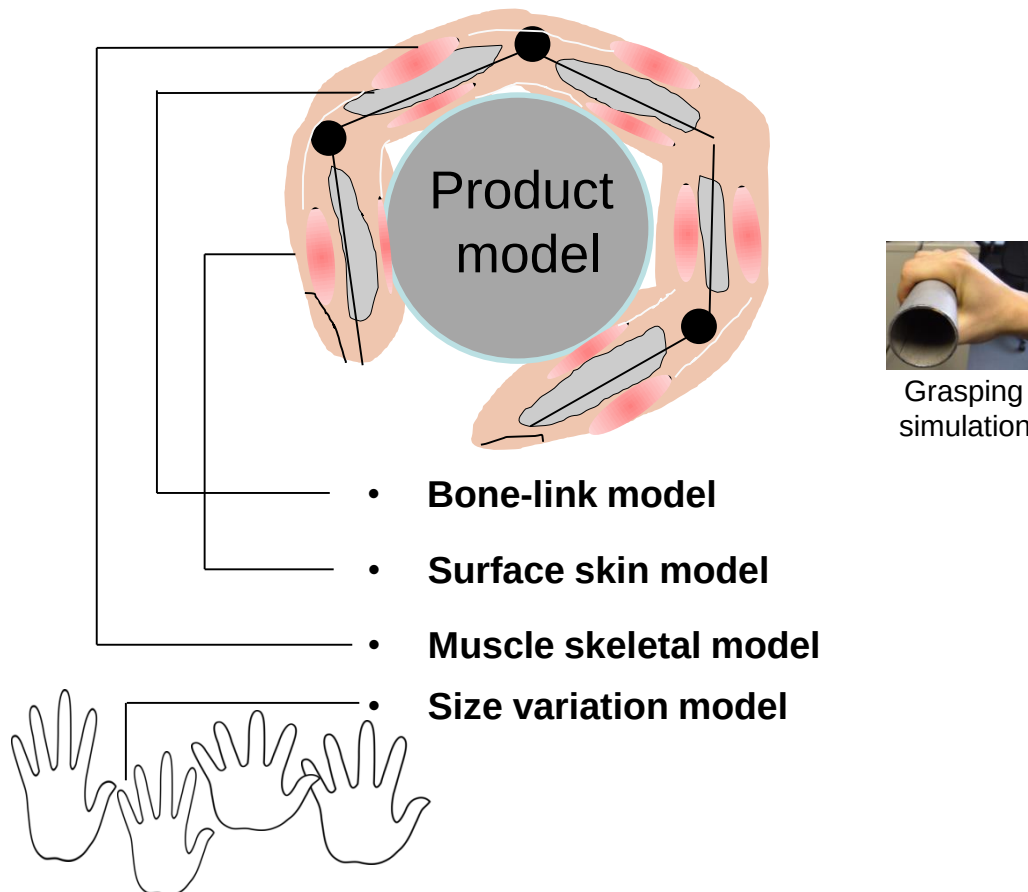


Fig. 1-3 Digital Hand and its structure

To these requirements, some of them have been satisfied; and the remaining are still open issues, which are described in next section.

1.2 Related work

1.2.1 Commercial digital human modeling software

Some digital human modeling software (for example, Jack and Process Simulate Human [4], Poser [5], and Santos[6] (**Fig. 1-4** (a))) has been commercialized, but they mainly aims to provide for industry use, e.g. car, aircraft and ship building, not to provide a plausible hand model for virtual ergonomic assessments. The hand models in the human hand modeling software have the following issues:

- The range of motion (ROM) of finger is not defined.
- Joint structure is rough.
- Skin geometry is rough and cannot be deformed.

1.2.2 Bone-link structure modeling

Some researches on the human hand modeling have been done. The Japanese generic hand model was developed by Kouchi [7], but the finger motion was not verified. Kurihara [8] (**Fig. 1-4 (b)**) proposed a precise 3D bone link model and surface skin model from X-ray CT scan, but their finger joint angle had many redundant D.O.Fs., which is not necessarily suitable of generating virtual grasp postures. Miyata [9] also developed the finger joint models from MRI images, but only the 1 D.O.F motion of flexion/extension at DIP, PIP and IP joints were modeled, and 2 D.O.F joint motion of thumb which is most important for realizing the oppositions of the human grasp was ignored.

1.2.3 Generation and evaluation of grasp postures

Endo et al. [10-12] (**Fig. 1-4 (c)**) proposed the *Digital Hand* which is a 3D virtual hand model and a virtual ergonomic assessment system for handheld product. The simulation in the Digital Hand software enables the user to generate plausible grasp postures and to predict the quantitative measures of grasp such as *grasp stability*, *ease of grasp* and *grasp fitness* based on these models. And the skin deformation along with finger joint motion was realized.

However, due to the lack of simulating the contact between hand skin and product surface, several important quantitative indices for ergonomic assessments, such as contact area, contact force and contact pressure distribution, cannot be obtained from this system.

1.2.4 Skin contact deformation simulation

Many studies of skin contact deformation simulation have been done in many fields; robotics, biomechanics, computer graphics, etc.. FEM-based method [13-19] is accurate but time consuming, e.g. in [19] the generation of a facial skin deformation took about 5 min, which is too long for a virtual ergonomic assessment system. Other physics-based methods [20, 21] (**Fig. 1-4 (d)**) can realize visually realistic deformations. However, they choose the material parameters arbitrarily which do not resemble human skin in the real world. In addition, their studies are lack of experimental validations.

1.2.5 Variational hand modeling

Kouchi et al. [7] utilized factor analysis to evaluate 82 measurements from 103 Japanese subjects, and then found two principle factors to represent the dimensions of Japanese hands. The individual hand skin models could be created by scaling a generic hand by the optimization process. However, there is a lack in the variation for the internal joint-link structure. Rhee et al. [22] proposed a variational hand modeling method based on a palm side photo, and the finger joint centers were estimated by the main creases on the palm side. However, the thickness of the hand was ignored in their method, and the estimated joint centers were not verified dynamically in different hand postures. Similarly, Albrecht et al. [23] employed an image-based hand deformation method to generate individual hand models. However, the accuracy of hand posture in 3D position cannot be guaranteed, because the correspondences can only be obtained between 3D feature points in reference hand model and the 2D hand picture. Shimizu et al. [24] and Kurihara and Miyata [8] have made use of medical images (MRI and CT) to construct person-specific hand which includes skin and the estimation of joint locations, however medical image based method is costly and time-consuming.

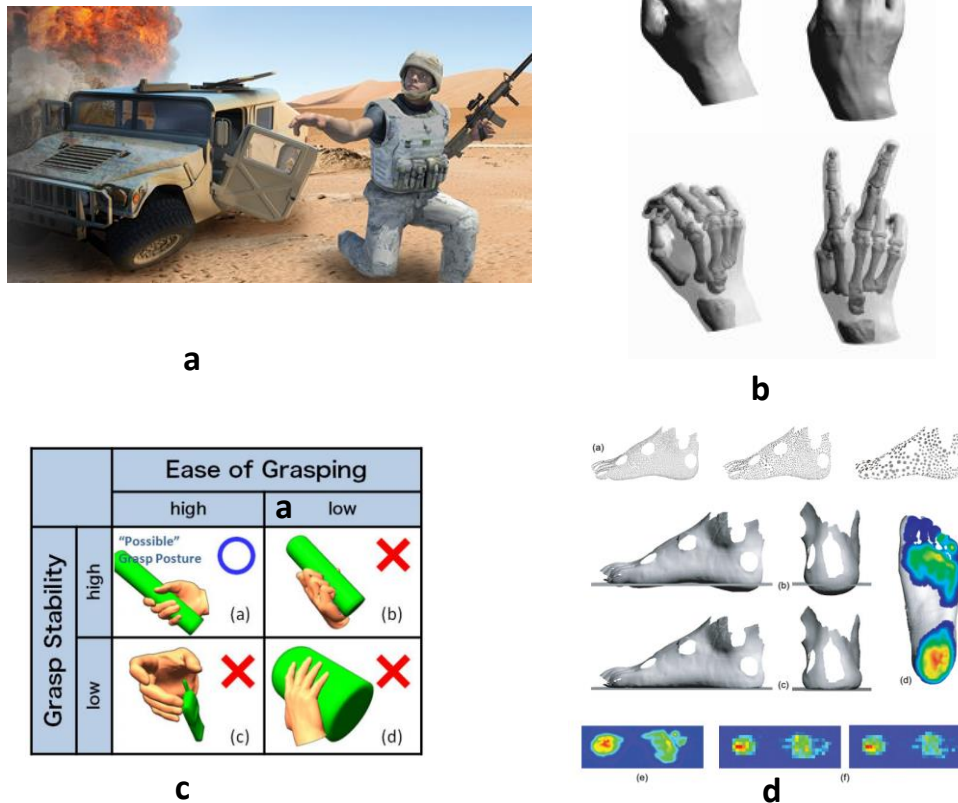


Fig. 1-4 The related work. (a) Santos digital human [6], (b) Skin shape and bone shape reconstructed from CT images [8], (c) Ease of grasp [12], and (d) Contact of a deformable human foot with a rigid ground plane [20]

1.3 Objectives

The goal of this research is to develop a software system for virtual ergonomic assessment of handheld products with an acceptable simulation accuracy and efficiency. To achieve this goal, the objectives of this thesis are summarized as follows:

- 1) A method to model the main properties of human hand including surface skin model, joint-link structure, and skin contact deformation property in a 3D hand model is proposed.
- 2) Based on the above-mentioned precise hand model as a template model, a method to generate hand model instances with individual hand sizes or with specific people's anthropometric statistical characteristics is proposed.

1.4 Approaches and organization of this thesis

This thesis is divided into 6 chapters including the current chapter 1. The main body of this thesis consists of Chapter 2 ~ 4, and their organization is shown in **Fig. 1-5**.

The first objective of this thesis is solved in Chapter 2 and Chapter 3. As shown in the upper part of **Fig. 1-5**, in Chapter 2 and Chapter 3 we describe how to construct a precise hand model which has a similar structure and functionality with a real human hand.

In Chapter 2, based on accurate MRI (Magnetic Resonance Imaging) measurements, a hand model is constructed which has an external skin model and internal joint-link structure. Human hand finger motions and skin deformation caused by finger motions can be reproduced realistically. Verification of this model is given in the last part of this chapter.

Based on the hand modeling method of Chapter 2, how to efficiently simulate skin contact deformation is described in Chapter 3. Two vital properties of human skin, non-linear elasticity and compressing-swelling effect are realized. The estimated contact force, area, and pressure distribution which are validated experimentally, are given in the last part of this chapter.

The second objective of this thesis is solved in Chapter 4 and Chapter 5. As shown in the lower part of **Fig. 1-5**, Chapter 4 and Chapter 5 describe how to generate hand model variation from a template hand model generated by the method proposed in Chapter 2 and Chapter 3.

In Chapter 4, individual hand model which includes skin model and joint-link structure can be generated by an image-based 3D hand model reconstruction technique. The results are compared with MRI-based hand modeling method in aspects of modeling time and the accuracy.

In Chapter 5, based on correlation analysis between hand dimensions obtained from subject tests, the sampling major dimension from a Japanese hand dimension database are inputted into the hand modeling system proposed in Chapter 4 to generate hand model instances. Through grasping a variety of product models in the environment of Digital Hand system using the generated hand model instances, the statistical information for ergonomic assessment is given.

Chapter 6, the final chapter, draws on the general conclusions of the previous chapters.

1.5 Originalities

The originalities of this thesis are listed as follows.

- 1) A MRI-based hand modeling method is proposed. It accurately model individual hand skin surface geometry with the skin surface deformation around the ball of the thumb caused by the joint's motion, and joint-link structure which approximate the 3D motion of thumb carpometacarpal (CMC) joint.
- 2) An efficient hand skin contact deformation simulation is presented. Two important properties of human skin, non-linear elasticity and compressing-swelling effect are realized, which enables to accurately estimate contact area, force, and pressure distribution.
- 3) An image-based variational hand modeling method is proposed. Only low-cost commercial cameras are requested. 3D hand models with individual sizes and joint-link structure with acceptable accuracy can be obtained efficiently.
- 4) A statistical variational hand generation method is presented. Hand model instances which follow specific people's anthropometric statistical characteristics can be generated. By grasping products using these hand model instances, the statistical distributions of grasping evaluation indices such as contact area and contact pressure distribution are given for ergonomic assessments.

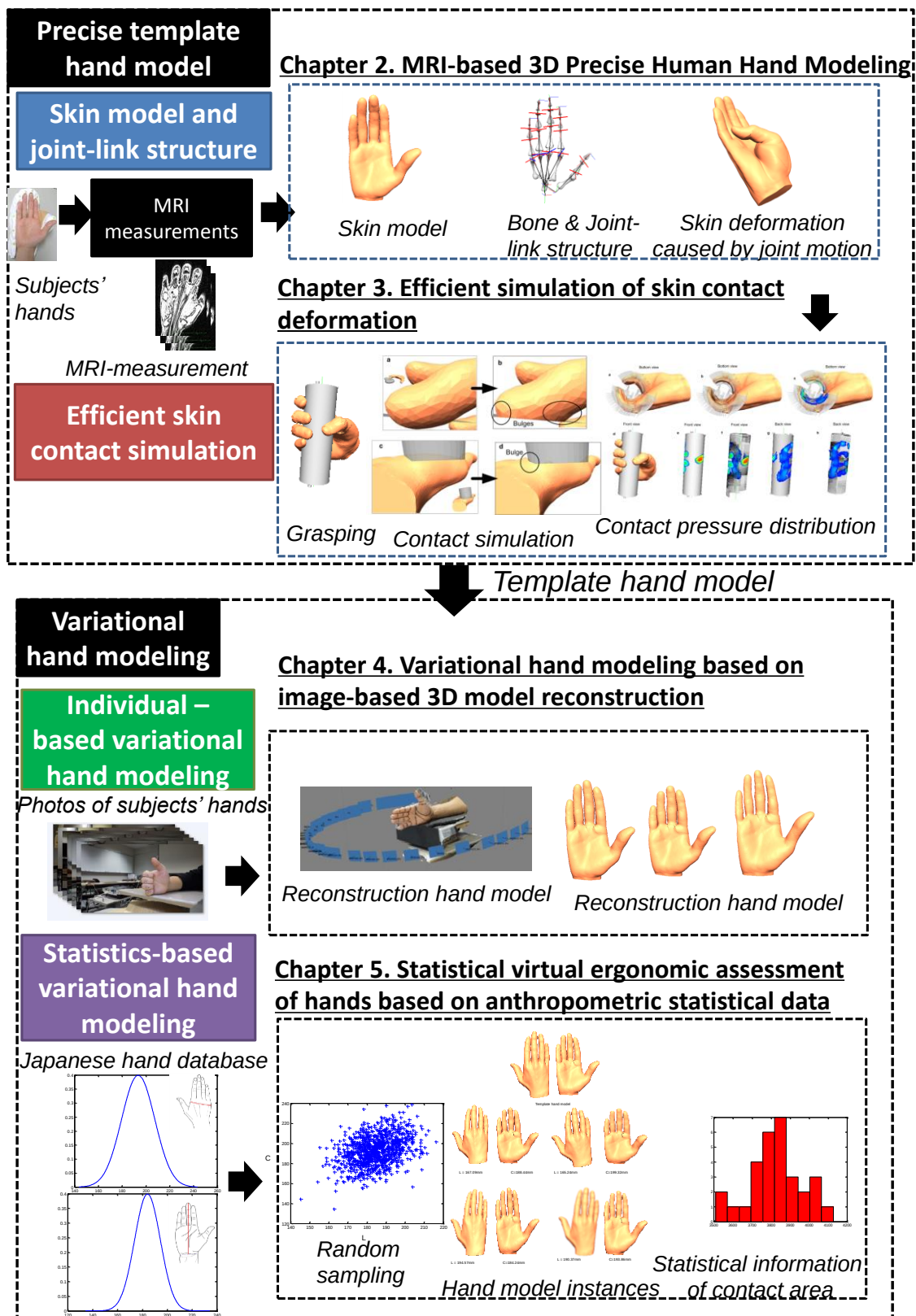


Fig. 1-5 Organization of this thesis

Chapter 2

MRI-based 3D Precise Human Hand

Modeling

2.1 Introduction

Recently, ergonomic assessments for hand-held products such as mobile phones, cameras, beverage containers are becoming important to gain their market competitiveness. Conventional ergonomic assessments are carried out in the form of user-tests which need many human subjects and the physical mockups. Unfortunately, fabricating physical mockups and ensuring sufficient number of subjects costs much, and subjective evaluations are only obtained from the tests which are insufficient for quantitative and objective evaluation of ergonomics and for their redesign.

Virtual ergonomic assessment for hand-held products have been recently studied to reduce the prototyping and user-test costs, and to perform quantitative and objective assessments of quality of grasping the products. In these studies, both a precise 3D model of a human hand and a 3D CAD model of the product were first built in a computer, and virtual grasp posture is then generated automatically or manually. A few of them already implemented functions of assessing quality of grasp at virtual grasp postures. Force closure and 3D grasp quality which were originally introduced as the metrics of robotic grasping were already used for evaluating grasp postures of human hands[10, 25] and for selecting desirable virtual grasp postures[26]. The other metrics of assessing quality of grasp have been

also studied based-on dynamics[27], finger-joint angle distribution [12, 28] and grasp fitness between finger shape and product shape[29].

As mentioned in Section 1.1, Digital Hand is a virtual hand model with hand-like functionalities. At first stage, as a basis of other functionalities of hand, a hand model which can reproduce the finger motion and skin deformation of human hand is strongly needed. Some researches on the human hand modeling have been done. The Japanese generic hand model was developed by Kouchi [7], but the finger motion was not verified. Kurihara [8] proposed a precise 3D bone link model and surface skin model from X-ray CT scan (**Fig. 2-1**), but their finger joint angle had many redundant D.O.Fs., which is not necessarily suitable of generating virtual grasp postures. Miyata [9] also developed the finger joint models from MRI images, but only the 1 D.O.F motion of flexion/extension at DIP, PIP and IP joints were modeled, and 2 D.O.F joint motion of thumb which is most important for realizing the oppositions of the human grasp was ignored. Therefore, the digital hands in previous researches could not fully approximate the 3D motion of the thumb carpometacarpal (CMC) joint and the skin surface deformation around the ball of the thumb caused by the finger or thumb joint's motion.

MRI measurement (**Fig. 2-2**) has a higher accuracy, and by changing the valued of intensity, fine skin shape geometry and bone geometry can be extracted. Therefore, in this chapter, we propose a new method of MRI-based modeling of a digital hand whose precision is sufficient to reproduce virtual grasp postures for ergonomic assessments.



Fig. 2-1 Skin shape and bone shape reconstructed from CT image [8]

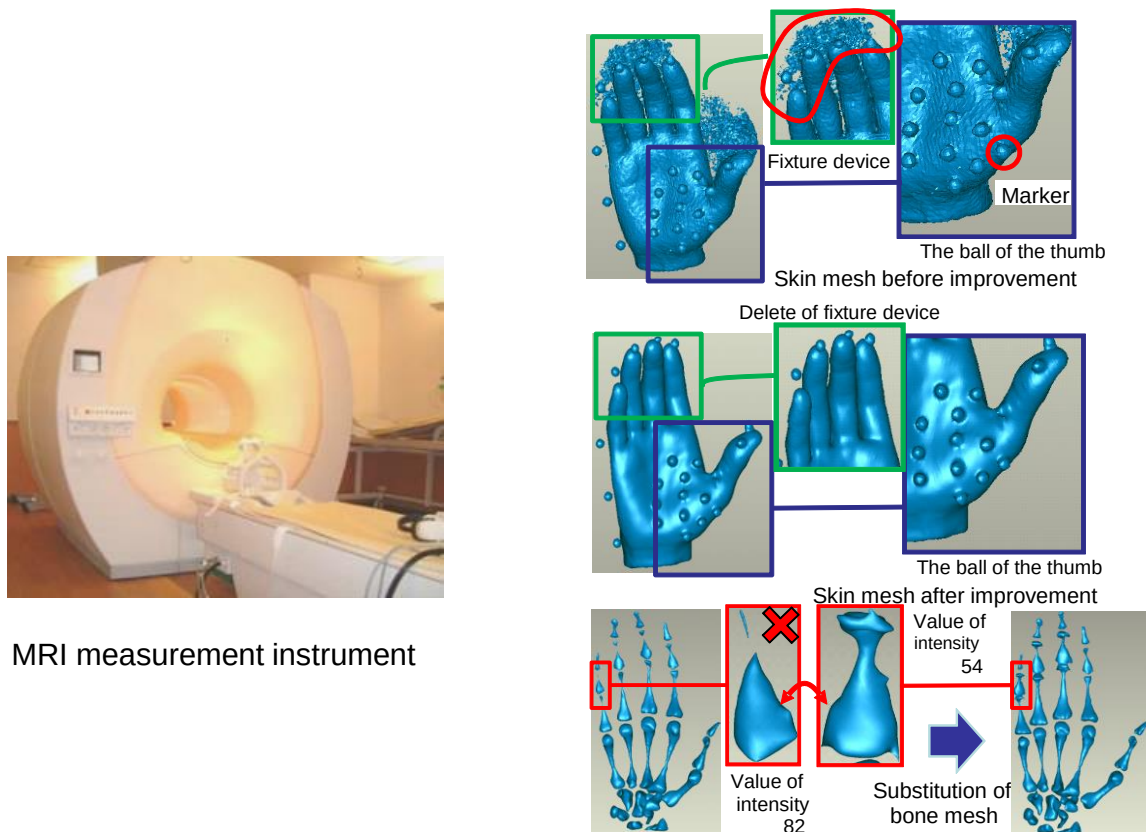


Fig. 2-2 MRI measurement instrument and the processes extracting skin and bone shape geometry

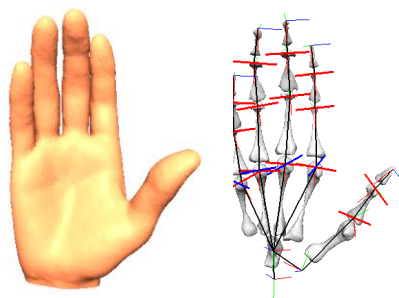


Fig. 2-3 The skin surface model and bone-link model of Digital Hand

2.2 Human hand modeling methods

2.2.1 Outline of the human hand modeling method

The digital hand model in our study mainly consists of a *bone link model* and a *skin surface model* as shown in **Fig. 2-3**. Both models are created from MRI measurements of a

real human hand by using the proposed method. The outline of the method is shown in **Fig. 2-4**.

- I. Multiple postures of a subject's hand shown in **Fig. 2-6** are measured by MRI (A1).
- II. 3D triangle mesh of bones and a skin of a hand are extracted from the MRI images using a Marching cubes [30], and there noise in the images is eliminated and the vertex positions of the models are smoothed (A2).
- III. Relative positions and orientations of meshes of a particular bone at different postures are matched each other using ICP algorithm. A single rotation or quaternion interpolation joint motion is derived from the obtained 3D transformation, the calculated center of rotations and the rotation axis direction [8, 9] in order to complete the bone link model (A3).
- IV. A portion of the vertices of the skin surface model is assigned to a certain bone automatically to enable the surface skin deformation using skeletal-subspace deformation (SSD). Moreover, by comparing the deformed skin surface simulated by SSD to an actual skin at the flexion, the accuracy of skin deformation around the ball of the thumb is improved by applying RBF interpolation to SSD [8] (A4).
- V. For the bone link model and the surface skin model derived in III and IV, precision verification is performed. The motion errors of the bones and grasp contact area are evaluated (A5).

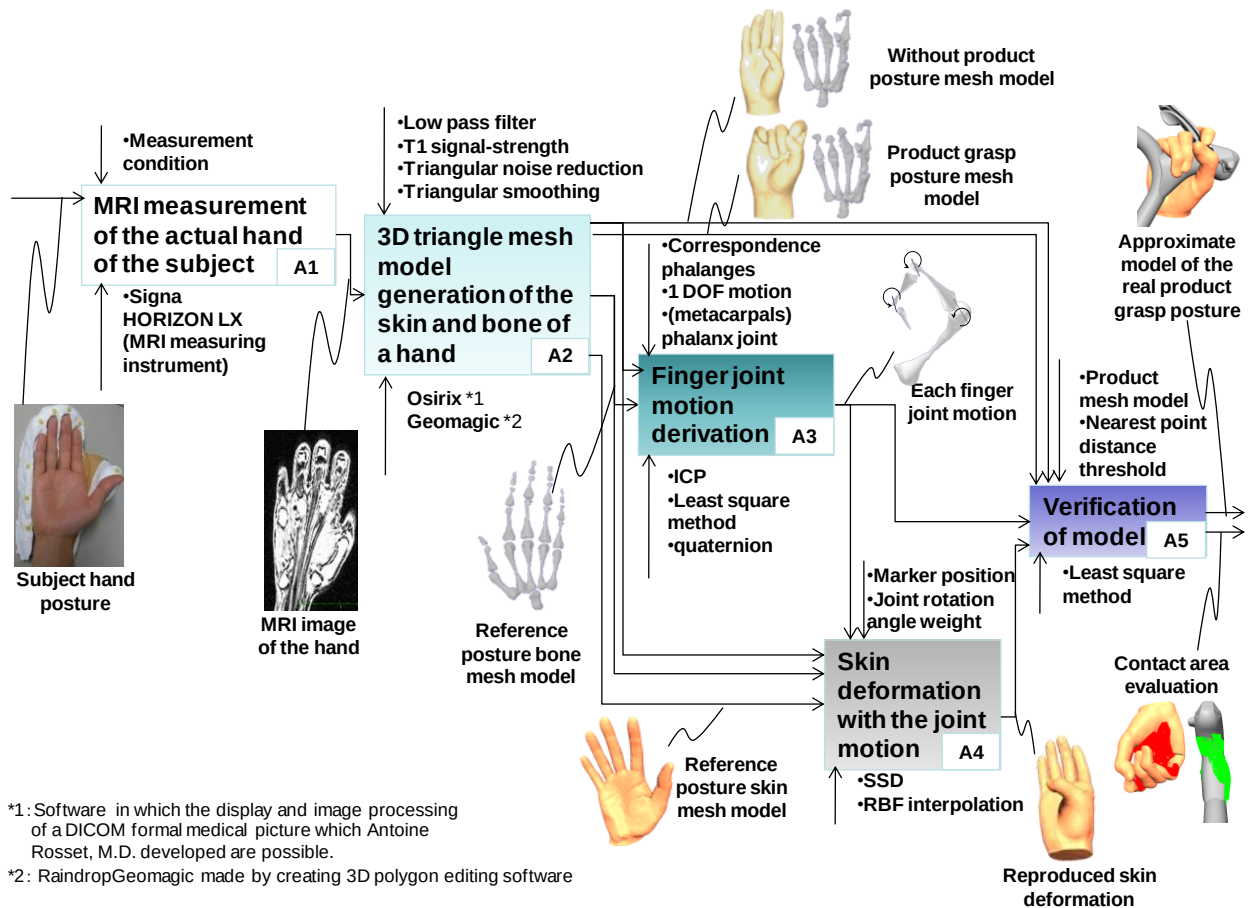


Fig. 2-4 Outline of the proposed precise human hand modeling method.

2.2.2 Structure of bone link model

The bone link model in this study has the link and joint structures shown in **Fig. 2-5**. The degrees of freedom (DOF) of the joint structures are modeled based on anatomical knowledge [31]. Each metacarpophalangeal (MP) joint of four fingers has 2DOF rotations; flexion/extension and adduction/abduction. Each proximal interphalangeal (PIP) joint and distal interphalangeal (DIP) joint of them has 1DOF rotation of flexion/extension. While the CMC joint of a thumb has 2DOF where both flexion/extension and adduction/abduction accompanied with pronation/supination motions cannot be simply modeled as simple rotations [31]. On the other hand, the MP and IP joints of a thumb have 1DOF of simple rotation.

2.2.3 MRI measurement of a subject's hand

MRI measurement is performed with multiple postures as shown in **Fig. 2-6** for two male subjects without any medical injuries in their hands. The measurement condition is shown in **Table 2-1**. Twelve small markers of 5mm diameter were placed on the skin around the ball of the thumb when the postures of **Fig. 2-6(a)** and (b-1) ~ (b-4) were measured to acquire the actual skin surface deformations.

2.2.4 3D triangle mesh model generation of the bone and skin of hand

In order to extract the 3D triangle mesh model obtained MRI images, medical image-processing software (Osirix [32]) and 3D mesh processing software (Geomagic [33]) were used. The MRI volume images are first smoothed by a low pass filter, and iso-surfaces of the bones and the skin surfaces are extracted respectively in the form of triangular mesh models by setting different threshold values of intensity using Marching cube algorithm [30]. Moreover, unwanted minute objects caused by the measurement noise were deleted manually, and the mesh models of bones and skins were converted into subdivision surfaces to improve their surface smoothness.

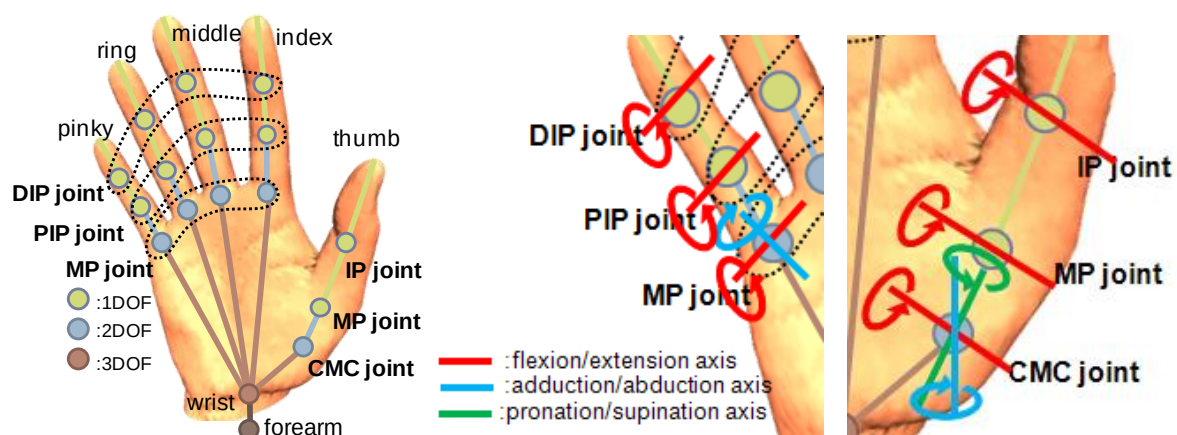


Fig. 2-5 Joint degree of freedom and joint axis arrangement model based on anatomical insight.



Fig. 2-6 MRI measurement postures.

Table 2-1 MRI measurement condition

Scanning image	T1 weighted magnetic resonance image
Magnetic field strength	1.5T
Resolution	256×256
Thickness of the slice	1.0mm
Number of slice	124
Pixel size	0.78mm
Measuring time	3 min 56 sec
Marker	Oral refreshing capsule
Fixture device material	Paper clay

2.2.5 Deriving finger joint motions of the bone link model

Joint motions are derived from comparing 3D positions and orientations of phalanges at different grasp postures. First, the mesh model of a phalange at the reference posture (relaxed natural posture) and the one of the same phalange at a bended posture are chosen manually in our developed software. Then the position and orientation of these two mesh

models are matched together using ICP algorithm as shown in **Fig. 2-7**. The 4×4 rigid body transformation matrix $\mathbf{T}^{ICP}$ which gives the minimum matching error between a vertex $\mathbf{v}_{c(i)}^T$ of the model at the bended posture and its corresponding vertex $\mathbf{v}_i^S$ at the reference posture is derived by calculating the least square solution of the equation (2-1).

$$\min_{\mathbf{T}^{ICP}} \sum_{i=1}^{N_s} \left\| \mathbf{T}^{ICP} \mathbf{v}_i^S - \mathbf{v}_{c(i)}^T \right\|^2 \quad (2-1)$$

where N_s is the number of vertices of the model of reference posture, and $\mathbf{v}_i^S, \mathbf{v}_{c(i)}^T$ homogeneous coordinates of a vertex and its correspondence vertex.

If we assume that $\mathbf{T}^{ICP}$ can only be expressed as a single axis rotation and $\mathbf{p}_a$ is an arbitrary point vector on the rotational axis (a rotation center), the single axis rotation matrix $\mathbf{T}^{Axis}$ can be expressed as equation (2-2) where $\mathbf{R}^{ICP}$ is 3×3 rotational sub-matrix in $\mathbf{T}^{ICP}$.

$$\mathbf{T}^{Axis} = \begin{bmatrix} \mathbf{E} & \mathbf{p}_a \\ \mathbf{0}^T & 1 \end{bmatrix} \begin{bmatrix} \mathbf{R}^{ICP} & \mathbf{0} \\ \mathbf{0}^T & 1 \end{bmatrix} \begin{bmatrix} \mathbf{E} & -\mathbf{p}_a \\ \mathbf{0}^T & 1 \end{bmatrix} = \begin{bmatrix} \mathbf{R}^{ICP} & -\mathbf{R}^{ICP} \mathbf{p}_a + \mathbf{p}_a \\ \mathbf{0} & 1 \end{bmatrix} \quad (2-2)$$

Therefore, by replacing $\mathbf{T}^{ICP}$ by $\mathbf{T}^{Axis}$ in equation (2-1) and by finding the least square solution of $\mathbf{T}^{Axis}$ for equation (2-1), we can obtain the optimum rotation center $\mathbf{p}_a$ as $\mathbf{p}_a = (\mathbf{E} - \mathbf{R}^{ICP})^{-1} \mathbf{t}^{Axis}$, where $\mathbf{t}^{Axis}$ is the 3×1 translation components of $\mathbf{T}^{Axis}$. Similarly, the optimum rotation axis direction can be derived from 3×3 rotational submatrix in $\mathbf{T}^{Axis}$ by the following equations:

Given a rotation matrix $\mathbf{R}$, a vector $\mathbf{u}$ parallel to the rotation axis must satisfy:

$$\mathbf{R}\mathbf{u} = \mathbf{u} \quad (2-3)$$

According to the definition of eigenvector:

$$\mathbf{R}\mathbf{u} = \lambda \mathbf{u} \quad (2-4)$$

Therefore, $\mathbf{u}$ is an eigen vector of $\mathbf{R}$ correspond to the eigen value $\lambda=1$, which can be solved by finding the eigen vectors of $\mathbf{R}$.

The derived single joint rotation axis from the models of **Fig. 2-7** is shown in **Fig. 2-8**.

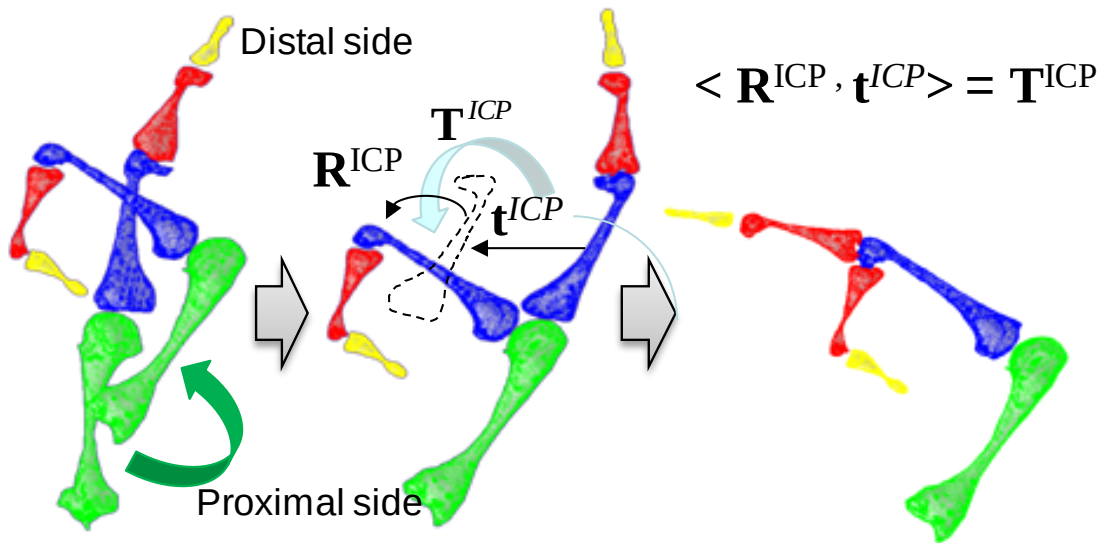


Fig. 2-7 ICP matching of the same phalange.

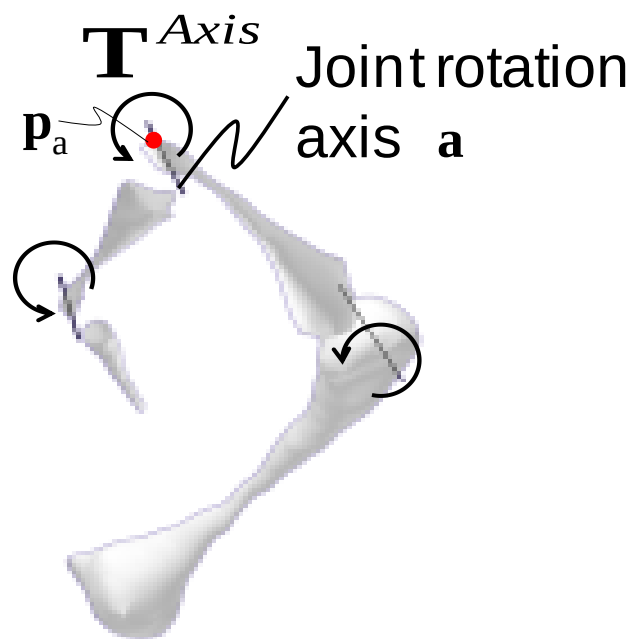


Fig. 2-8 The single joint rotation axis.

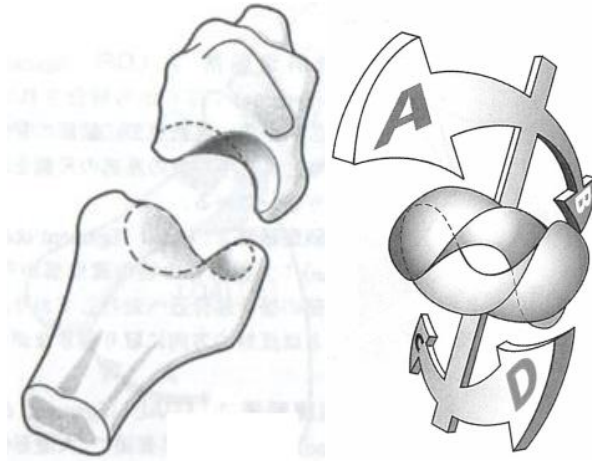


Fig. 2-9 The anatomical model of the thumb CMC joint.

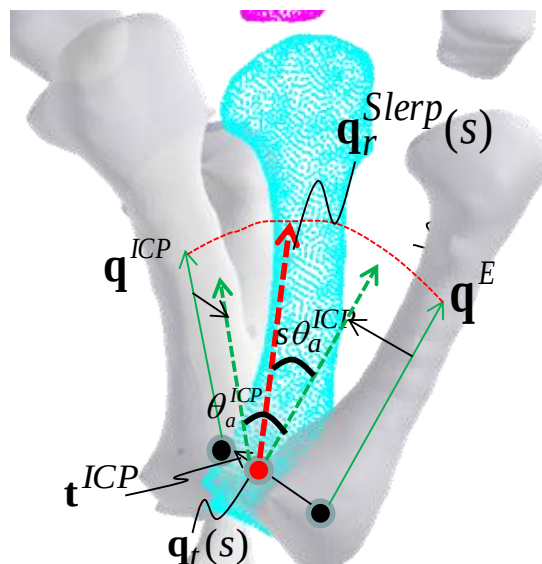


Fig. 2-10 Joint motion including the spherical linear interpolation by the quaternion.

On the other hand, since, as the anatomical knowledge, contact surfaces at CMC joint of a thumb is known to have saddle-like geometries as indicated in **Fig. 2-9**, if we approximate the CMC joint motion as a single axis rotation, the bone link model cannot accurately reproduce the actual joint motion. Therefore, in our model, the combination of the linear interpolation of translation and the spherical linear interpolation of the quaternion is adopted as the CMC joint motion of the thumb. In the interpolations, the translation vector $\mathbf{t}^{ICP}$ of $\mathbf{T}^{ICP}$ and the quaternion expression $\mathbf{q}^{ICP}$ of the rotation component $\mathbf{R}^{ICP}$ can be simultaneously interpolated by the equations (2-5) and (2-6) using an interpolation coefficient $s(0 \leq s \leq 1)$ as shown in **Fig. 2-10**.

$$\mathbf{q}_t(s) = \mathbf{s} \mathbf{t}^{ICP} \quad (2-5)$$

$$\mathbf{q}_r^{Slep}(s) = \frac{\sin(1-s)\theta_a^{ICP}}{\sin\theta_a^{ICP}} \mathbf{q}^E + \frac{\sin s\theta_a^{ICP}}{\sin\theta_a^{ICP}} \mathbf{q}^{ICP} \quad (2-6)$$

where θ_a^{ICP} is a rotation angle about the axis of single axis of rotation derived from $\mathbf{R}^{ICP}$, $\mathbf{q}^E$ a quaternion of unit matrix, $\mathbf{q}_t(s)$ an interpolated translation vector, and $\mathbf{q}_r^{Slep}(s)$ an interpolated quaternion.

2.2.6 Modeling skin deformation with the joint motions

Next, in order to reproduce accurate skin deformation especially in flexion postures, a skin deformation model along with the finger's and thumb joint motions is generated. The surfaces of four fingers and a thumb in the skin surface model are deformed followed by each joint rotation angles. The deformation is based on SSD [8] where an object surface can be smoothly deformed by rotating skeletons placed inside the object.

In our skin surface model, the vertex positions on the finger skin before and after the deformation are governed by the rotation angles of each joint, and are expressed as;

$$^{Skin}\mathbf{v}_i^j = Rot(\mathbf{u}_{ICP}, w_{1,i}^j w_{2,i}^j \theta^j) ^{Skin}\mathbf{v}_i^j \quad (2-7)$$

where $^{Skin}\mathbf{v}_i^j$, $^{Skin}\mathbf{v}_i^j$ are vertex positions after/before the deformation, $\mathbf{u}_{ICP}$ the rotation axis vector of $\mathbf{R}^{ICP}$, θ^j the rotation angle of the joint j .

$w_{1,i}^j$ and $w_{2,i}^j$ are the weights assigned to each vertex i of the skin surface model, and they express how the position of vertex i should be rotated along with the rotation of a joint j . $w_{1,i}^j$ is the weight that controls the palm side contraction and the back side extension of the surface area near the joint as shown in **Fig. 2-11(a)**. The weights of vertices in the steady area are set to 0, and those in the rigid transformed area set to 1. Those in the contracted and the extended areas are assigned to the weights ranging from 0 to 1 which change linearly to the joint rotation angle. Meanwhile, $w_{2,i}^j$ is weight which sets up the amount of the influence of the j -th joint rotation on the i -th vertex, the value is predetermined based on the relative position of the vertex in two ellipses shown in **Fig. 2-11(b)**, and controls of the influence of the joint rotation on the skin deformation.

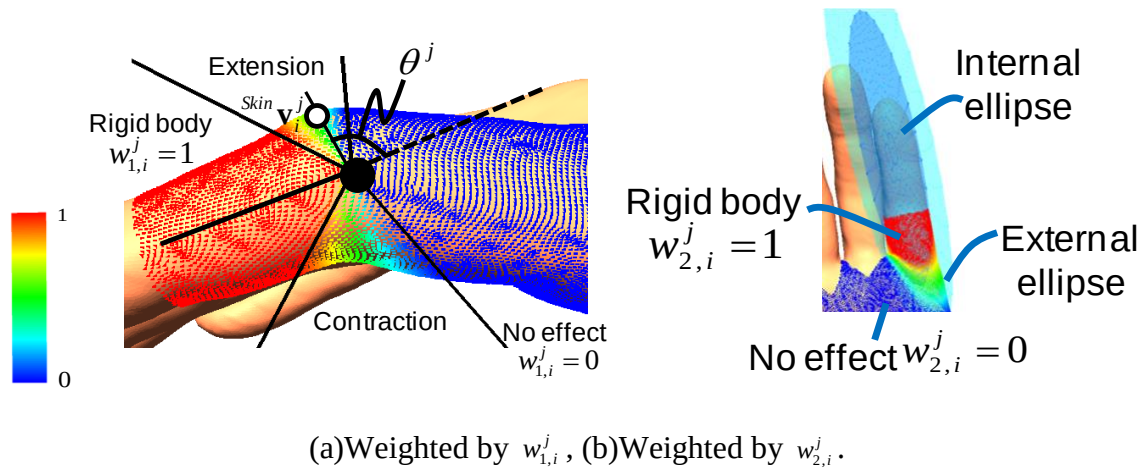
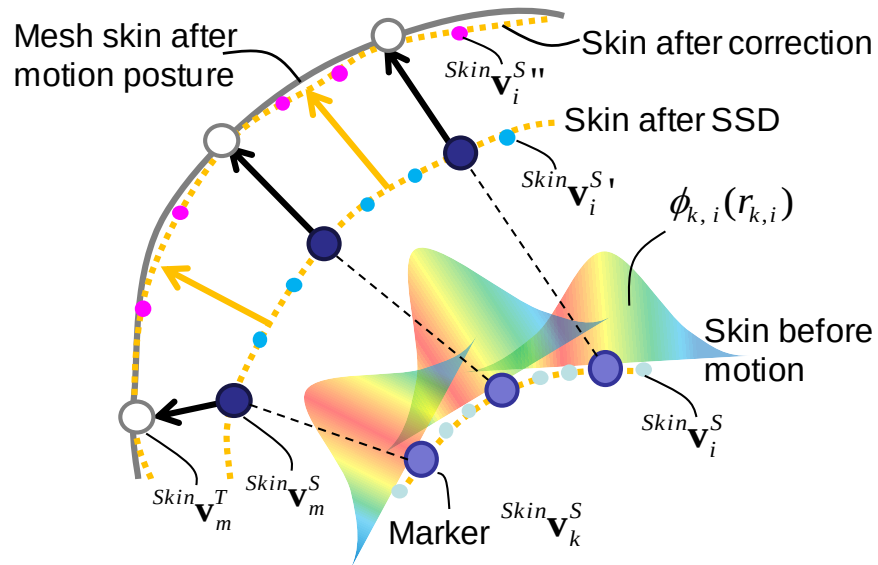


Fig. 2-11 Weight distribution and deformation.



Since skin surface deformation according to the motion of the thumb's CMC joint is much larger than the one according to the motion of the other joints, sufficient amount of skin deformation cannot be produced around the thumb's CMC joint only by using SSD. Therefore, the deformation shortfall generated by SSD is compensated by measuring the positions of markers placed on a real deformed skin surface at four limit postures such as flexion. In the compensation, first, the vertex on the real skin surface mesh which is closest to a marker around the ball of the thumb is selected as a *marker vertex*. The displacement between the marker vertex and the surface skin deformed only by SSD is then compensated. For this, a compensation vector is added to every vertex on the skin surface model where the displacements measured at the discrete marker vertices are interpolated by RBF in equation (2-8) (**Fig. 2-12**).

$$^{Skin}\mathbf{v}_i^{S'} = ^{Skin}\mathbf{v}_i^S + s \left(\sum_{k=1}^{N_{marker}} \phi_{k,i}(r_{k,i}) \mathbf{d}_k \right) \quad (2-8)$$

where $^{Skin}\mathbf{v}_i^{S'}$ is a vertex position for $^{Skin}\mathbf{v}_i^S$ after compensation, $r_{k,i}$ a distance from a marker vertex $^{Skin}\mathbf{v}_k^S$ to a vertex $^{Skin}\mathbf{v}_i^S$ on the skin surface model, N_{marker} the number of markers. $\phi_{k,i}(r_{k,i})$ is an exponential-type radial basis function with a constant $\beta = 3.6 \times 10^{-3}$ which is defined by equation (2-9), s an interpolation coefficient defined in Section 2.2.5.

$$\phi_{k,i} = \exp(-\beta r_{k,i}^2) \quad (2-9)$$

The compensation vector $\mathbf{d}_k$ must be determined so that the marker vertex position $^{Skin}\mathbf{v}_m^{S'}$ should be identical with the one of the marker vertex $^{Skin}\mathbf{v}_m^T$ measured from MRI at a limit posture.

$$s \left(\sum_{k=1}^{N_{marker}} \phi_{k,m}(r_{k,m}) \mathbf{d}_k \right) = ^{Skin}\mathbf{v}_m^T - ^{Skin}\mathbf{v}_m^S \quad (2-10)$$

This deformation compensation by RBF is only applied to the skin area near the ball of the thumb, and enables a precise skin deformation of the palm side of our digital hand.

2.3 Verification of the models

The average motion error of each phalange moved from the reference posture to each limit posture is shown in **Table 2-2** and **Table 2-3**. For the reference, the motion errors only generated by using ICP are also indicated in the Tables which show inevitable lower limits of

the errors. The errors were estimated by taking the average results of two adult male subjects (ranging aged from 22 to 24 years).

From **Table 2-2** and **Fig. 2-13**, the average motion errors of the four fingers generated by our proposed method (single axis rotation) became 0.44~1.06 mm, and the difference in the errors between the ICP and our method did 0.15mm or less. On the other hand, from **Table 2-3** and **Fig. 2-14**, the average motion errors of the thumb generated by the single axis rotation became 0.80~1.22 mm, while those generated by our method (quaternion interpolation for CMC joint) were reduced to 0.35~0.96mm as shown in **Fig. 2-15**. The difference in the error between the ICP and the single axis rotation becomes a maximum of 0.87mm, while the one between the ICP and our method were reduced to 0.49mm or less. Moreover, **Table 2-4** shows the average motion error when reproducing a grasp posture for a product using the proposed bone link model. The average motion errors of all fingers in the proposed model were within 1.5mm. So, it can be said that the approximations grasp posture is reproducible with high precision.

Table 2-2 Four fingers: average motion error at the time of each limit posture motion [mm].

Phalange	Flexion posture			Abduction posture
	Proximal	Middle	Distal	Proximal
ICP	0.55	0.88	0.89	0.36
Proposed method(single axis rotation)	0.63	0.96	1.06	0.44

Number of Subject = 2

Table 2-3 Thumb: average motion error at the time of each limit posture motion [mm].

Phalange	Metacarpal	Proximal	Distal
ICP	0.35	0.43	0.47
Proposed method(single axis rotation)	1.22	0.80	1.14
Proposed method (CMC: Quaternion interpolation, MP,IP: Single axis rotation)	0.35	0.47	0.96

Number of Subject = 2

Table 2-4 Average motion error at the time of product posture reproduction [mm].

Brake grasp posture			
Phalange	Proximal(thumb: Metacarpal)	Middle(thumb: Proximal)	Distal
ICP	0.5	0.6	0.73
Proposed method	1.22	1.24	1.95

Number of Subject = 2

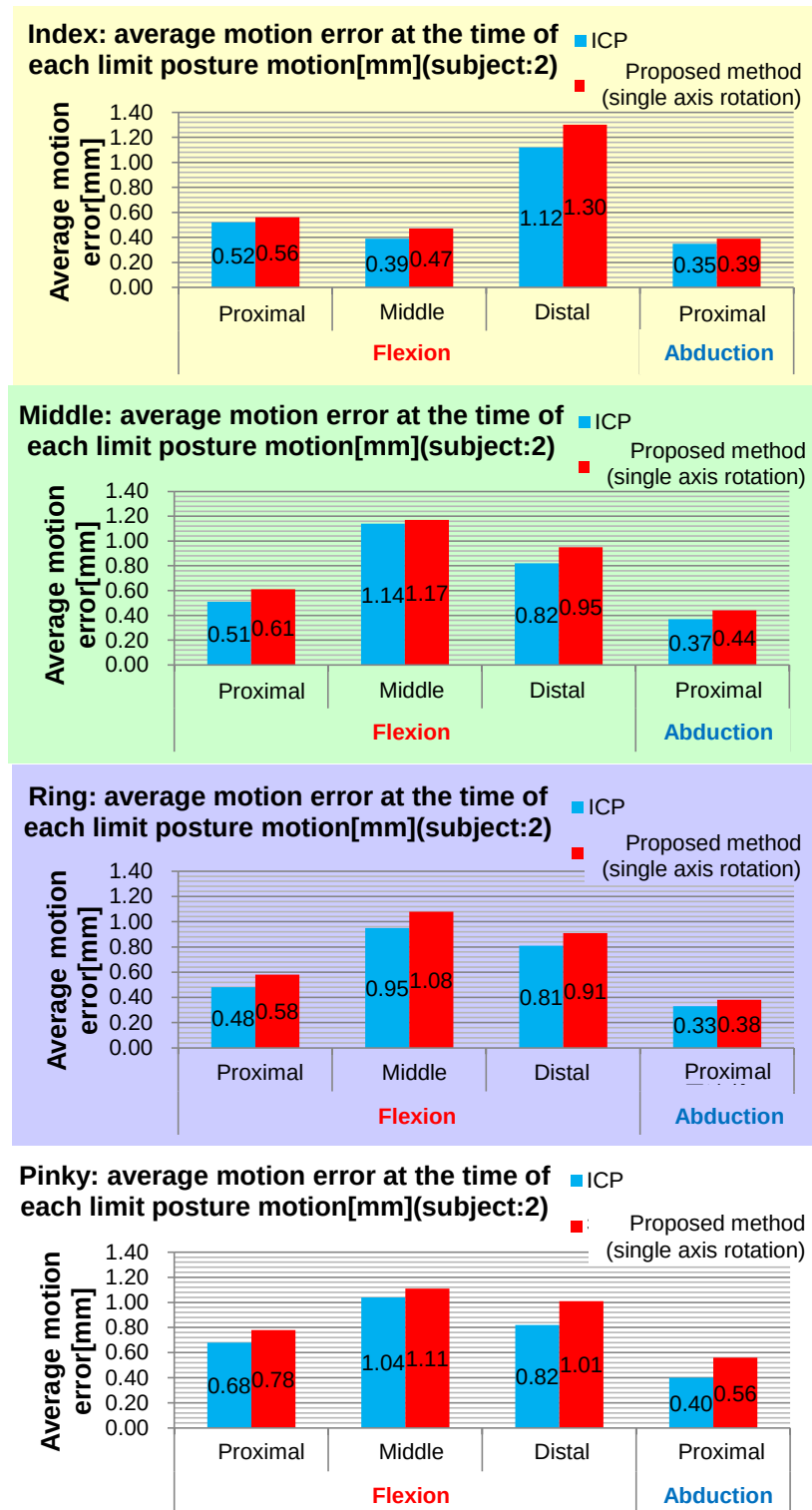


Fig. 2-13 Average motion error at the time of each limit posture motion (Four fingers)

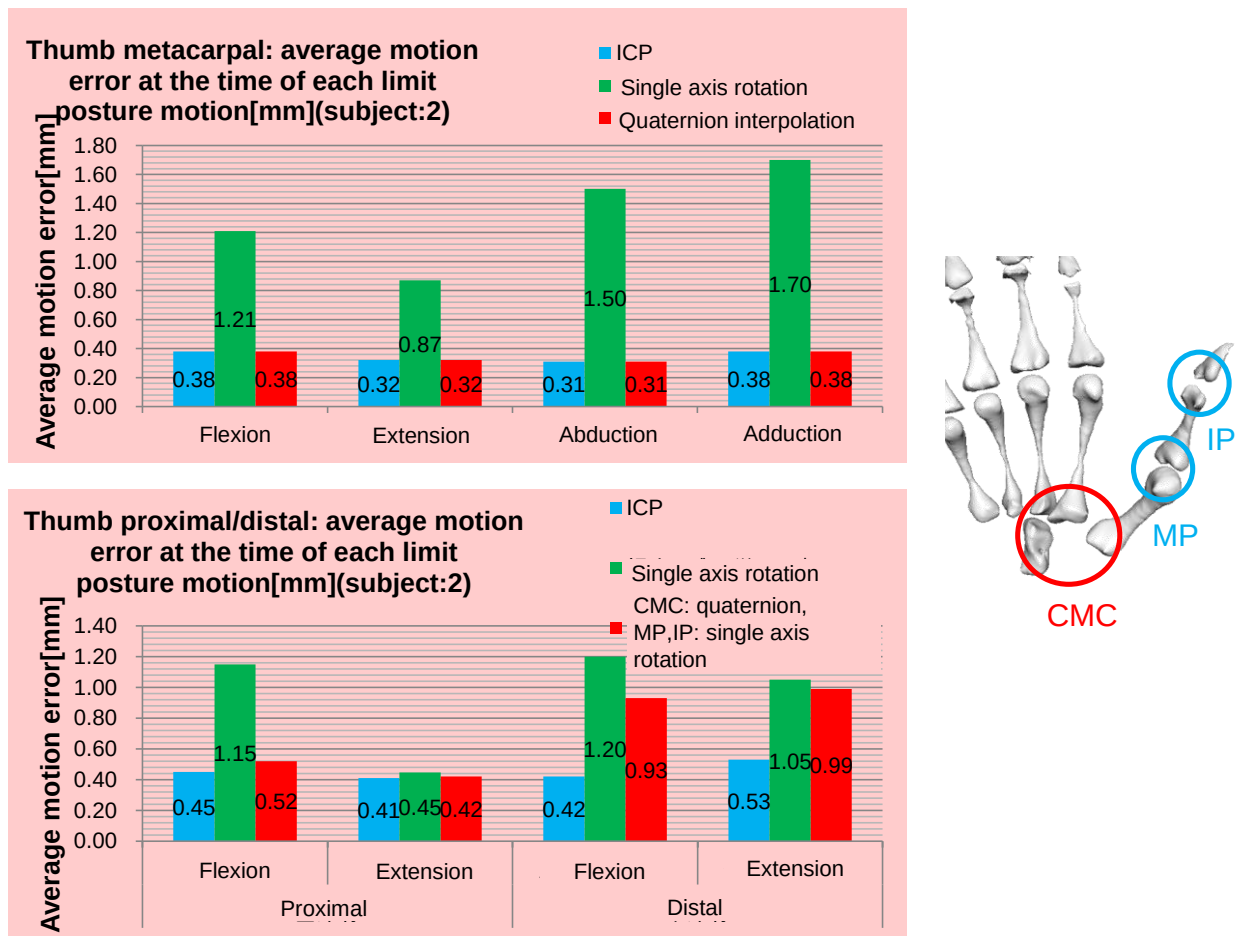


Fig. 2-14 Average motion error at the time of each limit posture motion (**Thumb**)

As a result of these results, it can be said that the proposed joint modeling for the bone link model is precise enough for reproducing the virtual grasp postures.

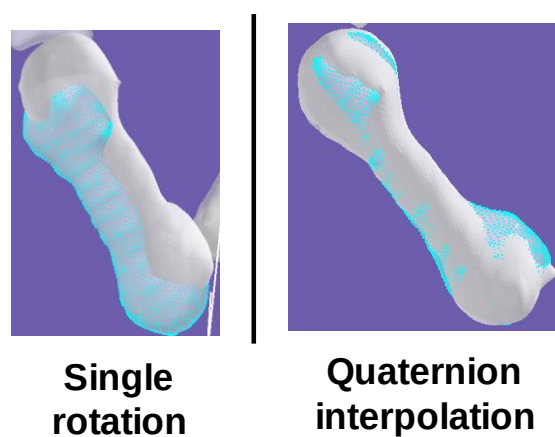
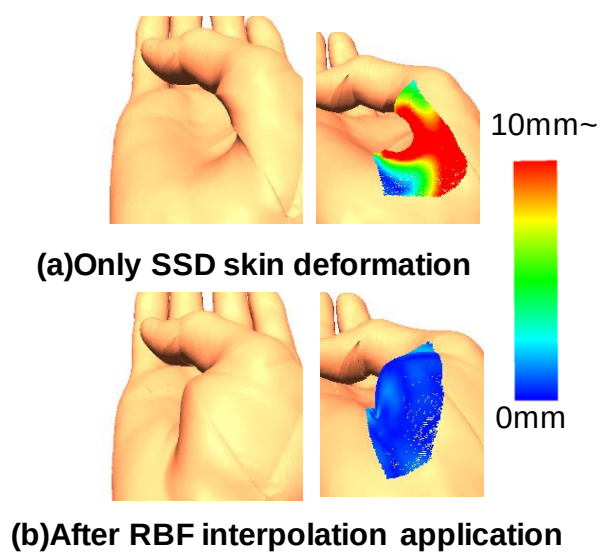
Next, the skin surface deformation of the digital hand at the maximum flexion of thumb CMC joint is graphically shown in **Fig. 2-16**. Displacement distribution between the skin surface model of the digital hand and the real skin surface measured by MRI at this posture is shown in **Table 2-5**.

When only using the SSD (**Fig. 2-16** (a)) in the deformation, the skin swelling of the thumb's root is clearly insufficient. But the proposed skin deformation compensation by RBF enables our skin surface model to precisely reproduce the real swelling (**Fig. 2-16** (b)). As shown in **Table 2-5**, the average deformation errors were improved from 3.7mm to 0.6mm. Very precise deformation could be reproduced.

Table 2-5 Skin deformation distance error at the time of each thumb joint motion[mm].

Skin deformation method	Only SSD	After RBF interpolation
Flexion	7.0	0.6
Extension	4.5	0.6
Abduction	2.6	0.6
Adduction	2.9	0.6
Average	4.3	0.6

Number of Subject = 2

**Fig. 2-15** The error of the metacarpal at the time of the thumb CMC joint motion reproduction.**Fig. 2-16** Skin deformation at the time of the thumb CMC joint maximum flexion.

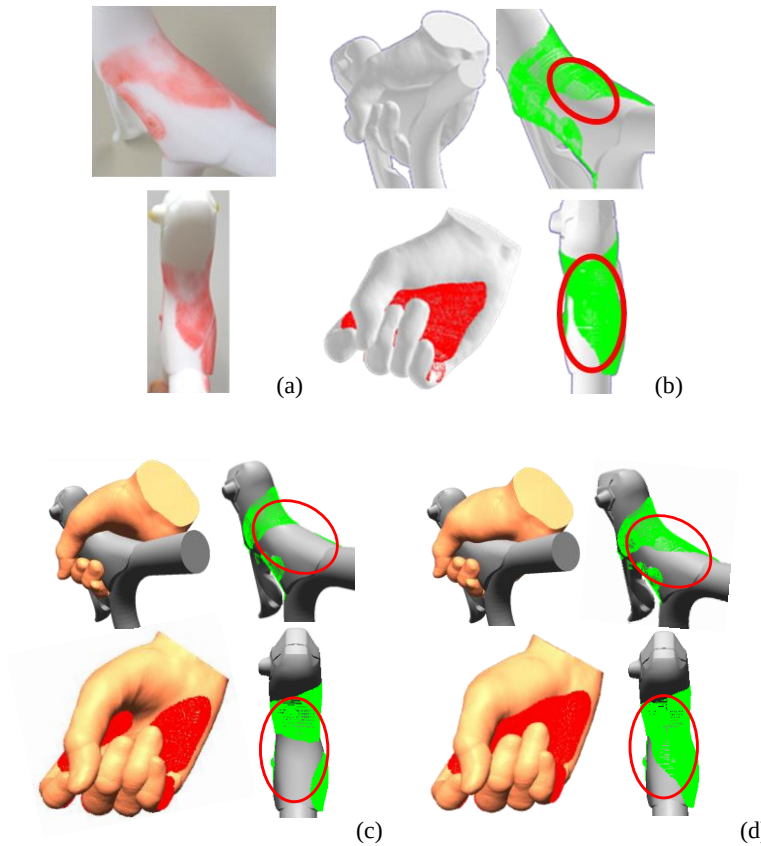


Fig. 2-17 Contact area evaluation with the product.

(a)Real product (Red portion is handprint), (b)Estimated from MRI measurement data, (c)Simulated by Digital hand (only SSD skin deformation),(d) Simulated by Digital hand (After RBF interpolation application).

Finally, the contact area between the product model surface and the digital hand surface was verified in case of grasping a bicycle handle bar. **Fig. 2-17** (a) indicates a real contact area by a human subject obtained by stamping method in a real grasp experiment. **Fig. 2-17** (b) is a real grasp posture and estimated contact area (red and green) generated by a skin surface model extracted from the MRI measurement and the product mesh model. The contact area was extracted by collecting the vertices where distance between the skin surface model and the product model are less than 2.0mm. **Fig. 2-17** (c) indicates the simulated contact area between the digital hand and the product model using the same extraction criterion above when using the SSD only as the skin surface deformation. From **Fig. 2-17** (c), the swelling of the skin surface around the ball of the thumb was insufficient, and contact area on the product surface was evaluated too small. Meanwhile, from **Fig. 2-17** (d), when using the compensation by RBF, it was found that the swelling of the skin was well reproduced and the simulated contact area (green area in **Fig. 2-17** (d)) approximated the

estimated contact area (**Fig. 2-17 (b)**) and the real contact area (**Fig. 2-17 (a)**) much better than those of **Fig. 2-17 (c)**. By the analysis of contact area between the estimated one by MRI-measurement and the estimated one by Digital Hand, we found the common area take about 80% of the estimated contact area by Digital Hand.

2.4 Summary

A new method of MRI-based modeling of a digital hand was proposed whose precision was sufficient to reproduce virtual grasp postures for ergonomic assessments. The finger joint motion of the bone link model and the large skin surface deformation along with the finger flexion were modeled from MRI images. The proposed bone link model which enabled CMC joint motion with quaternion-based interpolation could reproduce the phalange motion within 1.06 mm error without grasp and within 1.95 mm error in case of grasp. The proposed skin surface model whose skin deformation was compensated by RBF interpolation could reproduce the real skin deformation within the 0.6mm error. The comparison of the simulated contact area of our hand model with the real one showed the effectiveness of the proposed model.

Chapter 3

Efficient simulation of skin contact deformation

3.1 Introduction

Handheld products, such as portable digital appliances, have been widely used in daily life and production activities. For their customers, an ergonomic design is always desired for better user experience and high productivity. Therefore, during the development process of handheld products, many grasp factors need to be assessed, for instance, grasp stability, grasp comfort, and grasp safety.

3D human hand modeling and simulation, such as [34] and [10, 12, 35], provides significant advantages for ergonomic assessments when incorporated into the early stage of the design process of handheld products. They can, especially, reduce the need for sensory tests on human subjects and also for expensive prototypes, thus reducing costs and time to market. However, one challenge is mimicking the skin deformation caused by physical contact with a product surface.

The biomechanical property of human skin plays a fundamental role in the tactile sense of humans [15, 36]. Its structure and the material behavior exhibit extreme complexities: layered structure, nonlinear elasticity, near incompressibility, spatially distributed heterogeneity, etc. [37]. The skin contact conditions, such as contact force, contact area, and contact pressure distribution, between the grasping hand and the grasped objects directly affect grasp factors including grasp stability, comfort, safety, etc. Hence the contact

conditions always serve as important indicators for ergonomic assessments of handheld products.

Many studies [16, 38-44] have reported that the contact conditions of grasp postures are used in the grasp factors evaluation. Although, it is still difficult to deal with complex contact configurations where the products have irregular and curved geometrical shapes, due to the limitation of the resolution or shape of sensors.

Our research group [10, 12, 24, 35] has been proposing the *Digital Hand* which is a 3D virtual hand model and a virtual ergonomic assessment system for handheld products. As shown in **Fig. 3-1** (a) and (b), the Digital Hand is composed of a surface skin model represented by a triangular mesh and an internal skeletal structure model. The geometries of its surface skin and the inner bones are derived from MRI measurements of different grasp postures of a specific subject. Moreover, it can generate plausible grasp postures shown in **Fig. 3-1** (c) by optimization techniques, and quantitatively estimate the grasp stability and the ease of grasp in different grasp postures.

However, the Digital Hand has not simulated skin contact deformation, and instead approximated it in a simple way where the interpenetration within a specific threshold was allowed between the skin and the surfaces. Accordingly, the contact force can not be estimated at all, which was against the valid and precise evaluation of the grasp stability. In addition, the ease of grasp was still estimated based on the subjective evaluations. However, an objective evaluation is desired for excluding personal preferences.

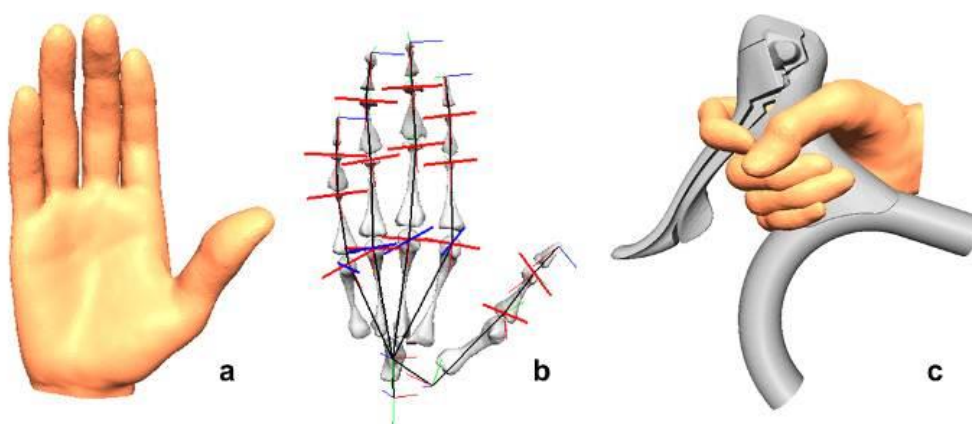


Fig. 3-1 Digital Hand: (a) surface skin model, (b) internal skeletal structure model, (c) generated grasp posture.

The objective of the chapter 3 is to propose an efficient method to simulate the contact deformation of human hand skin for satisfying the requirements of virtual ergonomic assessment of handheld products in the Digital Hand: sufficient accuracy, efficiency, and extensibility in a complex contact configuration with product surfaces. To realize the purpose, first, a physical model of the deformation based on the Boussinesq approximation is introduced in the simulation. In this model, nonlinear elasticity and a compressing-swelling effect on human skin are modeled. Moreover, the palmar surface is partitioned into different regions for consideration of the spatially distributed heterogeneity of the human hand. The parameters needed in the physical model are estimated by fitting the empirical data. Finally, based on the physical model, an online process based on a quasi-rigid object approximation realizes the efficient simulation of the skin contact deformation.

The effectiveness and accuracy of our proposed simulation method are demonstrated for simple fingertip as well as palm skin deformations and for complex contact configurations, grasping cylinders or other handheld products where the basic grasp posture of the human hand model for the skin contact deformation is given by the Digital Hand.

3.2 Related work on the skin contact deformation simulation

As for the skin contact deformation simulation, the studies have been done in many fields; robotics, biomechanics, computer graphics, etc.. However, the simulation methods are basically classified into FEM-based methods and other physics-based methods.

3.2.1 FEM-based methods

Finite element analysis is commonly preferred for the accurate simulation of skin deformation [13-16]. Some studies based on the FEM can estimate the pressure distribution of grasping hand [17] and foot [18]. Despite its high accuracy involving the large computation time, FEM obviously is not appropriate for a practical virtual ergonomic assessment system for handheld products. This is because in such system, a large number of grasp postures with different hand sizes need to be evaluated within an acceptable period of design, and therefore the simulation of skin contact deformation for one posture needs to finish as quickly as possible.

3.2.2 Other physics-based methods

Different from the FEM-based methods, the simulation in computer graphics aims for approximate but efficient contact deformation between general objects. The work [20] efficiently simulates the contact deformation and estimates surface pressure distribution. The Boussinesq approximation, which is a linear constitutive model, is adopted as the basic physical model for their work. Also, their technique treats the deformable model as a “quasi-rigid” object for efficient online process of the simulation.

Our proposed approach shares the strategy of Pauly’s work [20], but, unlike theirs, the physical model is extended to realize the nonlinear elasticity of human hand skin. Moreover, their work assumes objects are homogeneous. However, our study treats the human hand as a heterogeneous material which has spatially varying material parameters, such as Young’s modulus.

[21] realizes a physics-based deformation simulation of soft contact where the human skeleton is comprised of articulated bones, each of which is surrounded by a set of mass points representing the deformable skin surface. The deformation is also confined to a subset of the vertices around the contact site.

However, these two studies in computer graphics mainly aim to realize visually realistic deformations. They choose the material parameters arbitrarily which do not resemble human skin in the real world. In addition, their studies are lack of experimental validations.

3.3 Methods

The simulation method is composed of two main parts: 1) a physical model of the deformation, and 2) a deformation simulation algorithm.

In the first part, a linear physical model of skin contact deformation, called Boussinesq approximation, is adopted and is extended with nonlinear elasticity and a compressing-swelling effect in order to mimic realistic deformation of human hand skin. The material parameters of this effect were determined by the experimental data (Section 3.3.1.5).

In the second part as shown in **Fig. 3-2**, based on the proposed physical model, an algorithm including a pre-process and an online process in order to simulate skin deformation is developed. In the pre-process, the surface skin model is partitioned into 19 sub-surfaces according to hand surface anatomical knowledge (A1). Then, the point-force-based discretization of the physical model in each sub-surface is executed (A2). For one Digital

Hand model, the pre-process has to be executed only once. In the online process, first of all, a collision detection algorithm is done to find collision regions (A3), and they are locally enlarged to get an active region (A4). After that, the active region is separated into sub-active regions (A5). For each sub-active region, a response matrix is composed and a sub-matrix is extracted from it (A6). Finally, the contact deformations over the sub-active regions are simulated by solving the Linear Complementarity Problem (LCP) (A7). The relation between the shear modulus and the maximum penetration depth is tuned until the output best fits the experimental data. The details of the processes are described in the following sections.

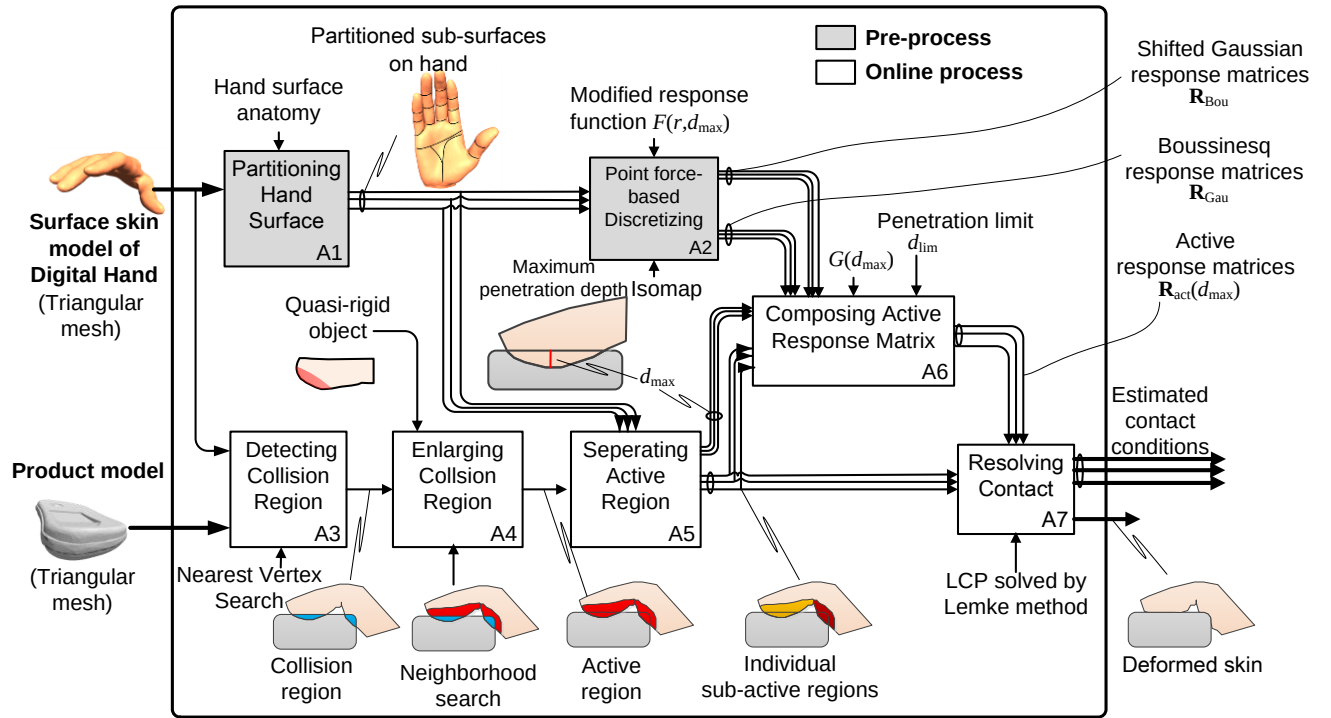


Fig. 3-2 Our proposed simulation method of skin contact deformation.

Three arrow lines with a circle mean multiple components in the pipeline.

For example, in A1, the surface skin model is partitioned into multiple sub-surfaces

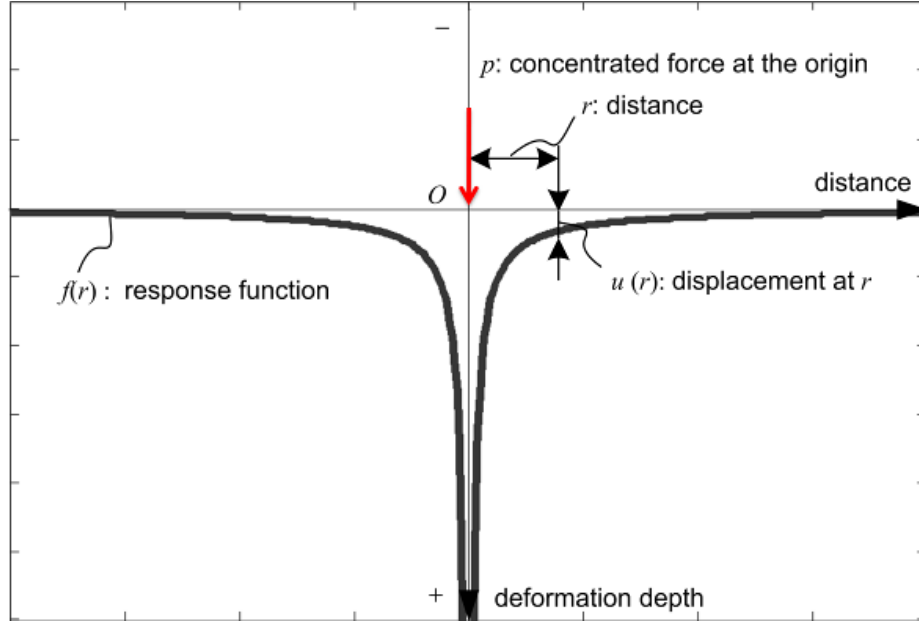


Fig. 3-3 Response function of the Boussinesq approximation.

3.3.1 Physical model of skin contact deformation

3.3.1.1 Boussinesq approximation

Boussinesq approximation, a widely used method in contact mechanics, models linear elasticity with a constant shear modulus in small deformation. It approximates the surface deformation around a contact point within an elastic half space [45]. As shown in **Fig. 3-3**, when a normal compressive force with a magnitude p acts at the origin of a plane, the displacement $u(r)$ at any position is expressed by Equation (3-1):

$$u(r) = \frac{(1-\nu)p}{2\pi Gr} = f(r)p \quad (3-1)$$

$$f(r) = \begin{cases} \frac{(1-\nu)p}{2\pi Gr} & (r \geq r_0) \\ \frac{(1-\nu)p}{2\pi Gr_0} & (r < r_0) \end{cases} \quad (3-2)$$

where, r is the distance between an arbitrary point and the origin, $u(r)$ the displacement at the point due to a force p , ν Poisson's ratio, G shear modulus, $f(r)$ defined by Equation (3-2) is called a *response function* as shown in **Fig. 3-3**. In order to avoid the singularity problem of $f(r)$ when $r = 0$, there is a special treatment. If $r < r_0$, where $r_0 = 0.5\text{mm}$, then $f(r) = f(r_0)$.

3.3.1.2 Nonlinear elasticity of skin

Human skin has a complicated biological structure and presents nonlinear elasticity in the stress-strain relation [15, 36, 46]. For ergonomic assessments of the handheld products, the external geometry of hands is mainly considered, and therefore hand skin could be treated as a bulk material [47]. This means that the layered structure of skin is ignored, and the physical property presented by external skin is used to represent that of the entire skin structure. In most indentation studies on skin and subcutaneous tissue, researchers have assigned Poisson's ratio ν within a range of 0.45 to 0.5 in order to simulate the nearly incompressible behavior of the soft tissue [48, 49]. Similar to them, and to our proposed physical model simplistic, ν was fixed at 0.5.

Dandekar, Raju and Srinivasan [15] indicate that G of the human hand skin ranges from 0.004Mpa to 0.08Mpa depending on the nonlinear elasticity. This range is referred to for our proposed physical model. However, choosing the right material parameters of the model is still a difficult and time-consuming process. When involving nonlinearity, the process becomes more challenging. Hence, the shear modulus G was tuned until it best fits the experimental data (Section 4.1), similar to the other measurement-based models [50, 51].

3.3.1.3 Compressing-swelling effect

As human skin is a nearly incompressible material [47], in the skin deformation simulation of our study, the *compressing-swelling effect* on human skin needs to be realized. It means that a compressive force causes not only volume compression in the region to which the force is applied (force-applied region), but also volume swelling right outside the region due to the near volume preserving property. However, as shown in **Fig. 3-4**, the volume after deformation is obviously reduced when only using the original Boussinesq approximation, and this leads to physically behave as a sponge-like material. The compressing-swelling effect of an incompressible material, such as a soft tissue, is shown in **Fig. 3-4**. In the hand skin simulation, the effect was realized by modifying the original Boussinesq approximation which was described in Section 3.3.1.5, for producing a more realistic visual deformation.

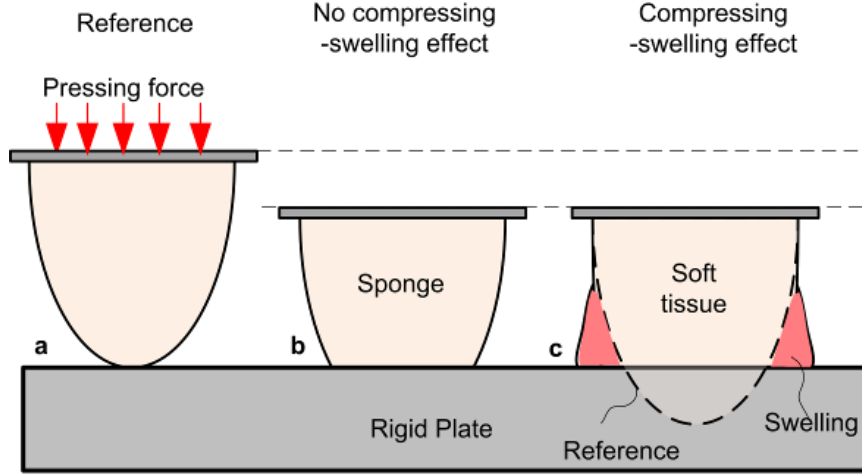


Fig. 3-4 Compressing-swelling effect: (a) reference, (b) compressible sponge (without compressing-swelling effect), (c) incompressible soft tissue (with compressing-swelling effect).

3.3.1.4 Modified physical model with nonlinear elasticity

For realizing nonlinear elasticity in the physical model, shear modulus G is regarded as a linear function of the maximum penetration depth, $d_{\max}$, among the vertices in the force-applied region as Equation (3-3):

$$G(d_{\max}) = G_0 + (G_{\lim} - G_0) \frac{d_{\max}}{d_{\lim}}, \quad (0 \leq d_{\max} \leq d_{\lim}) \quad (3-3)$$

where G_0 is an initial shear modulus, $G_{\lim}$ a limit shear modulus, and $d_{\lim}$ a limit penetration depth.

From the experiments of Section 3.4.1, the actual value of $d_{\lim}$ was measured for simple fingertip and palm deformation. Moreover, G_0 and $G_{\lim}$ were chosen by fitting the empirical data of the maximum penetration depth versus the contact force. Therefore, by substituting Equation (3-3) into Equation (3-1), the response function $f(r)$ of the linear case in Equation (3-1) is rewritten into the nonlinear case as Equation (3-4). To keep it simple, $f(r)$ is still used to express Equation (3-4) in Section 3.3.1.5.

$$f(r, d_{\max}) = \frac{1}{4\pi G(d_{\max})r} \quad (3-4)$$

3.3.1.5 The compressing-swelling effect and indentation test

Moreover, to realize the compressing-swelling effect in the Boussinesq approximation, as shown in **Fig. 3-5** we modulated the original Boussinesq approximation (the dashed curve), by adding a shifted negative Gaussian function (the red curve). As a result, the modified response function (the thick blue curve) $F(r)$ can be obtained as Equation (3-5):

$$F(r) = f(r) + \{-g(r)\} = f(r) + \left\{ -ae^{-\frac{(r-b)^2}{2c^2}} \right\} \quad (3-5)$$

where $g(r)$ is the shifted Gaussian function.

Indentation tests were conducted both on finger and palm skin, in order to find the proper parameter setting of a , b , and c of $g(r)$ in Equation (3-5). **Fig. 3-6** (a), (b), and Table 3-1 show the experimental setting. The 2D sectional curve of the 3D point clouds obtained by the 3D laser scanner was evaluated as shown in **Fig. 3-6** (c). A shifted Gaussian function $g(r)$ was used to approximate the 2D curve. The final setting of $g(r)$ is listed in Table 3-2, when 1N was applied to the indenter whose diameter was 2mm.

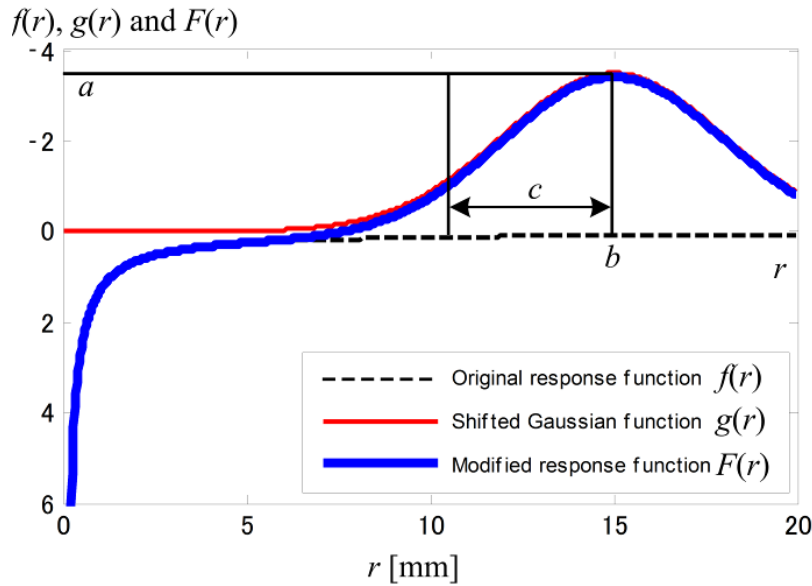


Fig. 3-5 Our modified response function.

Table 3-1 The setting of indentation test

Subjects (fingertip deformation)	3 males, 23-27 years, right hand
Force gauge (IMADA DPS-20R)	Measuring the indentation force
3D laser scanner (Konica Minolta Vivid 910)	Taking 3D point clouds on skin shapes before and after indentations
Fixture (a hard foam material)	Supporting and fixing the palm

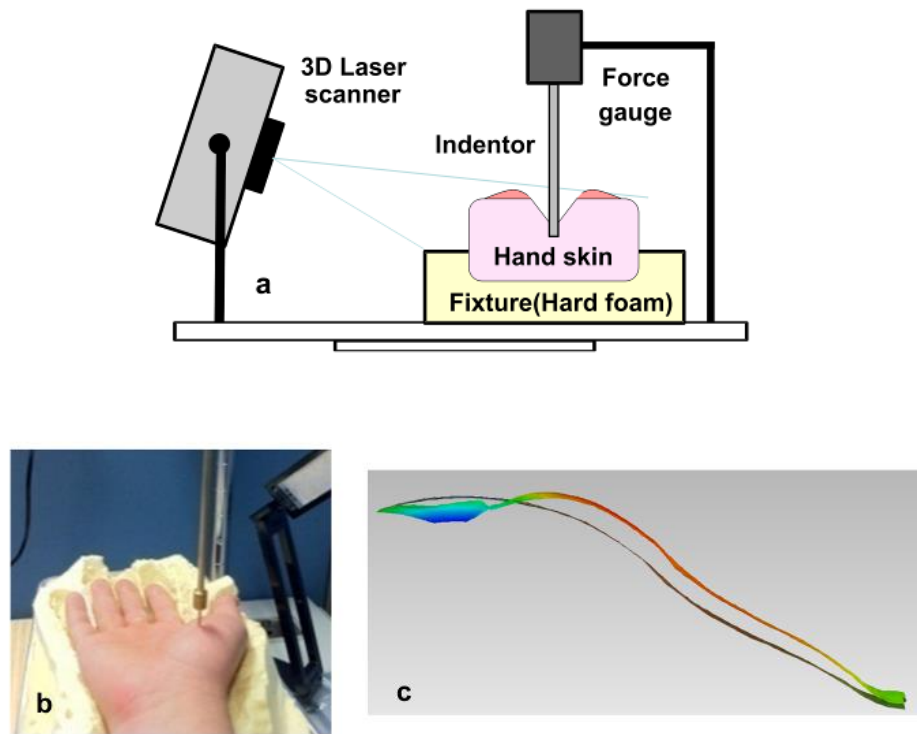


Fig. 3-6 Indentation test: (a) experimental setting, (b) real scene, and (c) a cross section of 3D deformation map (Geomagic).

Table 3-2 Setting of *a*, *b* and *c*

	Palm [mm] (average)	Finger [mm] (average)
<i>a</i>	3	2
<i>b</i>	15	8
<i>c</i>	2.5	2

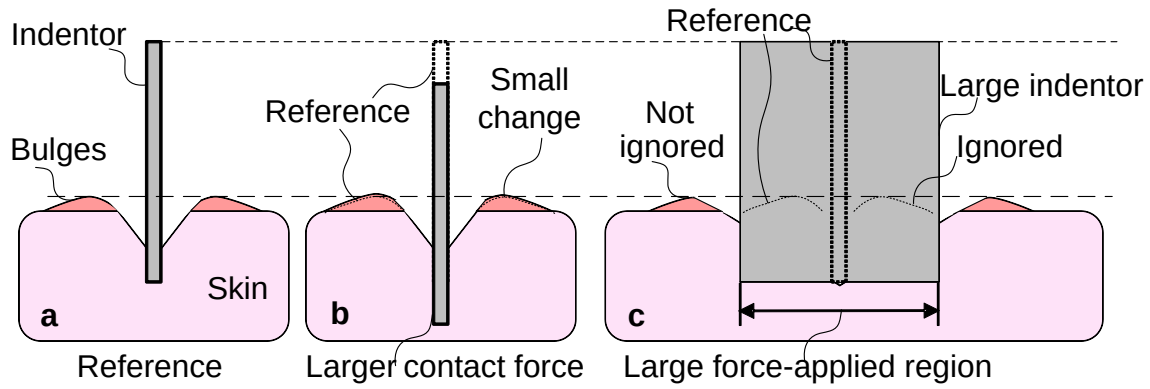


Fig. 3-7 Swelling bulge in different situations: (a) reference, (b) larger contact force, and (c) larger force-applied region

Moreover, physical properties of swelling bulges of skin were also tested. It was found that the change of a swelling bulge was very small when the compressing force varied, because the change of skin volume rapidly approaches a limit (i.e. the skin volume of the swelling bulge is approximately constant) caused by the nonlinear elasticity of skin. As shown in **Fig. 3-7** (b), the change of the height of the bulge between the red bulge (generated by an indenter) and the dashed bulge (generated by the indenter in **Fig. 3-7** (a)) was 0.1mm which could be neglected. Therefore, a in Equation (3-5) is regarded as a function of the maximum penetration depth $d_{\max}$ as Equation (3-6), which ensures different contact forces resulting in a constant height of a swelling bulge:

$$a(d_{\max}) = a_0 \frac{G_0}{G(d_{\max})} \quad (3-6)$$

where a_0 is an initial height of the shifted Gaussian function which is the height when 1N was applied to the indenter.

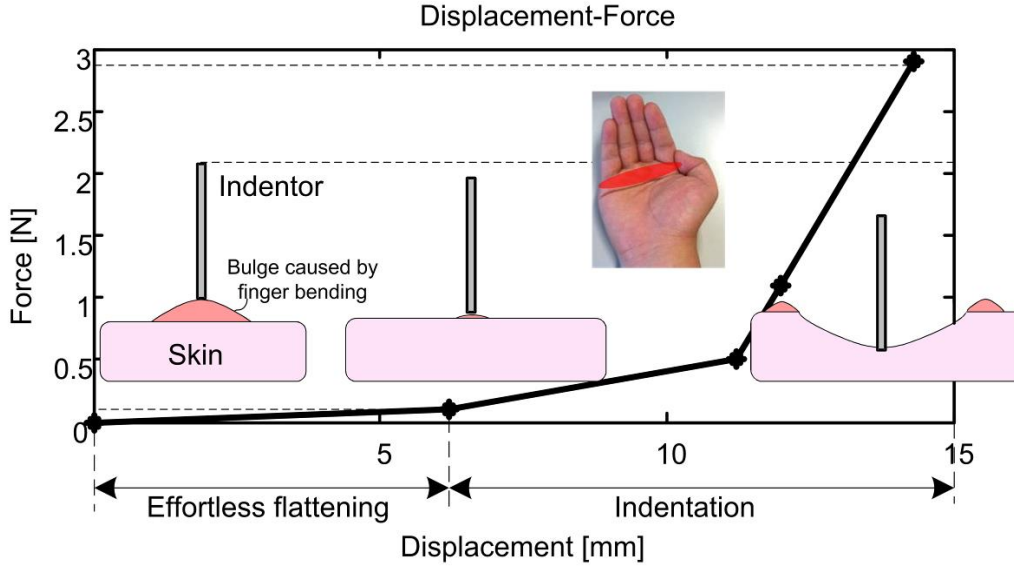


Fig. 3-8 Indentation test to swelling bulge: bulge is very soft, only a small portion of indentation force is used to flatten the bulge.

In addition, as shown in **Fig. 3-8**, an obvious bulge, which was formed by the root of the fingers caused by the finger bending, was pushed by the indenter. The swelling bulge exhibits extreme softness. They could be easily flattened almost effortlessly, differing from the case of the indentation test of **Fig. 3-7 (b)**. Therefore, as shown in **Fig. 3-7 (c)**, if the bulges (dashed one generated by the reference indenter) appear in a force-applied region, they will be ignored, as Equation (3-7), instead of Equation (3-6). And, only the swelling bulges (red ones) right outside the region needed to be simulated for visualization purposes.

$$a(d_{\max}) = 0 \quad (3-7)$$

By introducing this dependency of a with $d_{\max}$, the modified response function in Equation (3-5) becomes Equation (3-8). To keep it simple, $F(r)$ was still used to express Equation (3-8).

$$F(r, d_{\max}) = f(r, G(d_{\max})) + \left\{ -a(d_{\max}) e^{\frac{-(r-b)^2}{2c^2}} \right\} \quad (3-8)$$

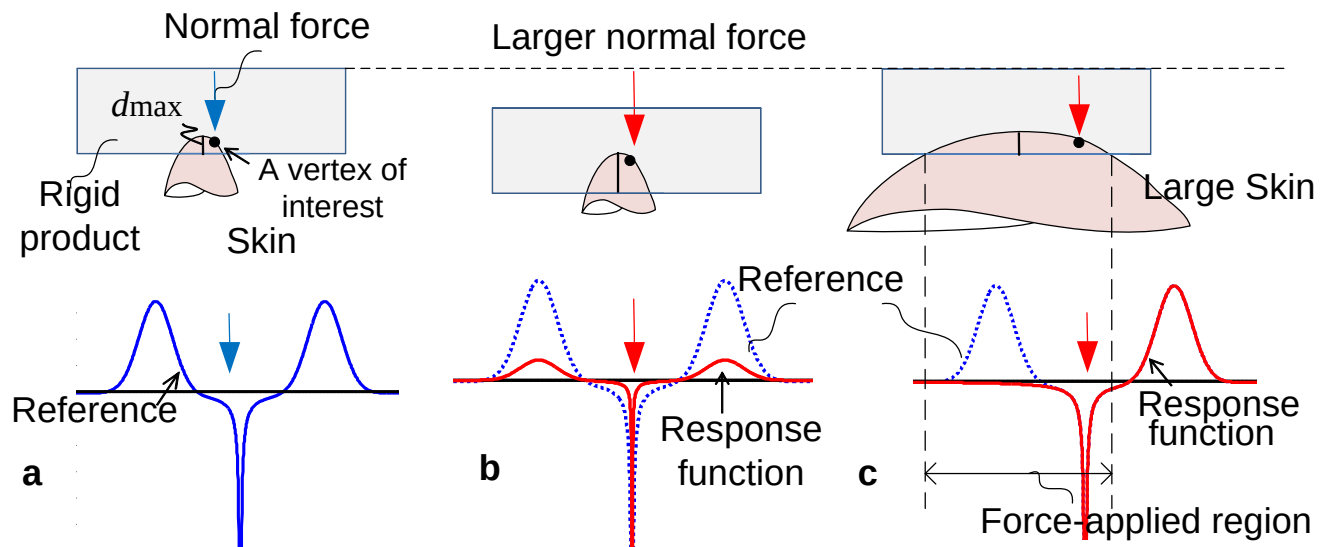


Fig. 3-9 Three typical deformation situations: a) reference, b) larger normal force and c) swelling within the force-applied region.

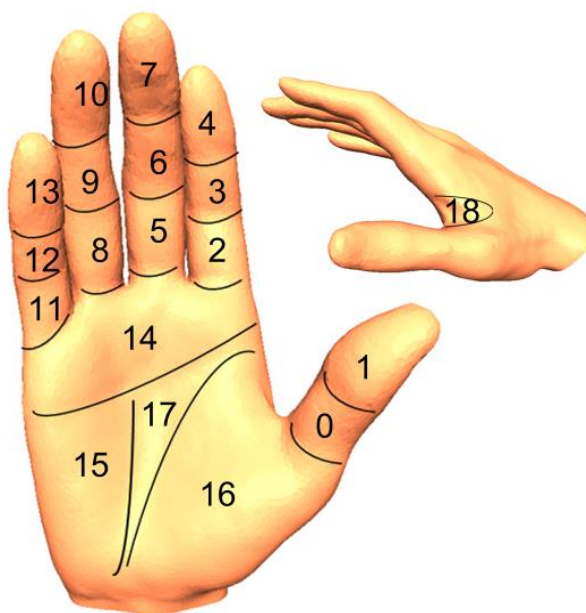


Fig. 3-10 Partition of hand surface by main creases.

Fig. 3-9 shows three typical deformation situations in the physical model and the shapes of the modified response function $F(r)$ at different vertices corresponding to the situations. **Fig. 3-9** (a) is a reference where the penetration depth is small. As shown in **Fig. 3-9** (b), when skin is being pressed with a larger $d_{\max}$, the skin becomes more rigid, and on

the contrary, the height of the response function becomes lower. However, as shown in **Fig. 3-9 (c)**, the swelling inside the force-applied region is ignored.

3.3.2 Skin deformation simulation

3.3.2.1 Partitioning hand surface (Fig. 3-2 (A1))

The palmar side of a hand surface is the main contact area when objects are grasped. The basic main creases have a strong relationship with the underlying bone structure [22]. In the Digital Hand, the motions of the internal skeletal structure, such as finger bending, cause surface skin deformation, which is consistent with real joint motions of humans. Therefore, the surface anatomy by the main creases was used for the partition of the palmar hand surface, as shown in **Fig. 3-10**, considering that different regions on the palm have different sensitivity to externally applied surface pressure [44].

Because the partitioned sub-surfaces by main creases exhibit independence to each other during hand motions, they were treated as individual deformable sub-surfaces. The G_0 and G_{lim} of Equation (3-3) in each partitioned sub-surfaces also could be specified independently. Moreover, the deformation simulation involving the entire hand surface mesh was inefficient, so the partition enabled the calculation of smaller response matrices introduced in Section 3.3.2.2 in smaller sub-surfaces instead of calculating a large-size response matrix of a whole hand surface mesh.

3.3.2.2 Point-force-based discretization (Fig. 3-2 (A2))

For a 3D triangular mesh, r in Equation (3-1) should be a geodesic distance between two vertices. Therefore, a geodesic distance preserving projecting algorithm, Isometric Mapping [52] was applied, which reduced the 3D geodesic distance evaluation to the 2D Euclidean one.

In a discrete setting, the relation R_{ij} needs to be found between a force p_i acting on a vertex $\mathbf{q}_i$ and a displacement u_j that a vertex $\mathbf{q}_j$ experiences. R_{ij} can be expressed in the matrix form as Equation (3-9):

$$\mathbf{u} = \mathbf{R}(d_{\max})\mathbf{p} \quad (3-9)$$

where

$\mathbf{R}(d_{\max}) = [R_{ij}(d_{\max})]$: response matrix,

$$R_{ij}(d_{\max}) = G(d_{\max}) \frac{1}{4\pi r_{ij}} + \{-a(d_{\max})\} \left\{ e^{\frac{-(r_{ij}-b)^2}{2c^2}} \right\} \quad (3-10)$$

$\mathbf{u} = [u_1, \dots, u_N]^T$ is a vector of displacements, N the number of vertices in a partitioned region, $\mathbf{p} = [p_1, \dots, p_N]^T$ a corresponding normal force vector, r_{ij} the geodesic distance between $\mathbf{q}_i$ and $\mathbf{q}_j$ on the skin surface mesh, $d_{\max}$ the maximum penetration depth among the vertices included in the active region described in Section 3.3.2.3.

However, in the nonlinear elasticity model of our study, G varies with $d_{\max}$. Therefore we needed to change $\mathbf{R}(d_{\max})$ with $d_{\max}$ in the online process. Fortunately, as Equation (3-11), $\mathbf{R}(d_{\max})$ is decomposed into a linear combination of $\mathbf{R}_{\text{Bou}}$ and $\mathbf{R}_{\text{Gau}}$. The two component-matrices in the pre-process can be calculated, and $\mathbf{R}(d_{\max})$ can be obtained simply by linearly combining $\mathbf{R}_{\text{Bou}}$ and $\mathbf{R}_{\text{Gau}}$ in the online process:

$$\mathbf{R}(d_{\max}) = G(d_{\max}) \mathbf{R}_{\text{Bou}} + \{-a(d_{\max})\} \mathbf{R}_{\text{Gau}} \quad (3-11)$$

where

$\mathbf{R}_{\text{Bou}} = [(R_{\text{Bou}})_{ij}]$: Boussinesq response matrix,

$$(R_{\text{Bou}})_{ij} = \frac{1}{4\pi r_{ij}}$$

$\mathbf{R}_{\text{Gau}} = [(R_{\text{Gau}})_{ij}]$: shifted Gaussian response matrix,

$$(R_{\text{Gau}})_{ij} = \exp \left\{ \frac{-(r_{ij}-b)^2}{2c^2} \right\}$$

$$a(d_{\max})(R_{\text{Gau}})_{ij} = \begin{cases} 0 & (\text{if } \mathbf{q}_j \text{ is in the force acting region}) \\ a \frac{G_0}{G(d_{\max})} (R_{\text{Gau}})_{ij} & (\text{otherwise}) \end{cases} \quad (3-12)$$

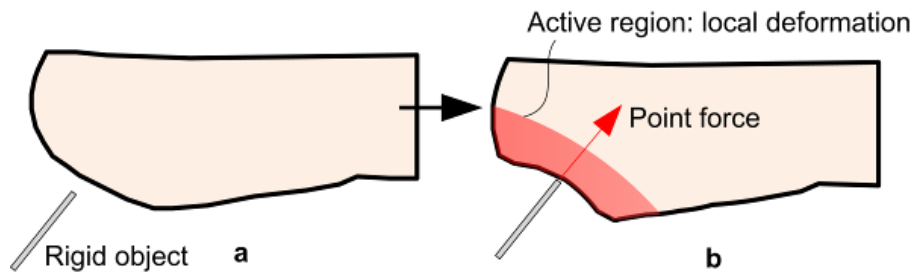


Fig. 3-11 Quasi-rigid object: (a) point force is going to be applied, and
(b) after that, local deformation is formed in active area.

By the decomposition of the response matrix as Equation (3-11), for one Digital Hand model, all the entries of $\mathbf{R}_{\text{Bou}}$ and $\mathbf{R}_{\text{Gau}}$ can be pre-computed in each partitioned region in the pre-process, which would enable a relatively fast simulation in the following online process.

3.3.2.3 Detecting and enlarging collision region (Fig. 3-2 (A3) and (A4))

Practical deformation simulations involving all the vertices lack efficiency; hence the human hand was modeled as a quasi-rigid object. Quasi-rigid object [20] indicates, as shown in **Fig. 3-11**, that, when the objects' surface undergoes small deformation within the vicinity of the force-applied region, called the active region, the remaining shape of the object still holds as it was. When the Digital Hand comes in contact with a product surface, a collision region (presented by a set of vertices) can be detected. However, the collision region is not sufficient to define the active region, since the forces on these vertices can lead to displacements of vertices outside of the collision region. To assume the required additional vertices, the fact that the modified response function has a limited effect range was considered (Section 3.3.1.1). Contrary to fully deformable objects where all vertices potentially experience a significant displacement, we can thus confine the active region to a local neighborhood around the collision region, which enables a faster simulation.

A collision detection algorithm in [10] was adopted in this research. The union of the collision region and its local neighboring vertices was defined as an active region. To cover the convex portion of the modified response function in Fig. 3-5, which corresponds to the bulges, a certain range of neighboring vertices were used as the local neighboring region for the fingers and palm. In our Digital Hand whose average distance of vertices in the Digital Hand model was about 2.5 mm, the local 5 and 7 ring neighboring vertices were used to cover the deformation range about 12.5mm and 17.5mm respectively, and we noticed that

this range could cover the larger portion of the deformation area observed from the result of the indentation test of **Fig. 3-6**. Of course, with a larger range, better simulation results could be obtained, but involving the computation efficiency, the 5 and 7 ring neighboring vertices were regarded as a proper setting. Also, if a mesh model with a different density is used, the range of local neighboring vertices will be adjusted accordingly.

3.3.2.4 Separating active region (Fig. 3-2 (A5))

If the active region partially or fully covers more than one partitioned region (Section 3.3.2.1), it will be separated into independent sub-active regions corresponding to each partitioned sub-surface with an independent maximum penetration depth $d_{\max}$. The following processes of Section 3.2.5 and 3.2.6 are executed for one sub-active region.

3.3.2.5 Composing active response matrix with varying shear modulus (Fig. 3-2 (A6))

Because $G(d_{\max})$ varies linearly or piecewise linearly with $d_{\max}$ (Equation (3-3)), the value of G can be obtained at a $d_{\max}$. Then, $\mathbf{R}(d_{\max})$ was composed by linearly combining $\mathbf{R}_{\text{Bou}}$ and $\mathbf{R}_{\text{Gau}}$ that were prepared in the pre-process as Equation (3-11). For one individual sub-active region, all of these entries of $\mathbf{R}(d_{\max})$ were not needed, but only those related to the sub-active region. Thus, one sub-matrix $\mathbf{R}_{\text{act}}(d_{\max})$ was extracted from $\mathbf{R}(d_{\max})$. It only includes the entries which are relevant to the vertices in the sub-active region.

3.3.2.6 Resolving contact using LCP (Fig. 3-2 (A7))

The goal of this step was to realize the deformed surfaces without interpenetration. To solve the appropriate displacement distribution without interpenetration, in a sub-active region, as shown in **Fig. 3-12** (a), the contact state vector was introduced whose component s_i indicated the contact, collision or separations state at a vertex $\mathbf{q}_i$, and formulated as Equation 13:

$$\mathbf{s} = \mathbf{R}_{\text{act}}(d_{\max})\mathbf{p} + \mathbf{d} \quad (3-13)$$

where $\mathbf{s} = [s_1, \dots, s_M]^T$ is a state vector, M the number of vertices in a sub-active region, $\mathbf{d} = [d_1, \dots, d_M]^T$ a vector of the penetration depth at each vertex in the sub-active region: d_i is defined as the signed distance between $\mathbf{q}_i$ and its nearest triangle face on the product surface

mesh, $\mathbf{p} = [p_1, \dots, p_N]^T$ a vector of the force at each vertex in the sub-active region: p_i is the normal force acting on $\mathbf{q}_i$. In s_i , $s_i > 0$ indicates the *separation* state, $s_i = 0$ the *contact* state, and $s_i < 0$, the *collision* state.

The right solution of $\mathbf{s}$ and $\mathbf{p}$ must be found in order to resolve the contact which satisfied Equation (3-13). In **Fig. 3-12** (b), it was observed that the state s_i and the force p_i were complementary, because for all i , $s_i \cdot p_i = 0$ at each vertex i as Equation (3-14). To have a non-zero force ($p_i > 0$), there must be a zero state ($s_i = 0$, the contact state), and to have a non-zero state ($s_i > 0$, the separation state) there must be a zero force ($p_i = 0$). Therefore, Equation (3-13) and the linear complementarity constraint (Equation (3-14)) can be combined, leading to a Linear Complementarity Problem (LCP),

$$\mathbf{s} \geq 0, \quad \mathbf{p} \geq 0, \quad \mathbf{s}^T \mathbf{p} = 0 \quad (3-14)$$

A solution of the LCP can be found by the Lemke's method [53]. Once $\mathbf{p}$ is solved, according to Equation (3-1), the displacements vector $\mathbf{u}$ ($\mathbf{u} = [u_1, \dots, u_N]^T$) can be found for all vertices in the sub-active region. Therefore, for each vertex in a sub active region, the vertex portion on hand skin before and after the deformation is expressed as:

$${}^{Skin} \mathbf{v}_i' = trans(\mathbf{t}_i) {}^{Skin} \mathbf{v}_i \quad (3-15)$$

where ${}^{Skin} \mathbf{v}_i$ and ${}^{Skin} \mathbf{v}_i'$ are vertex position after/before the deformation, $trans()$ is a 4×4 pure translation matrix, $\mathbf{t}_i = \mathbf{n}_i \cdot \mathbf{u}_i$, $\mathbf{n}_i$ is the normal of ${}^{Skin} \mathbf{v}_i$.

Finally, by resolving the contact in different individual sub-active regions, the skin deformation of the entire active region can be realized.

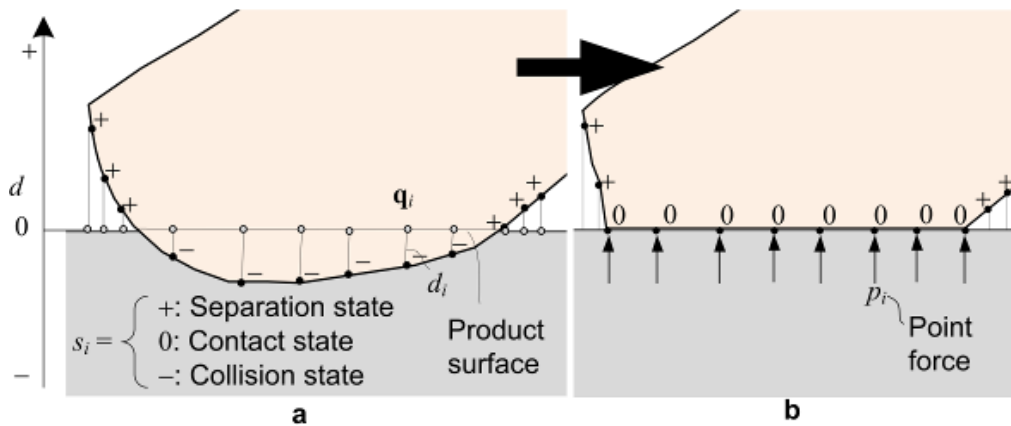


Fig. 3-12 LCP: (a) initial situation, and (b) contact situation.

3.4 Simulation results and validation experiment

The skin deformation simulation was tested in the simple finger and palm deformation and the complex deformation of a grasping hand for obtaining various contact conditions.

3.4.1 Simple Finger and Palm Skin Deformation

Fig. 3-13 (a) and (c) which were captured from dynamic contact motions show the intersection between a rigid product surface and the fingertip and palm of a Digital Hand model. **Fig. 3-13** (b) and (d) illustrate the visual contact deformation after this simulation. The bulging due to the compressing-swelling effect could be observed. The time performance of the simulation is summarized in **Table 3-3**. The online processes for fingertip deformation were almost in real time, and for palm deformation, they only took from 0.26 to 1.98s depending on the maximum penetration depth, and the time can be considered as acceptable for virtual ergonomic assessment.

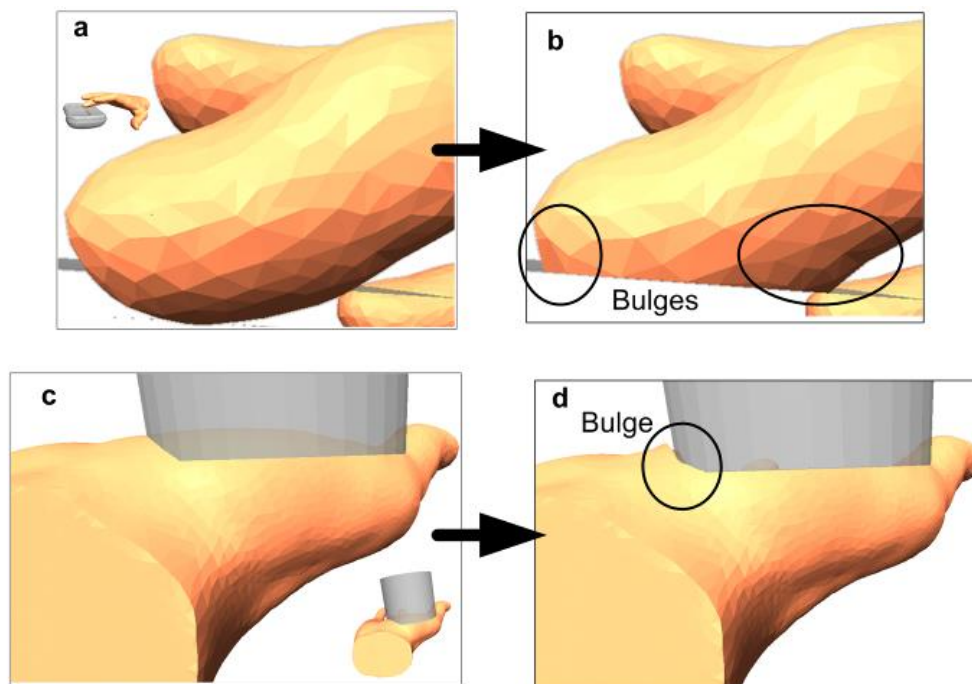


Fig. 3-13 Simulation effect of finger and palm: (a) before fingertip deformation, (b) after fingertip deformation, bulges can be observed, (c) before palm deformation, and (d) after palm deformation, a bulge can be observed.

Table 3-3 Time performance of skin deformation simulation of fingertip and palm

	Fingertip	Palm
Number of vertices	234	869
Number of vertices displaced in Fig.13(a) or (c)	121	566
The maximum penetration depth	0.26 – 4.13 mm	0.61– 6.90 mm
The maximum penetration depth in Fig.13(a) or (c)	2.98 mm	6.1mm
Pre-process for $\mathbf{R}_{\text{Bou}}$ and $\mathbf{R}_{\text{Gau}}$	34s	460s
Online process	42 – 82 ms	0.26 – 1.98 s
Hardware	Intel Core i5 1.70GHz, 4GB main memory	

Table 3-4 The setting of fingertip and palm deformation experiments

Subjects (fingertip deformation)	4 males, 23-26 years, right middle finger
Subjects (palm deformation)	5 males, 24-51 years, right hand palm
Laser ranger (Keyence IL-030)	Measuring the maximum penetration depth
Digital scale (AND EW-12Ki)	Measuring the contact force
Camera (Logitech Webcam C910)	Measuring the contact area
Computer	Image processing (OpenCV) and synchronous data acquisition
Fixture (a hard foam material)	Supporting and fixing the palm

Next, finding the setting of $G(d_{\max})$ was attempted by fitting the empirical data. The experiments were conducted which recorded the contact deformation of the fingertip and the palm. The experimental settings are shown in **Fig. 3-14**, **Fig. 3-15** and **Table 3-4**. In the fingertip measurement, the subjects were asked to press the rigid transparent plate covered by a semitransparent paper using their inked fingertip. In the palm measurement, a rigid plate covered by a semitransparent paper was pressed by the inked palms of subjects. Also, from the experiments, it was found that the limit penetration depth d_{lim} in Equation (3-3) of the fingertip and palm was about 4mm and 7mm respectively.

As shown in **Fig. 3-16**, the estimated results of several fingertip and palm contact motions are compared with the measured data. **Fig. 3-16** (a) and (c) is the relation between the maximum penetration depth and the contact force (the sum of the point force at each vertex in the contact region). The results showed that the estimation range (between the blue and the green curve) based on the proposed nonlinear elasticity model could effectively agree with the range of the measured contact force (the red curves) of the different subjects. This means by adjusting the values of G_0 and G_{lim} , the shape of the blue and green curves could be controlled to best fit the experimental data (those red curves). G_0 was from 5kPa in the

fingertip and 5 kPa to 50kPa in the palm, G_{lim} was from 70 kPa to 120kPa in the fingertip and 40 kPa to 80 kPa in the palm in the physical model.

On the contrary, those based on the linear elasticity model (G was fixed at a specified value) had difficulties to fully fit the measurements.

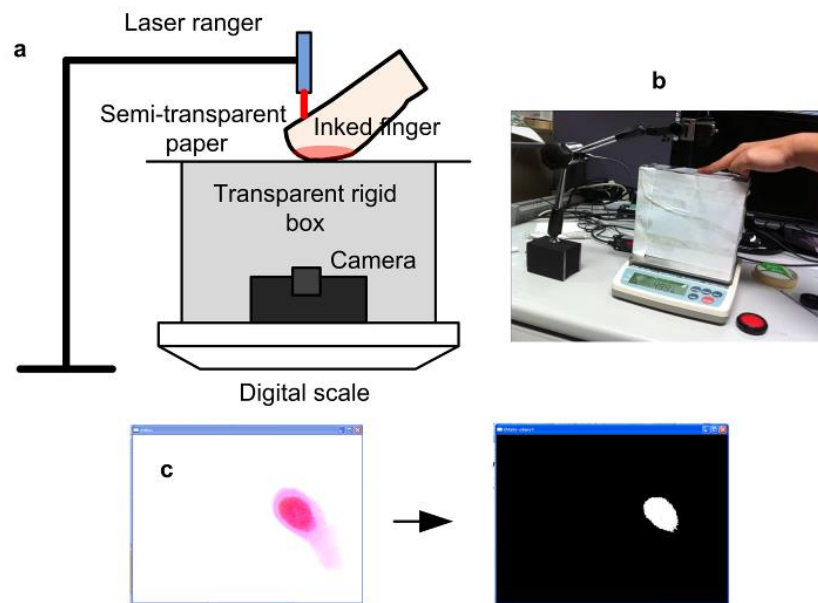


Fig. 3-14 Experiment verifying finger deformation: (a) experiment setting, (b) real scene, and (c) image of contact area before and after the imaging process.

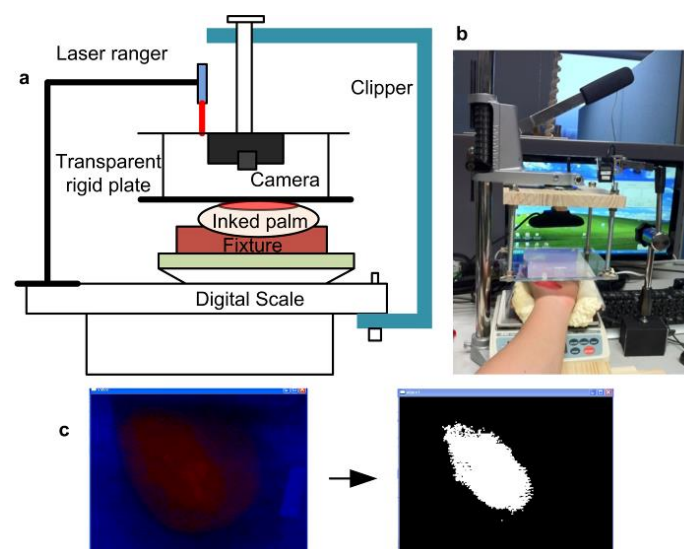
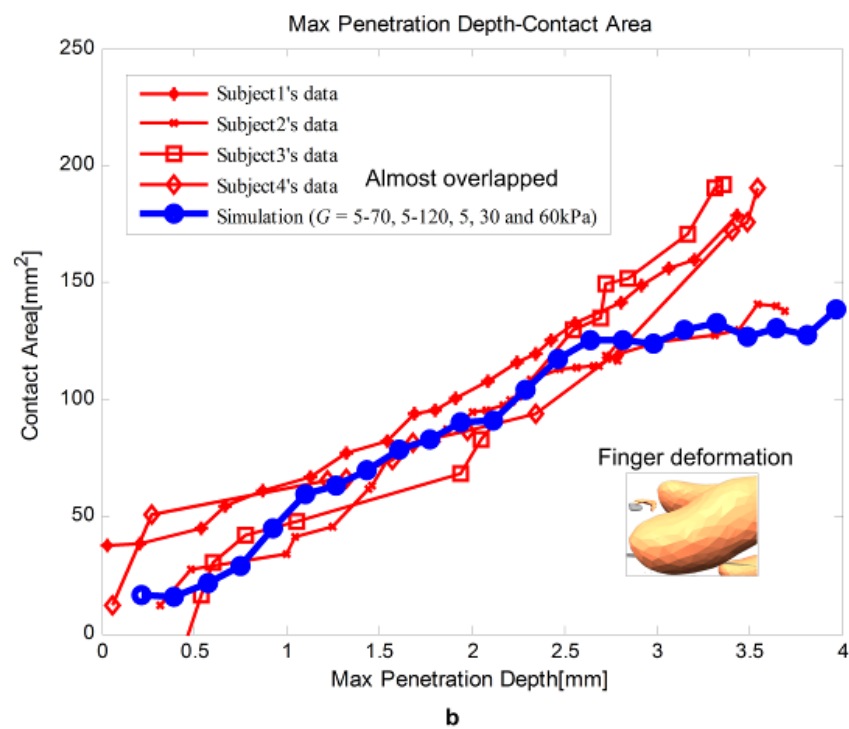
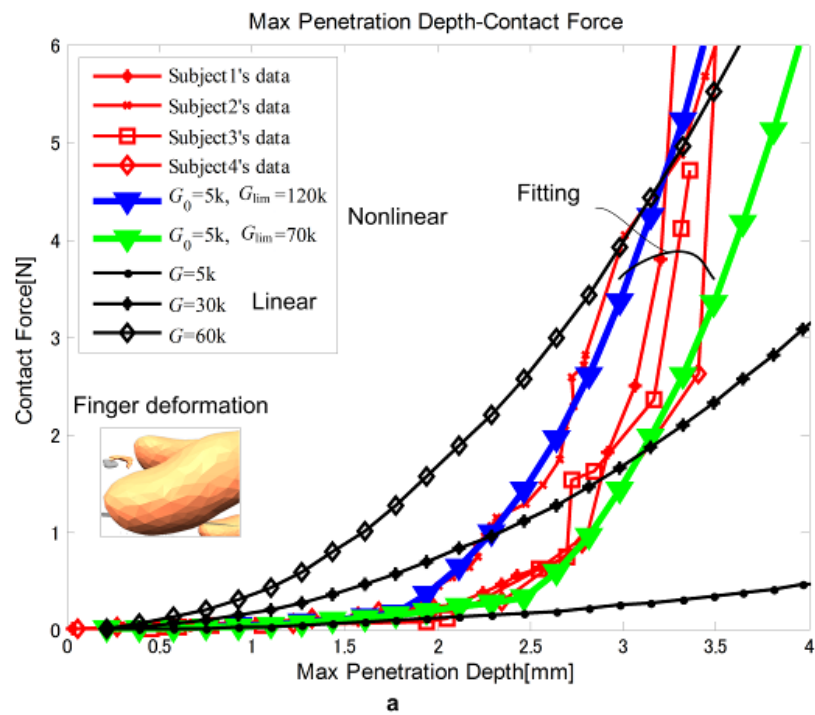


Fig. 3-15 Experiment verifying palm deformation: (a) experiment setting, (b) real scene, and (c) image of contact area before and after the imaging process.



(Continue to next page)

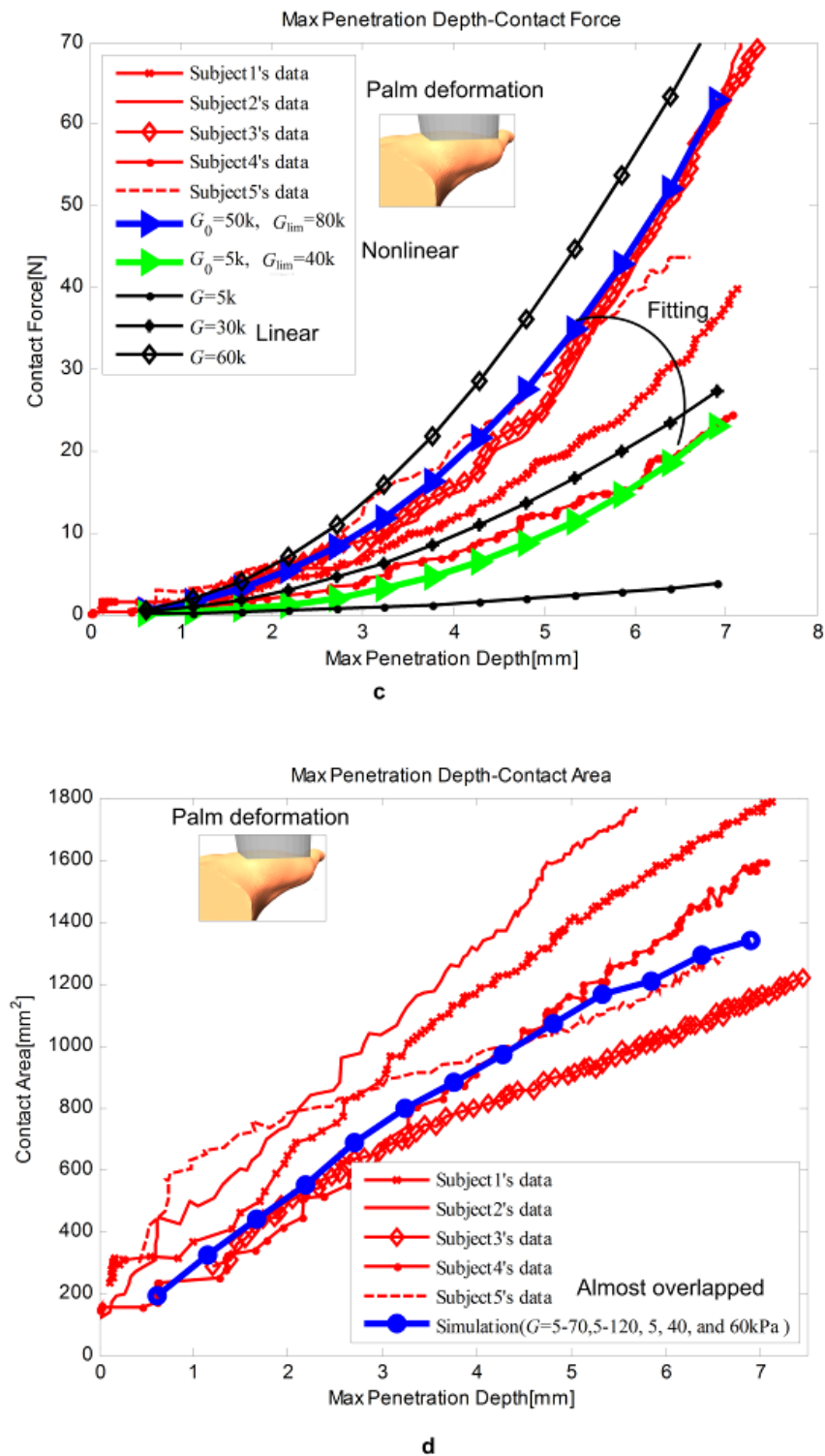


Fig. 3-16 Validation of deformation of finger and palm: (a) and (c) relation between maximum penetration depth and contact force (from top to bottom: finger, palm), (b) and (d) relation between maximum penetration depth and contact area (from top to bottom: finger, palm).

Table 3-5 Time performance of skin deformation simulation of a grasping hand

	Grasping hand
Number of vertices	9693
Number of triangles	19382
Number of partitioned regions	19
Calculated number of component-matrices ($\mathbf{R}_{\text{Bou}}$ and $\mathbf{R}_{\text{Gau}}$)	19×2
The largest size of the matrices	869×869
Pre-process	19 minutes
Online process	About 20 s
Hardware	Intel Core i5 1.70GHz, 4GB main memory

Moreover, **Fig. 3-16** (b) and (d) shows the relation between the maximum penetration depth and contact area (the sum of the area of each triangle in the contact region). The estimations fell within the range of the experimental data, and almost overlapping curves were obtained with different shear modulus, because different contact forces resulted in a relatively constant height of the swelling bulge (Section 3.3.1.5). For a concise expression, these overlapping curves were drawn as one.

3.4.2 Complex Skin Deformation of the Grasping Hand

As shown in **Fig. 3-17**, a subject (male, 27, right hand) was asked to take MRI measurements to obtain hand postures grasping a set of cylinders whose diameters were $\phi 48\text{mm}$ (**Fig. 3-17** (a)), $\phi 60\text{mm}$, and $\phi 100\text{mm}$. Next, the subject was also asked to take pressure distribution measurements (**Fig. 3-17** (b)). It was attempted to keep the two postures the same by matching them with a handprint. **Fig. 3-18** shows the experimental setting. A sheet type of pressure sensor mat (Nitta FSCAN) with 4.2 sensors/cm^2 was wrapped around the cylinders, and then it was covered by one white paper with the same shape. The subject grasped the cylinder with an inked hand during 30s measurements, so that the handprints could be obtained which indicated the cumulative contact area during the measurements.

In contrast, a Digital Hand model of the same subject was made from the MRI measurements. By carefully manually matching the surface skin mesh and the internal bone meshes, very similar grasp postures (**Fig. 3-17** (c)) of the Digital Hand to the MRI recorded ones were reconstructed. As shown in **Fig. 3-19** (b) and (c), the other two grasps also were generated in the same way. The time performance of this simulation is described in **Table 3-5**. The online process of the deformation only needed about 20s. The calculated $\mathbf{R}_{\text{Bou}}$ and

$\mathbf{R}_{\text{Gau}}$ could be reused in different generated grasp postures of this Digital Hand model. The $G(d_{\text{max}})$ obtained in Section 3.4.1 was adopted for partitioned regions with slight modification of G_0 and G_{lim} for fitting empirical data in the online process.

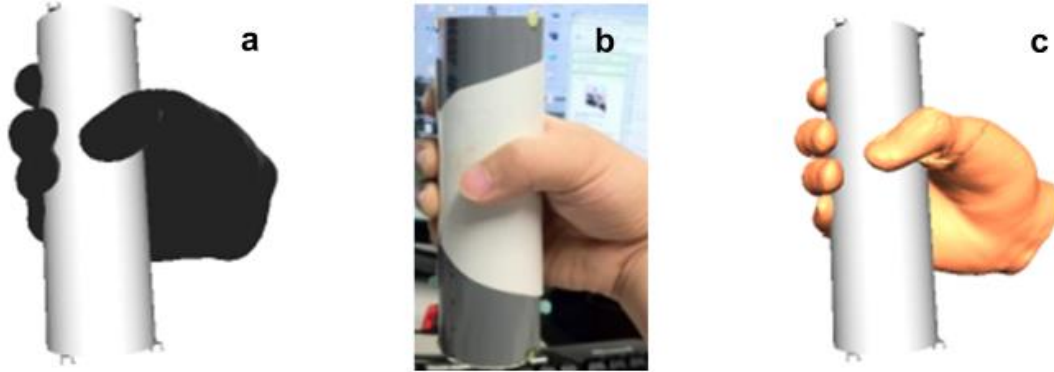


Fig. 3-17 Similar grasp postures gripping a cylinder of $\phi 48\text{mm}$: (a) MRI measured grasp posture, (b) Real grasp posture photo, and (c) Simulated grasp posture generated by Digital Hand.

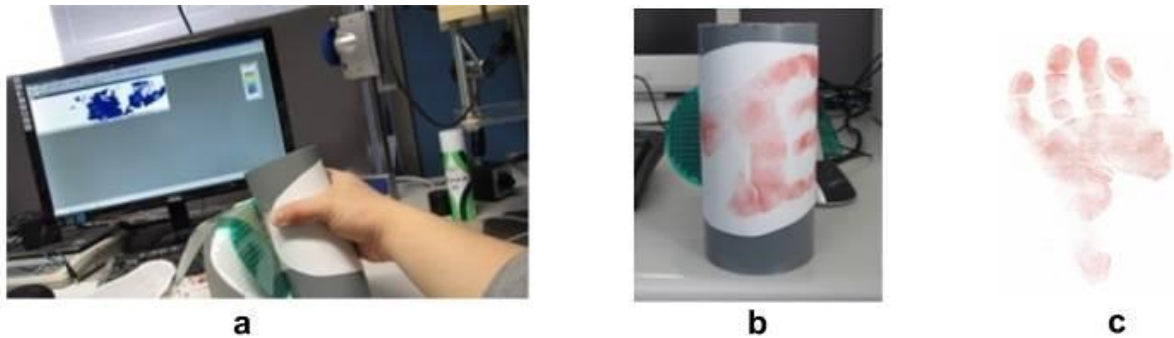


Fig. 3-18 Experiment validating pressure distribution of grasp posture: (a) FSCAN system, (b) Sensors mat covered by handprint, and (c) Handprint.



Fig. 3-19 Grasp posture generated by Digital Hand: (a) $\phi 48\text{mm}$ cylinder, (b) $\phi 60\text{mm}$ cylinder, and (c) $\phi 100\text{mm}$ cylinder.

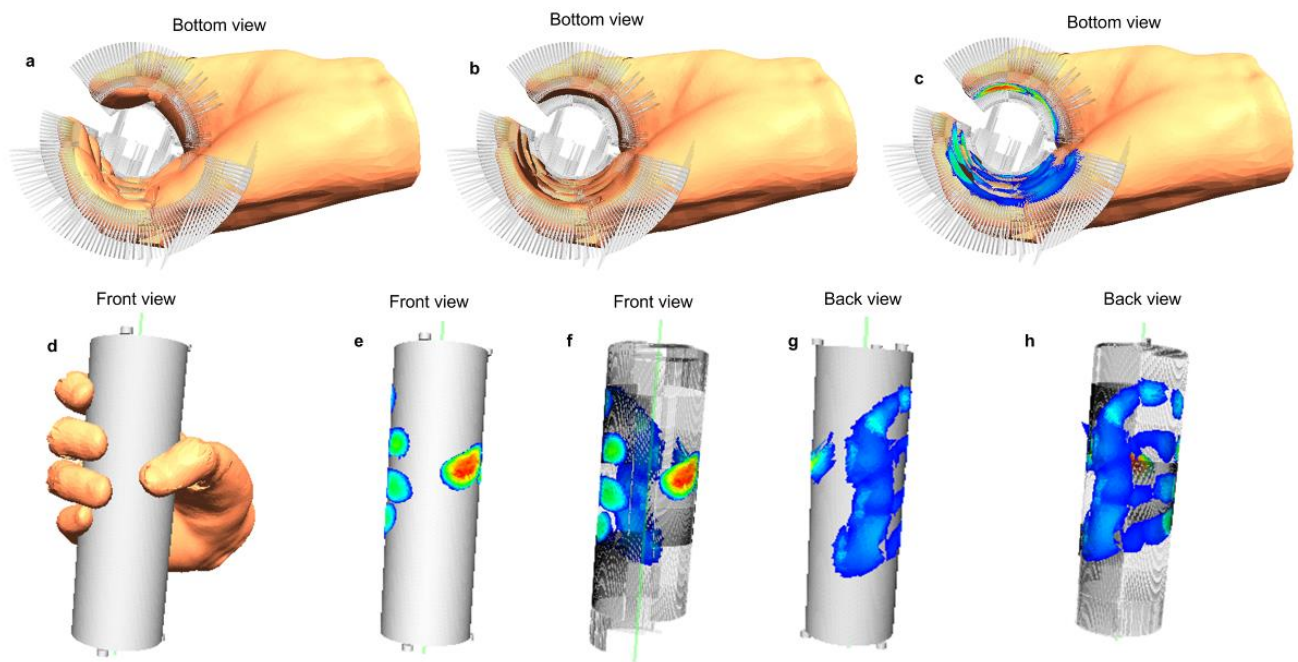


Fig. 3-20 Simulation of grasp posture gripping a $\phi 48\text{mm}$ cylinder:

(a) skin before deformation, (b) skin after deformation, (c) estimated pressure distribution map, (d) grasp posture, and (e) ~ (h) estimated pressure distribution map.

Fig. 3-20 shows the visual skin deformation of the hand's grasp with the cylinder ($\phi 48\text{ mm}$). **Fig. 3-20** (a) shows the skin without this simulation. On the contrary, **Fig. 3-20** (b) shows the results of the hand touching the cylinder. **Fig. 3-20** (c) shows the estimated pressure distribution map on palmar skin. **Fig. 3-20** (e) ~ (h) show the pressure map on the solid or half-transparent surface of the cylinder.

During the 30s measurements of grasping the three cylinders, the total contact force varied with time. It could be read from the pressure sensor mat. The ranges of the varying force were more than 100N. The time frames of the maximum, the mean and the minimum contact force, respectively, were extracted from the recorded frame sequence. The three pressure distributions were simulated by slightly adjusting the positions of fingers in grasp postures. The maximum difference between the estimated contact forces and the measured ones is 14N. **Fig. 3-21** shows the comparisons between the measurements and the simulations of the maximum (**Fig. 3-21** (a)), the mean (**Fig. 3-21** (b)), and the minimum (**Fig. 3-21** (c)) contact force frames for the $\phi 48\text{mm}$ cylinder grasping. The red boundaries are the contours of the handprints. The comparisons indicate that this simulation can effectively match the entire range of the contact force varying with time. Moreover, the mean force grasping posture was

regarded as a natural grasp posture (**Fig. 3-21(b)**), therefore mainly the mean force grasping posture was simulated. **Fig. 3-22** shows the same comparison of the mean frames for the $\phi 60\text{mm}$ and $\phi 100\text{mm}$ cylinder grasping. By referring to the handprints shown in **Fig. 3-21** and **Fig. 3-22**, it was observed that the positions of local high pressures between the simulation and the measurement were very close to each other. Also, the highest contact pressures could be observed on both the fingertips in the simulation and the measurement.

The quantitative comparison results for the mean contact force (**Fig. 3-21 (b)**, and **Fig. 3-22**) were summarized in **Table 3-6**. The estimated peak pressures, average pressures, and total contact forces were similar to the measured ones. As for the contact area, the overlapping between the simulation and the handprints accounted for 69-77% in the handprints.

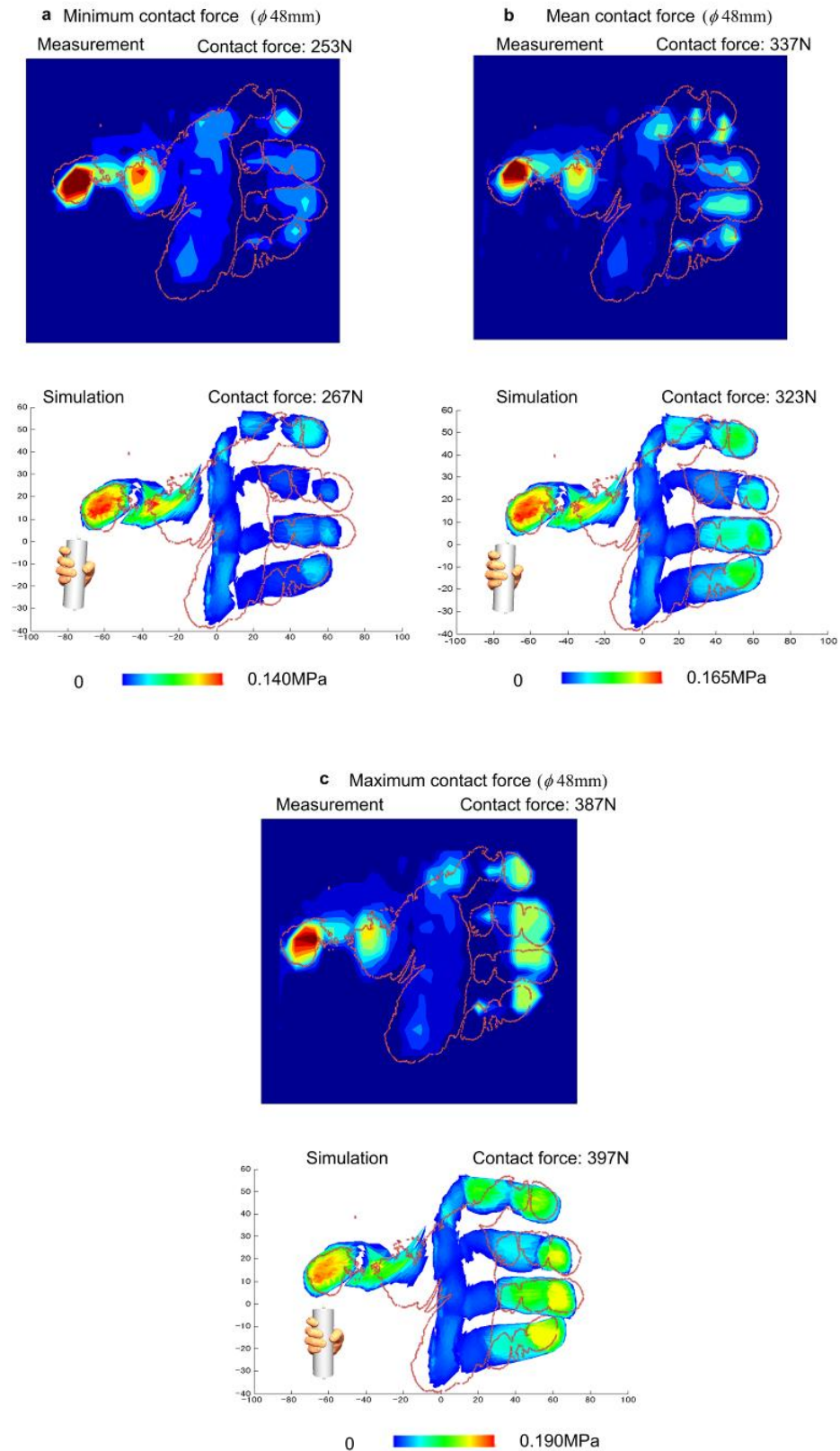


Fig. 3-21 Pressure distribution validation ($\phi 48\text{mm}$ cylinder grasp): (a), (b) and (c) are the comparisons between measurement and simulation in the minimum, the mean and the maximum contact force

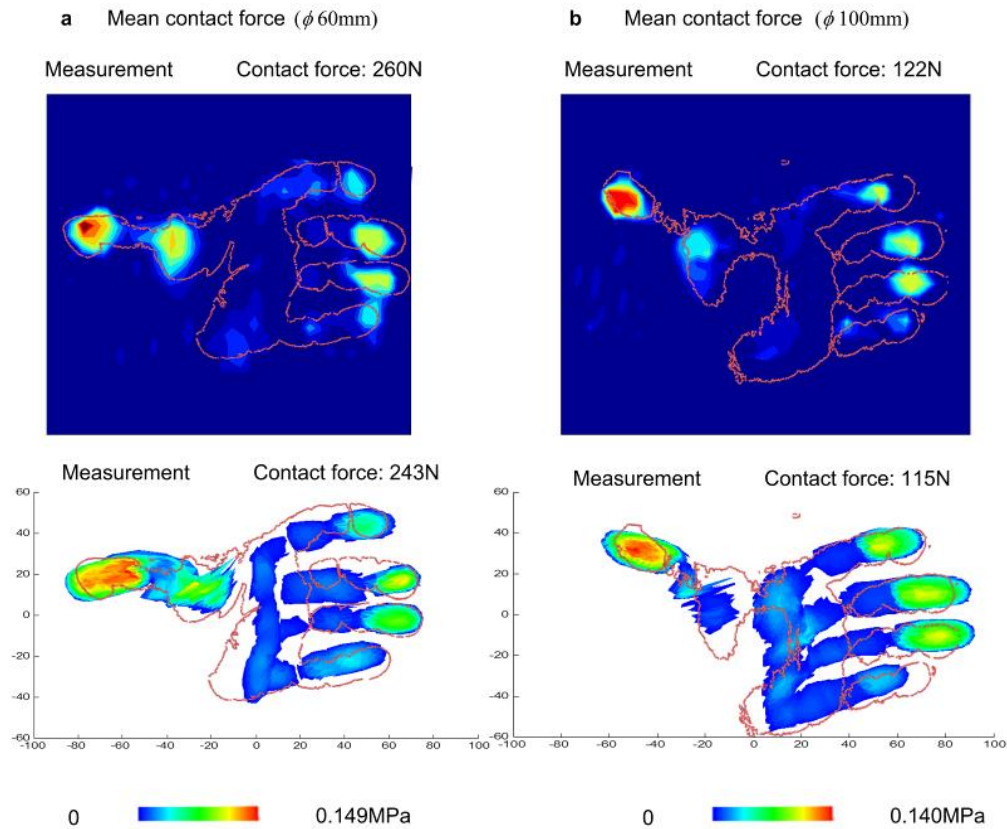


Fig. 3-22 Pressure distribution validation ($\phi 60\text{mm}$ and $\phi 100\text{mm}$ cylinder grasps): (a) and (b) are the comparisons between measurement and simulation in the mean contact

Table 3-6 Comparison of pressure distribution between measurements (mean force) and simulations

Cylinder diameter	$\phi 48\text{mm}$		$\phi 60\text{mm}$		$\phi 100\text{mm}$	
	Measurement	Simulation	Measurement	Simulation	Measurement	Simulation
Peak pressure [MPa]	0.165	0.165	0.150	0.150	0.138	0.138
Average pressure [MPa]	0.033	0.028	0.029	0.027	0.028	0.022
Total contact force [N]	337	323	260	243	122	115
Overlapped area in handprint	-	69%	-	77%	-	77%

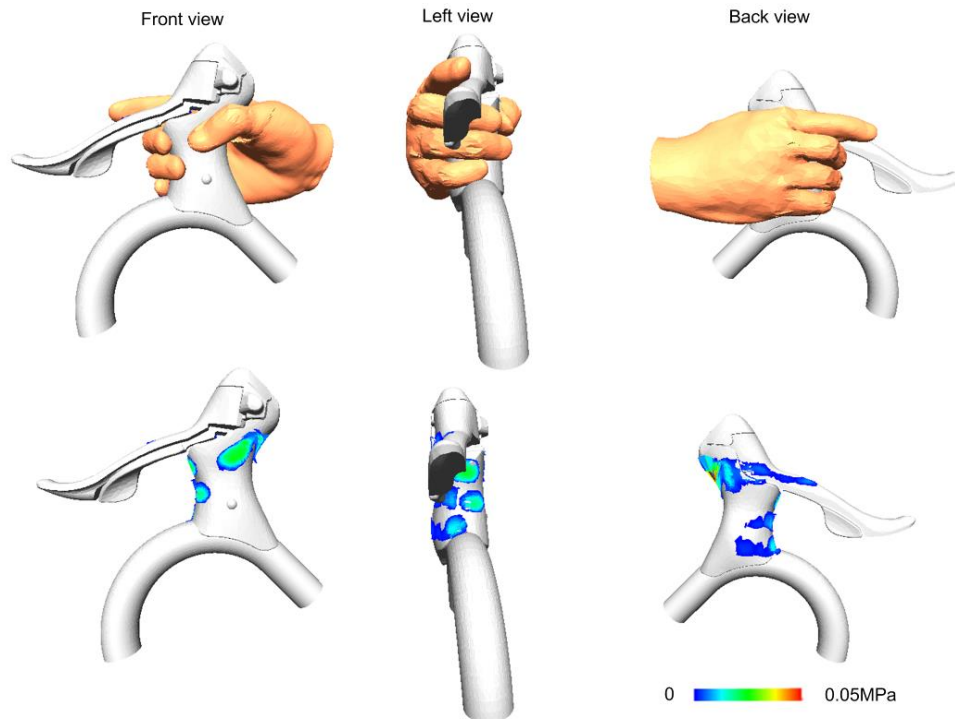


Fig. 3-23 The skin deformation simulation of grasping a bicycle handlebar.

Finally, it was attempted to introduce this simulation method in an ergonomic analysis to a CAD model of the mockup of a bicycle handlebar. As shown in **Fig. 3-23**, a plausible grasp posture was manually generated and a corresponding pressure distribution was estimated on the surface of the model. It showed the possibility to incorporate this simulation method in a practical virtual ergonomic assessment into the early stage of the design of handheld products. For example, a designer could use the estimated local high pressure to evaluate the comfort of an early CAD model of a product.

3.5 Discussion and Summary

In this chapter, an efficient simulation method of skin contact deformation is proposed. Compared with FEM-based methods, this simulation, whose online process just needs tens of seconds for complex contact configuration, has a higher efficiency and does not burden the assessment system where there are other tasks than contact condition estimation.

The previous work [20] could effectively estimate the contact condition, but ignores some real properties of real human skin. On the contrary, our proposed method realizes two important properties of human skin, the nonlinear elasticity and the compressing-swelling effect. The spatially distributed heterogeneity of the human hand is achieved by a reasonable

partition by main creases on the hand surface similar to [22]. Therefore, our proposed method has enough extensibility to deal with a complex contact configuration.

The relation $G(d_{\max})$, between the shear modulus and the maximum penetration in our study, is obtained by fitting experimental data. Fortunately, the range of G obtained by the experimental measurement on human hand skin [15] is within the scope of G in the physical model of our study.

A designer of the handheld product always wants to know the pressure distribution on the surface when grasping it. Hall [44] points out that local high external pressure plays an essential role in the efficiency of the work and the consumer's satisfaction. By experimental validation, the estimated pressure distributions in the simulation are closed to the real ones. Moreover, the results of the grasp simulation with different cylinders are similar to Seo's experimental conclusions [54].

Because the skin biomechanical properties of the human hand vary with the different individuals, ages, genders and nationalities, the tests on a small number of subjects are insufficient for finding the right parameter ranges of the physical model. Therefore, a database, including the parameter setting of various typical human hands, will be needed as a future work. Moreover, so far, the conditions where the contract forces act normal to the surface, i.e., the frictionless case is only considered in this paper. Further research is expected to add the friction analysis.

Chapter 4

Variational hand modeling based on image-based 3D model reconstruction

4.1 Introduction

In Chapter 2, a MRI-based hand modeling method is proposed. However, the MRI-based hand modeling requested subjects to take a long time and difficult measurements. Also, constructing a hand model is very time-consuming, because it needs numerous manual operations for segmentations and joint axis estimation. Thus, this technique could not generate a lot of hand models in a short amount of time. However human hands have a variety of sizes depending on different individuals, ages, genders and nationalities. Therefore, a variational hand modeling method is needed to generate different individual human hand models with variations in a relatively simpler way than that of the previous works.

To solve the problem, the purpose of this research was to propose a variational hand modeling method where a 3D hand model with specific sizes can be efficiently generated from an existing template hand model in a simpler way, and where the size variation both of the surface skin model and the specific internal joint-link structure can be easily obtained.

There have been some similar works. Kouchi, Miyata and Mochimaru [7] utilized factor analysis to evaluate 82 measurements from 103 Japanese subjects, and then found two principle factors to represent the dimensions of Japanese hands. The individual hand models could be created by scaling a generic hand by the optimization process. However, because this work only dealt with the hand skin variation in a static hand posture, there was a lack in

the variation for the internal joint-link structure. On the other hand, Rhee, Neumann and Lewis [22] proposed a variational hand modeling method based on a palm side photo, and the finger joint centers were estimated according to the position of the main creases on the palm side. However, the thickness of the hand was ignored in their method, and the estimated joint centers were not verified dynamically in different hand postures. Similarly, Albrecht, Haber and Seidel [23] employed an image-based hand deformation method to generate individual hand models. Their method used an image and scattered interpolation to deform a generic hand model. However, the accuracy of hand posture in 3D position cannot be guaranteed, because the correspondences can only be obtained between 3D feature points in reference hand model and the 2D hand picture.

In order to realize modeling the surface of individual hand with specific size and estimating the internal joint-link structure in a simpler way, a variational hand modeling method is proposed. The overview of the proposed method is shown in **Fig. 4-1**. And the processes (B1~B7) are listed as follows,

- B1~B2: First, multi-view photographs of an individual hand of a subject, whose back side are painted with dot markers and the main crease on the palm are also painted, are taken by proposed experimental equipment. Then they are used to reconstruct the models of different hand postures based on a multi-view 3D model reconstruction.
- B3: According to anatomical knowledge, the main creases on palm side were used to partition the hand skin surface into 15 segments.
- B4: Based on the partition, hand surface feature dimensions of an individual were measured directly from the reconstructed hand model.
- B5: Then, a hand model with size variation was constructed by scaling the segments of a template hand model to those with the feature dimensions of the reconstructed model.
- B6: The extracted positions of markers were used to estimate the joint parameters (joint centers and their axis directions) using a single axis rotation assumption based on anatomical knowledge.
- B7: Finally, the scaled segments of the template hand model were registered to the corresponding ones of the reconstructed hand model by an alignment process for minimizing the errors between the positions and orientations of the segments of the template hand model and those of the reconstructed hand model. A

complete Digital Hand with the individual hand size and the derived individual joint-link structure could be obtained.

In the latter part of this chapter, the dimensions of the generated hand model with the size variation were also verified by comparing them with the precise MRI measurements of the hand of the same subject. Also, the derived joint-link structure was verified by comparing it with a Digital Hand model based on MRI measurement ([24]).

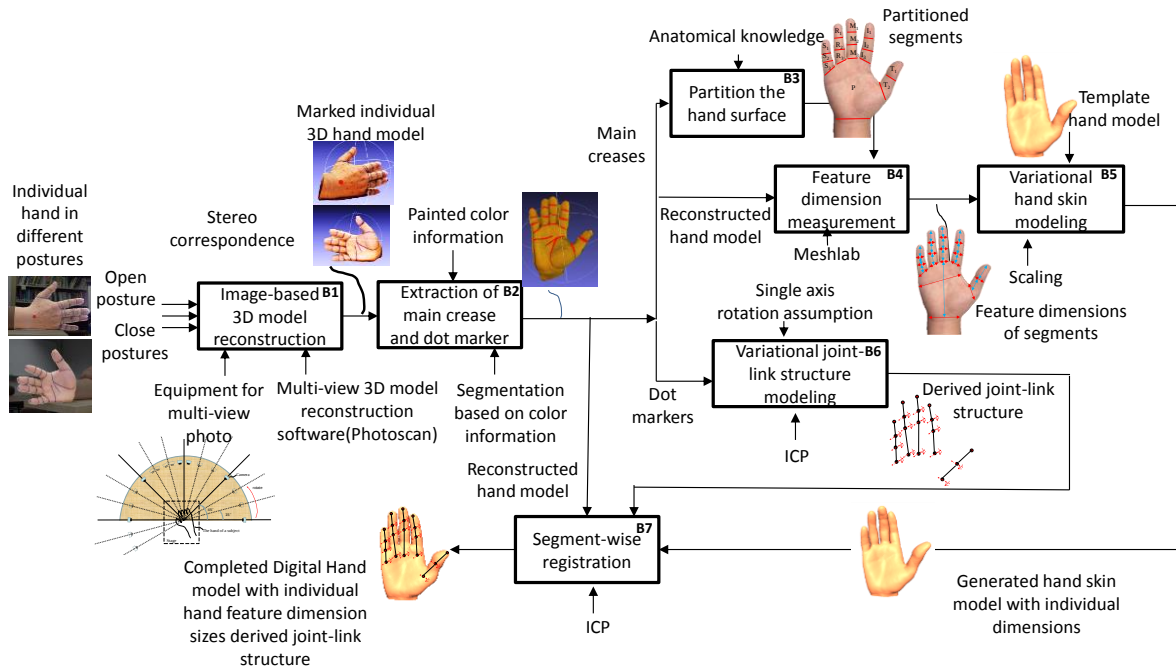


Fig. 4-1 Outline of the proposed variational hand modeling method.

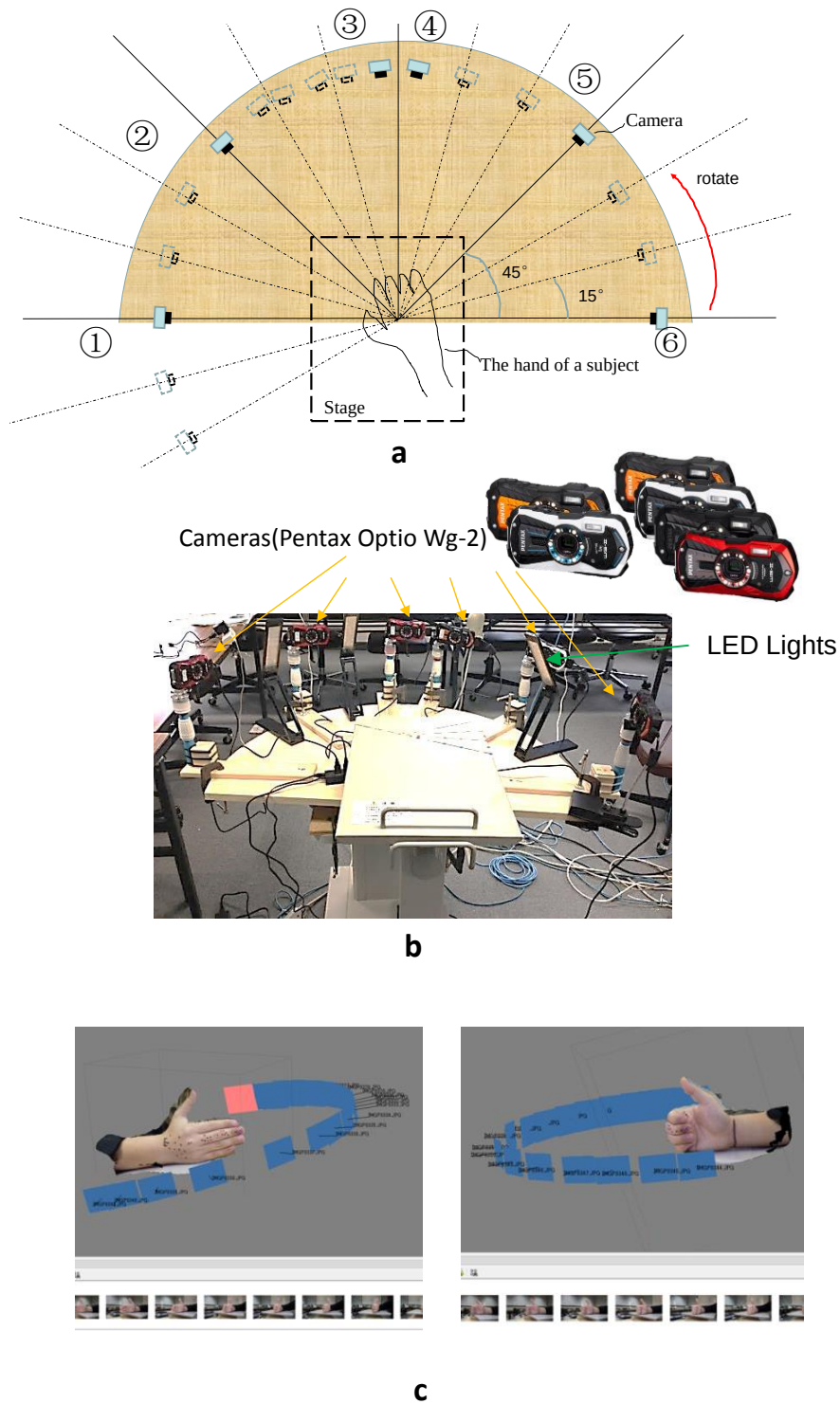


Fig. 4-2 (a) Experimental setting, (b) Experimental scene, (c) A series of photographs of the hand

4.2 Image-based 3D model reconstruction

4.2.1 Experiments for the reconstruction of hand model

The MRI-based hand modeling requested subjects to take a long time and difficult measurements which also cost much. Instead, in order to realize hand modeling in a subject-friendly and inexpensive way, an experimental system for image-based multi-view 3D modeling reconstruction was introduced, owing to its user-friendliness and low cost. As shown in **Fig. 4-2** (a) and (b), in an enough illumination condition, 6 common commercial cameras were placed on a rotatable plate. They could be controlled by a remote controller for simultaneous shots. Behind the cameras, LED lights were installed for the illumination.

During the measurement, the hand of a subject was roughly placed at the center of the rotatable plate on a stage. By rotating the plate discontinuously and shooting in around every 15 degree, a series of clear and stable photographs of the hand could be taken as shown as the blue rectangles in **Fig. 4-2** (c).

As shown in **Fig. 4-3** (a), some dots were marked on the back side of the subject's hand as markers. Also, the main creases of the hand were also painted for the partition of the model. A relaxed natural posture, a full flexion posture and a full abduction posture were measured as shown in **Fig. 4-3** (b). For each posture, 36 photographs were taken during 30 sec to get a model in each posture with acceptable quality.

4.2.2 Image-based 3D reconstruction

Based on commercial multi-view 3D reconstruction software (Photoscan [55]), the photographs were inputted to an image-based 3D model reconstruction process which includes three steps. The first step is photograph alignment where the common points on photographs were searched and matched, as well as the position and orientation of the camera for each photograph was estimated. The next step is building the mesh. Based on the estimated camera position and pictures themselves, a 3D polygon mesh representing the object surface was built. Finally, after the hand mesh model was constructed, it was textured as shown in **Fig. 4-3** (c). The accuracy of the reconstruction evaluated by reconstructing a paper box with known dimensions was 0.65mm (**Fig. 4-4**).

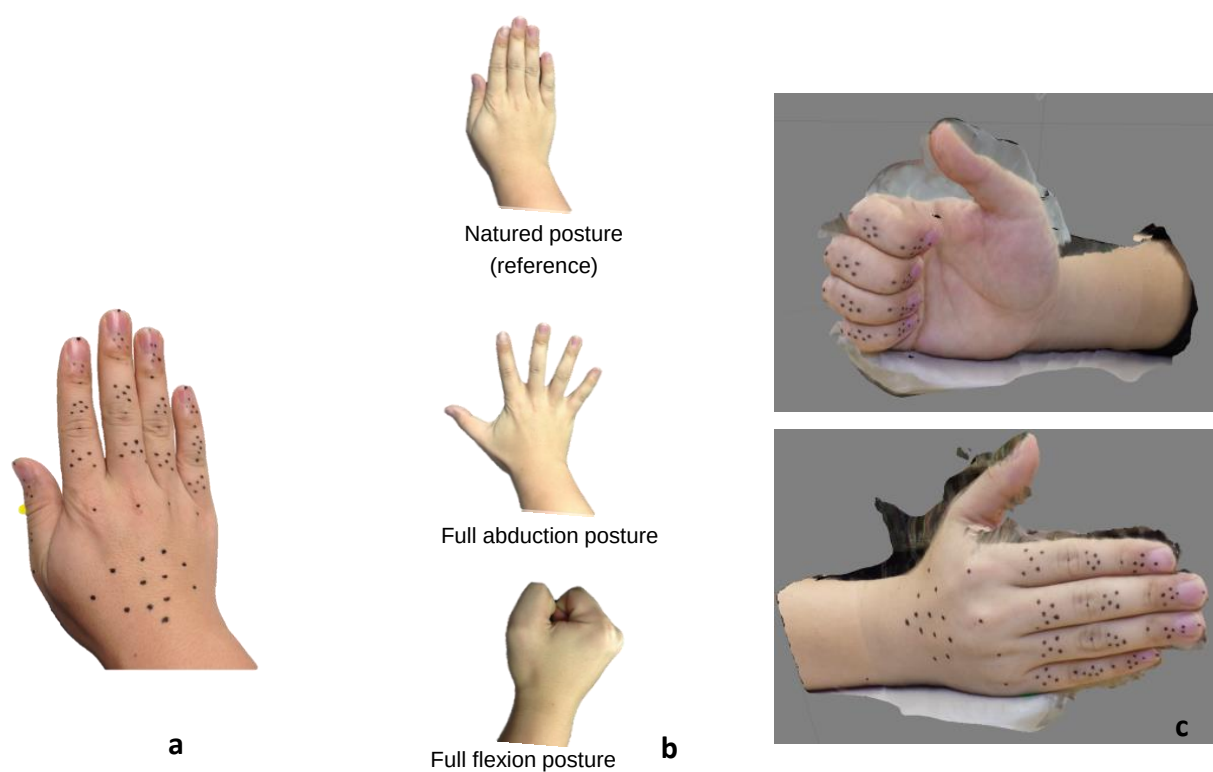


Fig. 4-3 (a) A hand with markers, (b) Different hand posture, (c) Reconstructed hand models

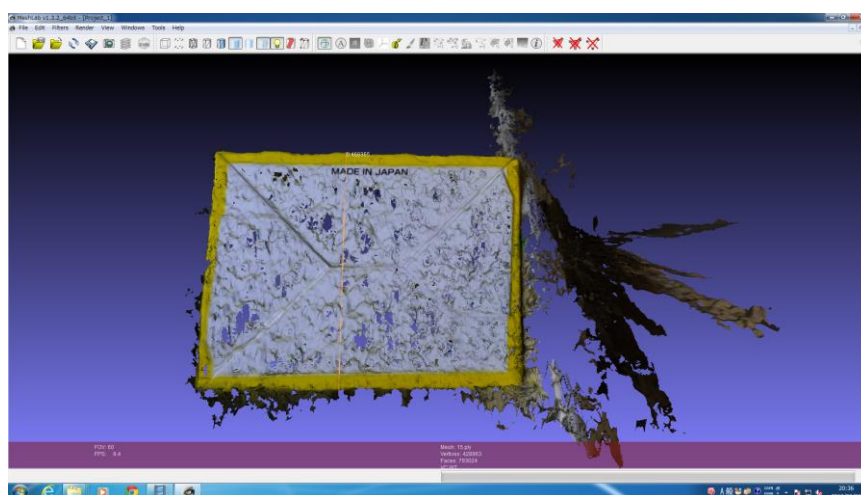


Fig. 4-4 The reconstruction model of a paper box with known dimensions

4.2.3 Extraction of main creases and dot markers

The crease meshes were extracted from the reconstructed hand model by a mesh segmentation process. In this process, only the meshes with the HSV color information in a specified range, whose center was the color information the painted crease, were extracted (Meshlab [56]) as shown in **Fig. 4-5 (a)**. According to the extracted creases, the reconstructed hand model was partitioned into 15 segments. This partition is described in Section 4.3.1.

4.3 Variational skin modeling

4.3.1 Partition of the hand surface

The surface anatomy of the main creases on the palm is a common landmark in hand surgery, since the basic main creases have a strong relationship with the underlying bone structure [22]. Furthermore, they are commonly used in anthropometric measurements [7].

Similarly, as shown in **Fig. 4-5 (b)**, according to the anatomical knowledge, the hand surface was partitioned into 15 segments which were relatively independent to each other, so that one segment could be scaled independently to fit the corresponding one of an individual hand. The palm was treated as one segment for simplification.

4.3.2 Hand surface feature dimension measurement

For the surface feature dimension measurement as shown in **Fig. 4-5 (c)**, the traditional sliding caliper measurement is time-consuming, which causes the measurement error magnification due to the natural tremble of the subject hand during a long time measurement. Instead of measuring the real hand of a subject, the reconstructed hand model of the subject was used for extracting the hand surface feature dimensions (the length, breadth, and thickness of the partitioned segments of the hand) as shown in **Fig. 4-5 (d)**. In Meshlab software, the feature points on the painted creases were directly measured on the 3D model.

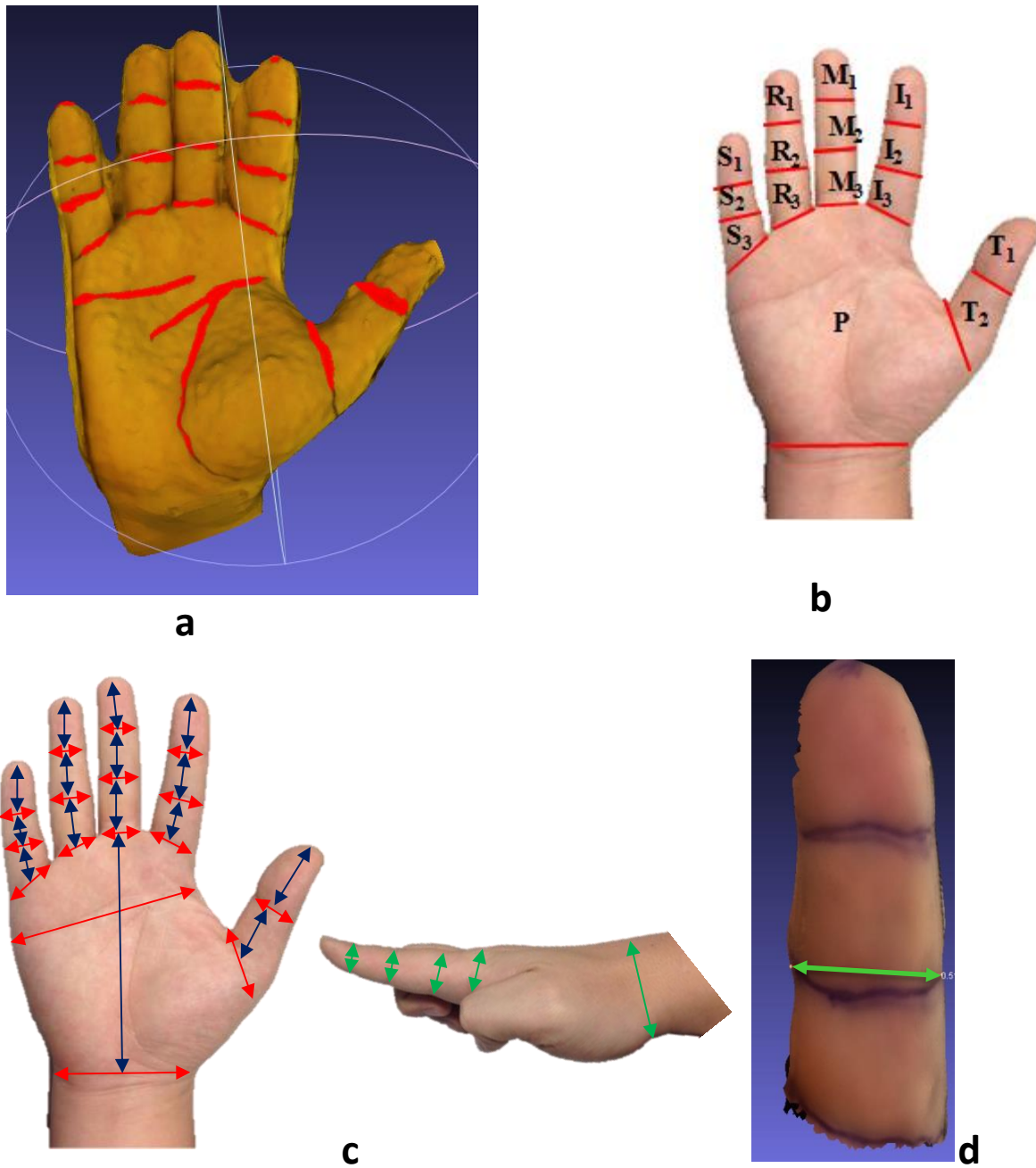


Fig. 4-5 (a) Extracted creases of reconstructed hand model, (b) Partition of hand surface, (c) Feature dimensions of hand surface, (d) Feature dimension measurement directly by the reconstructed hand model

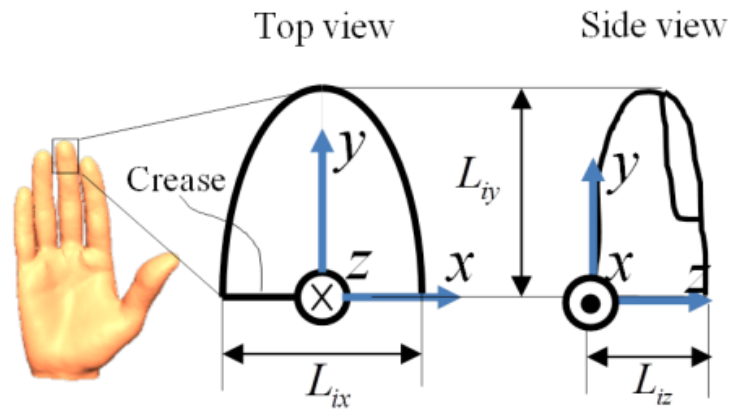


Fig. 4-6 The local coordinate frame and the dimensions of one segment

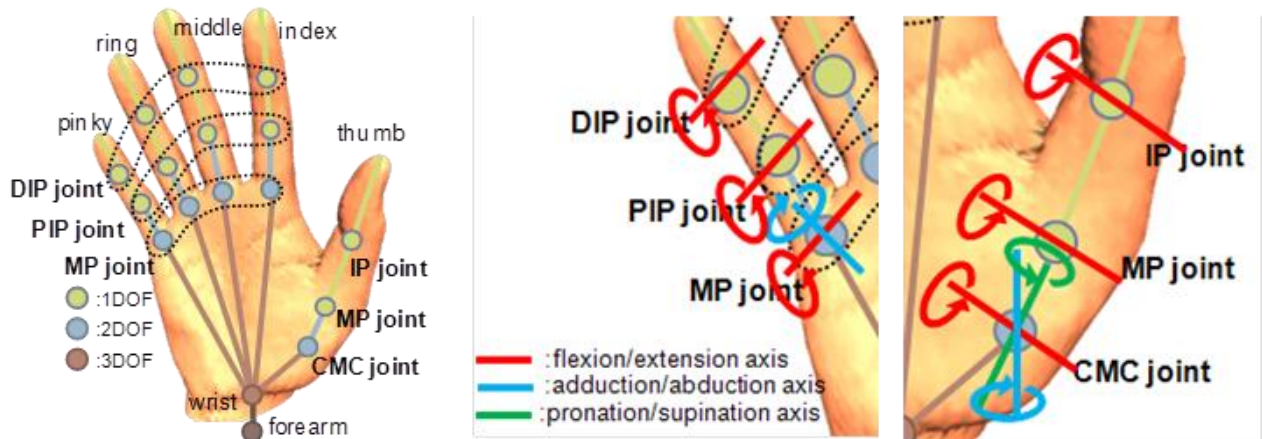


Fig. 4-7 Configuration of the joint-link structure model

4.3.3 Scaling the hand segments of the template hand model

An MRI-based Digital Hand model [24] which was well partitioned into the segments according to the main surface creases was used for the template hand model. As shown in Fig. 4-6, a local coordinate frame was defined in each segment. All the coordinate frames have z-axes paralleled to a normal vector of a plane on which the subject's palm was laid. In each coordinate frame, the x-axis direction was defined along the direction of the creases and the wrist. An origin was defined as the middle point of the crease and wrist both of which were assumed to be placed in a 2D plane.

For each segment, it was scaled along its local coordinate axes independently along x , y and z according to the anisotropic scale factors f_x , f_y and f_z defined in Equation (4-1).

$$f_x = \frac{L_{ix}^M}{L_{ix}^G}, \quad f_y = \frac{L_{iy}^M}{L_{iy}^G}, \quad f_z = \frac{L_{iz}^M}{L_{iz}^G} \quad (4-1)$$

where i is the ID of the segment, and L_{ix}^M , L_{iy}^M , and L_{iz}^M the measured feature dimensions respectively in the x , y , and z directions, and L_{ix}^G , L_{iy}^G , and L_{iz}^G are the corresponding feature dimensions of the segment of the template hand model, as shown in **Fig. 4-6**.

4.4 Variational joint-link structure modeling

4.4.1 Joint-link structure and single axis rotation assumption

The joint-link model in this study had the link-joint structure shown in **Fig. 4-7**. The degrees of freedom (DOF) of the joint were modeled based on anatomical knowledge [31]. For four fingers, each metacarpophalangeal (MP) joint of the fingers had 2DOF rotations: flexion/extension and adduction/abduction. Each proximal interphalangeal (PIP) joint and distal interphalangeal (DIP) joint had 1DOF rotation of flexion/extension. For a thumb, the MP and IP joints have 1DOF of simple rotation. And 1DOF could be approximately treated as one single axis rotation. The CMC joint had 2DOF where both flexion/extension and adduction/abduction accompanied pronation/supination motions.

4.4.2 Deriving finger joint parameters of the joint-link structure

Joint parameters (joint center and its axis direction) were derived by comparing 3D positions and orientations of two corresponding markers taken from a segment of the reconstructed hand mesh model at two different grasp postures. First, the marker positions at the reference posture (natural extended posture) and the ones at a bended posture either of a full flexion posture or a full abduction posture were extracted from mesh processing software extracted (Meshlab [56]). Then the position and orientation of these two sets of markers were matched using ICP the algorithm [57] as shown in **Fig. 4-8 (a)**.

The rigid body transformation matrix $\mathbf{T}^{ICP}$ which gives the minimum matching error between a marker position of the homogeneous coordinates $\mathbf{v}_i^T$ at the bended posture and its corresponding one $\mathbf{v}_i^S$ at the reference posture could be derived by finding the least square solution of Equation (4-3) and **Fig. 4-8 (b)**.

$$\mathbf{T}^{ICP} = \begin{bmatrix} \mathbf{R}^{ICP} & \mathbf{t}^{ICP} \\ \mathbf{0} & 1 \end{bmatrix} \quad (4-2)$$

$$\mathbf{T}^{ICP} = \arg \min_{\mathbf{T}} \sum_{i=1}^{N_s} \left\| \mathbf{T} \mathbf{v}_i^S - \mathbf{v}_i^T \right\|^2 \quad (4-3)$$

where $\mathbf{T}$ is the 4x4 rigid transformation matrix, N_s the number of markers.

If it is assumed that $\mathbf{T}^{ICP}$ can only be expressed as a single axis rotation for the finger joints except MC and $\mathbf{p}_a$ as an arbitrary point on the rotational axis (a rotation center), the single axis rotation matrix $\mathbf{T}^{Axis}$ can be expressed as Equation (4-4) where $\mathbf{R}^{ICP}$ is a 3x3 rotational sub-matrix in $\mathbf{T}^{ICP}$.

$$\mathbf{T}^{Axis} = \begin{bmatrix} \mathbf{E} & \mathbf{p}_a \\ \mathbf{0}^T & 1 \end{bmatrix} \begin{bmatrix} \mathbf{R}^{ICP} & \mathbf{0} \\ \mathbf{0}^T & 1 \end{bmatrix} \begin{bmatrix} \mathbf{E} & -\mathbf{p}_a \\ \mathbf{0}^T & 1 \end{bmatrix} = \begin{bmatrix} \mathbf{R}^{ICP} & -\mathbf{R}^{ICP} \mathbf{p}_a + \mathbf{p}_a \\ \mathbf{0} & 1 \end{bmatrix} \quad (4-4)$$

Therefore, by comparing Equation (4-3) and Equation (4-4) and $\mathbf{T}^{Axis} = \mathbf{T}^{ICP}$, we can obtain $\mathbf{t}^{ICP} = -\mathbf{R}^{ICP} \mathbf{p}_a + \mathbf{p}_a$, and from this equation, the optimum rotation center $\mathbf{p}_a = (\mathbf{E} - \mathbf{R}^{ICP})^{-1} \mathbf{t}^{Axis}$ is derived, where $\mathbf{t}^{Axis}$ is the translation vector of $\mathbf{T}^{Axis}$. Similarly, the optimum rotation axis direction $\mathbf{a}$ could be derived from 3x3 rotational submatrix in $\mathbf{T}^{Axis}$ by solving a simple simultaneous linear equation (Section 2.2.5). The derived single joint rotation axis from the markers at one finger is shown in **Fig. 4-8(c)**.

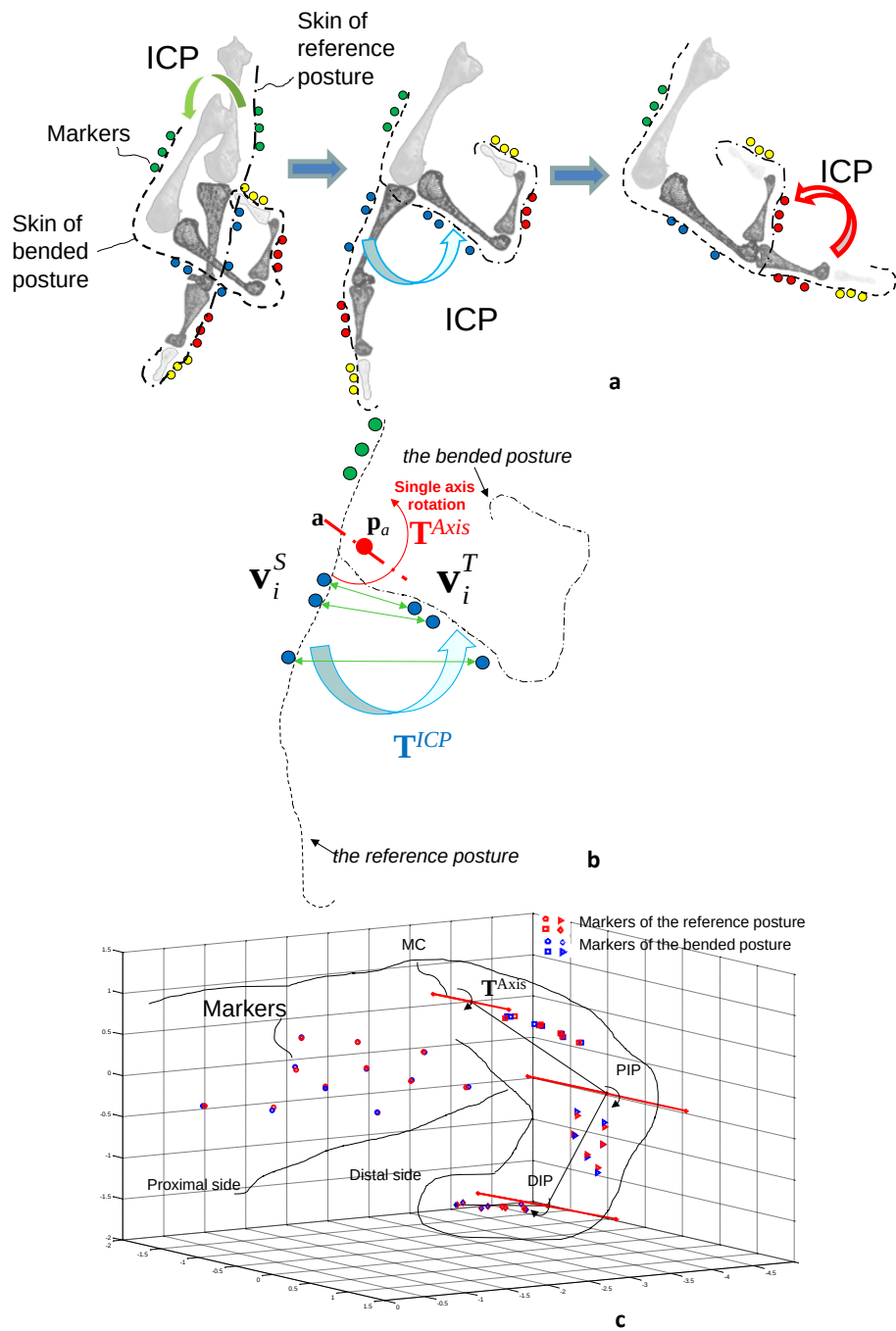


Fig. 4-8 (a) ICP matching of the same markers, (b) Correspondence of markers in different postures (c) The estimation result of the single joint rotation axes in middle finger

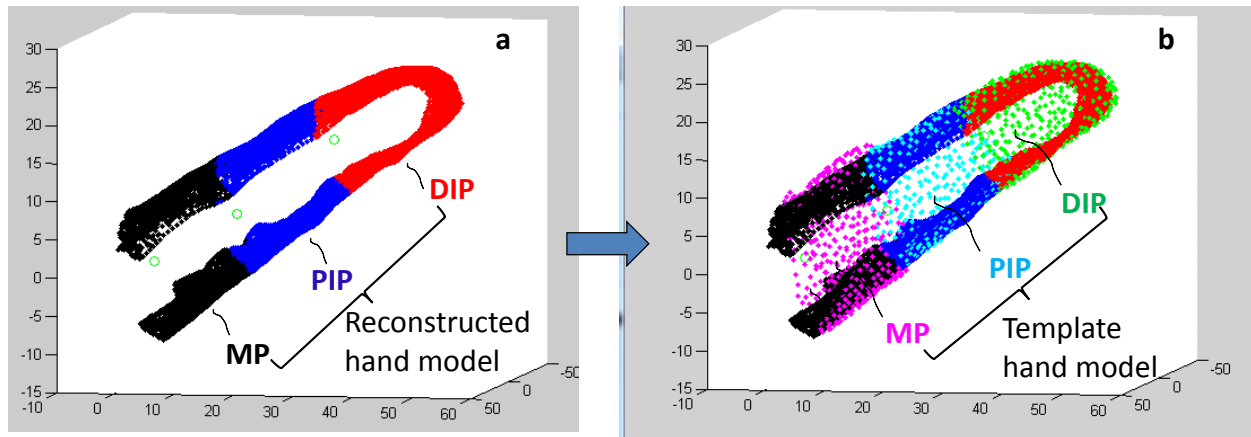


Fig. 4-9 The registration process for index finger:

(a) Segments of the reconstructed hand model (the red, blue and black color vertices indicate the DIP, PIP and MP segment respectively), (b) Registered segments of the template hand model with those of the reconstructed hand model (the green, light blue and purple color vertices indicate the DIP, PIP and MP segment respectively)

4.5 Segment-wise registration

By scaling the partitioned template hand model, the scaled segments were prepared (Section 4.3). On the other hand, the joint-link structure was derived in the reconstructed hand model (Section 4.4). However, the difference in the positions and orientations between the segments of the template hand model and the corresponding ones of the reconstructed model is inevitable. Therefore, a registration process including a rough alignment and a fine alignment was presented for registering the segments of the template hand model to corresponding ones of the reconstructed hand model as shown in **Fig. 4-10**.

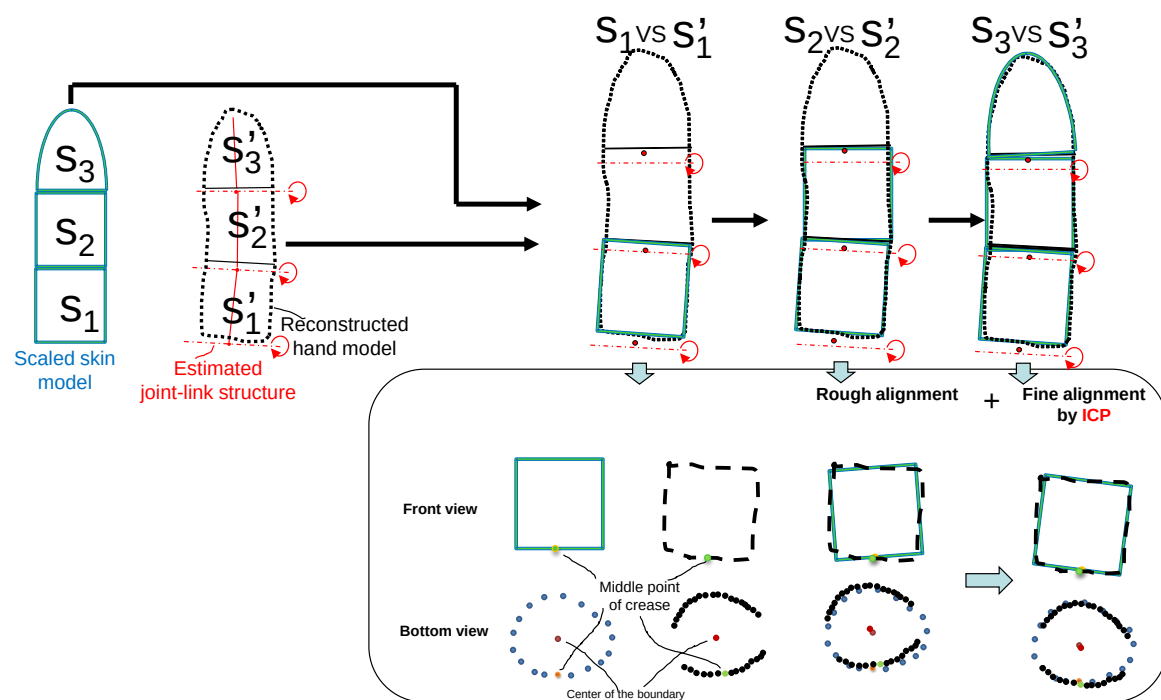


Fig. 4-10 Registration process including of a rough alignment and a fine alignment

In the rough alignment, by aligning the centers of vertices on the segment boundary and the middle point of the crease on palmar side, a scaled segment of the template hand model was roughly aligned to its corresponding segment of the reconstructed hand model. In the fine alignment, ICP algorithm[57] was used to register all of vertices of the roughly aligned segment to those of the corresponding segment of reconstructed hand model as shown in **Fig. 4-9**.

After the fine alignment, the scaled segments of template Digital Hand model were incorporated with the derived joint-link structure.

4.6 Result and verification

A precise Digital Hand model based on MRI measurement (**Fig. 4-11** (a), Shimizu et al., 2010) from one subject (S_0) was used as the template hand model (M_0). Two hand models M_1 and M_2 with different sizes from M_0 were respectively generated from two subjects (S_1 who has a smaller size hand than S_0 , male, 28, right hand, and S_2 who has a larger size hand, male, 35, right hand) as shown in **Fig. 4-11** (b) and (c).

For verifying variational skin modeling, the variational hand skin models were compared with the corresponding MRI measurement of the hand of S_1 and S_2 . The feature dimensions could be measured with mesh modeling software. It was found that the average differences in size between the corresponding segments were 1.2mm, 1.1mm and 0.9mm for S_1 , 1.2mm, 1.1mm and 1.0mm for S_2 in x (breadth), y (length) and z (thickness) directions, respectively. It is an acceptable accuracy for virtual ergonomic assessments of handheld products.

Moreover, the joint-link structure of the hand S_1 was estimated as shown in **Fig. 4-12** (a). **Fig. 4-12** (b) shows the complete Digital Hand model in different views. For verifying variational joint-link modeling, the derived joint-link structure was compared with the one of the same subject by the previous MRI-based hand modeling method. As shown in **Fig. 4-13**, the axis and its center of MP joint of the index finger of two joint-link structures were aligned in the fully extended reference posture for evaluating the position and angle differences in PIP, DIP and fingertip. Moreover, the joints derived the proposed method described in Section 4.2 were rotated by the same joint angles from the virtual reference where the angle between two links takes zero degree to the limit bended one of MRI-based joint-link structure, also for evaluating the position and angle differences of the axis joint PIP, DIP and the position difference in fingertip. The verification results for S_1 and S_2 were listed in **Table 4-1** and **Table 4-2**.

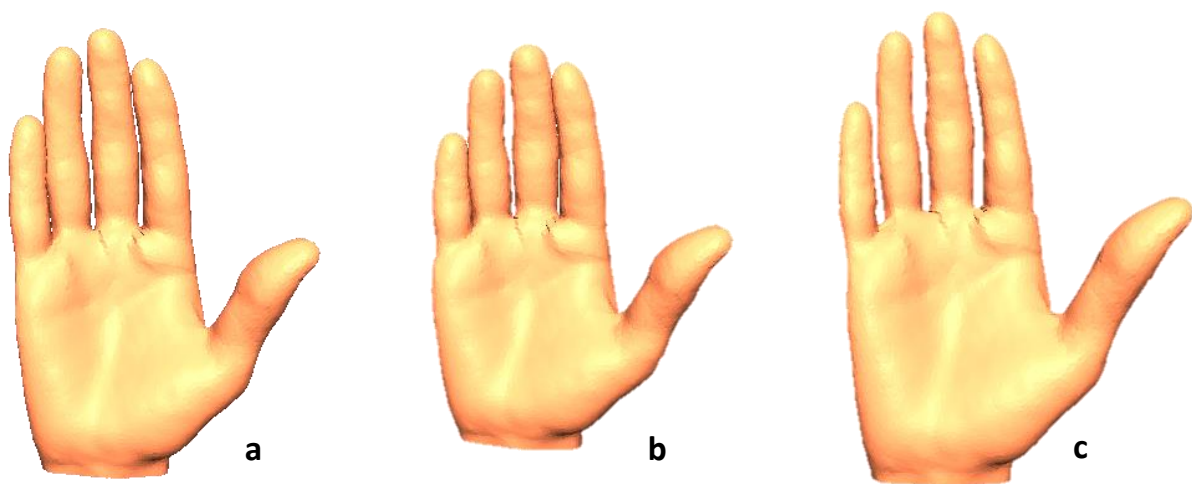


Fig. 4-11 The results of skin variational modeling: (a) The template hand model M_0 , (b) The generated hand model M_1 with feature dimensions of S_1 , (c) The generated hand model M_2 with feature dimensions of S_2

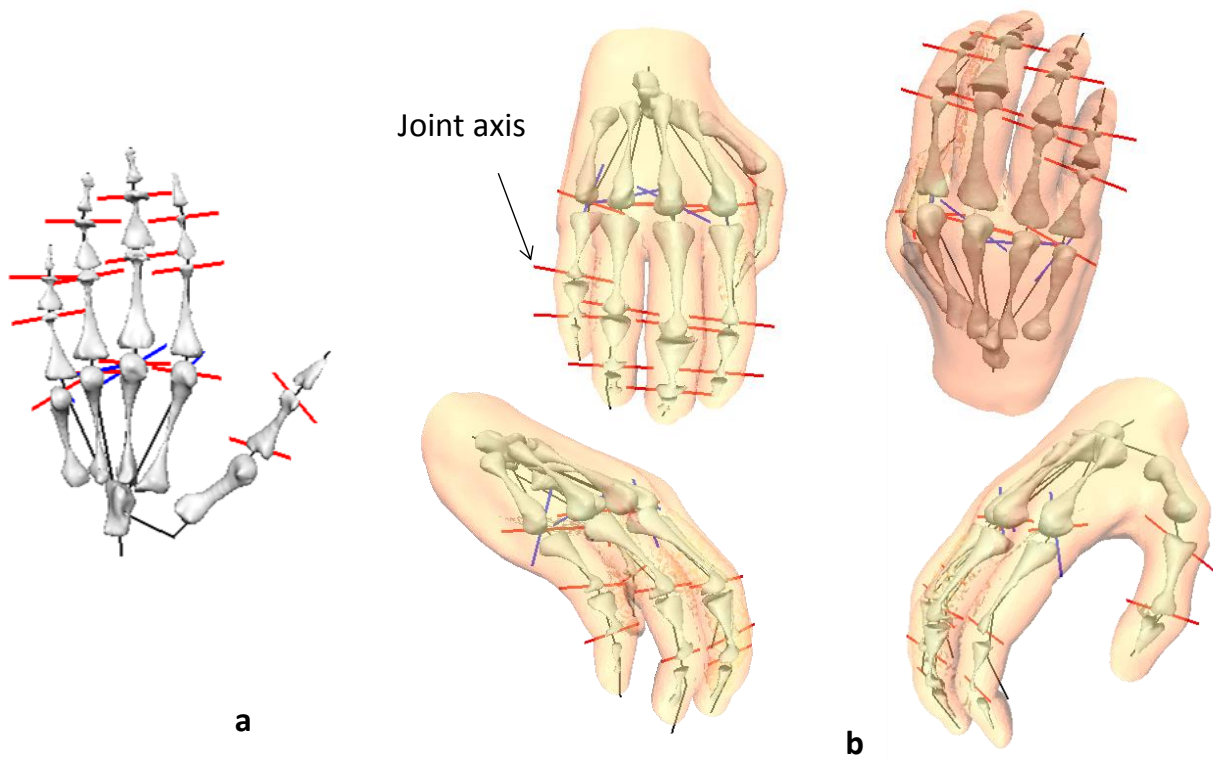


Fig. 4-12 (a) Derived joint-link structure of S_1 's hand, (b) Complete Digital Hand model in different views

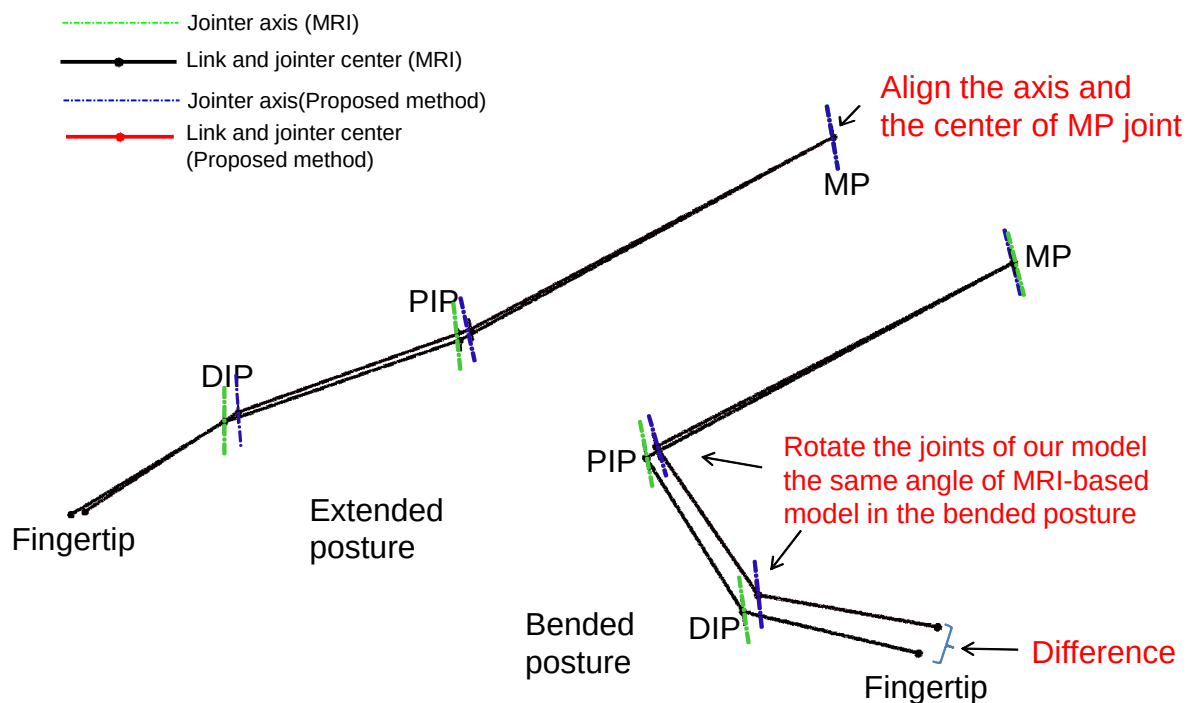


Fig. 4-13 Verification of estimated joint link structure

Table 4-1 Average position errors and orientation errors of four fingers at fully extended posture and limit bended posture (S_1).

Difference	Full flexion posture			Full abduction posture
	PIP	DIP	Fingertip	PIP
Natural extended posture[mm]	1.8	2.1	3.4	2.2
Limit bended posture[mm]	2.0	2.7	4.0	2.6
Joint axis angle deviation [deg]	5.6°	6.1°	-	7.1°

Table 4-2 Average position errors and orientation errors of four fingers at fully extended posture and limit bended posture (S_2).

Difference	Full flexion posture			Full abduction posture
	PIP	DIP*	Fingertip*	PIP
Natural extended posture[mm]	1.9	-	-	2.1
Limit bended posture[mm]	2.0	-	-	2.9
Joint axis angle deviation [deg]	21.6°	-	-	22.5°

* Only PIP joints of the hand model of S_2 are available

The errors were mainly caused from the single axis rotation assumption itself, the sliding of the hand skin in different hand postures, the pointing error in the extraction of the marker position, and the error of image-based 3D model reconstruction. The accuracy could satisfy the virtual ergonomic assessments of handheld products where the products need to be held by a power grasp, such as a bicycle hand bar, because the accuracy of PIP and DIP joint is the major consideration in such assessments.

But for the virtual ergonomic assessments of handheld products where accuracy of a pinch operation or a human interface operation using a fingertip is mainly concerned, such as a mobile phone with small size bottoms, the accuracy of the proposed method needs to be evaluated further.

4.7 Summary

A new variational hand modeling method using image-based 3D model reconstruction was proposed which is simpler, subject-friendly and inexpensive compared to previous work.

The variation of the external skin model was generated by scaling the segments of a template hand model with verified accuracy. For the variations of the internal joint-link structure, the center and the axis of each joint of the fingers were estimated by the position of markers on the reconstructed hand model in different hand postures. The derived joint parameters were verified by comparing them with those based on MRI measurement. The two models were combined by a segment-wise registration process in the term of the minimum error of the positions and originations of the segments between the scaled template hand model and those of the reconstructed hand model. The skin variational modeling had acceptable accuracy for virtual ergonomic assessments of handheld products. The accuracy of the joint-link variational modeling could satisfy the requirement of virtual ergonomic assessments of handheld products which are held by a power grasp. But the accuracy for those handheld products involving the human interface operation using a fingertip needs to be evaluated further.

However, the CMC joint of the thumb has not been modeled in this research, because it cannot be modeled as a simple single axis rotation. In the future, the CMC joint motion of the thumb will be modeled utilizing the interpolation between the reference posture and the limit posture.

Chapter 5

Statistical virtual ergonomic assessment of hands based on anthropometric statistical data

5.1 Introduction

Anthropometric measurement of human hand plays an important role in design of workplace, clothes, hand tools, manual tasks or access spaces for the hand and many products for human use. Statistical data which can depict the overall distribution of anthropometric measures of a specific people group is also a vital reference to handheld product design. In virtual ergonomic assessments of handheld products, statistical anthropometric data is also useful to generate a number of hand instances representing the overall characteristic of a specific people group, instead of generating an individual hand model (Chapter 4).

[58] provides a Japanese hand dimension database which includes the general statistical information, such mean, and standard deviation, for various hand dimensions. However it does not give any correlation between different dimensions. Chandra et al. [59] presents much detail about the statistical analysis of hands of male industrial workers of Haryana State, India. The statistical analysis was carried out to correlate a part of hand dimensions and to obtain prediction equation between them. However it also does not provide

all correlation between different dimensions and due to the difference between two races the prediction equations cannot be directly used in the Japanese hand database.

On the other hand, some literatures have studied the relationship between objective measurement and subjective experienced comfort and discomfort in using hand tool. Kuijt-Evers et al. [1, 42] point out the pressure area during static measurement was the best predictor of subjective discomfort. Hall et al.[44] conclude that subjective rating of pressure and discomfort is significantly correlated with external pressure. Fraser and Yun et al. [60, 61] present that high local external pressure may result the discomfort in hand and reduce both the efficiency of the work and the consumer's satisfaction with tool.

Naturally, there is a possibility that by generating hand model instances following the statistical characteristics of certain people, and then integrating them with 3D CAD model of a handheld product, the obtained objective estimation in a virtual simulation environment could be used to predict some subjective evaluations of the product.

Therefore, the purpose of this research is to generate hand model instances which follow certain people's anthropometric statistical characteristics for further virtual ergonomic assessments.

The outline of the proposed variational hand modeling method is shown in **Fig. 5-1**. First, the statistical correlations (A2) between hand dimensions by measuring hands of subjects (A1) are found. Furthermore, the prediction equations of hand dimensions from major dimensions are obtained through linear regression analysis (A3) between major dimensions and other dimension. By utilizing the prediction equations, and by randomly sampling the major dimensions from the Japanese database [58] (A4 and A5), the hand instances could be generated in our Digital Hand software (Chapter 4) (A6). Finally, the generated hand instances are used to complete some grasping task to obtain statistical information of some grasping evaluation indices, such as contact area and contact pressure distribution (A7). Comfort analysis is out of range of this research.

5.2 Anthropometric measurement

5.2.1 Subjects

81

**a****b**

Fig. 5-2 (a) An example of reconstructed hand model (from different viewpoints), (b) The reconstructed hand models of 20 subjects

5.2.2 3D model measurement

The image-based 3D model reconstruction (Section 4.2) is used to reconstruct 3D hand model. An example is shown in **Fig. 5-2**. Compared with traditional sliding caliper measurement, measuring 3D model has two advantages: avoiding natural tremble of hand and enabling repeatable measurement.

5.2.3 Hand dimensions

The surface anatomy of the main creases on the palm side is a common landmark in hand surgery, since the basic main creases have a strong relationship with the underlying bone structure [22]. Furthermore, they are commonly used in anthropometric measurements [7]. In section 4.3, the hand surface was partitioned into 15 segments which were relatively independent to each other, so that one segment could be scaled independently to fit the corresponding one of an individual hand.

4 major dimensions including of hand length (L), circumference (C), width (W) and thickness (T) are defined in **Table 5-1** and **Fig. 5-3**. The length, width and thickness dimension of each segment are defined in **Table 5-2**, **Fig. 5-4** and **Fig. 5-5**.

Table 5-1 IDs of major dimensions

L	Hand length
C	Hand circumference
W	Hand width
T	Hand thick ness

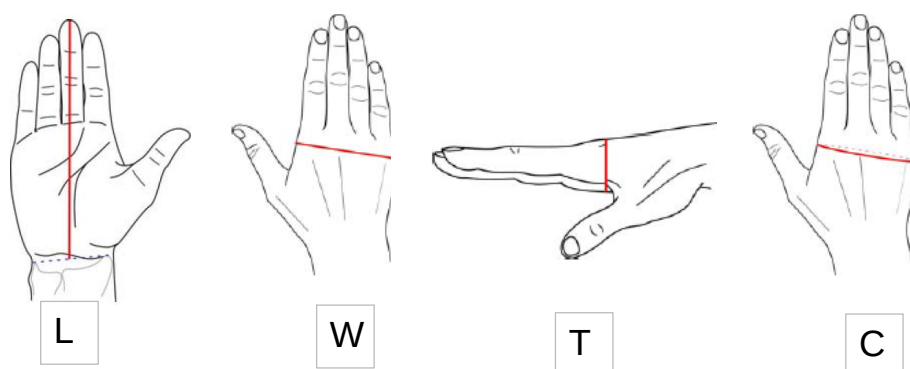


Fig. 5-3 Hand major dimensions

Table 5-2 IDs of hand segment dimensions

Length dimension	Width dimension	Thickness dimension
L1	W1	T1
L3	W3	T3
L4	W4	T4
L6	W6	T6
L7	W7	T7
L8	W8	T8
L10	W10	T10
L11	W11	T11
L12	W12	T12
L14	W14	T14
L15	W15	T15
L16	W16	T16
L18	W18	T18
L19	W19	T19
L20	W20	T20

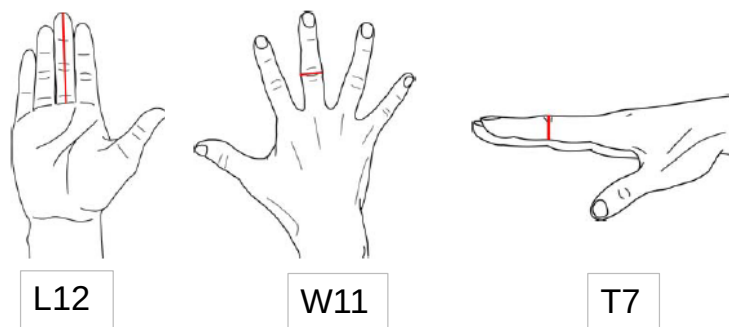
**Fig. 5-4** Examples of hand segment dimensions



Fig. 5-5 Hand segments and their IDs

5.3 Correlation analysis and linear regression analysis

Table 5-3 and **Table 5-4** show the correlation coefficients between different hand anthropometric dimensions from our measurements. These coefficients were calculated to see to what extent these dimensions are related to each other and to what extent equipment design decisions could be based on such correlation.

Correlations among measured hand segments were performed among hand length and circumference, width and thickness, indicating that hand length (L) has a strong correlation with segment length dimensions; hand circumference (C) has a stronger correlation with segment width and thickness dimensions than hand width (W) and thickness (T). Testing the significance of correlation revealed that almost all values are significant and positively correlated between the hand length and hand circumference, suggest that it is possible to predict hand dimensions with 95% confidence, by measuring the hand length and hand circumference alone.

The simple regression analyses were done between hand length, hand circumference and other hand dimensions in order to find out the best set of predictors related to hand length and hand circumference, and linear regression equations are provided in **Table 5-5**, **Table 5-6** and **Table 5-7**. An example of linear regression equation between L and L1 is shown in **Fig. 5-6**.

Table 5-3 Correlation coefficients between major dimensions

	L	C	W	T
L	1	0.36	0.17	0.39
C	0.36	1	0.78	0.42
W	0.17	0.78	1	0.16
T	0.39	0.42	0.16	1

* Correlation is significant at the 0.05 level

Table 5-4 Correlation coefficients between major dimensions and other dimensions

	L	C	W	T		L	C	W	T		L	C	W	T
L1	0.83	0.11	-0.05	0.15	W1	0.17	0.78	1	0.16	T1	0.39	0.42	0.16	1
L3	0.49	0.23	0.24	0.27	W3	0.13	0.63	0.53	0.24	T3	0.34	0.39	0.19	0.29
L4	0.68	0.37	0.18	0.21	W4	0.27	0.61	0.46	0.28	T4	0.41	0.45	0.23	0.34
L6	0.56	0.16	0.28	0.29	W6	0.22	0.59	0.42	0.19	T6	0.35	0.42	0.2	0.26
L7	0.62	0.21	0.25	0.31	W7	0.31	0.66	0.45	0.27	T7	0.35	0.44	0.21	0.27
L8	0.65	0.3	0.31	0.31	W8	0.27	0.62	0.43	0.28	T8	0.35	0.46	0.22	0.22
L10	0.45	0.05	0.14	-0.05	W10	0.25	0.63	0.54	0.3	T10	0.42	0.45	0.24	0.35
L11	0.7	0.3	0.25	0.27	W11	0.31	0.65	0.75	0.27	T11	0.44	0.34	0.14	0.28
L12	0.73	0.36	0.3	0.25	W12	0.28	0.62	0.6	0.31	T12	0.4	0.46	0.16	0.44
L14	0.44	0.2	0.28	0.23	W14	0.24	0.66	0.57	0.33	T14	0.43	0.39	0.22	0.33
L15	0.66	0.28	0.3	0.29	W15	0.15	0.59	0.46	0.19	T15	0.4	0.45	0.22	0.32
L16	0.71	0.36	0.3	0.3	W16	0.21	0.69	0.5	0.27	T16	0.38	0.42	0.19	0.24
L18	0.45	0.63	0.72	0.07	W18	0.15	0.36	0.53	0	T18	0.39	0.49	0.33	0.23
L19	0.67	0.51	0.56	0.3	W19	0.54	0.48	0.56	0.14	T19	0.47	0.34	0.13	0.24
L20	0.68	0.48	0.5	0.18	W20	0.36	0.38	0.42	0.1	T20	0.39	0.43	0.11	0.26

* Correlation is significant at the 0.05 level

Table 5-5 Linear regression equations (the hand lengths (L) relates segment length dimension (L1~L20))

$=kL+b$		
	k	b [mm]
L1	0.66	-15.24
L3	0.12	7.98
L4	0.24	12.73
L6	0.15	-3.29
L7	0.29	-9.14
L8	0.40	-4.18
L10	0.13	2.85
L11	0.31	-3.99
L12	0.36	9.96
L14	0.11	3.71
L15	0.24	4.41
L16	0.36	6.39
L18	0.13	-3.68
L19	0.28	-14.52
L20	0.42	-15.20

* Significant at the 0.05 level

Table 5-6 Linear regression equations (the hand circumference (C) relates segment width dimension (W1~W20))

$=kC+b$		
	k	b [mm]
W1	0.35	11.54
W3	0.19	-8.45
W4	0.13	-5.33
W6	0.12	-5.47
W7	0.13	-8.54
W8	0.10	-5.19
W10	0.12	-5.19
W11	0.13	-7.47
W12	0.11	-5.16
W14	0.12	-6.21
W15	0.10	-3.36
W16	0.10	-4.71
W18	0.13	-6.58
W19	0.11	-3.80
W20	0.07	-0.34

* Significant at the 0.05 level

Table 5-7 Linear regression equations (the hand circumference (C) relates
segment thickness dimension (T1~T20))

	$=kC+b$	
	k	b [mm]
T1	0.08	9.64
T3	0.12	0.83
T4	0.11	-3.26
T6	0.10	-0.78
T7	0.10	-1.71
T8	0.09	-3.90
T10	0.13	-4.25
T11	0.09	2.35
T12	0.13	-9.15
T14	0.11	-2.48
T15	0.10	-2.72
T16	0.07	-1.51
T18	0.12	-5.21
T19	0.07	1.40
T20	0.08	-3.23

* Significant at the 0.05 level

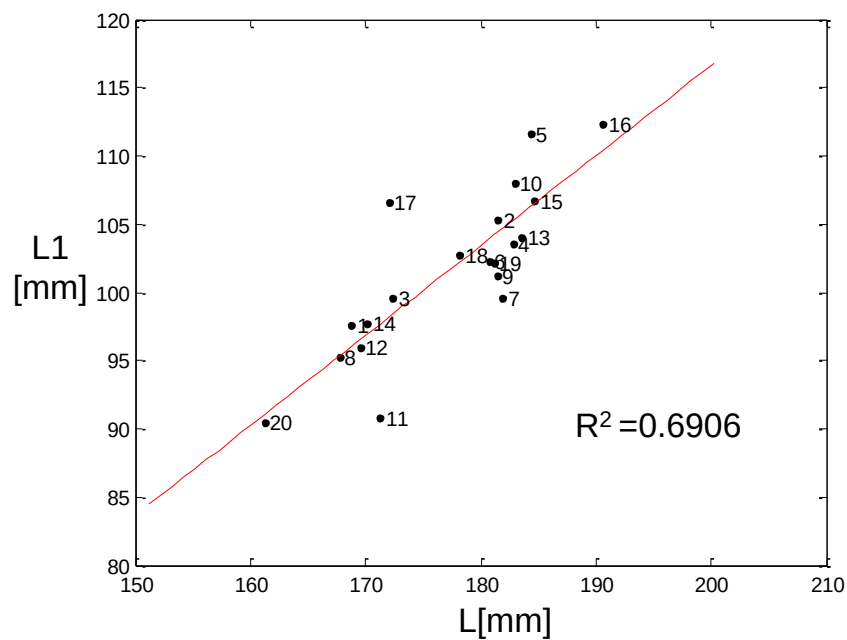


Fig. 5-6 An example of linear regression equation between L and L1

5.4 Variational hand generation based on statistical data

According to **Table 5-3**, the linear correlation coefficient between two major hand dimensions, L and C, is 0.36. The Japanese hand dimension database [58] indicates that hand length (L) follow a normal distribution with a mean 184 mm and a standard deviation 10.4 mm; hand circumference (C) follow a normal distribution with a mean 193 mm and a standard deviation 14.0 mm. Therefore, a random sampling following two-dimensional normal distribution is used to generate a sample of two major dimensions L and C. A sampling with size 500 is shown in **Fig. 5-7**.

Once a set of hand length and hand circumference is generate, according to the prediction equations in **Table 5-5**, **Table 5-6** and **Table 5-7** other dimensions which are used to generate hand instances in Digital Hand software (Section 4.3) can be calculated. **Fig. 5-8** show four examples of generated hand model instances with different major dimensions.

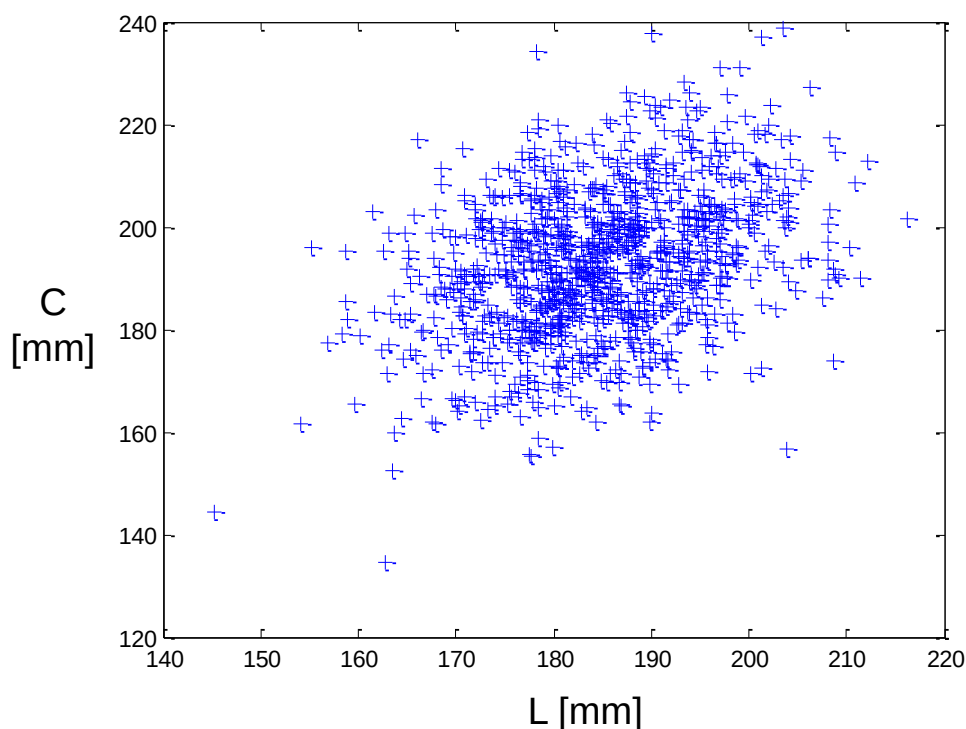


Fig. 5-7 A random sampling with size 500 following two-dimensional normal distribution



Fig. 5-8 Generated hand model instances with different major dimensions

5.5 Statistical analysis of grasping evaluation and redesign

For handheld product designing, it is always desirable to obtain the overall statistical evaluation indices, such as contact area, and contact pressure distribution. For example, a necessary contact area for a design of a handheld product is better to cover the hand sizes of the larger proportion of its aiming customer group. However, involving a number of subject tests is costly and timing consuming, or is impractical in the beginning stage of a product designing.

Virtual ergonomic assessment based on Digital Hand can solve this problem. The hand model instances following the overall statistical characteristic of a specific people group can be generated in a relatively short time. And then they can be used to complete tasks of grasping product to obtain grasping evaluation indices, such as contact area and contact pressure distribution.

5.5.1 Grasping strategy

The generated hand model instances (Section 5.4) were used to grasp a product model in a power grasp situation. **Fig. 5-9** shows the situation. According to the conclusion in Section 3.4.1 that the limit penetration depth d_{lim} of the finger and palm was about 4mm and 7mm respectively, the generated hand models grasp the cylinder using a power grasp, by closing the joints until the penetration depth of each segment approaching their limit penetration depth. According to this grasping strategy, 30 generated hand model instances (L: 165.2 ~ 201.6mm, C: 160.7 ~ 221.8 mm) were used to grasp product models.

5.5.2 Contact area simulation

Contact area is an important index for grasping. The contact area can be estimated by calculating the surface area of hand model in contact situation. Three examples of estimated contact area with different hand model instances are shown in **Fig. 5-10**. **Fig. 5-11** is a histogram of contact area of 30 generated hand model instances grasping 35mm cylinder, which indicates that a large portion of hands have the contact area from 3700 mm² to 4000 mm², and the mode appears at 3850~3900 mm².

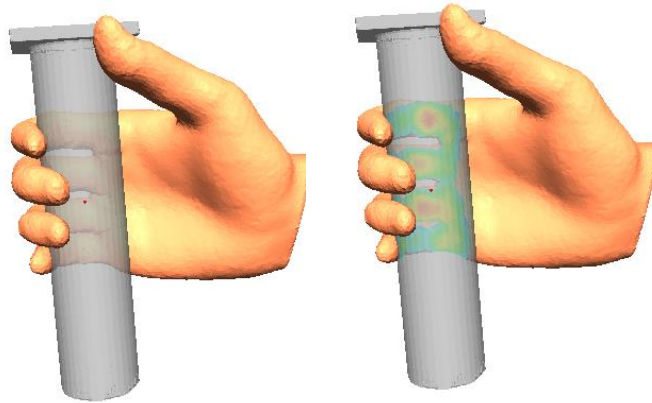


Fig. 5-9 Grasping a cylinder of a diameter 35mm with estimated pressure distribution

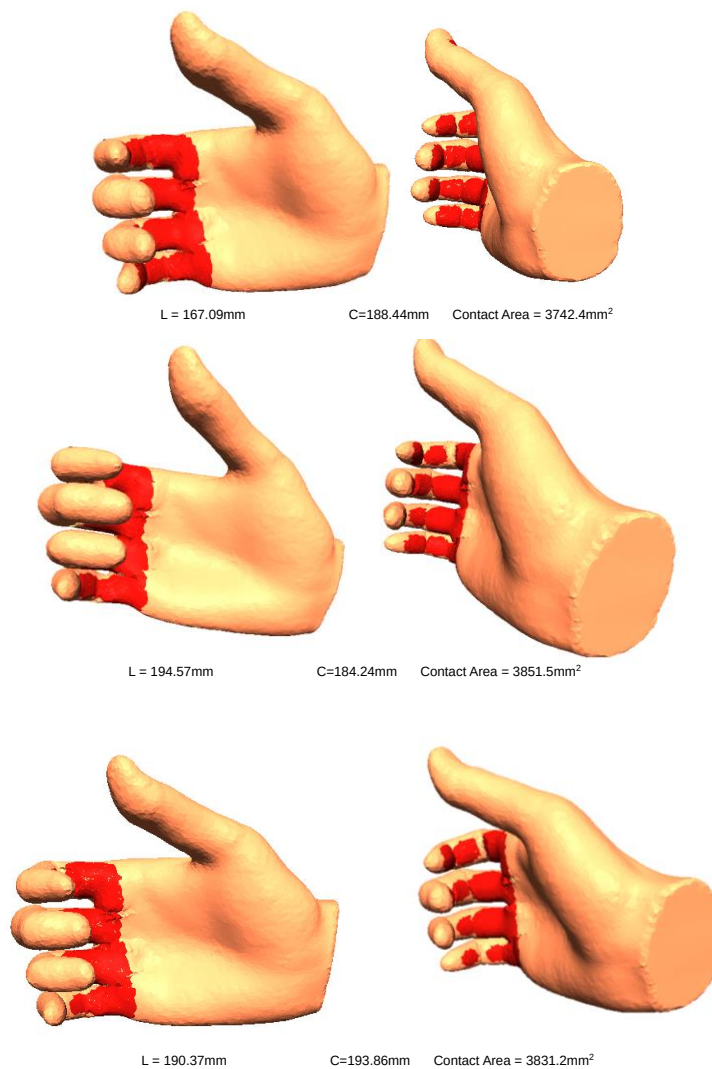


Fig. 5-10 Examples of estimated contact area with different hand model instances

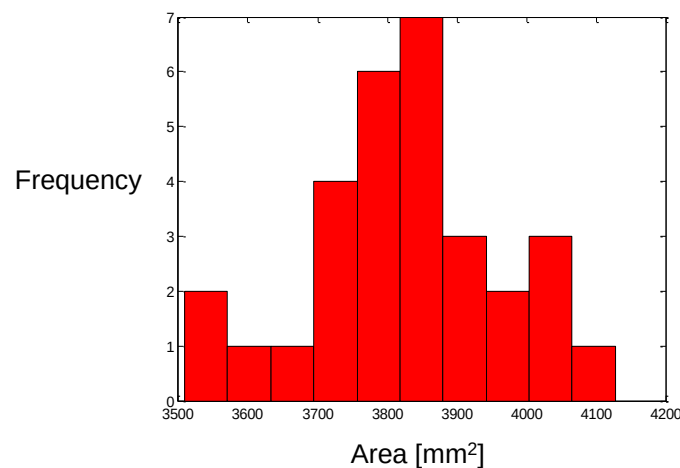


Fig. 5-11 Histogram of contact area of 30 hand model instances grasping 35mm cylinder

5.5.3 Contact pressure distribution simulation

Contact pressure distribution is also an important index for grasping. The contact pressure distribution can be estimated by our proposed skin contact simulation method (Chapter 3) as shown in the color map in **Fig. 5-12**.

In our Digital Hand software environment, 30 hand model instances grasped a prism (35×35×200mm) with fillet $r = 3\text{mm}$ with a power grasp (two examples are shown in **Fig. 5-12** (a) and **Fig. 5-13** (a)). Moreover, the same posture of the hand model is used to grasp a same size prism with larger fillet $r = 10\text{mm}$ (**Fig. 5-12** (b) and **Fig. 5-13** (b)). It can be observed, when grasping the prism with small fillet, higher peak pressure takes place in the fillet, while with larger fillet the peak pressure is smaller than the former.

The statistical peak pressure distributions and average pressured distribution of the two prisms are given in **Fig. 5-14** and **Fig. 5-15**. It can be observed the sharper edge of prism results in higher peak pressure (red bars), and those with smoothing fillet leads to lower peak pressure (green bars), which indicates the latter are better design in term of grasping comfort.

5.5.4 Product redesign based on contact pressure distribution

Because the peak pressure is negatively correlated to grasping comfort, in order to get a better grasping comfortable, product redesign needs to decrease the peak pressure. Therefore, a redesign (redesign 1) is made on the original prism with fillet $r = 3\text{mm}$, where the intersection surface of the prism is slightly depressed to form concaves of finger shape

(**Fig. 5-12** (c) and **Fig. 5-13** (c)) for decreasing the peak pressure. However, considering the difficulties to process such irregular shape of finger, the other redesign (redesign 2) was proposed. The contact region was imported into 3D CAD software which was used to design the CAD model of product (**Fig. 5-16** (a)). According to the contact region, a design with geometric shapes was performed (**Fig. 5-16** (b)).

The statistical peak pressure distributions and average pressure distribution of the two prisms with redesign 1 and redesign 2 are given in **Fig. 5-14** and **Fig. 5-15** (light blue and purple bars). By comparing the two redesigns with the prism with fillet $r = 3\text{mm}$ and fillet $r = 10\text{mm}$, they bring about smaller peak pressure, at the same time; they can keep the basic overall shape of its original design, which suggests that the two designs can have both grasp comfort and functionality brought by the sharp fillet. Moreover, although the redesign 1 has smallest peak pressure and average pressure, it has difficulties to process irregular shape of finger. In comparison, the redesign 2 is easier to process than redesign 1. Therefore the two redesigns can be used in different situations according to the requirements to the product.

Moreover, the 30 hand model instances were also used to grasp a larger size prism with sharper and smoothing edge, and redesign based on the one with shaper edge. An example is shown in **Fig. 5-17**, and statistical peak pressure distribution is given in **Fig. 5-18**.

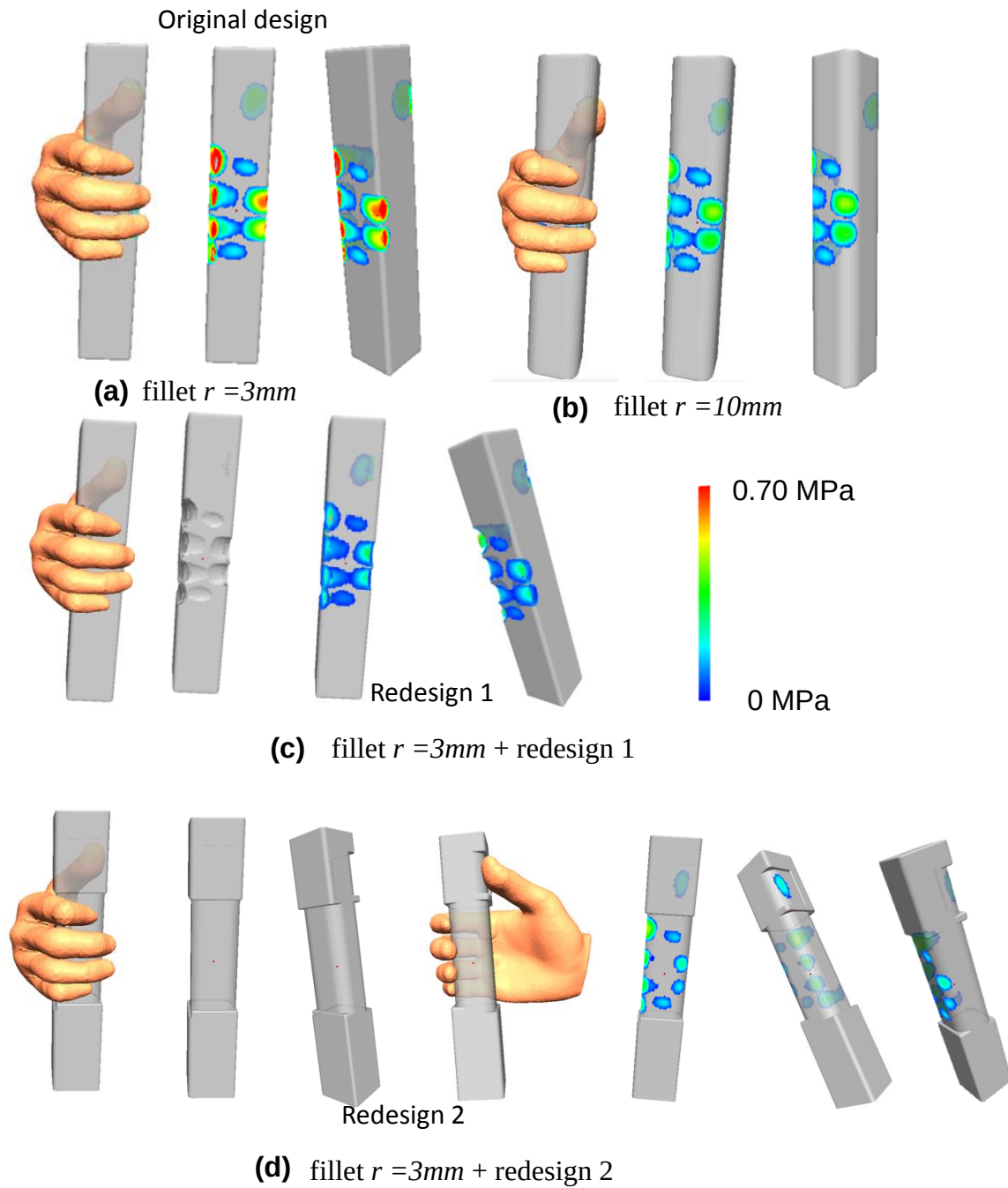


Fig. 5-12 A hand model ($L = 165\text{mm}$ and $C = 199\text{mm}$) grasping: (a) a prism ($35 \times 35 \times 200\text{mm}$) with fillet $r = 3\text{mm}$. (b) the same size prim with fillet $r = 10\text{mm}$. (c) a redesign with concaves of finger shape. (d) a redesign with processes of irregular geometric shape

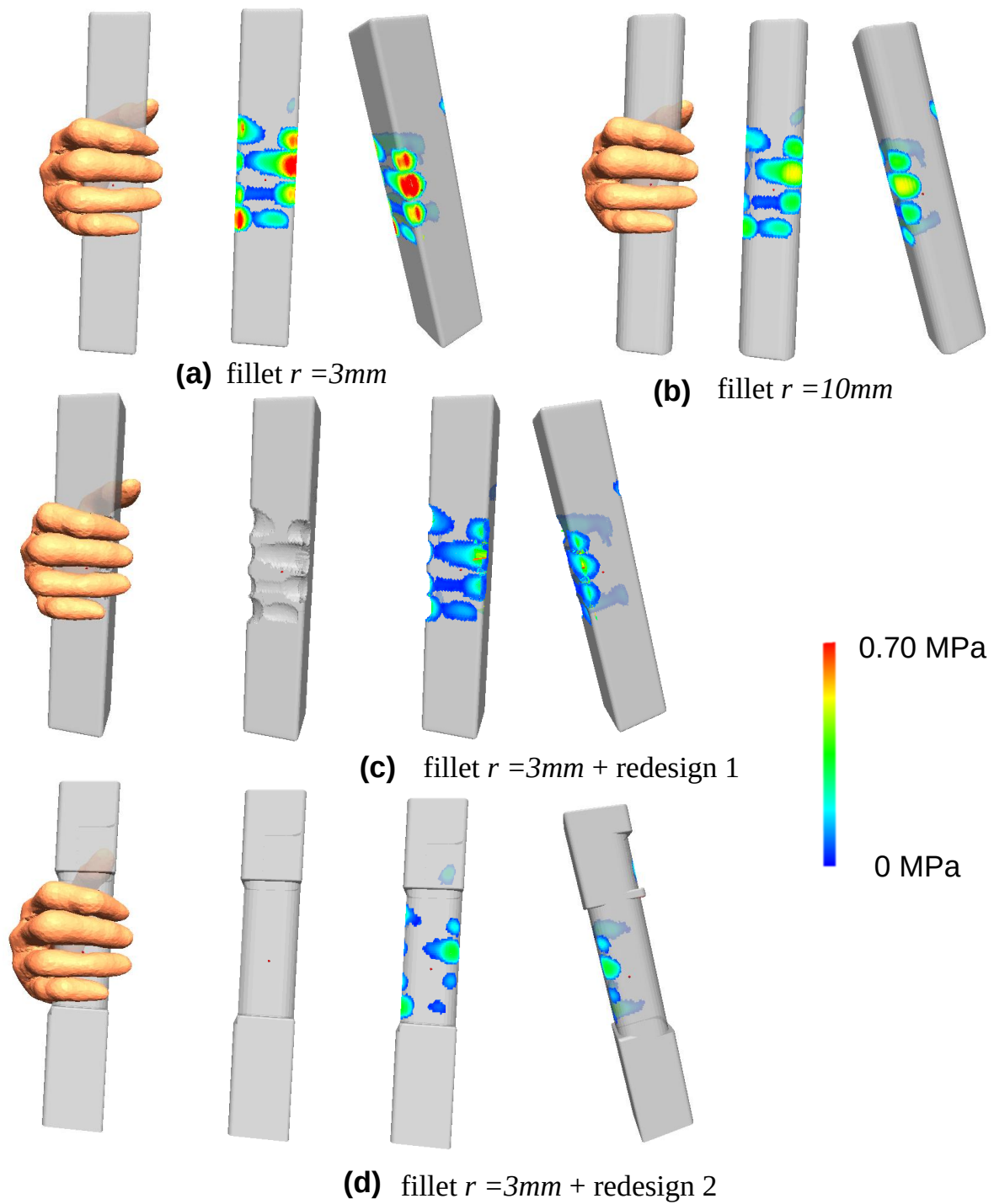


Fig. 5-13 A hand model ($L = 194\text{mm}$ and $C = 184\text{mm}$) grasping: (a) a prism ($35 \times 35 \times 200\text{mm}$) with fillet $r = 3\text{mm}$. (b) the same size prim with fillet $r = 10\text{mm}$. (c) a redesign with concaves of finger shape. (d) a redesign with processes of irregular geometric shape

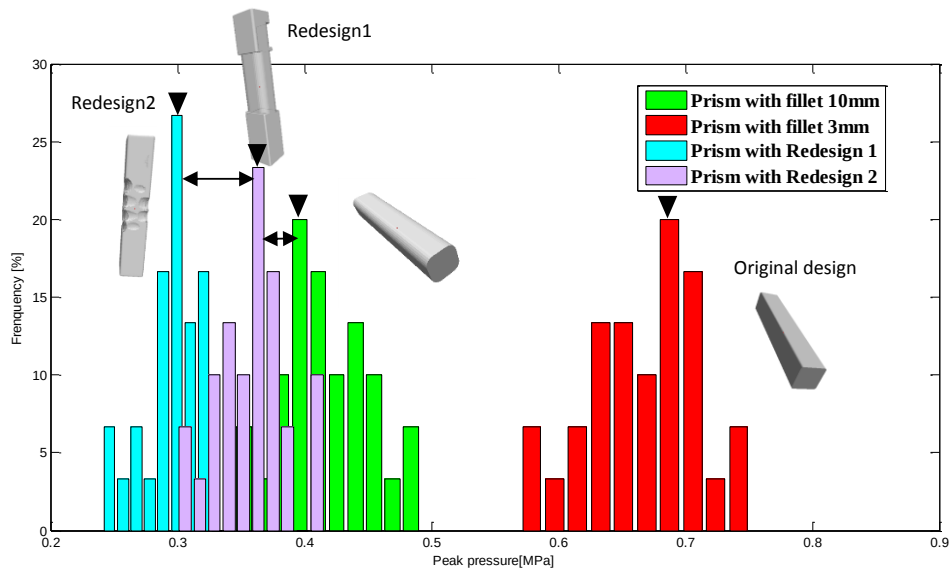


Fig. 5-14 Histogram of peak pressure distribution of 30 hand model instances grasping 4 kinds of prim. Average differences have notable statistical significance (t-Testing($P < 0.01$))

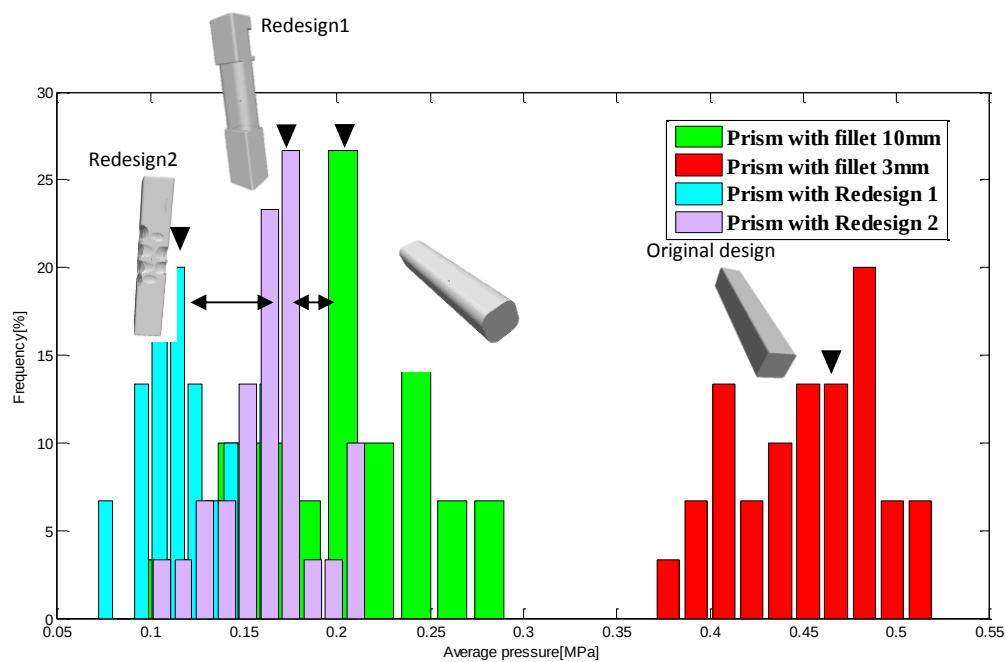


Fig. 5-15 Histogram of average pressure distribution of 30 hand model instances grasping 4 kinds of prims.

Average differences have notable statistical significance (t-Testing($P < 0.01$))

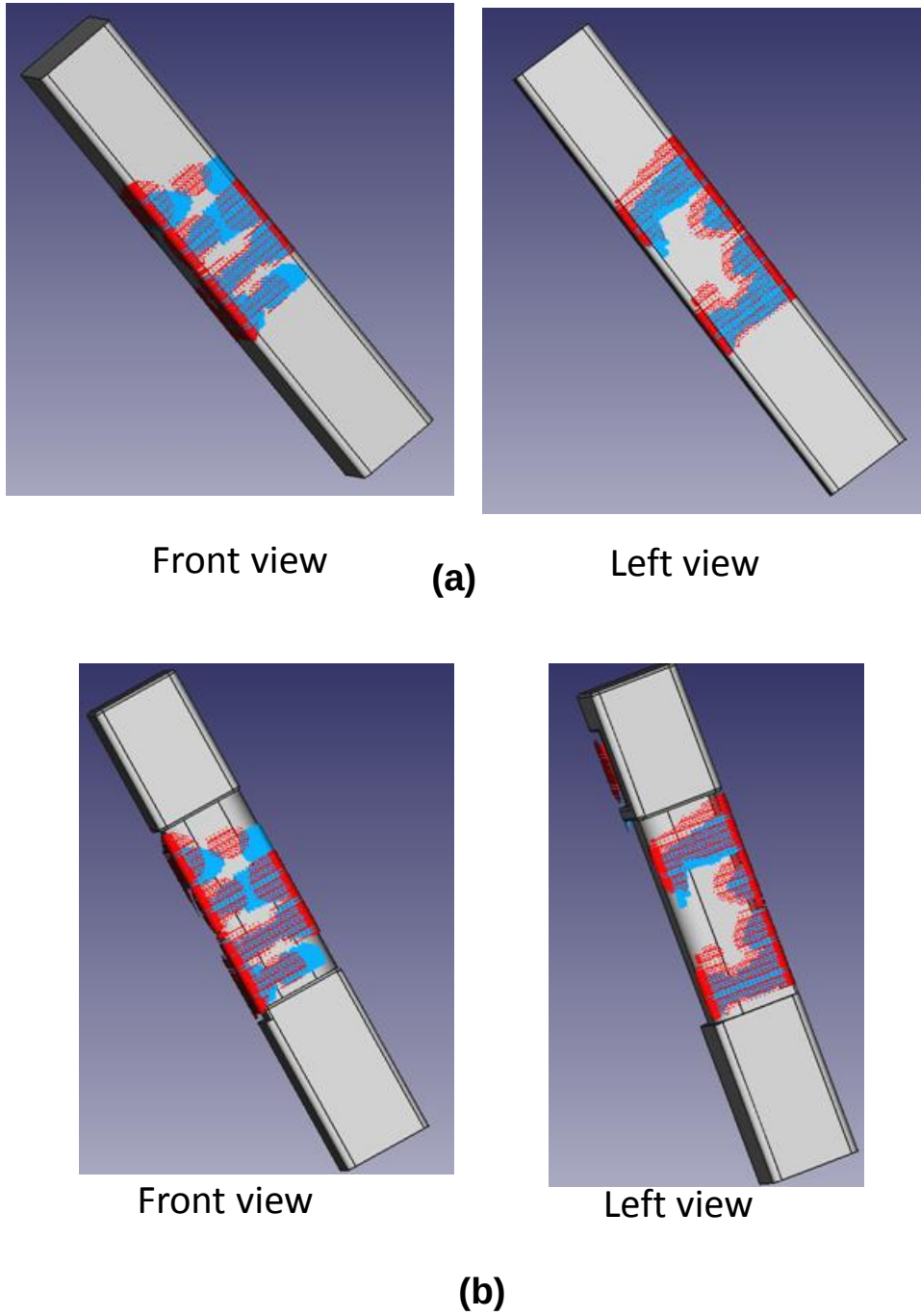


Fig. 5-16 (a) Original product CAD model with contact region (red and blue), and (b) Redesigned product CAD model with contact region (red and blue)

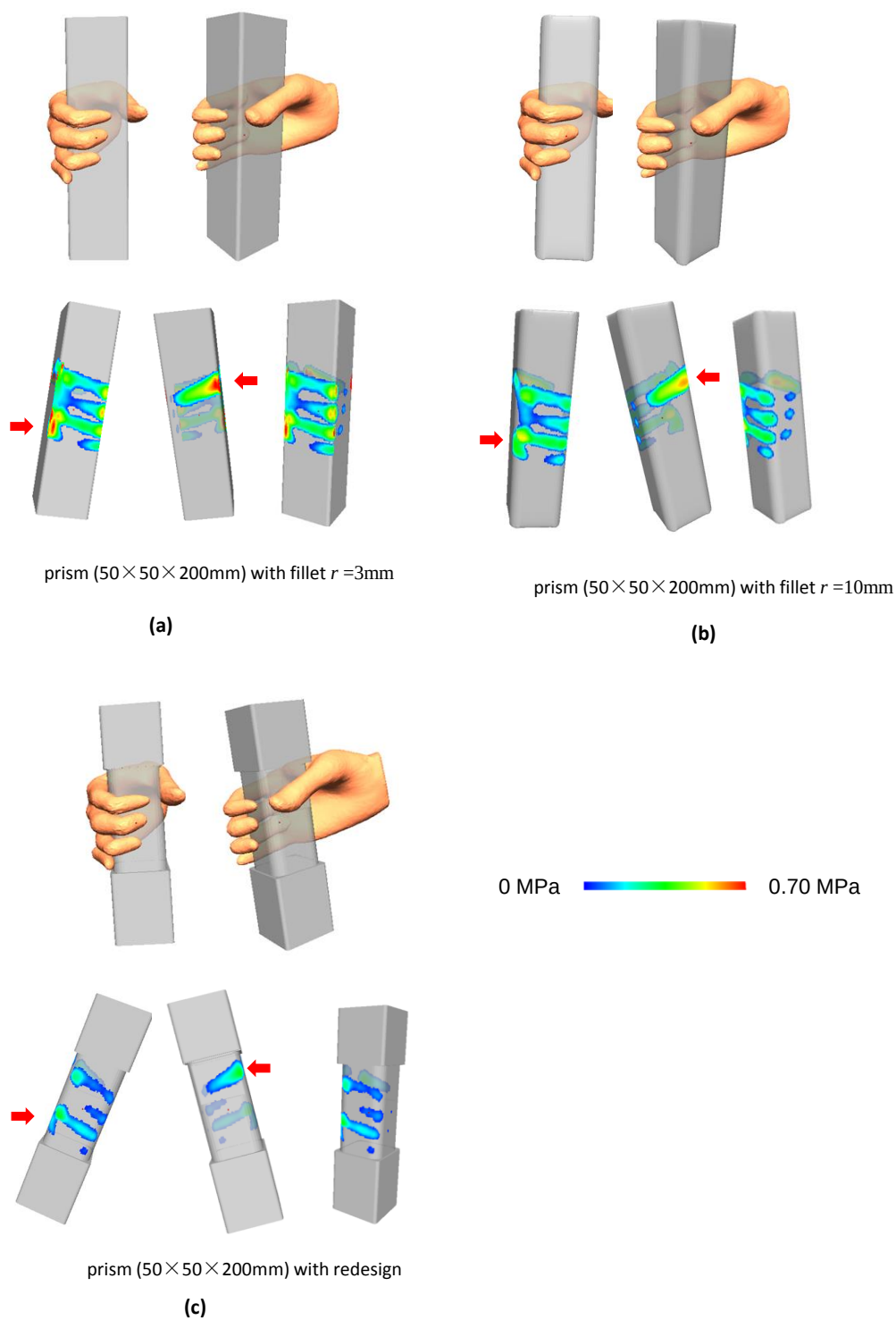


Fig. 5-17 A hand model ($L = 194\text{mm}$ and $C = 184\text{mm}$) grasping: (a) a prism ($50 \times 50 \times 200\text{mm}$) with fillet $r = 3\text{mm}$. (b) the same size prim with fillet $r = 10\text{mm}$. (c) a redesign with processes of irregular geometric shape

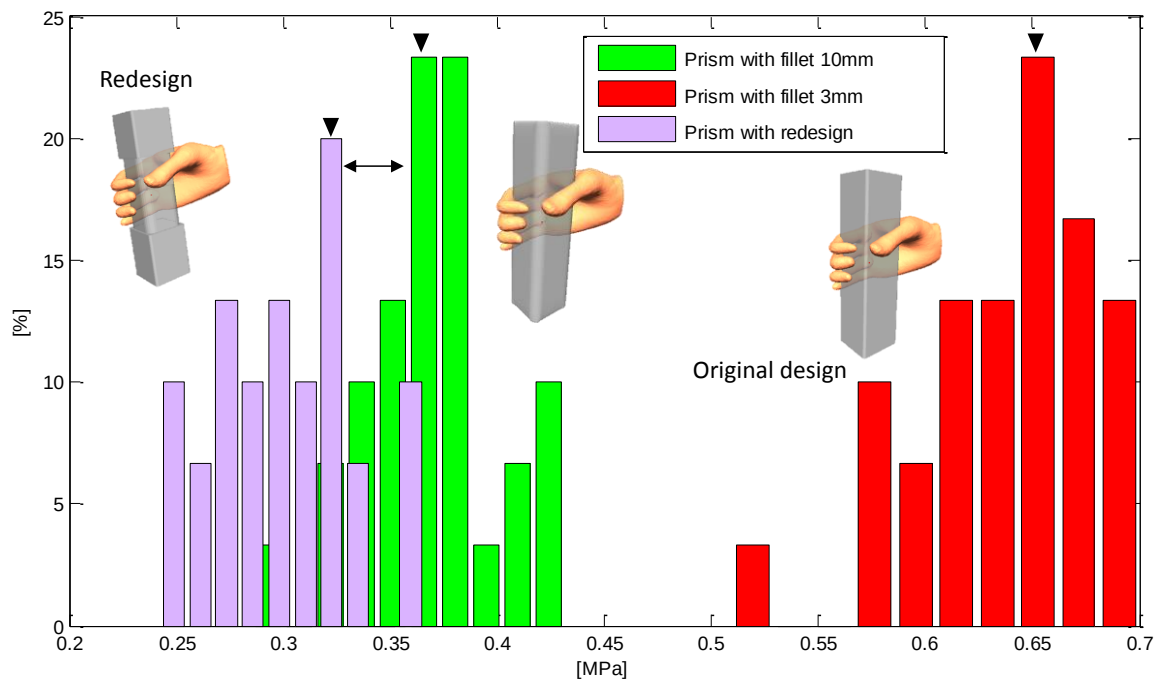


Fig. 5-18 Histogram of peak pressure distribution of 30 hand model instances grasping 3 kinds of prim (50×50×200mm). Average differences have notable statistical significance (t-Testing($P < 0.01$))

5.6 Discussion and summary

The relation between the objective evaluation and the subjective evaluation for a handheld product is a vital problem in common ergonomic assessment. In virtual ergonomic assessments, the same problem is faced.

According to the conclusion of [42], during a power grasp, the larger contact area will bring about higher discomfort feeling, because when the average pressure goes beyond a critical pressure, larger area bring larger grasp force which will bring about discomfort if the power grasp sustain for relatively long time.

According to [44], subjective ratings of discomfort are positively correlated to external pressure. Therefore, the statistical data can provide an index for product designer to judge whether the product satisfies a certain requirement for average pressure. Moreover,

local high pressure will cause perceived pain in hand, which may result in blistering and lower efficiency of the work [60, 61]. Similar statistical data of **Fig. 5-14** and **Fig. 5-15** can provide information for designer about the range and distribution of peak pressure and average pressure of a product for a certain people. And redesign is significantly effective from the aspect of the peak/average pressure distribution.

Considering the real application of this method in a practical product design work, some critical values need to be known by the designer. For example, if there is a critical peak pressure for a saw, through obtaining the statistical data similar to **Fig. 5-14**, the design which has a larger portion of peak pressures below the critical value is better than the one which has a larger portion of peak pressure above the critical value.

In summary, in this chapter, the statistical variational hand modeling method which can generate hand model instances following certain populations' anthropometric statistical distribution for further virtual ergonomic assessments is proposed.

Chapter 6

Conclusions

The research objective of this thesis is to develop a software system for virtual ergonomic assessment of handheld products with an acceptable accuracy, where the integration of digital hand models and digital mockups replaces “real” human subjects and physical mockups for the ergonomic assessment. For this objective, the main properties of human hand including surface skin, joint-link structure, and skin contact deformation property were simulated. Moreover, based on a fine template hand model owning these properties, hand variational modeling methods were proposed to generate hand model instances with individual hand size or with specific people’s anthropometric statistical characteristics, for virtual ergonomic assessments. The conclusions of the thesis were summarized as follows:

- (1) Based on MRI measurements of human hand, 3D precise human hand modeling for product ergonomic assessments was proposed. The surface skin, the joint-link structure, and the skin deformation caused by joint motion were modeled and experimentally verified. And it was found that the derived bone-link structure has a higher accuracy and the sufficient skin deformation caused by joint motion is generated.
- (2) The skin deformation caused by contact was efficiently simulated for virtual ergonomic assessment of handheld products. The main properties of human hand skin, nonlinear elasticity and compressing-swelling effect, were realized for precise simulation. The results including estimated contact force, contact area,

contact pressure distributions in grasping posture were experimentally verified. And it was found that this skin contact simulation method has higher accuracy and efficiency.

- (3) Variational hand modeling based on image-based 3D model reconstruction was proposed for modeling a hand of a particular person. Experimental verification indicated that the modeling method could model individual hands including hand surface and joint-link structure in a relatively shorter period and with acceptable accuracy for virtual ergonomic assessments of handheld products. And it was found that this method can realize individual hand modeling in a higher efficiency and lower cost, and in a subjective-friendly way.
- (4) Based on correlation analysis between anthropometric dimensions from subjects, two major dimensions, hand length and circumference, which can be sampled from a Japanese hand database, are used to predict other hand dimensions for generating hand model instances. By grasping products using these instances in our Digital Hand software, the statistical grasping evaluation indices such as contact area and contact pressure distribution are given. And it was found that this method can generate hand model instances which follow the statistical features of a certain of people, and the evaluation based on these hand model instances and product model can aid the product designer in the process of product redesign.

From these conclusions, it was concluded that the proposed virtual ergonomic assessment system could aid designers of the handheld product to redesign the product shape in term of the ergonomics design.

In order to enhance or enrich the current studies, future researches are going to be carried out in the following aspects:

- 1) MRI-based hand modeling method involves many manual operations which are time consuming; therefore its degree of automation will be increased to improve its efficiency.

- 2) More subjects testing will be carried out for deciding the range of the physical parameters of the physical model used in the skin contact deformation simulation method.
- 3) In variational hand modeling based on image-based 3D model reconstruction, because the segment-wise registration is based on the feature points matching, the variational deformed template hand model cannot reproduce the contour of the individual hand. Therefore, from the corresponding features we can warp entire geometry using scattered data interpolation based on the radial basis functions (RBFs).
- 4) In statistical virtual ergonomic assessment, the correlation analysis of anthropometric measures is based on 20 subjects. The number of subjects will be increased to enhance the reliability of the results of the correlation analysis. Moreover, more product model with different geometric shapes will be evaluated.
- 5) So far, only simple redesign of product's geometric shape was carried out, therefore based on the results of the virtual ergonomic assessments using Digital Hand system, more researches will be touched in this new area.

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