Journal of Computational Design and Engineering, Vol. 1, No. 1 (2014) 1~12
www.jcde.org

Reconstructing individual hand models from motion capture data

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(Manuscript Received September 3, 2013; Revised October 26, 2013; Accepted November 1, 2013)

Abstract

In this paper, we propose a new method of reconstructing the hand models for individuals, which include the link structure models, the homologous skin surface models and the homologous tetrahedral mesh models in a reference posture. As for the link structure model, the local coordinate system related to each link consists of the joint rotation center and the axes of joint rotation, which can be estimated based on the trajectories of optimal markers on the relative skin surface region of the subject obtained from the motion capture system. The skin surface model is defined as a three-dimensional triangular mesh, obtained by deforming a template mesh so as to fit the landmark vertices to the relative marker positions obtained motion capture system. In this process, anatomical dimensions for the subject, manually measured by a caliper, are also used as the deformation constraints.

Keywords: Digital human modeling; Digital hand; Motion capture; Joint center estimation

1. Introduction

These days, product design based on a CAD system, so-called digital style design, has spread widely enabling rapid product design. Product development with advanced ergonomic design aimed at high safety and easiness to grasp and operate, has been required, while ergonomic evaluations have been conducted using conventional methods, which require human subjects and physical mockups. It takes a long time and high cost to produce physical mockups for a number of design ideas and to secure various kinds of subjects, which can be a bottleneck in product design. The possibility of conducting human-centered product design quickly with less cost, by performing ergonomic evaluation virtually and quantitatively, has been expected for some time in order to address the problem mentioned above.

So far, we have developed a system to aid human-centered design by conducting virtual ergonomic evaluations on many kinds of three-dimensional products. We have created a digital model of the human hand, with its dimensions and shape of representative Japanese adult. The primary result of our studies is that we have proposed a method to semi-automatically generate grasp postures against product models, in order to perform virtual ergonomic evaluations in a quantitative way using evaluation indices such as ease and stability of grasp [7-9].

When virtual ergonomic evaluation is performed using the above method, we consider that evaluation results with high reliability can be obtained by understanding how humans grasp and control a target product model, and modeling its principle behavior. To conduct this method, we measure and reconstruct motions of human subjects in grasping and operating a target product model, and then calculate and visualize contact areas between the product models and the hand models which reconstruct dimensions, shapes and functions of the human hands. Statistical construction of data obtained from various kinds of human subjects enables us to assume all the possible grasp and operation models of mankind for products.

So, the challenge is to reconstruct the hand models which reflect individual human hand geometrically and kinematically with high accuracy. The following four functional requirements are necessary, in order to reconstruct appropriate hand models for the various virtual ergonomic evaluations.

1) A three-dimensional triangular mesh model of the skin surface of a hand in a reference posture (hereafter referred to as “the skin surface model”) should be generated, that has same anatomical dimensions as the target human subject.
2) The skin surface model should be homologous to the template hand skin surface model (hereafter referred to as “template model”).
3) Position of a rotation center (for all joints) and rotation axes (only for 1DOF joints) of each finger joint in a link model should be calculated, in order to ac-

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doi: 10.7315/JCDE.2014.001

curately reflect the finger movement of an individual human.

4) A homologous tetrahedral mesh model which represents the shape of an individual hand should be generated.
5) The hand models that satisfy all the above requirements should be accurately modeled based on many human subjects in a realistic processing time.

Where, a homologous model for a skin surface or a tetrahedral mesh model is that, the topology of skin mesh (joint structure of vertices and faces) and index of each vertex tagged as an anatomical landmark point on the skin mesh must correspond and be equal to corresponding of the template model. Creating these models as a homologous model enables the analysis of size differentiation of anatomical corresponding points, and performing of skin surface model modifications in a unified way based on a rotational angle of each joint in a link model. In addition, tetrahedral mesh models of hand models have been used for automatically generating grasp postures of reconstructing hand postures for motion capture data, so we also need to generate the homologous tetrahedral mesh models for individuals.

The objective of our research is to reconstruct the individual hand models geometrically and kinematically with high accuracy, which satisfy all the requirements described above.

2. Related works

As for the method used to reconstruct the homologous skin surface model of the full body for an individual subject; most commomly-used method is the one that fits vertices and land mark points on the skin surface of a template model to the ones obtained by scanning the whole body of an individual by 3D range scanner (hereafter referred to as "landmark fitting method"). Creating a skin surface model for an individual hand is challenging since it is difficult to locate and fix the hand without scanner screening. In addition, motions of the skin surface model cannot be obtained from range scanners. Thus, accurate estimation of the link structure model for the fingers related to the reconstructed posture of skin surface model is challenging. So no appropriate methods for generating skin surface model for an individual hand has yet been developed.

Albecht et al. [1] and Kurihara et al. [16] have proposed a method to generate an individual hand model and reconstruct arbitrary posture. The former group uses the landmark fitting method to reconstruct the skin surface model. Landmark point set is specified by the user from photos of the hand. Link structure model is represented as the set of meshes of reconstructed bones. Individual hand model is generated based on deformation of the skin surface model from the template model. This method takes rather less processing time. However, there is no guarantee that the obtained hand models have high accuracy of reconstructing the hand dimensions such as width and thickness of fingers except for finger length. The latter group generated a skin surface model and link structure model for an individual hand, using examples of individual skin surface models in several postures taken by CT. However, taking scan data of many different kinds of the hand postures from a large number of human subjects using CT and MRI takes a long time and high cost, which is not a realistic method in present circumstance.

Huang et al. [13] proposed a method to generate a skin surface model for an individual hand in arbitrary posture. This method uses examples of the skin surface models in various postures of an individual subject and landmark positions of the target posture. A link structure model is not necessary for this method. However, as mentioned above case of Kurihara et al. [16], it is not a realistic method that requires the examples of the hand surface of a large number of different postures of human subjects.

Miyata et al. [18] proposed a method to reconstruct a hand model of human subject by measuring data of the hand size of individual taken by mockups and image scanner. In this method, link structure model is assumed by regression analysis based on the hand dimensions and MR images. As for a skin surface mesh of a reference posture, it is constructed applying partial scaling to a template model. This would increase estimated errors of rotation center position and rotation axes for each joint. Also, it is challenging to reconstruct an accurate skin surface mesh of a reference posture applying only the scaling based on dimensions of the hand.

There are other research groups working on developing hand models. Their main goal is to generate a skin surface model of realistic, human-like motions and postures of humans. They use single or several hand models representing

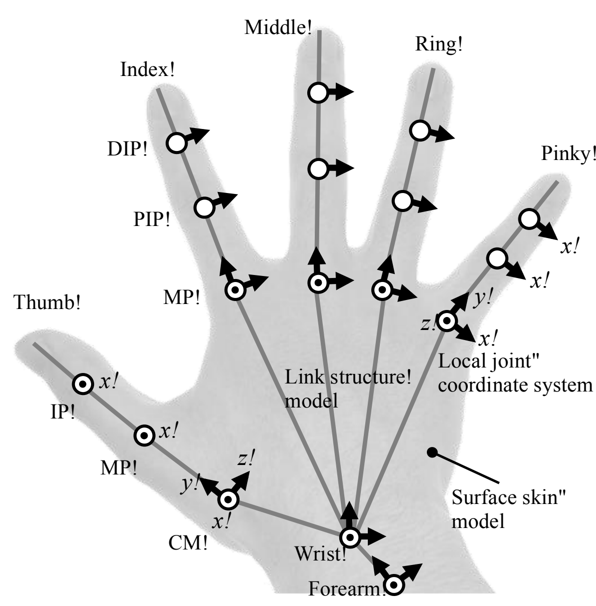


Figure 1. Link structure model and surface model of DhaibaHand.

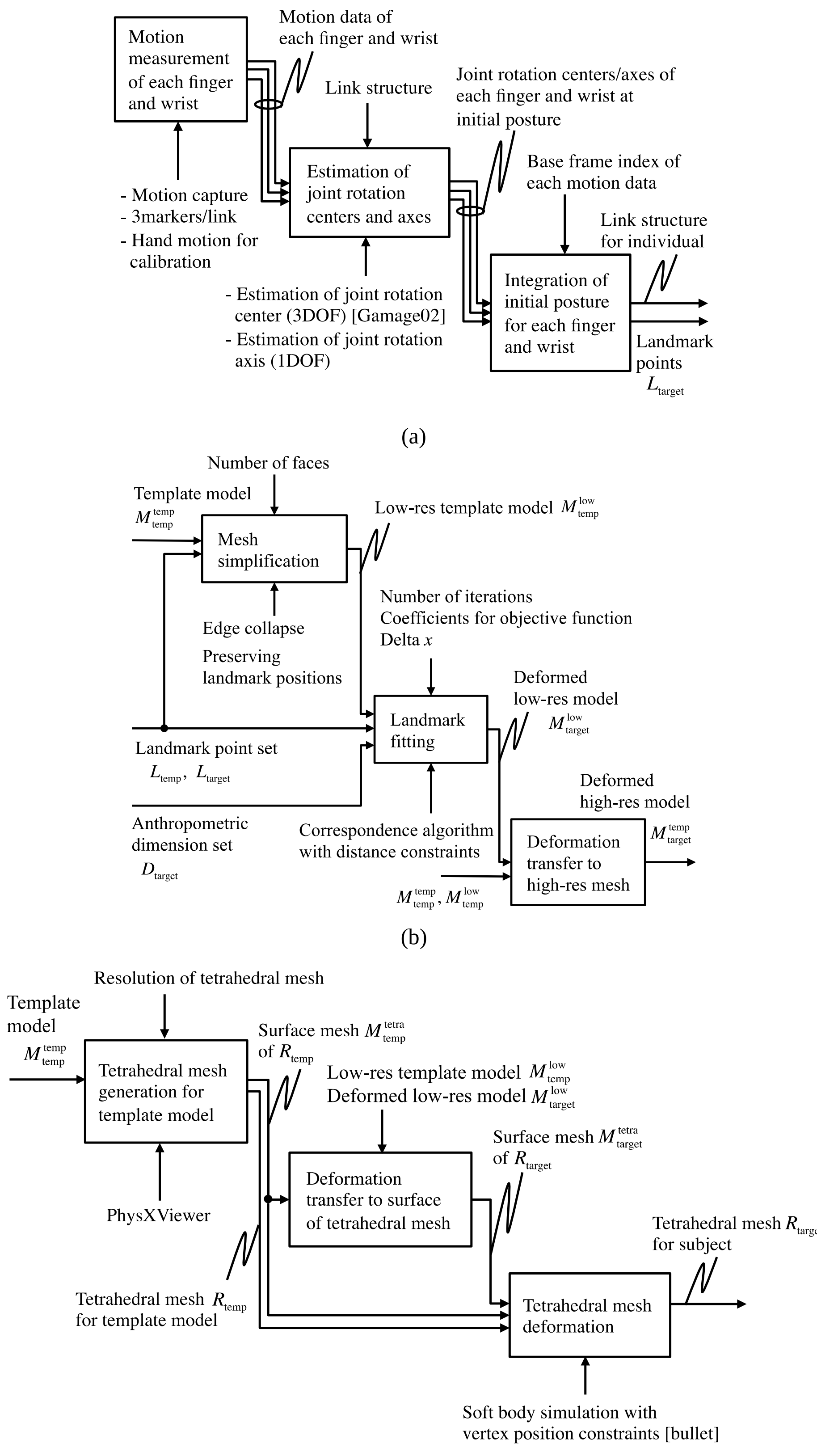


Figure 2. Overview of our hand model reconstruction method: (a) reconstruction of the link structure model, (b) reconstruction of the skin surface model, (c) reconstruction of the tetrahedral mesh model.

the hand dimensions of human. Any methods to reconstruct a hand model that reconstruct the hand dimensions of an individual have never been proposed yet.

3. Reconstruction of an individual hand model

3.1 Hand model

The structure of a hand model proposed by Kouchi [14], “DhaibaHand”, is used in our research.

As Figure 1 shows, DhaibaHand consists of the following models and a function: 1) a link structure model with 31 degrees of freedom, 2) a skin surface model in a reference posture represented by a triangular mesh, and 3) deformation function for the skin surface model based on rotation of each joint of the link structure model [7].

Each link of link structure model has one joint at the edge of a parent link side. Forearm joint has 6 degrees of freedom. Wrist joint, Thumb CM joint, and MP joint of Index to Pinky fingers have 3 degrees of freedom, and the rest of joints have 1 degree of freedom.

Each link has a local coordinate system having its origin as a relative joint position, in order to express it's link rotation to a parent link. As to an 1DOF joint, the local coordinate system is set to make rotation axis to be *x*. As to five links related to Wrist joint, each link rotates independently, even though they have a same local coordinate system in the reference posture.

In this study, we use a tetrahedral mesh model representing the hand shape in addition to DhaibaHand.

3.2 Overview of the proposed method

Figure 2 shows the overview of our proposed method. First, a link structure model and landmark points of a subject are created using calibration motions of the wrist and each fingers of the subject obtained from motion capture system. Next, a skin surface model in a reference posture of the subject is generated by an optimization algorithm based on 1) a template model of the human hand in the reference posture created by designers in advance, 2) landmark points relative to the 1), 3) land mark points in the reference posture of the subject. 4) a set of anatomical dimensions of human hand. At last, a tetrahedral mesh model in a reference posture of the subject is generated by the deformation of the tetrahedral mesh model for the template model, using soft body simulation. The features of our method is described as follows:

1) It is possible to generate the skin surface model with anatomical di dimensions of a subject, using landmark fitting to the marker positions obtained by motion capture and optimization method for the surface reconstruction with constraints of manually-measured anatomical dimensions.
2) It is possible to generate the skin surface model, which is homologous among all the subjects, using the template model as an initial value of optimization method for the surface reconstruction.
3) It is possible to accurately estimate an individual link structure model, by proposing calibration motions of 3 markers per a link and calculate the position of joint rotation center and rotation axes related to the link.
4) It is possible to generate the tetrahedral mesh model, which is homologous among all the subjects, by the deformation of the tetrahedral mesh model for the template model, using soft body simulation.
5) It is possible to perform the above method within an hour from experiment for measurement to post processing. It allows to reconstruct hand models for a large number of human subjects.

Details of the proposed method are described in the following section.

3.3 Measurement of marker sequence using motion capture system

In order to accurately estimate rotation center of each joint from sequence of marker positions obtained by motion capture (hereafter referred to as “marker sequence”), it is necessary to measure calibration motions enough to estimate rotation center position and axes of each joint after attaching minimum three markers on a skin surface around a link of the joint and it's parent link. As to motion measurement, it is difficult to measure all markers simultaneously since a large number of markers must be located in a very narrow area. Therefore, we measure the calibration motion of each finger and wrist by itself, integrate them at a reference frame in the motion using coordinate transformation, and then estimate and calculate the local coordinate system of each link in a reference posture.

1) As Figure 3(b) shows, 4 markers on a back of the hand skin surface and 3 markers on arm are attached.
2) As Figure 3(b) shows, plates attached 3 markers are placed on skin surface around each link of a finger to be measured.
3) The hand of a subject is then located on the seating (Figure 3(a)) to start a motion measurement from a reference posture. The hand is removed from the seating and two kinds of calibration motion are measured following instructions displayed in a monitor in front of the subject (Figure 3(d)): Measurement 1) First, rotate proximal phalanx as if the locus of fingertips follow a circumference and it's inner line, while not moving fingers and wrist, and then, Measurement 2) move intermediate and distal phalanxes simultaneously until making “drag rake” posture from opened condition, while not moving wrist and proximal phalanx. After measurement, remove markers attached on fingers. Among obtained motion sequence of marker set, one key frame that the hand is placed in the seating is defined as the reference frame fr_0 for the measured finger.

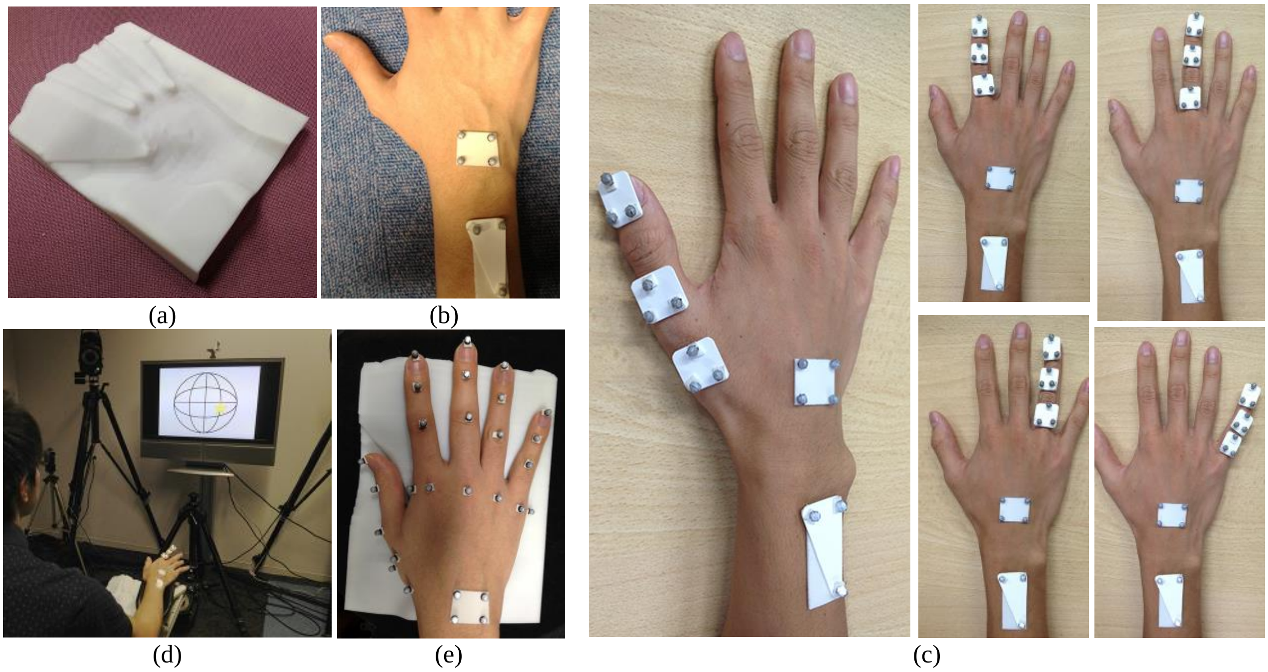


Figure 3. Measurement of marker motions by using the motion capture system: (a) the seat for the hand, (b) marker attachment for estimating the wrist joint and (c) for the joints of fingers, (d) a picture of the experiment, (e) marker attachment for calculating the skin surface.

4) Perform Step 2-3 to all the fingers.
5) Perform the measurement in Step 3 to the wrist. Rotate the hand having wrist joint as a calibration movement, as if tips of fingers follow the locus used at measurement 1 in Step 3.

6) As Figure 3(e) shows, one point of marker on the surface skin around each joint and nail of finger, two points at nearby median point of metacarpals of the first finger, one point at lateral surface around MP joint of each second and fifth finger are attached. At this time, measurement is done having the static posture hand placed at the seating as the reference posture. Also, one frame measured here is defined as the global reference frame fr_0^{all}. The marker set measured in this frame is defined as a landmark set L_{target} of a subject in the reference posture.

3.4 Construction of link structure model

In order to reconstruct a link structure model of an individual hand model, it is necessary to estimate positions of joint rotation center for 3DOF joints and rotation axes of 1DOF joints. Figure 4 shows finger structure for estimating joint rotation center and axes for each link. Marker sequence of calibration motions for each finger and wrist obtained in Section 3.3 is used on this estimation method.

We define $m_{j,k} (k = 0,1,2)$ as a marker related to a link that has a joint j as the rotation center, and ${}^{w}\mathbf{p}_{j,k}^{fr}$ as a position vector for $m_{j,k}$ in world coordinate system at frame fr of the marker sequence. We represent the trajectory of marker $m_{j,k}$ as a set of the position vector ${}^{fr_0}\mathbf{p}_{j,k}^{fr}$ in world coordinate system at the reference frame fr_0 for the relative finger (or wrist) of joint j. This vector is defined as ${}^{fr_0}\mathbf{p}_{j,k}^{fr} = \left({}^{fr_0}T_{fr}^{j-1}\right)^{w}\mathbf{p}_{j,k}^{fr}$. Where, the 4 x 4 matrix ${}^{fr_0}T_{fr}^{j-1}$ represents affine transformation and obtained as a least squares solution

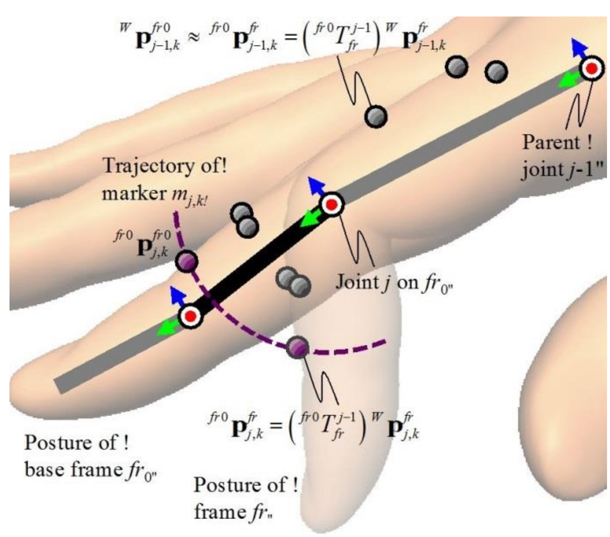
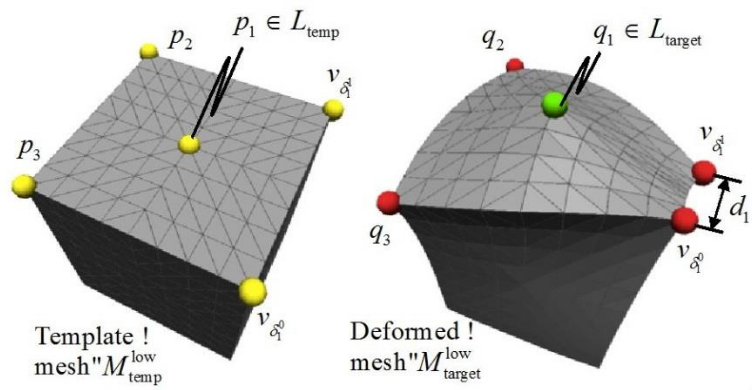


Figure 4. Estimation of joint coordinate system.



(a) (b)

Figure 5. Overview of our landmark fitting algorithm: (a) template mesh, (b) deformed mesh.

of the following equation:

$$\sum_{k=0,1,2} \left\| {}^{w}\mathbf{p}_{j-1,k}^{fr_0} - \left({}^{fr_0}T_{fr}^{j-1}\right)^{w}\mathbf{p}_{j-1,k}^{fr} \right\|^2 \rightarrow \min \qquad (1)$$

In this study, as a solving method of the above equation, the closed-form solution proposed by Horn et al. [12] (hereafter referred to as “landmark transform algorithm”) is used. As markers related to the parent joint of MP joint for each finger, 4 markers $m_{palm,k}$ are used.

Here, assuming that each ${}^{fr_0}\mathbf{p}_{j,k}^{fr}$ exists on a spherical surface $S_{j,k}$, we estimate a position vector $\mathbf{c}_j$ for common center of the $S_{j,k}$ as the rotation center of a joint *j*. In addition to this estimation, as for 1DOF joints, assuming each ${}^{fr_0}\mathbf{p}_{j,k}^{fr}$ exists on a place $L_{j,k}$, we estimate a common normal vector $\mathbf{n}_j$ of the $L_{j,k}$ as the rotation axis of the joint *j*.

In this study, as an estimation method for rotation center and axis from marker trajectories, we use the one proposed by Gamage et al. [10].

As described above, vectors for rotation center and axis of each joint, which are in the world coordinate system at the reference frame fr_0 for the relative finger or wrist, are estimated. Next, as for each finger, the world coordinate system at the relative reference frame fr_0 is transformed to the one at the global reference frame fr_0^{all}. This transformation is done by a homogeneous transformation matrix ${}^{fr_0^{all}}T_{fr_0}^{palm}$, which is calculated by applying the landmark transform algorithm to the 4 markers $m_{palm,k}$ attached on palm, as well. As the result, vectors for rotation center and axis of each joint, which are in the world coordinate system at the global reference frame $fr_0^{all}$for the relative finger or wrist, are estimated. Where, as for each 1DOF joint, we use obtained rotation axis vector as *x* axis of the relative local coordinate system. the *y* and *z* axes for each 1DOF joint and the *x*, *y* and *z* axes for each 3DOF joint of the relative local coordinate system are appropriately defined so that the rotation angle can be controlled intuitively by roll, pitch and yaw angles.

As described above, the link structure model for the individual is reconstructed. At the same time, from the measurement in Section 3.3, the landmark points L_{target} is obtained.

3.5 Reconstruction of a skin surface mesh in reference posture

In order to obtain a triangular mesh of the skin surface model in reference posture of a subject, skin mesh of template model M_{temp}^{temp} is optimized, as to fit landmark points L_{temp} on skin mesh of the template model to landmark points L_{target} of the subject obtained in the previous section. In this paper, we use a landmark fitting method based on the correspondence optimization algorithm proposed by Sumner et al. [21]. In our optimization method, the hand dimensions are additionally used as the constraints (Figure 5). This method deforms global shape of a mesh by the optimization, in order to make the position of specified landmark vertex $p < L_{temp}$ identical to the target point of $q \in L_{target}$ as well as to make the distance between specified two vertices $\{\boldsymbol{v}_{\delta^0}, \boldsymbol{v}_{\delta^1}\}$ identical to a specified target value *d*. In case when the posture of landmark points L_{temp} significantly differs from the one of L_{target}, it might take a long processing time to solve optimization problem mentioned in the following section. Therefore, as a preprocess of the optimization, a homogeneous transformation is applied for each point of L_{temp} and each vertex of M_{temp}^{temp}, in order to fit the position of 4 points attached at the back hand of L_{temp} to each relative point of L_{target}. The homogeneous transformation matrix applied above is calculated by the landmark transform algorithm same as the previous section. This method takes high calculation cost and not a realistic processing time to apply a template model with millions of surfaces. Thus, the number of faces of mesh M_{temp}^{temp} is reduced by edge reduction method using quadric error metrics [11] to generate a simplified mesh M_{temp}^{low} that has less than thousands of faces. This method allows to obtain an deformed skin mesh M_{target}^{low} by landmark fitting method, solving the following optimization problem:

$$
\begin{aligned}
&\min E\left(\mathbf{v}_1^{low},\cdots,\mathbf{v}_{N_v^{low}}^{low}\right) = \\
&w_S E_S\left(\mathbf{v}_1^{low},\cdots,\mathbf{v}_{N_v^{low}}^{low}\right) + w_I E_I\left(\mathbf{v}_1^{low},\cdots,\mathbf{v}_{N_v^{low}}^{low}\right) \\
&\text{subject to} \qquad (2) \\
&\mathbf{v}_{nearest(p_i)}^{low} + s_i \mathbf{n}_{nearest(p_i)}^{low} = \mathbf{q}_i \;(i = 1,\cdots,N_p) \\
&\left\| \mathbf{v}_{\delta_n^0}^{low} - \mathbf{v}_{\delta_n^1}^{low} \right\| = d_n
\end{aligned}
$$

Where, $\mathbf{v}_1^{low},\cdots,\mathbf{v}_{N_v^{low}}^{low}$ is defined as the position vector for each vertex on the M_{temp}^{low}, E_S and E_I is the energy functions defined in the correspondence optimization algorithm [21], w_s and w_I is user-specified coefficients, $\mathbf{v}_{nearest(p_i)}^{low}$ and $\mathbf{n}_{nearest(p_i)}^{low}$ are defined as the position and the normal vectors for a vertex on the M_{temp}^{low}, which is the nearest to the landmark point $p_i \in L_{temp}$ in the reference posture, $\mathbf{q}_i$ is the position vector for the land mark point $q_i \in L_{target}$ related to the p_i, s_i is the minimum distance between the hand skin surface and the center of the optical marker, and δ_n^0, δ_n^1 and d_n are defined as user-specified two vertices on the M_{temp}^{low} and the anatomical dimension between relative two points on the subject, manually measured by the user with a caliper.

Finally we obtain the skin surface model M_{target}^{temp} for the subject in the reference posture, applying the deformation result for the low-resolution skin mesh to the original high-resolution skin mesh M_{temp}^{temp} (Figure 6). The position vector $\tilde{\mathbf{v}}$ for a vertex $\tilde{v}$ on the M_{target}^{temp} which has the same index as the v, is calculated as the following equation:

$$\tilde{\mathbf{v}} = {}^{W}T_{\tilde{f}} \left({}^{W}T_f\right)^{-1} \mathbf{v} \qquad (3)$$

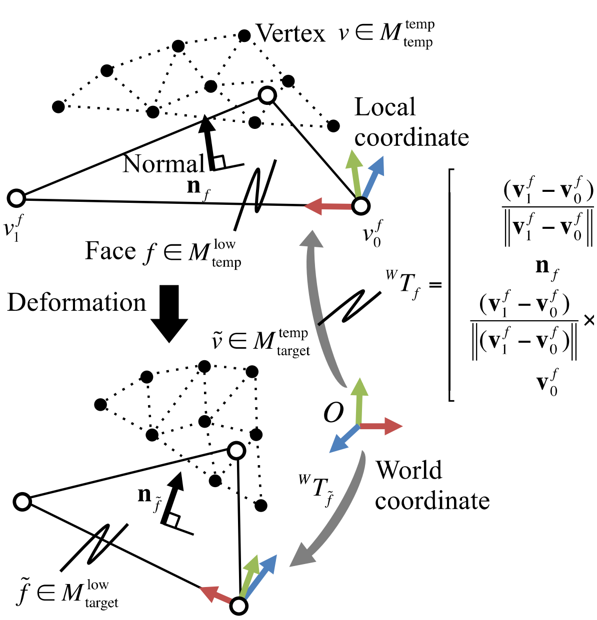


Figure 6. Deformation transfer to high resolution mesh.

Table 1. Dimensions used as constraints of landmark fitting algorithm.

Wrist breadth
Wrist thickness
Hand breadth, diagonal
Hand thickness at metacarpal 3 head
1st – 5th finger breadth, proximal
1st – 5th finger thickness, proximal
2nd – 5th finger breadth, distal
2nd – 5th finger thickness, distal

Where, f is a face on the M_{temp}^{low} which is the nearest to the vertex v on the M_{temp}^{temp}, $\tilde{f}$ is a face on the M_{target}^{low} which has the same index as the f, and ${}^{W}T_f$ is a homogeneous transformation matrix from the world coordinate system to a local coordinate system which has the normal and one edge of the f as its axes.

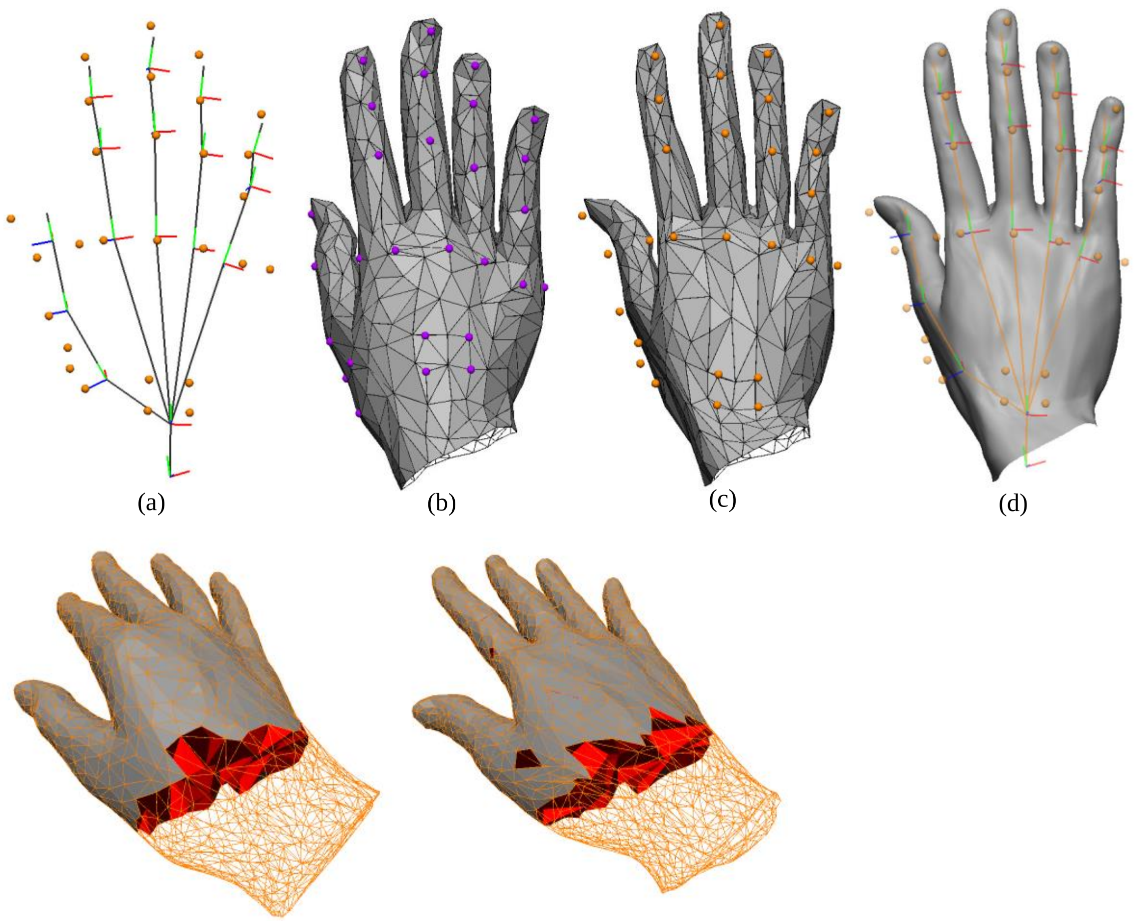
3.6 Modification on the rotation center for 1DOF joints

The rotation center of each 1DOF joint obtained at section 3.4 might be slightly separated from actual junction area between two hand bones, as it is estimated from marker trajectory approximately existed on an arc. Obtained joint rotation center will be referred to calculate a weight of each link for each vertex of mesh, when realizing skin mesh deformation according to joint rotation. It is ideal to locate the position of each joint rotation center at around center of cross-sectional shape of hand skin surface, in order to calculate appropriate weight set to realize realistic deformation. Therefore, we search a point on the rotation axis line that is the closest from two vertices on M_{target}^{temp} representing the edge points of finger width around this junction, and set this point to be the modified position of each joint rotation center.

3.7 Reconstruction of a tetrahedral mesh model in reference posture

As the final step of our method, a tetrahedral mesh model R_{target} for the subject in the reference posture is generated as follows:

1) A tetrahedral mesh model R_{temp} for the template model in the reference posture is generated from the skin surface mesh M_{temp}^{temp} of the template model. We use “PhysXViewer” [19] included in NVIDIA PhysX SDK as tetrahedral mesh generator from a surface mesh because of its ease of operation. We define M_{temp}^{tetra} as the surface mesh for the R_{temp}, which has the vertices and the faces on the surface of the R_{temp}.
2) The surface mesh M_{target}^{tetra} for the R_{target} is generated by applying the deformation transfer algorithm, as shown in the equation (3) in Section 3.5, to the mesh M_{temp}^{tetra} instead of the M_{target}^{temp}.



(a) (b) (c) (d)

(e) (f)

Figure 7. Reconstruction results of the hand model for a subject: (a) the link structure model, (b) the simplified template model, (c) the simplified deformed model, (d) the high-resolutional individual hand model, (e) the tetrahedral mesh for the template model, (f) the tetrahedral mesh for the individual.

3) The R_{temp} is located as a soft body in physics simulation environment. Each vertex on the R_{temp} which is at the same position of each vertex on the M_{temp}^{tetra} is constrained to the position of relative vertex on the M_{target}^{tetra}, and run the simulation. After waiting stabilized state of the soft body, the R_{target} is obtained as the result of the deformation of the R_{temp} in this simulation.

4. Reconstruction results of individual hand model

Figure 7 shows the results of reconstructing a hand model for the subject indicated at Figure 3(e). Here, Figure 7(a) shows the link structure model obtained in Section 3.4, Figure 7(b) shows simplified template model M_{temp}^{low} and landmark points L_{temp}, Figure 7(c) is simplified skin mesh M_{target}^{low} after landmark fitting and landmark points L_{target} obtained in Section 3.5 and Figure 7(d) shows deformed high-resolutional skin mesh M_{target}^{temp} and a link structure model modified in Section 3.6, Figures 7(e) and 7(f) show the tetrahedral mesh $R_{temp}$and R_{target} respectively. While measurement by the motion capture system, about 40 - 80s calibration motion measurement at 100fps was performed for each fingers and wrist. As to the simplification of skin mesh mentioned in Section 3.5, a simplified mesh with 992 faces from the original mesh with 59904 faces was created. As to the optimization for landmark fitting, w_s, w_I and s_i were set to 1.0 mm, 0.001 mm and 4.0 mm respectively. The iteration count for the optimization was set to 500. As to constraints of anatomical dimensions, 22 dimensions related to fingers and wrist were used as shown in Table 1. Mean and standard deviation of the error in dimensions of obtained high-resolutional skin mesh for relative user-specified dimensions was 0.04mm and 0.13mm respectively. Bullet [5], a software library for physics simulation, was used in Section 3.7 for simulating the physically-based behavior of the soft body with vertex constraints. We chose this library because it has a function of treating soft body with stable deformation

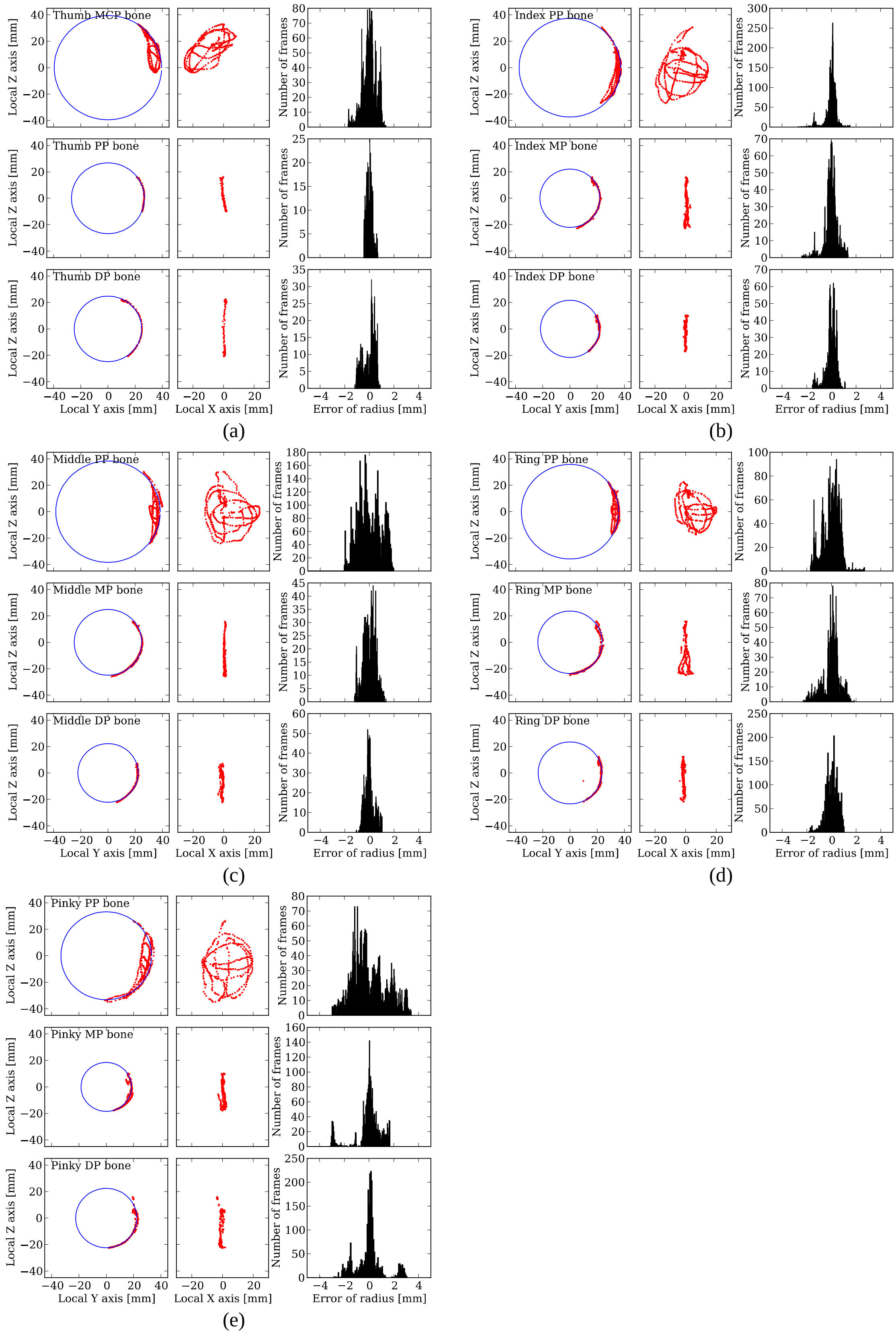


Figure 8. Validation results of the link structure model: (a) thumb, (b) index finger, (c) middle finger, (d) ring finger, (e) pinky finger.

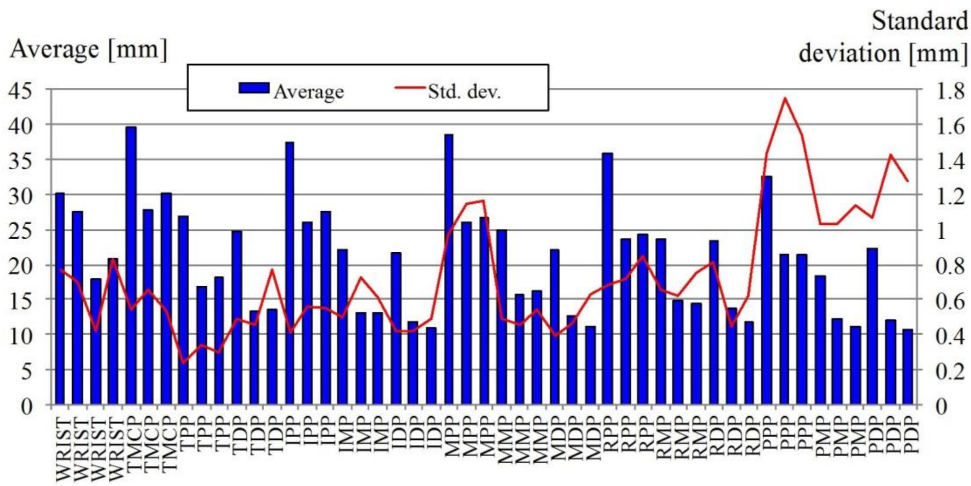


Figure 9. Radius distribution of estimated spheres for link structure model.

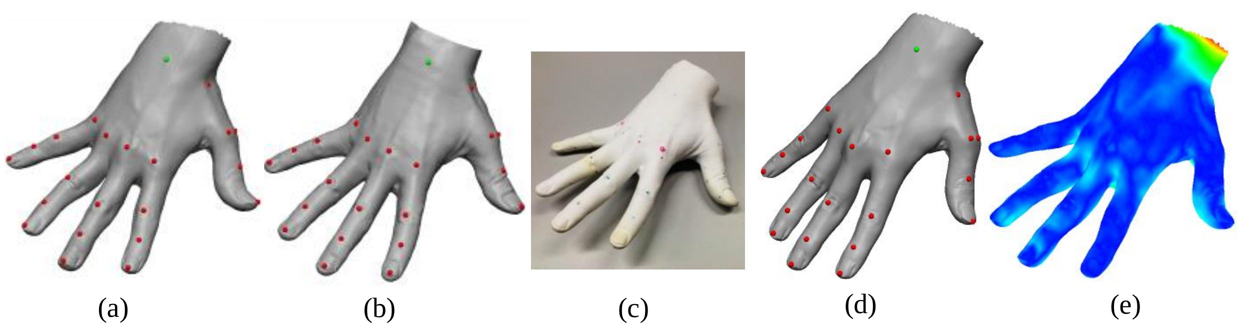


Figure 10. Validation results for proposed landmark fitting algorithm: (a) the skin surface mesh for the individual obtained from our method and (b) the one from CT scan, (c) the plaster hand model for the individual, (d) the template mesh model, (e) the error distribution map.

and collision detection and also it has been developed as the open-source code. Processing time on the computer except measurement time was approximately 15 minutes (MacBook Air, 1.8GHz Intel Core i7, 4GB RAM).

5. Discussion

5.1 Validation results for reconstruction method of link structure model

Figure 8 shows the results of the position of each joint rotation center obtained in Section 3.4. Red dots indicate the trajectory of each marker transformed to the local coordinate system of the parent joint at the reference frame. Blue lines show circle with mean distance between rotation center and each point as the radius. Error distribution of the distance of each point from the mean is shown as a histogram at right side. Where, Figure 8 shows only the result for one marker located the farthest from the position of rotation center.

Figure 9 shows mean and standard deviation of the distance between the rotation center and each point on the trajectory, for each marker. We can find that the trajectory for each marker related to 3DOF joint is on a sphere surface, and the one related to 1DOF joint is on a circle, with highly low error, so we can consider that our method enables the estimation of joint rotation centers with high accuracy.

We also measured calibration motions for MP, PIP and DIP joints of the index finger for a subject five times, then estimated joint rotation centers and axes, as described in Section 3.4. As the result, mean and standard deviation of the link length between MP and PIP joints are 45.54mm, 0.52mm respectively, the ones between PIP and DIP joints are 24.60mm and 0.92mm respectively. We can consider that our method has high reproducibility.

5.2 Validation results for reconstruction method of hand surface mesh

Validation of our reconstruction methods of hand surface mesh using a landmark fitting method, described in Section 3.5, was conducted as follows (Figure 10):

1) We take a plaster model of subject's right hand (Figure 10(c)). Then, we generate the mesh model (Figure 10(b)) by CT scan.
2) We specify landmark points L_{target} on the mesh obtained in Step 1.
3) A template model (Figure 10(d)) is deformed in order to fit landmark points L_{temp}(Figure 10(d)) to L_{target}, using the landmark fitting method.
4) We measure error of deformed hand surface mesh (Figure 10(a)) obtained in Step 3, to the hand surface mesh (Figure 10(b)) obtained in Step 1 (Figure 10(e)).

The mean, maximum and minimum error for each vertex on hand surface mesh was 1.63mm, 15.13mm, 0.0004mm respectively, and the standard deviation was 1.42mm. Even though the gap was slightly increased at interproximal area of mesh at a position of wrist, still it was within an acceptable range.

5.3 Further research

In this paper, a model reconstruction for one human subject was verified. The proposed method should be theoretically valid for a large number of human subjects. Therefore, it is necessary to apply our model reconstruction method to several human subjects and to validate it. Also, in measurement of calibration motions, the individual joints of each subject is supposed to have enough range of motion to enable the rotation center to be estimated. We need to develop a method that is also effective for subjects who, due to diseases or disorders, have only a small range of motion of joint rotation. For instance, a method that estimates missing marker data from the marker movement database obtained from a large number of subjects would solve the above issue and reduce measurement time.

6. Conclusions

We proposed the method which reconstructs a link structure model of a subject hand as well as homologous skin surface hand mesh to a template model, by using obtained marker sequence on fingers for a reference posture and calibration motions obtained from a motion capture system. As to the obtained hand model, we have confirmed the high accuracy of reconstruction for the hand dimensions, rotation center positions and axes of joints, also the skin surface model of the subject. All experiments with human subjects conducted in this study have been approved after an ethics investigation by the committee of ergonomic experiments at AIST.

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