Database-Driven Grasp Synthesis and Ergonomic Assessment for Handheld Product Design

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Abstract. Recently, simulation-based ergonomic assessments for handheld products, such as mobile phones, have seen a growing interest and have been increasingly studied. In these studies, the combination of 3D product models and "digital hands", which are a parametric 3D models of human hands, have been used. One of the keys to the ergonomic assessment using the digital hand is the "grasp synthesis" where plausible grasp postures for the product model have to be generated. In this paper, we propose a new database-driven grasp synthesis method considering the geometric constraints of grasping handheld products. The proposed method can generate more plausible grasp postures for handheld products in easier interactions than those of previous ones.

Keywords: digital hand, joint range of motion, grasp synthesis.

1 Background

Simulation-based ergonomic assessments have been applied into various product designs such as automobiles and aircrafts. On the other hand, simulation-based ergonomic assessments for handheld products such as mobile information appliances, handy tools, and containers have not been studied much.

Recently, in order to develop ergonomic-conscious handheld products, "digital hands" have been proposed and applied to the virtual assessment of ergonomics [1-6]. The digital hand is a deformable and precise 3D model of a human hand with rich dimensional variations. The key to assessing the ergonomics of the grasp, such as stability, easiness and fitness of the grasp are reliable "grasp synthesis" methods which can generate plausible grasp postures for products. So far, a grasp synthesis method where the user specifies corresponding contact points between a product model and a digital hand has been proposed [2]. However, inputting contact points which enable the generation of plausible grasp postures was difficult for users. Alternatively, data-driven grasp synthesis [6] has also been proposed. However, the generated postures included many where the user is unable to manipulate the products. Moreover, the other data-driven synthesis [7] based on a neural network has also been also proposed. However, the generated postures included many improper postures. Both of these data-driven algorithms only considered the geometry of the product model, therefore the generated postures wound up including many postures which were unsuitable for manipulating the products.

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The purpose of this study is to solve these grasp synthesis problems by proposing a new data-driven grasp synthesis method, one which can generate only those grasp postures that are suitable for manipulating the products.

2 Related Work

Applications of 3D models of a human hand have been previously studied. Some research has proposed applications for the digital hand. For example, in robotics a grasp planning system for a robotic hand design has been proposed [8]. In computer graphics, a system for generating the finger motions involved in playing the guitar was also proposed [9]. However, neither of them aimed for the product's ergonomic assessment and these hand models lacked the accuracy required for an assessment.

Grasp posture generation methods for assessing product models have also been studied. The posture generation methods are roughly classified into two types: a generative method [1, 2] and a variant one [6].

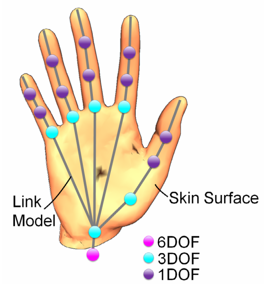
In the generative method described in [2], the grasp posture is generated by using a full-/semi-automatic grasping algorithm. Based on two pairs of contact points inputted by the user, this method can generate a grasp posture where the digital hand surfaces fits to the product model surfaces. However, selecting the two pairs of contact points needed to generate a plausible grasp posture required trained users.

Conversely, in the variant method in [6], the actual grasp postures of many subjects of sample objects have been measured using a data glove in order to build a grasp posture database. If a sample shape similar to a given product shape could be found in the database, a nearly appropriate grasp posture for the product could be obtained after a modification process. This method did not require the difficult task of inputting contact point pairs in [2]. However, the generated postures included many where the user is unable to manipulate the given product.

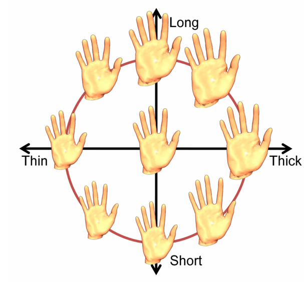
In this paper, in order to solve these problems described above, we propose a new data driven grasp synthesis method. By using the grasp posture in the database, the system does not require difficult inputs from the user. In addition, by imposing the grasping constraints on the joint range of motion of the human upper limb and the visibility of the fixation area on the synthesis, the system can generate a grasp posture where the user can manipulate the product. Furthermore, the modification process for wrist posture and finger posture enables the system to refine the synthesized grasp posture into a more plausible one.

3 Digital Hand

In our grasp synthesis method, we use the digital hand proposed in [1]. It consists of a link structure model and a surface skin model shown in **Fig. 1**(a). The link structure model simulates the rotational motion of human hand bones at each hand joint. The model was constructed based on measurements determined by MRI and motion capture. It has 17 links, and each one has a joint on both ends which has 1, 3 or 6 DOF. The surface skin model is composed of a 3D triangular mesh model. The skin model is able to be deformed using our developed surface skin deformation algorithm related



(a) Link structure and skin surface models



(b) Hand size variations model

Fig. 1. Digital hand

to the finger joint rotation angles [2].The digital hand has nine size variations derived from measuring several hundred Japanese subjects. As shown in **Fig. 1**(b), the hand sizes are classified into 9 variations based on its thickness and length [10].

4 Algorithm of Plausible Grasp Synthesis

Fig. 2. shows the process of our proposed plausible grasp synthesis. Details of the process are described in the following subsections.

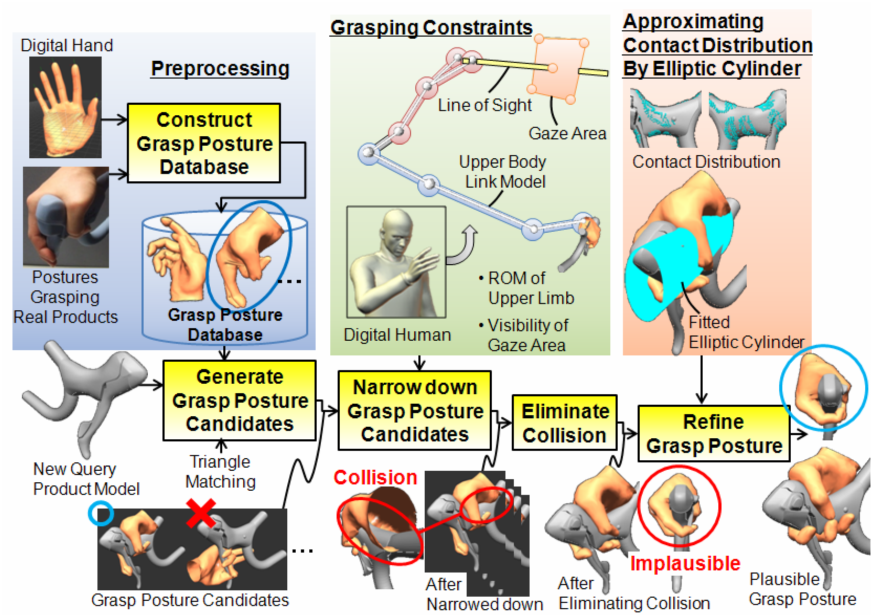
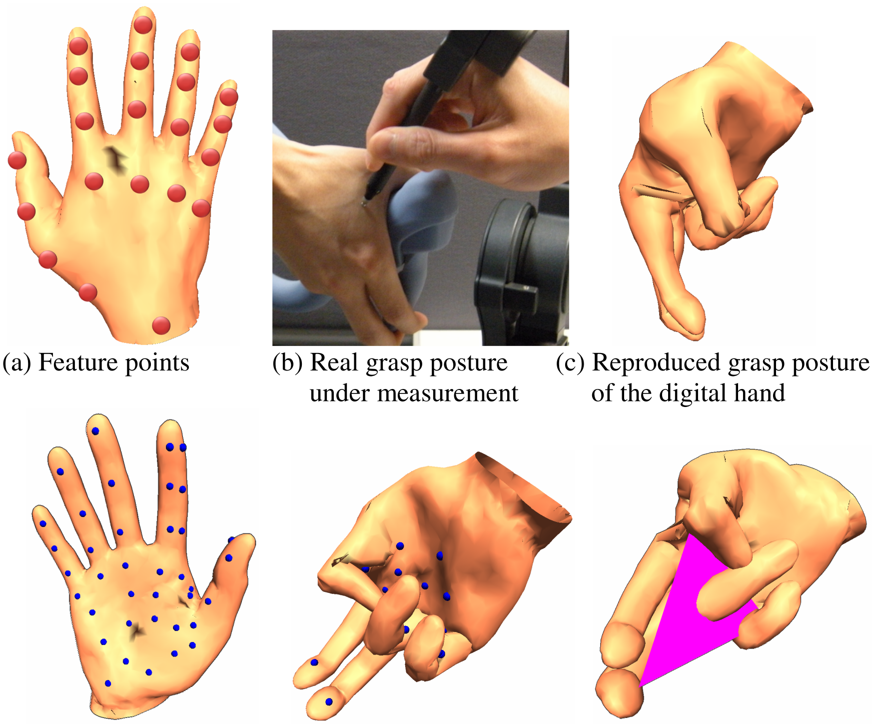


Fig. 2. Grasp Synthesis Process



(a) Feature points (b) Real grasp posture under measurement (c) Reproduced grasp posture of the digital hand

(d)Representative points (e)Contact points (f)Alignment triangle

Fig. 3. Constructing Grasp Posture Database

4.1 Constructing the Grasp Posture Database

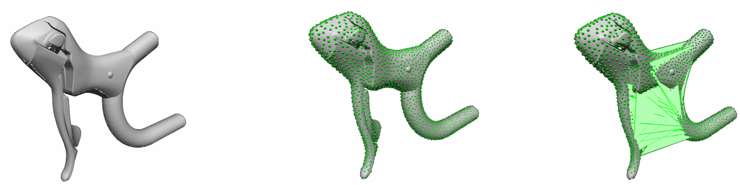
To store grasp posture data for a real product in the database, the locations of 21 feature points shown in **Fig. 3**(a) on the surface of a real human hand grasping an existing product were measured in advance by contact type 3D-CMM (MicroScribe). For example, the measurement is done as shown in **Fig. 3**(b). The grasp posture was then reproduced in the digital hand shown in **Fig. 3**(c) by fitting the feature points of the digital hand to the measured locations. Alternatively, in advance, representative points shown in **Fig. 3**(d) were placed on the surface of the digital hand. Then, a small set of contact points, shown in **Fig. 3**(e), which may come into contact with the real product surface were manually selected from the representative points of the hand with the grasp posture. Triangles were subsequently generated for all combinations of three contact points. The triangle with the largest area was selected as an alignment triangle, shown in **Fig. 3**(f), for the grasp posture. The combination of this grasp posture and its alignment triangle were stored in the grasp posture database.

4.2 Generating Grasp Posture Candidates

When a new query product model, as shown in **Fig. 4**(a), whose shape is different from the stored products is entered into the system, the system generates grasp posture candidates for the query using the following process. First, as shown in **Fig. 4**(b), a set of representative points is generated on the surface of the query product model. Then, a set of alignment triangles for the model, shown in **Fig. 4**(c), is generated by randomly selecting 3 points from the representative points. Finally, the system tries to match the alignment triangles of the query product model to that of the grasp postures stored in the database. As shown in **Fig. 5**(a), this matching is done based on the "triangle matching" whose details are the followings:

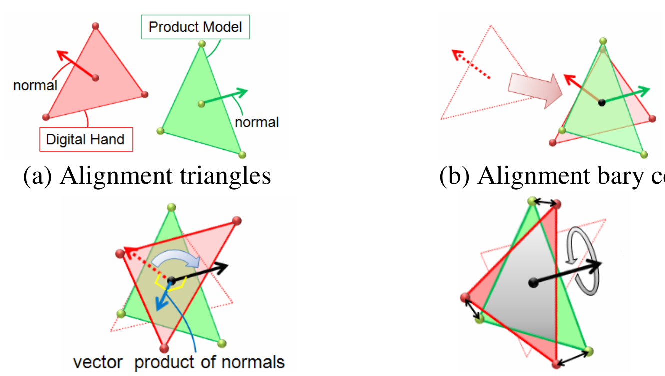
1. The system translates the bary-center of the alignment triangle of the digital hand to the product one, as shown in **Fig. 5**(b).
2. The system rotates the normal of the alignment triangle of the digital hand to the product one around the axis of the vector product of two normals so that the two normals of the alignment triangles coincide, as shown in **Fig. 5**(c).
3. The system rotates the alignment triangle of the digital hand around the axis of the matched triangle normal so as to minimize the sum of the distances between corresponding vertices of the two alignment triangles, as shown in **Fig. 5**(d).

Using the triangle matching, the system can generate grasp posture candidates. However, these candidates usually include many improper postures, where the user cannot manipulate the product. Therefore, the system needs to eliminate the improper postures.



(a) 3D mesh model to be grasped (b) Representative points (c) Some of alignment triangles

Fig. 4. Generation of the alignment triangles in a query product model



(a) Alignment triangles (b) Alignment bary centers

(c) Matching normals (d) Minimizing corresponding vertices

Fig. 5. Triangle Matching

4.3 Narrowing Down the Grasp Postures Based on Grasping Constraints

In improper grasping postures, the user cannot hold or manipulate the product in a natural attitude. For example, the user cannot view the fixation area from the correct angle and distance while holding the product. To eliminate such postures from the candidates, constraints on the joint ranges of motion (J-ROM) are introduced into the upper body link model. As shown in **Fig. 6**, the model consists of an upper limb link model and a head link model derived from a commercial digital human model (Poser).The digital hand is connected with the upper limb link model through the wrist joint with 3DOF. Eliminating improper grasp postures is done as the following.

First, as shown in **Fig. 6**, the user specifies the parameters φ and L_{eye} to situate the product model into the right position and orientation relative to the upper body link model. The positions of 4 corners of the fixation area in the model coordinates are also specified. φ denotes the neck rotational angle, and L_{eye} denotes the distance between the eyes and the fixation area surface. The system then automatically rotates the neck joint so that the angle between the line of sight and horizontal plane is identical to φ, and so that the fixation area is placed perpendicular to the line of sight with the length of L_{eye}.

After this placement, the grasp posture candidates are narrowed down by considering the constraints on the J-ROM. Twelve rotation angles for four upper limb joints are computed by solving the inverse kinematics based on the CCD (Cyclic-Coordinate Descent) Method [11] so that the wrist position and orientation of the upper body link model match the placed wrist of the grasp posture candidate. If the computed angles are beyond the J-ROM, the posture is eliminated from the list of candidates. The value of the J-ROM is summarized in **Table 1**.

Moreover, the grasp posture candidates are narrowed down by applying the constraint on the visibility of the fixation area. Two view frustums with bottom surfaces identical to the fixation area surface are constructed. If a portion of the digital hand collides with these frustums, the grasp posture candidate is eliminated.

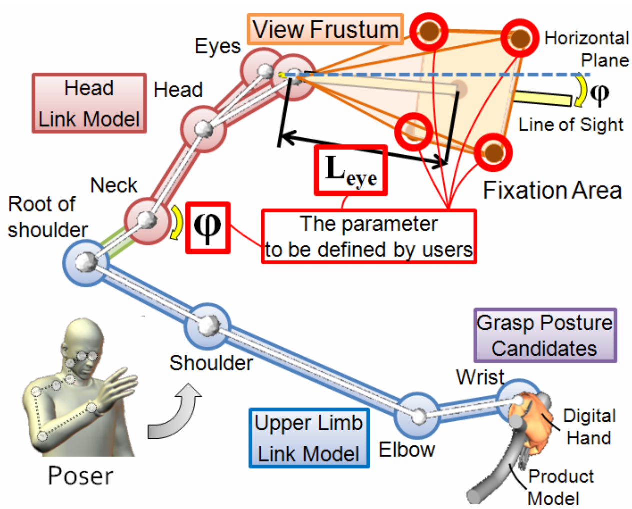


Fig. 6. Upper body link model

Table 1. Joint Range of motion [deg]

Joint	Axial Rotation	Bending and Stretching	
		Horizontal	Vertical
Root of Shoulder	-20～20	-55～35	-85～75
Shoulder	-85～110	-30～110	-30～90
Elbow	-30～150	-4～4	-20～120
Wrist	-20～20	-40～40	-52～25

4.4 Eliminating Collision between Digital Hand and Product Model

By considering the grasping constraints, the grasp posture candidates are narrowed down to ones where the user can manipulate the product. However, collisions between the digital hand and the product model may still exist among the selected candidates, because the inputted new product model has a different shape from the old one used during the construction of the grasp posture database. To deal with this issue, the system eliminates the collisions between the digital hand and the product model through the following process.

First, the system classifies the state of collision vertices on the digital hand surface into three states, as shown in **Fig. 7**. Each vertex is classified by comparing its penetration depth d_v from the product model surface to its threshold value τ. The threshold value τ reflects the difference of local skin contact stiffness. When $d_v \leq \tau$, the system classifies the vertex collision state as “contact”. When $d_v > \tau$, the system classifies the vertex collision state as “colliding”. When the vertex doesn’t collide with the product model, the system classifies the vertex collision state as “outside”.

After the classification, the system tries to eliminate the “colliding” vertices from the hand by changing the wrist position, wrist orientation, and finger posture. First, if any “colliding” vertex exists on the palm, the system derives the average normal from the normals of those vertices and translates the wrist position in the opposite direction to it. Then the system rotates the wrist joint to maximize the contact area on the palm. The system repeats these wrist modification processes until the “colliding” vertices on the palm do not exist. Finally, the system eliminates the collisions of the finger

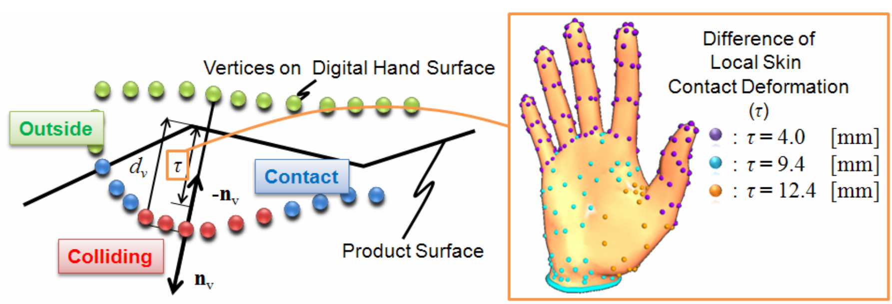


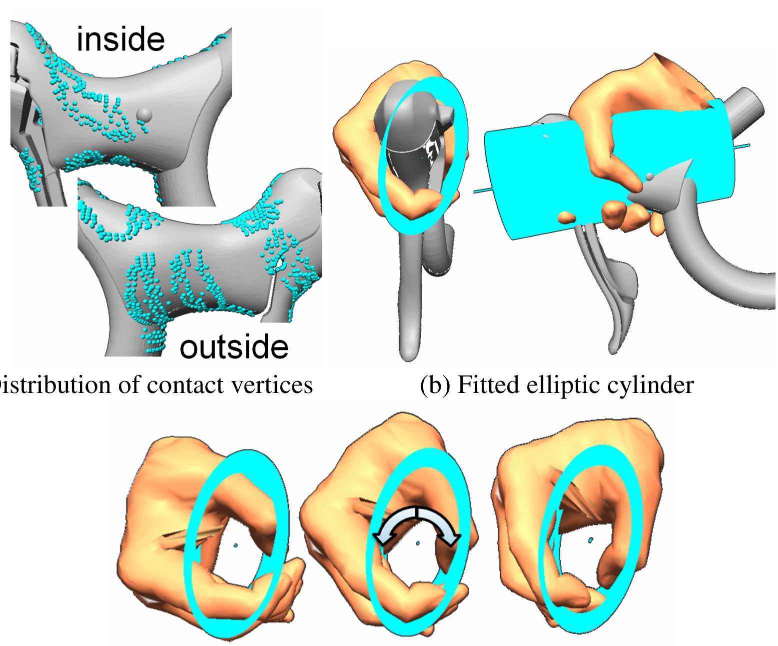
Fig. 7. Classfication of vertices on Digital Hand surface

vertices. It searches for each finger joint rotational angle so as to maximize the contact area on the finger among its range of motion.

4.5 Refining Grasp Posture Based on Contact Vertices Distribution

In spite of the collision elimination process in **3.4**, the wrist position and orientation of the derived grasp posture is not necessarily plausible for product manipulation. Therefore, the system tries to refine the derived grasp posture into a more plausible one by refining the grasp posture based on the elliptic cylinder approximation of the contact vertex distribution.

First, the system fits an elliptic cylinder to a set of the distributed contact vertices on the product model, as shown in **Fig. 8**(a). In this fitting, the system performs a nonlinear optimization where the distances between the contact vertices and the elliptic cylinder surface, shown in **Fig. 8**(b), is minimized, so that the medial axis of the contact vertices can be found as an axis of the cylinder. In this optimization, we use 8 control variables which consist of 2 lengths of major and minor axes of the ellipse, 3 angles representing the orientation of the cylinder, and 3 coordinates representing the position of the cylinder bary-center. An initial cylinder axis is derived from an analysis of the principal directions of contact vertices. After fitting the elliptic cylinder, the system rotates the digital hand about the cylinder axis at 5 degree interval in the range of ±30 degrees, as shown in **Fig. 8**(c). At each angle, the system rotates the wrist joint to maximize the contact area on the palm. Finally, by searching for each finger joint



(a) Distribution of contact vertices (b) Fitted elliptic cylinder

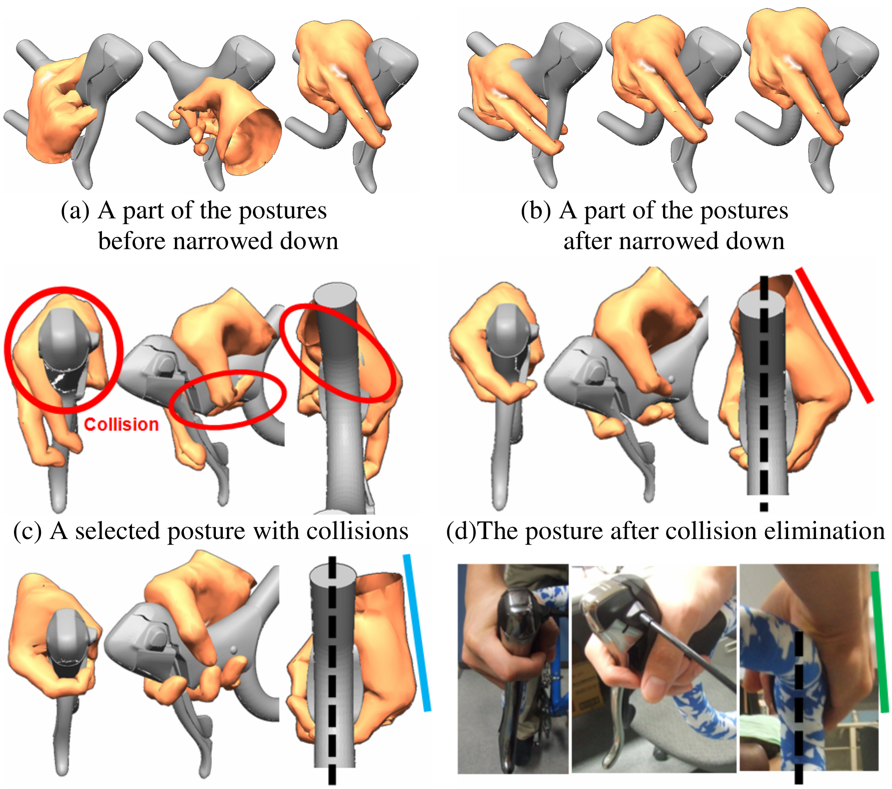
(c) Rotation about fitted cylinder axis

Fig. 8. Contact area approximation

rotation angle among its range of motion, the system refines the finger posture so that the contact area on the finger becomes maximized.

5 Results of Plausible Grasp Synthesis

Fig. 9 shows the result of a query conducted on a bicycle handle bar. In advance, a grasp posture for a different bicycle handle bar was stored in the database. By triangle matching using the grasp posture in the database, 4087 grasp posture candidates (**Fig. 9**(a)) were generated for the query product model. The candidates were then narrowed down to 75 postures which were regarded as good for grasp (**Fig. 9**(b)), applying the grasping constraints. Two parameters φ and L_{eye} were in agreement with the usual bicycle riding positions. But some collisions with the digital hand and the product model existed in these postures (**Fig. 9**(c)). To eliminate the collisions, wrist position, wrist orientation and finger joint rotational angles were modified (**Fig. 9**(d)). Those collisions were eliminated, but the wrist posture was very different from one of the experimental results (**Fig. 9**(f)). Finally, the grasp posture was refined based on the elliptic cylinder approximation of the contact vertices (**Fig. 9**(e)). By comparing the



(a) A part of the postures before narrowed down
(b) A part of the postures after narrowed down
(c) A selected posture with collisions
(d)The posture after collision elimination
(e) The posture after proposed refinement
(f) An experimental posture

Fig. 9. An example of plausible grasp synthesis for a bicycle handle bar

line along the back of the hand before and after the refinement to one from the experimental result, it was shown that the line after the refinement is more similar to the experimental one than before the refinement. From this result, it was verified qualitatively that the grasp posture was refined into a more plausible one by the proposed refinement process.

6 Conclusion and Future Work

A new data driven grasp synthesis method was proposed based on searching for a similar grasp posture example from a database. The search generated grasp posture candidates with triangle matching, narrowing down the candidates by applying grasping constraints consisting of the upper limb joint range of motion and the visibility of the fixation area. Collisions were eliminated between the digital hand and the product model by modifying the wrist posture and finger posture, and refinement of the grasp posture based on the elliptic cylinder approximation of the contact vertices. We verified the effectiveness of this method from the results of an experiment with a bicycle handle bar.

In our future work, we will implement a new grasp synthesis algorithm considering difficulties with product manipulation tasks based on the finger joint rotation angle.

References

1. Yui, E., Satoshi, K., et al.: Virtual ergonomic assessment on handheld products based on virtual grasping by digital hand. SAE Trans. J. of Passenger Cars: Electronic and Electrical Systems 116(7), 877–887 (2008)
2. Yui, E., Satoshi, K., et al.: An Application of a Digital Hand to Ergonomic Assessment of Handheld Information Appliances. In: Proceedings 2006 Digital Human Modeling for Design and Engineering Conference (2006) 2006-01-2325
3. Jingzhou, Y., Esteban, P.P., Joo, K., Abdel-Malek, K.: Posture Prediction and Force/Torque Analysis for Human Hands. In: Proceedings 2006 Digital Human Modeling for Design and Engineering Conference, 2006-01-2326 (2006)
4. Jaewon, C., Thomas, J.A.: Examination of a Collision Detection Algorithm for Predicting Grip Posture of Small to Large Cylindrical Handles. In: Proceedings 2006 Digital Human Modeling for Design and Engineering Conference, 2006-01-2328 (2006)
5. Natuki, M., Makiko, K., Masaaki, M.: Posture Estimation for Screening Design Alternatives by DhaibaHand - Cell Phone Operation. In: Proceedings 2006 Digital Human Modeling for Design and Engineering Conference, 2006-01-2327 (2006)
6. Ying, L., Jiaxin, L.F., Nancy, S.P.: Data Driven Grasp Synthesis using Shape Matching and Task-Based Pruning. IEEE Transactions on Visualization and Computer Graphics 13(4), 732–747 (2007)
7. Kyota, F., et al.: Detection and Evaluation of Grasping Positions. In: Proceedings of the 2005 ACM SIGGRAPH sketches, vol. 80 (2005)
8. Andrew, T.M., et al.: Grasp It!: A Versatile Simulator for Robotic Grasping. IEEE Robotics and Automaton Magazine, 110–122 (2004)

9. George, D.K., Karan, S.: Handrix: Animating the Human Hand. In: Proceedings of the 2003 ACM SIGGRAPH/Eurographics Symposium on Computer Animation, pp. 110–119 (2003)
10. Makiko, K., et al.: An Analysis of Hand Measurements for Obtaining Representative Japanese Hand Models. In: Proceedings of the 8th Annual Digital Human Modeling for Design and Engineering Symposium, 2005-01-2734 (2006)
11. Chris, W.: Inverse Kinematics and Geometric Constraints for Articulated Figure Manipulation. Simon Frasier University Master's Thesis (1993), ftp://fas.sfu.ca/pub/cs/TH/1993/ChrisWelmanMSc.ps.gz