Grasp Synthesis for Digital Hands with Limited Range of Motion in Their Thumb Using a Grasp Database

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Abstract. For virtual evaluation of universal design products, it is necessary to synthesize natural grasps for various hands including those with disability. As one of the disabilities, we focused on the limitation of the thumb's range of motion (ROM). For example, carpal tunnel syndrome (CTS) is a typical disease that limits thumb's ROM. Though there is no doubt that the range of motion affects the whole grasp, detailed grasp strategy has not been studied so far due to the difficulties in collecting data from such patients. Therefore, in this paper, we propose to synthesize grasping postures by the thumb's ROM-limited digital hands based on the observation of an actual subject whose hand is artificially-disabled. The synthesized postures of the healthy hand and the thumb's ROM-limited hand were obviously different. We applied a contact-region-based method for grasp synthesis for ROM-limited hand and succeeded in synthesizing the grasping postures that reflect the features of the thumb's ROM-limited hands' grasps.

Keywords. grasp synthesis, universal design, digital hands, virtual evaluation

1. Introduction

For the virtual evaluation using a digital hand, it is necessary to synthesize natural grasps for arbitrary product model. In [1], studies about data-driven grasp synthesis were surveyed. Examples of data-driven grasp synthesis approaches are [2]–[6]. Data-driven approaches use the database of real human grasps and the necessary data are identified based on known grasp classification (e.g., [7]–[11]). Therefore, it is possible to synthesize natural grasps that are more similar to human real grasps than analytical approaches. Previous studies on grasp synthesis have been focusing mainly on healthy hands. However, non-healthy hands should also be considered as designing universal design products. Grasps by non-healthy hands differ from those of healthy hands. Thus, in the virtual evaluation of universal design products, it is important to synthesize natural grasps by various hands including non-healthy ones.

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Grasps by hands with limited range of motion (ROM) are typical examples of grasps different from those of healthy hands. In particular, because the thumb is used for 98–99% of the grasps [12], the change of grasping posture becomes noticeable when the ROM of the thumb is limited. Therefore, in our research, hands with limited thumb's ROM are focused on. Patients with carpal tunnel syndrome (CTS) are a typical example of those whose thumbs' ROM is limited. CTS is the most common peripheral nerve entrapment syndrome worldwide [13]. Particularly in patients with severe CTS, it is known that the palmar abduction of the carpometacarpal (CM) joint is restricted (e.g., [14]). Since the opposition of the thumb is hindered, significant change in grasping posture of the hands is expected when their palmar abduction of the CM joint is limited.

We have investigated the grasp features when the ROM of palmar abduction of the thumb's CM joint was artificially limited [15] and attempted synthesizing the grasps when the thumb's palmar abduction is limited based on the features [16]. However, the grasps of the thumb's ROM-limited hand cannot be synthesized well. For thumb's ROM-limited hands, two grasp styles were observed, but it was not possible to control the two observed grasp styles in grasp synthesis using the method proposed in [16]. Therefore, in this paper, we present a newer method that can synthesize the grasps both of the healthy hand and the thumb's ROM-limited hand. Realization of grasp synthesis for ROM-limited hands would contribute to evaluation of usability of universal design products virtually.

2. Method of grasp synthesis

2.1. Algorithm of grasp synthesis

In this paper, the method of grasp synthesis for healthy hands proposed in [5] and [6] is applied to grasp synthesis for ROM-limited hands. This section explains an overview of the algorithm of grasp synthesis. It is cited from [16].

The greatest feature of this method is the use of grasp database based on the "contact regions." The outline of the method of grasp synthesis proposed in [5] and [6] is shown in Fig. 1. The contact regions are the hand surface areas that touch the object when grasping. Hirono et al. divided the hand surface into 34 regions, and classified grasps that appear in the taxonomy proposed in [7] and [8] based on the contact regions. Furthermore, additional grasping postures with different number of used fingers and with different inter-fingertip distance were selected, and finally, a grasp database including 801 natural grasps was created. The postures with different number of used fingers were added to the grasp database in order to cover expected possible grasps. In addition, the postures with different inter-fingertip distance were added to synthesize the grasp for a newly given object by interpolating a few postures in the grasp database.

The advantage of the grasp database based on the contact regions is that the posture in the grasp database whose contact regions are same as the input regions can be used to synthesize the initial posture even if the grasped object is different. Therefore, it is expected to have wide applicability to object variations of size and shape.

The input information of grasp synthesis is the contact regions and the points of grasping targets on the object surface. In the method, postures having the same contact regions as the input data are searched from the database firstly. Then, an initial posture is

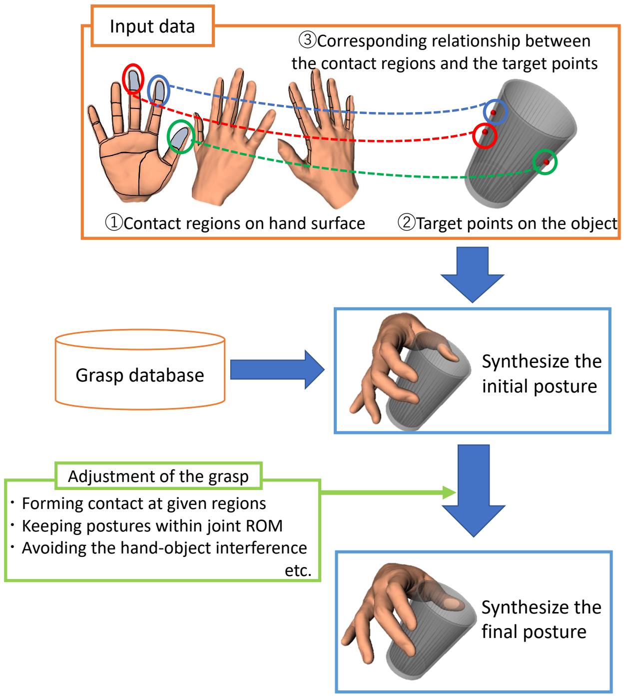


Figure 1. Outline of the method of grasp synthesis proposed in [5] and [6]

synthesized by interpolating the reference grasps whose contact regions are same as the input data based on the distance between the target points on the object surface. In this step, the hand model is also aligned with the object by matching the contact points on the hand with the corresponding contact target points on the object.

As the initial posture is not guaranteed to be a natural and proper grasp, the initial posture is adjusted through optimization, that considers following points: forming a contact in appropriate orientation, self-interference and hand-object interference avoidance, and keeping postures within joint ROM.

2.2. *Grasp synthesis method for thumb's ROM-limited hand*

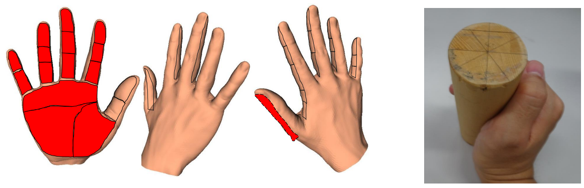
In [15], we observed the grasp features of the thumb's ROM-limited hand based on the contact regions. Two grasp styles were observed to be typically different from the healthy hand. One was the style that uses the same contact regions as the healthy hand and the other was the style that uses the thumb's lateral region. The style that uses the thumb's lateral region means the grasp style that uses the thumb's radial region in the power grasp, to wrap an object with fingers, and uses the palm and the thumb's ulnar region in the precision grasp, to support an object with fingertips.

In [16], we tried to synthesize the grasping postures using the Hirono et al.'s algorithm explained in Sec. 2 with the limited ROM data. However, it was not possible to control the two observed grasp styles in grasp synthesis. In other word, two typical styles of thumb's ROM-limited hands cannot be synthesized absolutely using the Hirono et al. 's method because this is developed for healthy hands.

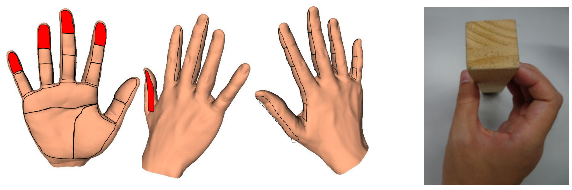
Therefore, in this paper, we add the postures that use the thumb's lateral region to the grasp database proposed by Hirono et al., and further modify the calculation algorithm when synthesizing the posture to synthesize the grasp that reflects the features of the thumb's ROM-limited hand. The algorithm was implemented on DhaibaWorks, a platform software developed by the National Institute of Advanced Industrial Science and Technology. The details of changing points from the method for healthy hands are described below.

2.2.1. Database extension

In our previous study [15], the grasp style that uses the thumb's lateral region was not observed in healthy hands. Therefore, the conventional grasp database for the healthy hand [6] did not include postures in the style. In [16], it was shown that it was possible to synthesize the grasp using the thumb's lateral region from the conventional database by changing the grasping target points, but it was also predisposed to synthesize an unnatural postures.



(a) Using the thumb's palmar side



(b) Using the thumb's ulnar side

Figure 2. Grasping styles of the thumb's ROM-limited hands

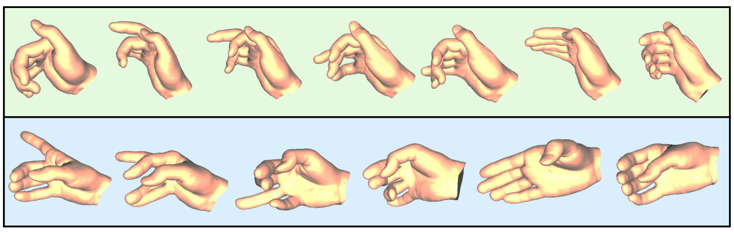


Figure 3. Added postures for the grasp database

Therefore, we aim to synthesize the grasps that reflects the features of the thumb's ROM-limited hand by adding grasping postures using the thumb's lateral region to the grasp database. For other postures, the database for healthy hands is used, and the limitation of their ROM is dealt with in the optimization calculation part. It is unrealistic to recreate all the database according to various hand function states considering the number of postures included in the database. Therefore, we try to synthesize the grasp that reflects the features peculiar to the hand function by adding only the necessary grasping postures to the database for healthy hands.

The grasp styles actually added to the database are shown in Fig. 2. We do not consider grasping styles with fewer fingers, which tend to be unstable in the thumb's ROM-limited hand. Therefore, the number of fingers is not changed, and the postures in which only the distance between the fingertips is changed are added to the database. Since an initial posture is synthesized by interpolation of postures in the database, it is necessary to include the postures with different distance between the fingertips for each finger in the database. The added postures are shown in Fig. 3. These postures were measured when grasping the actually objects. When measuring the postures in which one finger was extended, an object with a wide diameter at the contact position of that finger was used. The 13 postures that were newly measured as the unique grasping postures of the thumb's ROM-limited hand are added to the 801 postures obtained by converting the database by Hirono et al. according to the development environment of this study. Thus the new grasp database has 814 postures in total.

2.2.2. Changing the calculation algorithm

In this study, the following four points are used as the evaluation indices in the optimization process. (1) The degree of coincidence between the coordinates and the directions of the normal vectors of the contact regions and the grasp target points, (2) The margin for the ROM boundary that considers joint coordination, (3) The amount of interference between the hand model and the object model, (4) Degree of contact with the object between the contact regions where the grasp target points are not given. We implemented optimization calculation by Powell's method. The position of the wrist joint and the angles of all joints are used as variables.

In particular, the margin for the ROM boundary was determined by the maximum and minimum joint angles in the previous method [6]. However, due to joint coordination, the ROM should be expressed in a higher dimensional space. Therefore, the information of the joints' angles in the high-dimensional space are projected onto two-dimensional planes to model the ROM. In this modeling, the ROM data actually measured by a healthy hand or a ROM-limited hand is used. Although the thumb joint can move complicatedly, it is possible to properly reflect the ROM limitation of the thumb on the synthesized posture by considering the joint coordination for each two joint angles in this way.

3. Results and Discussions

Grasp synthesis was attempted using the proposal method. Grasping postures were synthesized under the following three conditions: (1) a healthy hand, (2) a thumb's ROM-limited hand using the same style as a healthy hand, (3) a thumb's ROM-limited hand

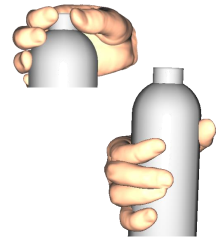
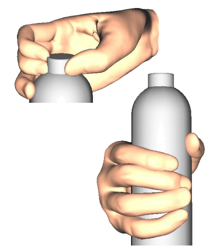
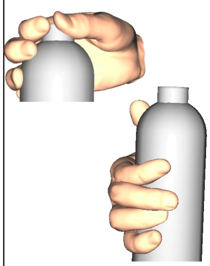
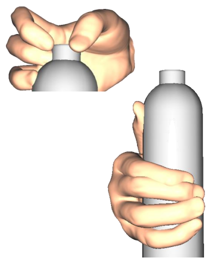
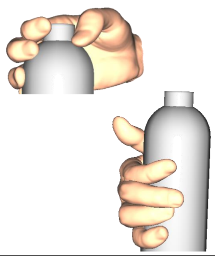
	Subject 1's hand model	Subject 2's hand model
(1) Healthy hand		
(2) ROM-limited hand Using the same contact regions as (1)		
(3) ROM-limited hand Using the thumb's lateral region		

Figure 4. Examples of the results of the grasp synthesis

using the thumb's lateral region. The same contact regions were given in (1) and (2), and the region on the thumb to be used was changed in (3). The measured ROM of a healthy hand was used in (1), and the measured ROM of a thumb's ROM-limited hand was used in (2) and (3). The grasp target points were changed by trials and errors under all conditions. We used hand models that imitate two different subjects. and confirmed that the grasps can be synthesized even if the hands' shapes and their ROMs are different.

Examples of synthesized grasping postures are shown in Fig. 4. The object to be grasped was a bottle, and two postures were synthesized for the bottle. One was the posture of power grasp with the whole hand, assuming to drink the bottle, and the other was the posture of precision grasp with fingertips assuming to open the cap. According to the previous study [6], the validity of the synthesized posture were confirmed visually. It was visually confirmed that the specified contact regions were in proper contact with the object in Fig. 4. In addition, it was also confirmed numerically that the joints' angles were inside the ROM. Therefore, it was concluded that valid grasps were synthesized under all conditions.

The self-interference seemed to remain slightly in Fig. 4. However, it was thought that this self-interference was an effect of skin deformation. The hand model could not reproduce skin deformation because it was defined as rigid body, so the range of possible skin deformation was excluded from the amount of self-interference in the optimization process. It was considered that the self-interference remaining in Fig. 4 had no problem because it was due to this skin deformation.

However, the angle of the index finger's metacarpophalangeal (MP) joint was unnatural in the power grasp of subject 1. The joint angle was inside the ROM and it could be realized as a hand posture, but it was seemed unnatural as a grasping posture. The index finger was expected to be oriented along the middle finger. This is a remaining problem, and it is necessary to consider how to eliminate these unnaturalness.

4. Conclusion

In this study, we synthesized grasps for the thumb's ROM-limited hand, which can be used to evaluate universal design products virtually. The grasp synthesis method for a healthy hand [6] was extended by augmented grasp database and consideration of joint coordination for this purpose. It was confirmed that both grasps for healthy hands and grasps that reflected the features of thumb's ROM-limited hands were synthesized using the proposed method.

In the future, we will increase the number of grasping objects, evaluate the validity of the synthesized postures, and improve the optimization process to synthesize more natural grasps. Also, the current program's calculation time is very long. Therefore, it is necessary to reduce the calculation time. In addition, adjustment of the grasp target points, which is made by trial and error in our current method, should be automated.

Acknowledgement

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