Grasps under Artificially-limited Thumb's Joint Range of Motion –Posture Analysis with ROM Boundary and Muscle Loads–

Reiko Takahashi[1], Natsuki Miyata[2], Yusuke Maeda[1], and Koji Fujita[3]
[1]Yokohama National University, Tokiwadai 79-5, Hodogaya-ku, Yokohama, Kanagawa 240-8501, Japan
[2]National Institute of Advanced Industrial Science and Technology, Tokyo 135-0064, Japan
[3]Tokyo Medical and Dental University, Tokyo 113-8510, Japan

Abstract:
This paper proposed a method to clarify the features of grasping styles of ROM-limited hands. We measured the contact regions and joint angles of grasping by a ROM-limited hand. The joint angles were analyzed with respect to ROM boundary. Muscle loads of grasps were also estimated. Grasping styles finally selected by the ROM-limited hand tend to use side region of the thumb. In the grasping styles finally selected by the ROM-limited hand, ROM-limited joints tend to be farther from ROM boundary. In addition, the influence of muscle loads is not confirmed.

1. Introduction

On designing a product, usability can be evaluated virtually by estimating grasps for the CAD model of the product using a digital hand [1]. It has two merits. One is cost saving, and the other is to be able to consider various hands' posture easily. Previous studies on grasp synthesis have been focusing mainly on healthy hands (e.g., [2][3][4]). However, in recent years, market size of universal design products tends to expand. Thus, it is important to synthesize grasps by various hand models including non-healthy hands (e.g., whose finger's range of motion, ROM, is restricted). Therefore, the purpose of this study is proposing a method to clarify the features of grasping styles of ROM-limited hands. This will contribute to grasp synthesis for ROM-limited hands and help to realize the virtual evaluation of universal design products.

The authors have studied to observe the grasps of ROM-limited healthy hands. In [5], we proposed an artificial limitation method for the thumb's carpometacarpal and metacarpal joints of a healthy hand using a rigid strapping tape and observed grasps for some objects qualitatively. The carpometacarpal joint was selected to resemble the disability of a patient with carpal tunnel syndrome. The metacarpal joint was selected because this joint was indicated to work to adapt to the object size change in [6].

In this paper, we aimed to observe the grasps of ROM-limited hands quantitatively. We conducted a grasp experiment to measure contact regions and joint angles with respect to the ROM boundary. We also evaluated muscle loads based on the experimental results.

2. Grasping Experiment By ROM-Limited Hand

2.1 Experimental procedure

The thumb's carpometacarpal and metacarpal joints of a healthy right hand were limited by the method proposed in [5]. Two rectangular boxes of different size were prepared for grasped objects in the experiment. The subject was asked to execute two kinds of tasks. One task was to bring one of the objects down like a hammer, and the other task was to move one of the objects changing its orientation. These tasks were selected because representative grasp forms, power grasp and precision grasp, were expected to be observed. A female subject grasped the objects by her healthy left hand and ROM-limited right hand alternately 10 times to compare grasp transition for the ROM-limited hand and that for the healthy hand.

2.2 Contact regions

The hand surface was divided into 34 regions to observe contact regions on the hand that touched the object surface when grasping [5]. The objects were cooled beforehand to observe contact regions using a thermal image (Fig. 1). The temperature of the hand surface regions which touched the object in grasping was dropped (The purple area in Fig. 1

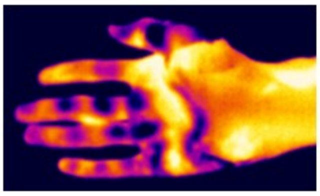

Fig. 1 A thermal image of the hand

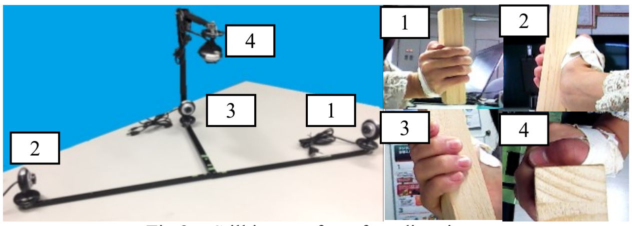

Fig.2 Still images from four directions

was the contact area). Still images from four directions (Fig. 2) were also captured to observe contact states in detail.

The result shows that, for the ROM-limited hand, several grasps were observed in 10 trials, and there was a tendency that one grasp was chosen finally. On the other hand, for the healthy hand, grasping style was generally constant in 10 trials. In addition, for the ROM-limited hand, there was also a tendency that the thumb's lateral region and the palm region were in contact with the object surface. The time required for the tasks became shorter as the grasping style converged.

3. Relation to ROM Boundary

Features of the grasping styles that were finally chosen by the ROM-limited hand were elucidated. The joint angles of grasping postures were measured by motion capture, and the postures were reproduced by a digital hand. The joint angles of grasps were compared with ROM boundary. Ideally, joint angles at the time of grasping experiment should be acquired. However, the markers for motion capture may interfere with the natural grasps. Therefore, the subject was asked to grasp the object after the experiment in the same posture as that at experimental time using results of contact regions and the still images captured in the experiment.

Fig. 3 shows an example in a task to move a small object. The joint angles were determined by the method proposed in [6] and [7]. In Fig. 3, red border means ROM boundary of the healthy hand, and green border means that of the ROM-limited hand. The axes in Fig. 3 are illustrated in Fig. 4. The grasps finally selected by the ROM-limited hand

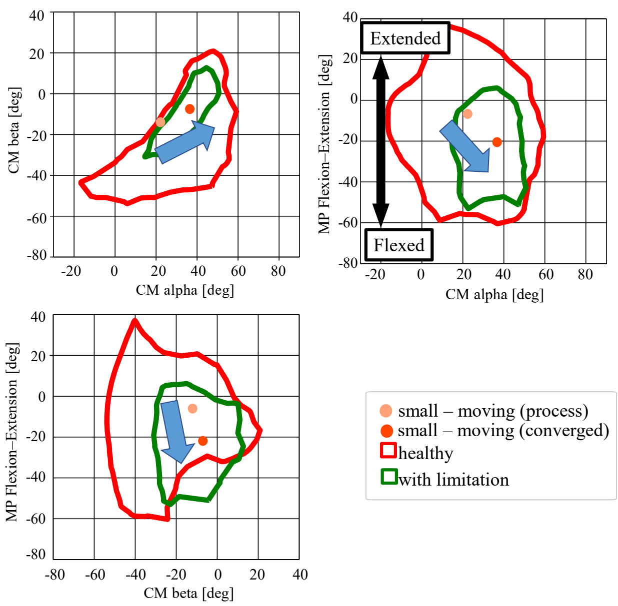

Fig. 3 An example of grasping posture with respect to ROM boundary

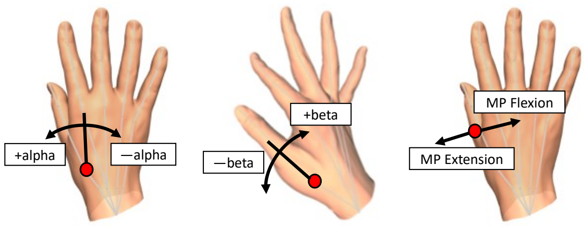

Fig. 4 The axes of Fig. 3

tended to be farther from ROM boundary than those temporarily appeared in the trial process. This tendency was especially noticeable in thumb's joints that were limited. It was presumed that the subject did not want to move her ROM-limited joints.

4. Effect of Muscle Loads

The muscle loads in the grasps found in the experiment were estimated from the postures reproduced by a digital hand. The approach of [8] was used for mechanical analysis. First, the contact points between the object model and hand model was estimated by interference detection. Contact points were considered to belong to the closest link of the hand model, and the centroid of the contacts points belonging to each link was regarded as a representative point of the contacts of the link. Then, the muscle loads were calculated by solving the following quadratic programming problem under the assumption that the object was grasped so as to minimize muscle load:

$$\underset{\boldsymbol{f},\boldsymbol{a},\boldsymbol{\tau}_{\mathrm{lock}}}{\text{minimize}} \quad E=\boldsymbol{a}^{\mathrm{T}}\boldsymbol{a}$$

$$\text{subject to} \begin{cases} \boldsymbol{G}\boldsymbol{f}=\boldsymbol{t} \\ \boldsymbol{J}^{\mathrm{T}}\boldsymbol{f}-\boldsymbol{M}^{\mathrm{T}}\boldsymbol{F}\boldsymbol{a}+\boldsymbol{\tau}_{\mathrm{lock}}=\boldsymbol{0} \\ \boldsymbol{n}_{kh}\boldsymbol{f}_k \leq \boldsymbol{0} \quad (k=1,\ldots,N,\ h=1,\ldots,8) \\ \boldsymbol{0}\leq \boldsymbol{a} \leq \boldsymbol{1} \\ \boldsymbol{\tau}_{\mathrm{lock}} \geq \boldsymbol{0}, \end{cases} \tag{1}$$

where E: Muscle load, $\boldsymbol{a}$: Muscle activity vector, $\boldsymbol{f}=[\boldsymbol{f}_1^{\mathrm{T}},\ldots,\boldsymbol{f}_N^{\mathrm{T}}]^{\mathrm{T}}$: Contact force vector, $\boldsymbol{t}$: Task wrench, $\boldsymbol{J}^{\mathrm{T}}$: Conversion matrix of contact force to joint torque, $\boldsymbol{M}$: Matrix of moment arm, $\boldsymbol{F}$: Diagonal matrix of maximum muscle force, $\boldsymbol{n}_{kh}$: Normal vector of the hth side of the regular octagonal pyramid that approximates the friction cone at the kth contact point, $\boldsymbol{\tau}_{\mathrm{lock}}$: Torque vector by joint lock.

If a joint is close to the ROM boundary, the joint cannot move even if it receives a large reaction force from the object. Therefore, at the ROM boundary, it was assumed that a mechanical lock occurs and this was represented by $\boldsymbol{\tau}_{\mathrm{lock}}$. There was a possibility that a mechanical torque may have been generated in the direction to get away from ROM boundary.

Task wrench ***t*** represents the force and torque to be applied to the object from the hand in order to stably grasp and manipulate the object. When executing a task, the required task wrench varies depending on a time. Therefore, we set two representative task wrenches, and solved the quadratic programming problem for both task wrenches. One was at the beginning of the task, and the other was in the middle of the task.

Comparing the muscle loads in the finally-selected grasp with those in the trial process, no common tendency was observed.

5. Conclusion

This paper proposed a method that clarifies the features of grasping styles of ROM-limited hands. The preliminary experimental results showed that there were several tendencies in the grasp finally selected for a ROM-limited hand. One was the use of the lateral area of the thumb in the grasp. The other was that the ROM-limited joints were far from the ROM boundary. It was presumed that the muscle load did not influence the determination of the grasp very much.

Our future works include the increase in the number of subjects and analysis of different features such as contact force, manipulability, and grasp stability to reveal universal features of grasping styles.

Acknowledgement

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