# A Basic Study for Tailor-made Body-powered Prosthetic Hand

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## ABSTRACT

***The objective of this research is to investigate a feasibility of tailor-made production for body-powered prosthetic hand. A body-powered prosthetic hand has been expected to be a common device because of its functionality and economical efficiency. In spite of the advantages, only 20% of Japanese amputees use the body-powered prosthetic hand. In order to improve amputees' satisfaction, there are two important topics to be solved. They are a user customization of prosthesis and an application of non-metal material. As a solution of the first topic, a framework of digital prototyping environment is introduced to customize prosthesis. The digital prototyping environment consist of four modules: 3D-CAD system, standard parts library, modeling rule base and rapid prototyping machine. A tentative implementation of the digital prototyping environment is employed to evaluate a tailor-made design process of an alternative-style prosthetic hand. Concerning to the second topic, a segment composition method is proposed to fabricate complex and hollow shape FRP parts. Prototype development of a hook shows proposed approach can fabricate complicated and hollow shape FRP parts. In this article, outline of proposed use-customization framework is explained. Then, a case study of design and evaluation of novel device is shown. Furthermore, FRP parts fabrication examples are also illustrated.***

**Keywords:** body-powered prosthetic hand, tailor-made production, rapid prototyping, FRP, hollow shape fabrication, parts segmentation

## INTRODUCTION

Prosthetic hands are essential devices for amputees who lost their hands. There are four types of prosthetic hands: decorative prosthesis, work arm, body-powered prosthetic hand and myoelectric hand. Depending on amputees' sense of value, each of them is employed. The body-powered prosthetic hand is expected to be a common device because it enables the amputees to manipulate objects with a low economic burden. From some surveys of prosthesis usage in Japan, it becomes clear that only 20% of amputees use the body-powered prosthetic hand. This low usage rate means amputees are not satisfied by the conventional body-powered prosthetic hands. There are some reports about reasons of low usage rate. They are bad appearances, weight of devices, inefficient manipulation function and so on. Because a design freedom of the prosthetic hand is limited in principle, it is difficult to satisfy all amputees by one unique design of the hook. Therefore, an alternative approach to increase the amputees' satisfaction is eagerly desired. Furthermore, in order to avoid too mechanical appearance and heavy weight, utilization of non-metal materials is eagerly desired.

Concerning amputees' satisfaction, a concept of "prosumer" has been introduced more than 25 years ago Toffler (1984). The prosumer is a coined word which is made from producer and consumer. It intends technology would enable user customization in various fields. Recently, as concretization of the prosumer concept, several proposals have been proposed with modern digital technologies Onosato (2001), Gershenfeld (2005), Tseng (2010). The objective of these proposals is to adapt devices to various user preferences. On the other hand, all conventional prosthetic hands are ready-made products which are designed to adapt average preference of amputees. Because circumstances of amputees have huge variety, user customization of prosthetics is a promising approach to increase the amputees' satisfaction of the prosthetic hand. Therefore, a digital prototyping environment for tailor-made body-powered prosthetic hand is developed to evaluate the possibility of user customization of prosthesis.

As an implementation of non-metal prosthetic hands, a segment composition based fabrication scheme is proposed. The proposed scheme enables to fabricate complex and hollow shape FRP (Fiber Reinforced Plastics) parts.

## FRAMEWORK FOR TAILOR-MADE BODY-POWERD RPOSTHETIC HAND

Figure 1 illustrates a framework of tailor-made production of prosthetic hands. It is expected that requirements of amputees will be reflected to the prosthesis easily. In order to realize this framework, support technologies for prototype fabrication is necessary because design of body-powered prosthetic hands have some difficulties; they are :

(1) movable elements,
(2) requirements of structural stiffness,
(3) interfaces to conventional equipments (cable system and sockets),
(4) complex shape definition.

Furthermore, evaluation methods for newly developed devices should be considered. Following issues should be investigated.

- strength evaluation from structural aspect
- kinematic evaluation of movable parts and force efficiency
- dexterity evaluation of objects manipulation
- subjective evaluation of product usability such as feeling, affinity, contentment and so on

First two topics can be evaluated based on standard FEM technologies and mechanical simulation technologies. It is difficult to evaluate the third topics because interaction between the end-effectors and target objects are complicated. Variety of objects and complexity of interaction make it difficult to evaluate by computational techniques. Therefore, physical prototype device should be implemented and employed to the evaluation. In order to evaluate subjective evaluation, a real usable device should be employed because human sense is quite complex and sensitive. It is obvious that subjective evaluation with the real usable device requires usability evaluations by actual amputees. This kind of evaluation costs very much. Therefore, agile and reliable evaluations of first three topics are necessary to shorten the development.

Based on the requirements for the design process, a digital prototyping environment which contains multi-aspect evaluation loops is proposed based on design knowledge organization, 3D-CAD technique and Rapid Prototyping (RP) technique. Figure 2 illustrates a schematic diagram of a proposed digital prototyping environment for tailor-made prosthetic hand. After designing the new prosthesis, implementation of designed parts with FRP material is also necessary to deliver the customized prosthesis.

In order to achieve the support, the digital prototyping environment consists of four modules: 3D-CAD system, standard parts library, modeling rule base and rapid prototyping machine.

Because machining accuracy of modern RP machine is rather poor. It is difficult to fabricate accurate parts like smooth kinematic pair and interface to the conventional parts. Therefore, two techniques are introduced. The first is utilizing standard movable elements such as bearing. The other is to prepare design rules which enable appropriate fabrication. Empirical rules of dimensions for screw and matching parts have been investigated through several preliminary experimental trials. Figure 3 illustrates examples of empirical rules application.

As a feasibility evolution of proposed framework, a novel end-effector which enables stable pickup and grasp is designed and tested. A fabrication example of prosthetic hand with FRP is also investigated in this paper.

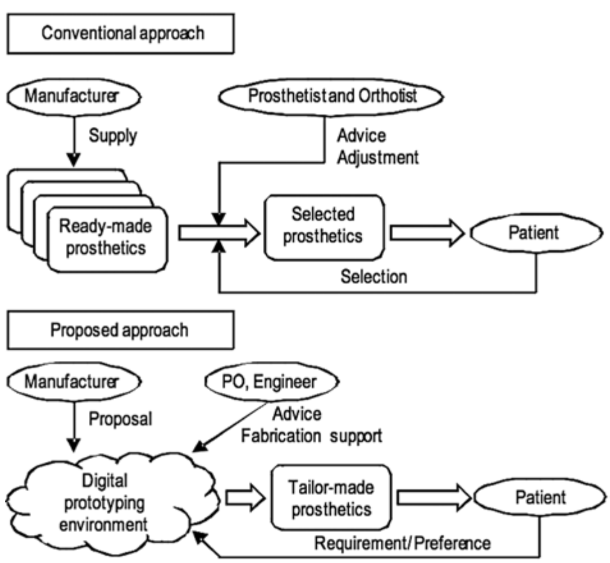



**Figure 1.** Framework of tailor-made production for prosthetic hands.

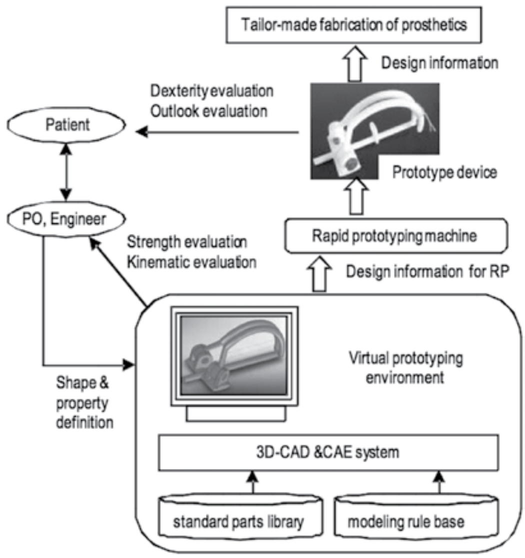



**Figure 2.** Digital prototyping environment for tailor-made prosthetics.

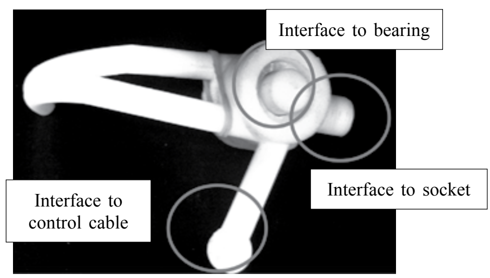



**Figure 3.** Interfaces to conventional equipments.

## DESIGN EXAMPLE

### *Design of end-effector*

In order to evaluate the proposed framework, a case study design of new end-effector is designed based on the proposed design scheme. In order utilize newly developed devices, it is necessary to evaluate form various aspects explained in Section 2. In this paper, procedures of dexterity evaluation are explained.

Firstly, based on interviews to the PO and amputees, drawbacks of existing devices are surveyed. They are,

(1) too mechanical appearance
(2) heavy end-effectors
(3) difficulties in initial movement
(4) unstable pick-up and holding

Because the first two items require subjective evaluation by amputees, last two items are investigated as a case study.

In order to realize stable holding and balanced control force, a three finger type device is designed as illustrated in Fig. 4. Features of the designed device are as follows:

- Holding objects are stabilized by three point contacts.
- Control force can be magnified by the pulley system.
- Moment at socket is minimized by centering control force.

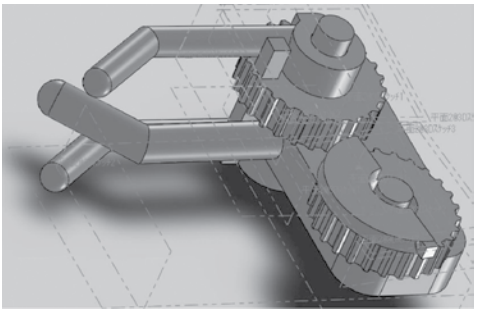


**Figure 4.** Designed three finger type device.

***Pick-up evaluation***

From the work analysis of human manipulation, there are two types of manipulation: pick-up and holding. Firstly, pick-up ability of developed device is evaluated. In order to regularize frictional conditions and the control force of device, conventional utility hook device is fabricated by the developed prototype system. Figure 5 and 6 show manipulation objects which are employed in the pick-up evaluation.

As pick-up evaluation, pick-up trials for each object are executed with the conventional hook and the developed three finger device. Power source of the devices are equalized with the common rubber band

Firstly, trials to the objects in Fig.7 are executed. Results of the pick-up trials are summarized in Tab. 1. The developed three finger device can pick up all objects successfully. On the other hand, conventional hook cannot pick up objects of large diameter. Because of the structural limitation of the conventional hook, it is difficult to manipulate large diameter objects.

Table 2 shows success rates of 50 times pick-up trials for objects in Fig.8. Because the conventional hook has large dependency to the relative orientation between the hook and objects, success rates are summarized separately. The results indicate developed device can pick-up without orientation dependency. Furthermore, several unstable holding states are observed in the hook trials. Therefore, picking up by conventional hook requires re-holding process to shift the object holding. On the contrary, developed device can smoothly shift to the object holding.

**Figure 5.** Objects for pickup evaluation.

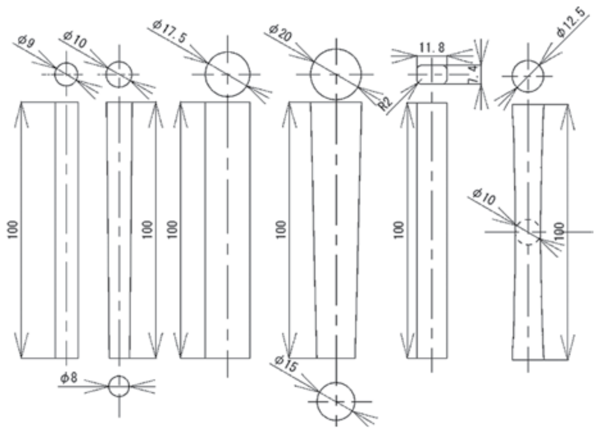



**Figure 6.** Objects for pickup and hold evaluation.

**Table 1.** Comparisons of pickup ability for Fig. 7 objects.

| | No. 1-1 | No.1-2 | No.1-3 | No.1-4 | No.1-5 | No.1-6 |
|---|---|---|---|---|---|---|
| Hook | Fail | Fail | Fail | success | success | success |
| 3 finger | success | success | success | success | success | success |

**Table 2.** Comparison of pickup ability for Fig. 8 objects (%).

| | No.2-1 | No.2-2 | No.2-3 | No.2-4 | No.2-5 | No.2-6 |
|---|---|---|---|---|---|---|
| Hook (vert.) | 94 | 16 | 6 | 2 | 56 | 54 |
| Hook (hori.) | 100 | 100 | 100 | 100 | 100 | 100 |
| 3 finger (both) | 100 | 94 | 100 | 100 | 84 | 100 |

***Hold evaluation***

As an evaluation of holding ability of developed devices, holding trials are executed with the fabricated conventional hook and developed device. Objects listed in Fig.8 are employed to the holding trials. In this evaluation, objects are fixed to the hook and device preliminarily as shown in Fig.7. Then, external forces are loaded to the hold objects and forces when the objects slip from the device are measured. Loading directions of external forces are illustrated in Fig.7.

Average and deviation of measured allowable external load in three directions are illustrated in Fig.8-10.

Results of holding evaluations show the developed device can hold the objects stably to the direction 1 and 3 external forces and the conventional hook is stable in direction 2 external force. Deviations of allowable force to the developed device are smaller than the conventional hook. It is important that the conventional hook is difficult to keep the holding to the direction 3 external force. It is considered that large deviations and low ability of holding in direction 3 are the causes of amputees' unsatisfaction.

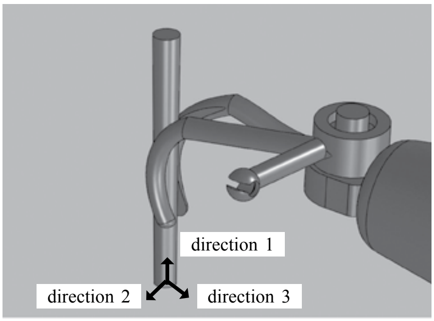
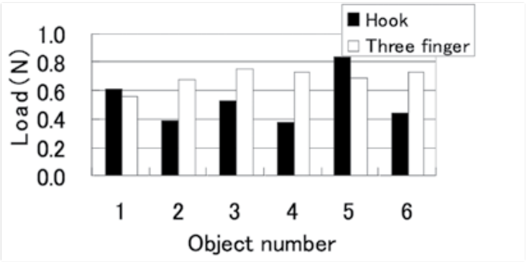
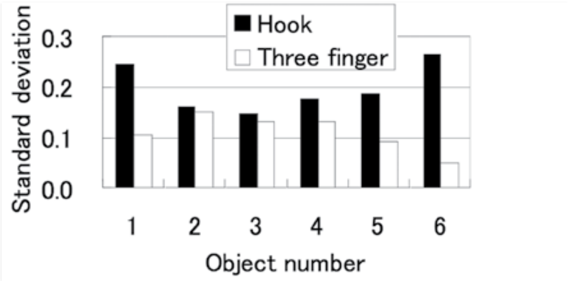



**Figure 7.** External force direction.

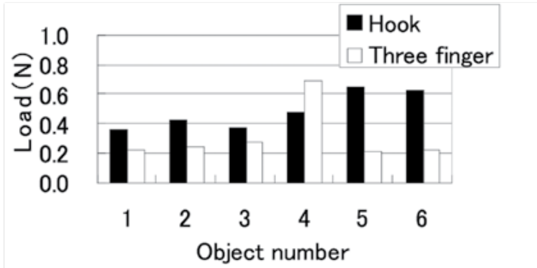



(a) Withstand load

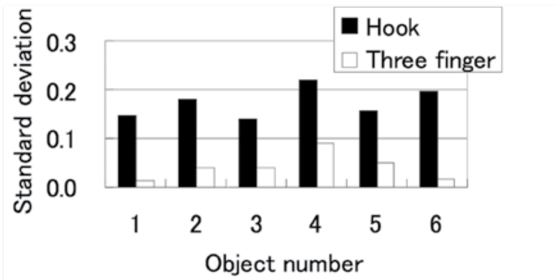



(b) Standard deviation

**Figure 8.** Comparison of holding ability (Direction1).

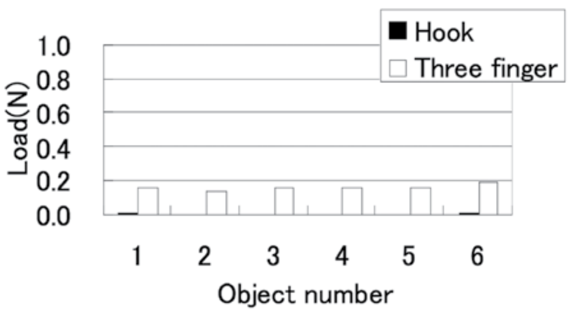



(a) Withstand load

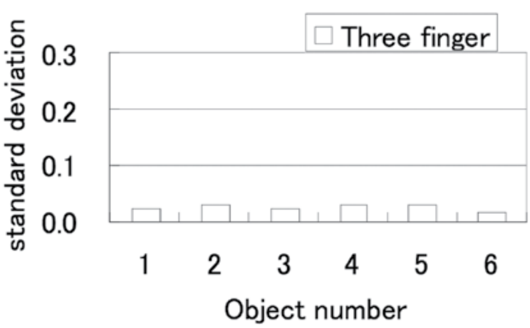



(b) Standard deviation

**Figure 9.** Comparison of holding ability (Direction2).




(a) Withstand load




(b) Standard deviation

**Figure 10.** Comparison of holding ability (Direction3).

## FABCRCATION EXAMPLE

As a fabrication method of hollow shape FRP parts, a segment composition approach is proposed to an accurate and small lot fabrication of the prosthesis. In the approach, complicated shapes are decomposed into rather simple segmented shapes firstly. Then, simplified segments are fabricated by using simplified molds. Because of the simplicity of the shape, it is easy to design and fabricate the mold. Finally, fabricated segments are combined into a part. Fig.11 shows a schematic diagram of the proposed fabrication approach.

By using the simplified mold to the appropriately segmented shapes, complicated and hollow shapes including large curvature can be fabricated with uniform thickness. For the agile and easy fabrication of the simplified mold, RP technique is applied as the rapid tooling of the mold.

In order to realize the proposed approach, it is necessary to achieve accurate and strong joint of segments. Recent advancement of the glue technologies is expected to realize reliable joints. Moreover, designing the matching surface at parts decomposition, it is possible to realize accurate positioning of segments

As an example trial of proposed fabrication procedures, an existing hook shape end-effector was modeled by using 3D-CAD system. Then, the modeled hook was disassembled into parts by considering the movable part. For each part of hook, they were divided into four kinds of intermediate segment parts based on the separation of hollow shape. All intermediate segments were decomposed into final segment parts. Based on the segment parts shape, shapes of inner molds and outer molds were modeled. Figure 12 shows the whole shape of hook and intermediate segments. They were modeled by using 3D-CAD system. Figure 13 illustrates an example of the intermediate segment parts of hook's claw and final shapes of segment parts that can be fabricated by mold. After modeling final segment parts, inner and outer molds for the segment were designed with simple geometrical calculation. The designed molds are fabricated by using RP machine. By using the fabricated molds, segment parts are fabricated and they are combined into a part.

As the fabrication method of the FRP segments, a hand lay-up method was employed. Firstly, FRP material was splayed at inside of the outer mold. Then, the inner mold was shoved to generate appropriate cavity space. After fixing the molds, the material was hardened by using hardening agent. By using this procedure, all FRP segment parts were fabricated. When all segment parts were fabricated, intermediate segment parts were fabricated by combining FRP segment parts. Finally, a hook of weight-reduce functional prosthetic hand was fabricated by combining FRP intermediate segment parts.

Figure 9 shows the hook shape end-effector which was fabricated by proposal method. From the picture, it is confirmed that the fabricated end-effector can be open and appearance of the hook is similar to the intended shape.

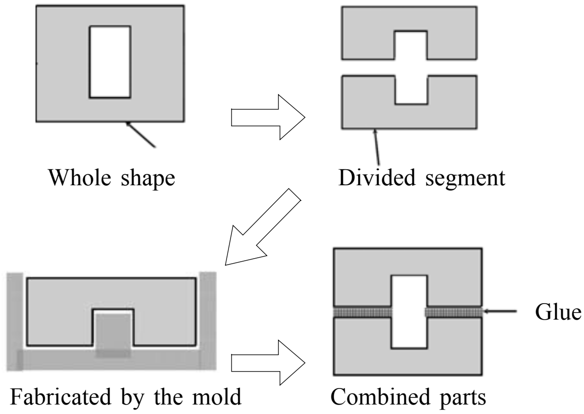



**Figure 11.** Proposed fabrication scheme for FRP parts.

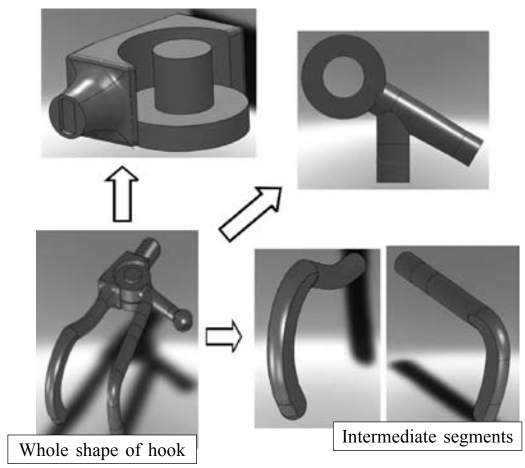
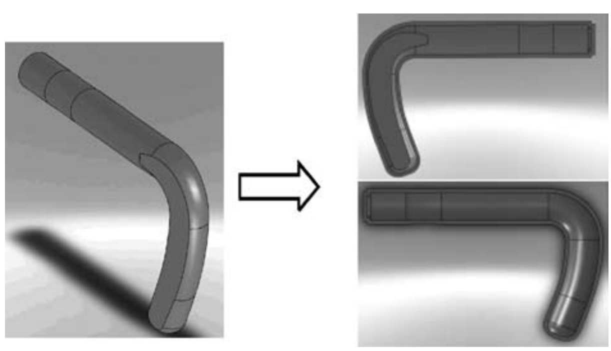



**Figure 12.** Whole shape and intermediate segment parts.



(a) Intermediate segments (b) Final segments

**Figure 13.** Intermediate segment parts of hook's claw and final segment parts.

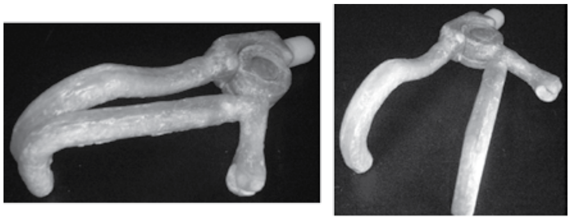


**Figure 14.** Fabricated FRP hook.

## CONCLUSION

In order to enhance the amputees' satisfaction, a framework for tailor-made production of prosthetic hand is proposed with the digital prototyping environment and FRP fabrication scheme which are necessary to realize the framework.

Based on a design experiment of the new device by the proposed framework, it was confirmed that the designed device can be evaluated with realistic situations. Furthermore, proposed fabrication scheme can implement complex and hollow shape FRP parts. These examples show the proposed framework is feasible and promising.

Designing a new device which is conscious to esthetics and usability is an important future work of the research.

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## REFERENCES

Gershenfeld N. 2005. FAB: The Coming Revolution on Your Desktop-From Personal Computers to Personal Fabrication. Basic Books.

Onosato M., N. Suppen, K. Teramoto, K. Iwata. 2001. From a factory to a person: one approach for sustainable and service-oriented manufacturing scheme. pp.66-671. Proceedings of EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing. Tokyo, 11 Dec-15 Dec 2001.

Toffler A. 1984. The Third Wave: The Classic Study of Tomorrow. Bantam.

Tseng, M.M., R.J. Jiao, and C. Wang. 2010. Design for Mass Personalization. Annals of CIRP 59/1: 175-178.

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