Finite Element Analysis and Application of a Flexure Hinge Based Fully Compliant Prosthetic Finger

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Abstract. Prosthetic hand is usually made by rigid body mechanism with ropes and pulleys. Such a hand is not "soft" to patients or to objects to be manipulated by the hand. In this paper, the concept of compliant mechanism is applied to prosthetic finger. The main challenge in designing and constructing such a finger lies in the design of flexure hinge. First, a fully compliant finger with a monolithic structure and flexure hinge was built. Then, finite element analysis for the compliant finger was implemented, and the results were compared with the experimental result to verify the design. Finally, the complaint finger was applied in a prosthetic hand design and worked excellent with the hand.

Keywords: Flexure hinge · Compliant finger · FEA · Prosthetic hand

1 Introduction

Human hand is a crucial tool for perceiving and manipulating objects in the external word [1]. When a hand is lost, there is a high desire to have a replacement, which is called prosthesis. The general function requirement (FR) of a prosthesis hand is of course the same function of a real hand, and the general condition requirement (CR) of a prosthesis hand is that a prosthesis hand should resemble a real hand (CR1) and should not interfere with other organs of the body (CR2).

The conventional prosthetic finger is built with "rigid" parts or links connected through revolute joints such as pins [2–9]. Rigid mechanisms have some disadvantages: (1) additional efforts to assemble parts together. (2) additional efforts to maintain the hand. (3) friction is presented in kinematic joints, resulting in wear in structure, backlash and damping in movement. (4) imprecision in motion and force transfer. Unlike rigid mechanisms, a compliant mechanism obtains at least one of its mobility from the deformation of its flexible members [10], transferring input motion/force to output motion/force.

Figure 1(a) shows a rigid four-bar mechanism, where all the links are rigid and connected through pin joints. In Fig. 1(b), short thin compliant segments (i.e., compliant joints or flexure hinges) are used to form a compliant mechanism. Figure 2(a) shows a fully compliant mechanism, while Fig. 2(b) is a partially compliant mechanism [2].

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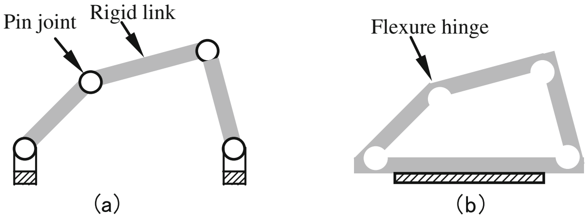


Fig. 1. Four-bar mechanism: (a) four-bar rigid mechanism, (b) four-bar compliant mechanism [2]

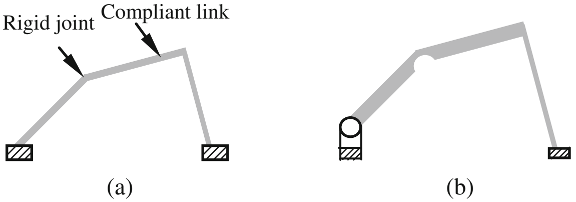


Fig. 2. Four-bar compliant mechanism: (a) four-bar fully compliant mechanism, (b) four-bar partially compliant mechanism [2]

A monolithic structure in the prosthetic finger, where a fully compliant mechanism is used, proves to be preferable due to its softness [11] as well as low cost in manufacturing. To the best of our knowledge, fully compliant mechanisms with a monolithic structure and lumped compliance were only found in mechanical grippers [12, 13] but not in prosthesis hands.

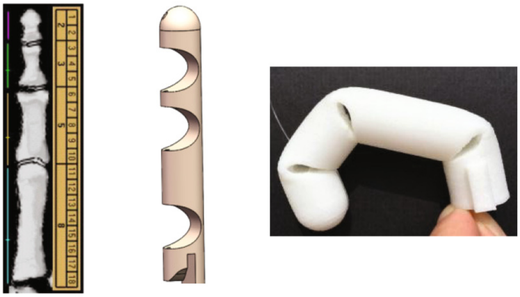
Based on our previous study [14], a compliant finger based on flexure hinges has been established. The main work of the previous paper 'Flexure hinge based fully compliant prosthetic finger' were as follows: (1) the design process for a fully compliant prosthetic finger based on cylinder body flexure hinges was claimed; (2) an evaluation system for the conceptual level design of the finger was developed. In this paper, based on the established flexure hinge model, further study was carried on to simulate on the complaint finger and apply the finger in a prosthetic hand design. The remainder of the paper is organized as follows. In Sect. 2, we outline the design process of a compliant finger with flexure hinges based on human anatomy. In Sect. 3, modeling and analysis of FEM are presented, and the simulation results are compared with the experiment results. The application of the complaint finger in a prosthetic hand prototype is also included. Section 4 gives a conclusion with discussion of future work.

2 Finger Model and Finite Element Analysis

2.1 Compliant Finger Model

For finger modeling, GB-T 10000-1988 and GB-T 16252-1996 standards were referred. The finger measurement data include length of finger, PIP and DIP as well as width of

PIP and DIP. It is necessary to simplify the parameters in the actual modeling process. The simplifying process was as follows: (1) ignore the changes of finger's thickness and take the width of PIP as the finger's width; (2) ignore the size differences among the 5 fingers and set the sizes of five fingers the same. Finally, the modeling data for the finger was: length 72 mm and diameter 17 mm. According to the human anatomy, the adjacent segments length ratio of each finger is about 0.618 [15] and they meet the Fibonacci sequence, see Fig. 3(a). A finger prototype was built based on this rule, and deep ellipse flexure hinge was used in the design, see Fig. 3(b). Figure 3(c) shows the printed finger.



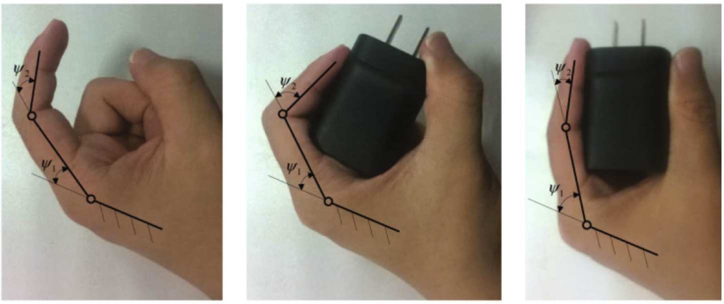
(a) (b) (c)

Fig. 3. Finger's model and prototype: (a) relation of finger segments' length, (b) finger model based on Ergonomics, (c) printed finger with deep elliptic flexure hinge

2.2 Finger Movement Patterns

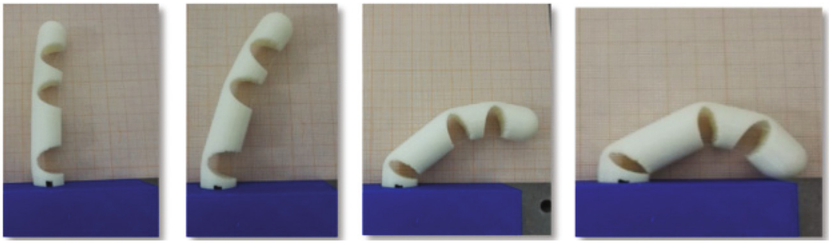
There are two kinds of movement modes when human finger bends, as shown in Fig. 4. Figure 4(a) is free bending movement, where the joint angles $\psi_1$and ψ_2 satisfy $\psi_1:\psi_2 = \text{constant}$. This mode can complete the fingertip grasp and side griping tasks. Figure 4(b) and (c) are finger's enveloped movements, and the enveloping motion is mainly used for adaptive grasping of irregularly shaped objects. For envelope motion, the joint angles ψ_1 and ψ_2 depends on the surface shape of the grasped object. The angle relation in Fig. 4(b) satisfies $\psi_1 < \psi_2$, and Fig. 4(c) satisfies $\psi_1 > \psi_2$ [16].

Like human fingers movement patterns, the compliant finger's bending process can be seen in Fig. 5. Figure 5(a) was the initial state, where the finger was relaxed with slightly curve. After force was applied, the PIP began to bend (Fig. 5(b)). Then the PIP sharply curved and DIP was less bended. Finally, DIP sharply bended. The bending pattern of the compliant finger was similar to that of human finger, which can realize the envelope movement and adaptive grasping.



(a) (b) (c)

Fig. 4. Finger movement patterns: (a) free motion (ψ_1:ψ_2 = constant), (b) enveloping motion ($\psi_1 < \psi_2$), (c) enveloping motion ($\psi_1 > \psi_2$)



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

Fig. 5. Finger bending process: (a) the initial state, (b) PIP begins to bend first, (c) PIP is sharply bended and DIP is less bended, (d) DIP sharply bends

The proposed compliant finger had the following advantages: (1) manufacturing and assembly process simple; (2) good bending performance; (3) low weight; (4) bending pattern similar to human finger.

2.3 FEA and Experiment

As an efficient numerical calculation and analysis method, finite element analysis has become an important method of innovative research and design in engineering field. In this paper, ANSYS 14.0 will be used to simulate the finger model, analyze the stress, strain and displacement in each direction when the finger is bent. Comparing with the experimental results, the simulation results can help with future model optimization.

To decrease the modeling difficultly, finger constraints and load application method need to be simplified in FEM: (1) Assuming that the force point is concentrated at the rope hole of the DIP when the finger is pulley by the rope; (2) Assuming that PIP remains fixed when the finger is bent. Based on the above simplifications, the finite element simulation of finger bending process is as follows:

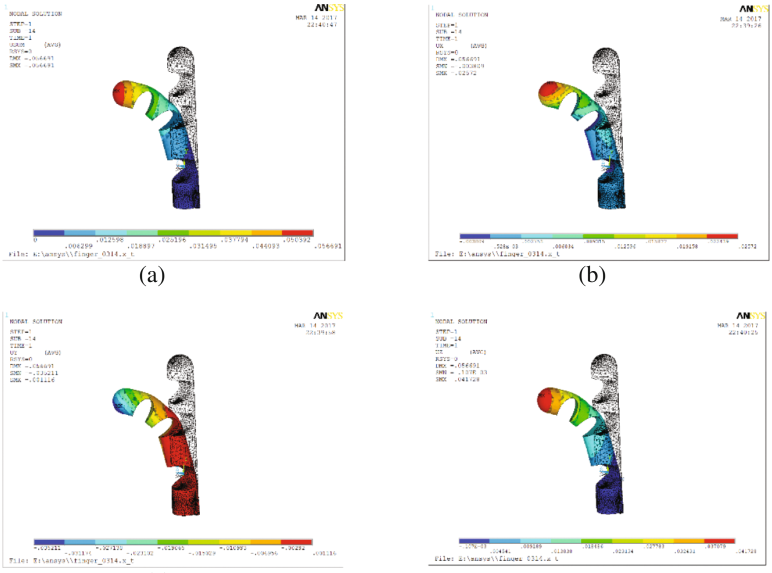
1. Export the .x_t finger model file from Solidworks and then import it into ANSYS to get the geometry model;

2. Add material: Add PolyFlex™ performance parameters to the library and assign it to the finger model;
3. Define contact: set the bottom of the finger to a fully fixed constraint;
4. Mesh: Select the program automatically divide the grid, the grid size is set to 1 mm;
5. Apply force: apply a concentration force at top of DIP. 5 groups of simulation were made with forces of 0.5 N, 1 N, 1.5 N, 2 N, 2.2 N (2.2 N was the maximum force needed to fully bend the finger);
6. Solve and result analysis.

3 Results and Discussions

3.1 FEA and Experiment Results

Figures 6 and 7 show the simulation results of finger displacement and stress under 1 N concentration force. Figure 6 showed the compliant finger's overall displacement and X, Y, Z direction of sub-displacement. According to the direction of the displacement vector and FEM analysis results, DIP produced the largest displacement and PIP produced the smallest displacement. Figure 7 presented the finger stress distribution status, according to the stress analysis results, the maximum stress located in the finger's hinges with stress concentration phenomenon, but still within the safety allowable range.



(a)

(b)

(c)

(d)

Fig. 6. Finite element result of finger's displacement: (a) displacement vector sum, (b) X-component of displacement, (c) Y-component of displacement, (d) Z-component of displacement

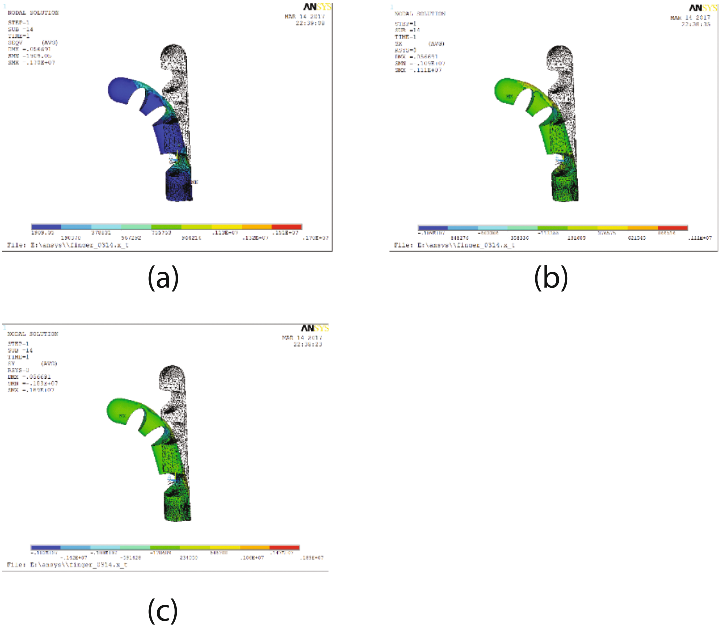


Fig. 7. Finite element result of finger's stress: (a) von Mises Stress, (b) X-component of stress, (c) Y-component of stress

In the finite element analysis, finger displacement can be obtained by changing the applied load. In order to verify the simulation results, the flexure hinge performance experiments were repeated for the compliant finger with 0.5 N, 1 N, 1.5 N, 2 N, and 2.2 N tension force, and five corresponding actual force-displacement relationship can be obtained. The force-displacement curves for experiment and simulation can be obtained by inputting the displacement vectors into Origin, as shown in Fig. 8. It can be seen that there were some errors between experiment and simulation results, and maximum error was 19.68%. But the overall trend was consistent, which verified the accuracy of the simulation model and method.

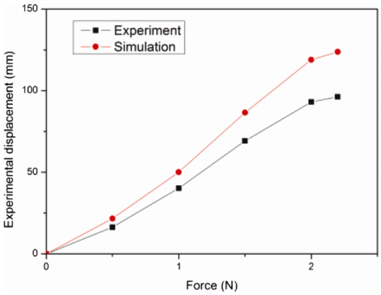


Fig. 8. Displacement of experiment and simulation result

3.2 Compliant Finger in Prosthetic Hand

Compliant finger with flexure hinge has been used in our prosthetic hand, see Fig. 9. The finger has proved to own excellent bending performance and easily manufacturing properties with low light. Adaptive grasping can be realized with this finger, and small, medium or large objects can be easily manipulated with this design.

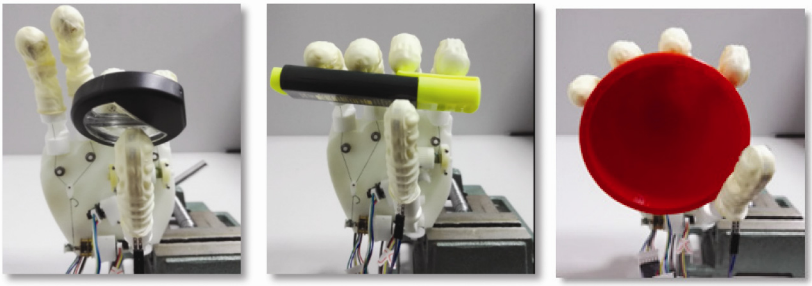


Fig. 9. Grasping experiments of various sizes of objects with complaint finger

4 Conclusion and Future Work

This paper proposed a fully compliant finger with a monolithic structure based on CB flexure hinge. A soft material PolyFlex^{TM} was used to fabricate the model with 3D printing technology. Various flexure hinges were designed, and the bending properties of them were compared. Then an evaluation system was brought up, and bending performance, appearance and mass were considered three evaluation criteria with their own weights. Deep elliptic flexure hinge was found to be the best with the score 4.4 of 5. Later, we applied the conclusion to a prosthetic finger design. FEA and experiment verification were implemented. Then the compliant finger was applied in a prosthetic hand with excellent performance.

Future work will include considering the flexure hinge's rebounding time as an evaluation criteria. Furthermore, FEA simulation can be improved by optimizing the model.

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