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Kinematic Analysis of a Hand Exoskeleton Structure

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Abstract – In this paper, a linkage structure of a hand exoskeleton system for interacting with virtual objects is proposed. Each finger has three degrees of freedom (DOF). Two DOFs come from the finger, and one DOF comes from an actuator. By combining the DOFs from the finger and the exoskeleton, the proposed linkage is able to apply force feedback to the fingertip while enabling the natural finger motion. The performance of the proposed linkage mechanism was verified by simulation.

Keywords – Human-robot interaction, Hand exoskeleton, Force feedback, Kinematic analysis

1. Introduction

Exoskeleton systems have been actively researched recently for physical human-robot interaction (pHRI) systems. The pHRI systems have been spread to many areas, and interaction with virtual reality is one of the most promising applications of the exoskeleton system. By interacting with virtual reality, the user feels improved sense of coexistence and understands the change of environment intuitively.

There have been a lot of researches to develop a wearable interaction system. Due to the complicated skeletal and muscular structure of the hand, however, a small and efficient wearable system has not been exploited yet. Previously developed hand exoskeleton systems can be distinguished into 1) cable-actuated glove systems, 2) cable-actuated frame systems, and 3) exoskeleton systems. The cable actuated glove system allows natural hand movement, but it is difficult to control and deliver the desired force accurately [1]. The cable-actuated frame system has a nice capability to transmit the force more accurately than the cable-actuated glove systems, but the cable mechanism makes the system heavy and bulky [2], [3]. The exoskeleton system can deliver the exact force to finger, but the structure is relatively complicated than the other methods [4], [5]. In this paper, the exoskeleton mechanism is selected since the high priority of the system is put on transmitting the desired force accurately.

The proposed linkage system has three degrees of freedom (DOF) to each finger for natural human-robot interaction. Two DOFs from the Proximal interphalangeal joint (PIP) and the Metacarpophalangeal joint (MCP), and one DOF is from actuating module. By combining the DOFs from the human and the actuator, the structure of hand exoskeleton does not interrupt the natural finger motion, and the generated force by the actuated linkage is exactly delivered to the fingertip.

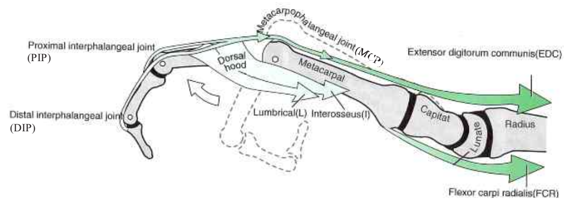

Fig. 1. Anatomy of the finger (Edited from [6])

2. Design of a linkage structure

2.1 Anatomy of the hand

The hand is a complex combination of bones, muscles and ligaments, and the direction and range of joint are determined by them. Understanding of the anatomical structure of the hand should be preceded to design a hand exoskeleton system interacting with the hand naturally. Inspired by the bone structure and the attached point of extensors in Fig. 1, the basic design of the linkage structure in Fig. 2 is established.

2.2 Design of a linkage structure

The structure of linkage should satisfy three DOFs for natural interaction. The movements of intermediate and proximal phalanxes are dominant in range of motion and the distal phalanx is important to force feedback while rarely influencing to range of motion. Thus, the linkage system has two passive DOFs at the PIP and MCP joints to flex independently one DOF from the actuator.

The exoskeleton system consists of supporting parts and delivering part for force feedback. Since the finger is too small to attach an actuator directly, the actuators will be placed to the exoskeleton on the back of the hand. The tips of exoskeleton are connected to the actuator by links. To avoid interference between links of each finger, the links are built above the finger.

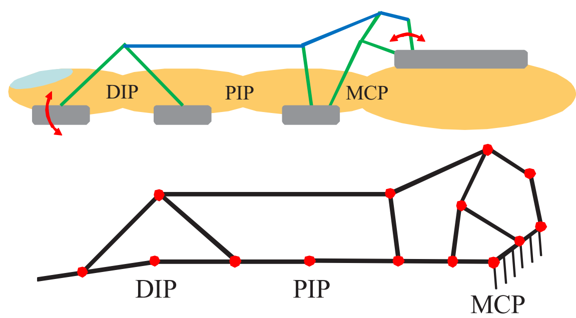

Fig. 2. Proposed design for the linkage structure and corresponding kinematic model

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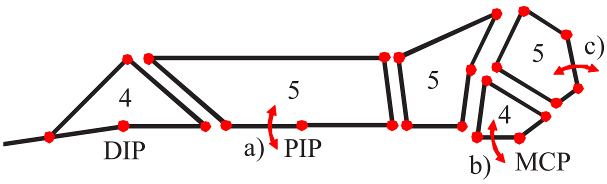

Fig. 3. Subdivided kinematic model of proposed linkage structure

3. Kinematic analysis of the proposed linkage structure

3.1 Kinematic analysis

The proposed linkage structure is kinematically analyzed to check how all links are interacted with the finger and the actuator. The proposed linkage model can be easily analyzed by separating the linkage. It can be subdivided into five sub structures as shown in Fig. 3: two four-bar linkages and three five-bar linkages.

The figure of far right four- and five-bar linkages are determined by actuated angle and MCP joint angle. [c) and b) in Fig. 3] Next five-bar linkage is also decided by angles from previous linkages and five-bar linkage including PIP joint is determined by output angle from previous five-bar linkage and PIP joint angle. [a) in Fig. 3] Finally, figure of the leftmost four-bar linkage is determined according to prevous linkge.

3.2 Performance verification by simulation

The performance of the proposed linkage structure was verified by simulation based on kinematic analysis. The linkage structure of one finger is drawn as shown in Fig. 4, and how the end-effector attached to the fingertip is moved by the actuated linkage is simulated. The areas with slanting lines are the touched parts to the finger. As the actuating link rotates (see pink dots and the corresponding red arrow in Fig. 4), the end-effector part is moved (see green dots and the corresponding red arrows in Fig. 4).

As shown in Fig. 5, the end-effector can rotate from 80° flexion to 30° hyperextension approximately. The flexion is enough to support the normal range of motion of the finger and the hyperextension is used for applying force feedback to the fingertip.

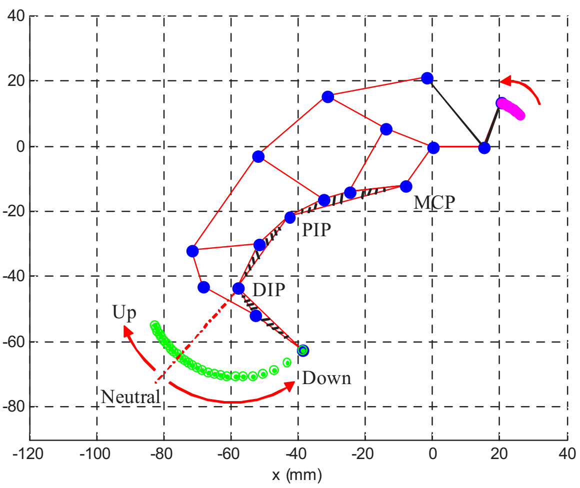

Fig. 4. Proposed design for the linkage structure and corresponding kinematic model

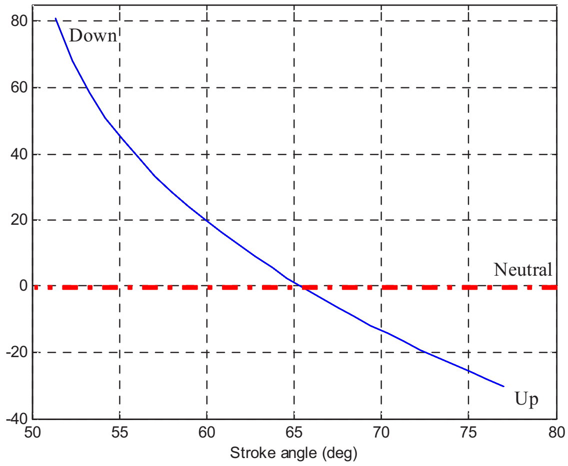

Fig. 5. End-effector angle according to the stroke angle

4. Conclusion

In this paper, a linkage structure for the hand exoskeleton, which aims to interact with virtual objects, was proposed. Three DOFs for each finger is derived from the finger and actuator. Combination of angles from finger and actuator makes natural finger motion. The proposed structure was kinematically analyzed and the performance was verified by simulation.

Acknowledgement

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