

# Development of Low Cost Supernumerary Robotic Fingers as an Assistive Device

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**Abstract**— This paper presents the development of new type of wearable robot namely Supernumerary Robotic Finger (SRF) as an assistive robot for healthy people or people with hemiparesis or hemiplegia. SRF comprises of two manipulators attached in user's wrist. Three flex sensors are utilized to measure the finger bending of the user's finger. The posture of SRF is driven by modified glove sensor. The kinematics of both robotic thumb (RT) and robotic finger (RF) is studied using D-H parameter method and RoboAnalyzer software in order to understand the kinematic behavior of this robot. Each of RT and RF has three degrees of freedom (DOF). The posture of RT and RF is controlled using bending angles of thumb and finger from the user that are read by flex sensor. Based on the experimental results for people with healthy hand, the proposed SRF can assist object manipulation task in grasping, holding, and manipulating an object by using single hand when normally it only can be done by using two hands. From the experimental results on a person with healthy hand, the proposed of SRF can be employed as an assistive device for people with hemiparesis or hemiplegia. This device will enable people with diminished hand function work more independently.

**Keywords**—supernumerary robot; flex sensor; assistive device, kinematics

## I. INTRODUCTION

The research of wearable robot has grown significantly in many years. Commonly, wearable robot is employed to assist human to do special task. The integration of wearable robot with human limb will give benefit for humanity to do Activity of Daily Living (ADL). Two types of commonly wearable robot have been studied and investigated by many researchers both in industry and university. The two commonly wearable robots are prosthesis and exoskeleton. These two types of wearable robots have been widely explored for augmenting human capabilities.

Prosthesis is employed to substitute lost limb of human body such as hand or foot. The research of Prosthesis has grown rapidly from research hand to commercial hand. Many researches in prosthetic hand are aimed to get the prosthesis more lightweight, easy to maintenance, and low cost. Low cost myoelectric prosthetic hands for transradial prosthesis have been studied and developed based on 3D print technology [1-4]. The prosthetic hands show the promising results in object

manipulation task such as grasp and hold an object in different size and shape.

For the second type of wearable robot, exoskeleton is employed in human joints such as finger, wrist, elbow, or knee to enhance the motion of the joints. Many of researchers have developed exoskeleton hand for rehabilitation purpose [5, 6] and assisting human finger joints motion for people with hand diminished function [7]. The developed exoskeleton robot shows promising results in robot-assisted hand rehabilitation.

The third type of wearable robot has been developed as an alternative to prostheses and exoskeletons. The research team from MIT has augmented the human finger with two extra robotic fingers [8-11]. The SRF and human finger work together to perform object manipulation tasks with single hand. The input of SRF come from stretch sensors that are attached on human fingers. Faye Wu [8-9] has successfully investigated natural and implicit control of six DOF supernumerary robotic fingers (SRF) on the remaining healthy hand. The results show that the robot can assist the user/wearer in one handed grasping and manipulation tasks. The team from MIT also developed four DOF supernumerary robotic fingers that comprises of robotic thumb (RT) and robotic finger (RF) as therapeutic device for hemi paretic patient [10-11]. The results show that the developed four DOF of SRF could allow a hemi paretic patient to perform tasks in object manipulation which would previously have been impossible to perform.

The research team form Italy [12-13] also has added human with one extra finger. The extra finger reads the human hand muscle by using electromyography (EMG) sensor. The developed extra finger could enlarge the workspace and manipulation capability of human hand.

In this research, we propose to develop a prototype of low cost SRF that comprises of three DOF robotic thumb and three DOF robotic finger. The robot will be attached on the user/wearer wrist to assist the user in activity of daily living. The robot must work together with human finger to perform bimanual tasks in ADL. The developed SRF will be implemented in the human wrist to assist human/user healthy hand to do "hold and manipulate" tasks. For the initial object grasping, human finger and SRF will work together to grasp an object. SRF will be mainly used to grasp and hold an object while the human finger will be utilized to manipulate an object.

The four objects vary in different shape and size. Four tasks of object manipulation with the assistance of SRF will be tested experimentally as follows

- Grasp, hold the bottle, while another robot open the bottle cap
- Grasp and lift a volley ball using one hand and SRF
- Lift the glass then stirring water with a spoon
- Hold and operate 8 inch tablet

It is easy to perform the bimanual tasks with two hands as shown in Fig. 1. But the previous bimanual four tasks are difficult to perform with single hand. The most challenging in controlling the SRF is how to communicate or coordinate the human finger with the two extra robotic fingers.



Fig. 1. Object manipulation tasks using two hands on ADLs (a) Grasp, hold the bottle, and the other hand open the bottle cap, (b) Grasp and lift a ball using two hands, (c) Lift the glass while another hand stirring water with a spoon, (d) One hand hold a tablet and another hand operate it

## II. HARDWARE DESIGN

### A. Design and Prototyping

3D design of the proposed SRF is developed using SolidWorks CAD Software because it is easy to operate and to use. The final 3D design of SRF is depicted in Fig. 2. SRF consists of two parts, robotic thumb (RT) placed near thumb and robotic finger (RF) placed near index. Both of each of RT and RF have three degree of freedom. Each DOF in RT and RF is actuated using metal gear servo motor. The total length of both RT and RF is 216 mm.

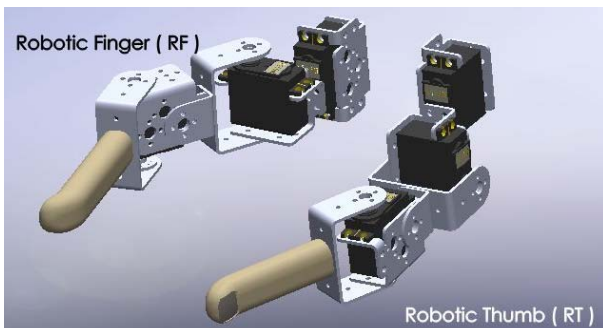


Fig. 2. Supernumerary robotic fingers design in CAD software

RT is designed like the thumb of human finger. It moves like a thumb in human hand and has motion for circumduction, abduction, and flexion. While the RF is designed like four human fingers: index, middle, little, and ring. It moves like one of the human hand fingers and has motion for abduction, and two flexions.

In object manipulation tasks, the SRF must work together with the human fingers. In order to the motion of human fingers can be measured, we use flex sensor 2.2 inch to measure the bending angle of human fingers. Three flex sensors are attached in the glove. We select the glove that can be used to operate smartphone or tablet. In this study, only thumb, index, and middle fingers are selected to drive the RT and RF. In our previous research, this flex sensor could provide the promising result in tele-operated robotic hand [14]. The attachment of three flex sensors is shown in Fig. 3.

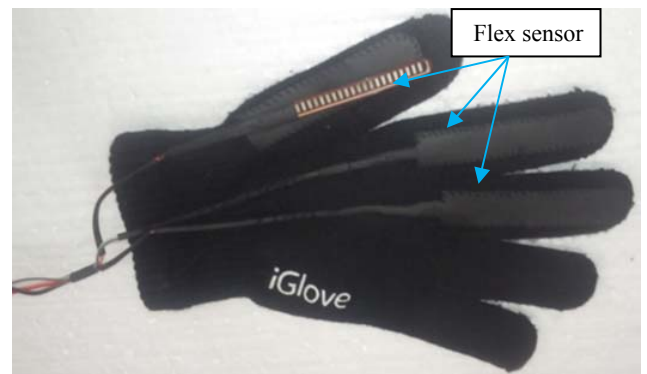


Fig. 3. Modified glove sensor with three flex sensors

The final prototype of SRF that mounted on the right hand wrist can be seen in Fig. 4. The weight of the final SRF is about 650 grams excluding battery. The battery is placed on the body of user to reduce the weight of SRF. Metal servo bracket is selected to join between two servos. The joint between two servos is selected as minimum as possible to reduce the required torque. Microcontroller is attached below wrist of the user. Servo motor Tower Pro MG 995 is chosen because it is cheap enough and can produce torque 9.40 kg-cm at 4.8 V.

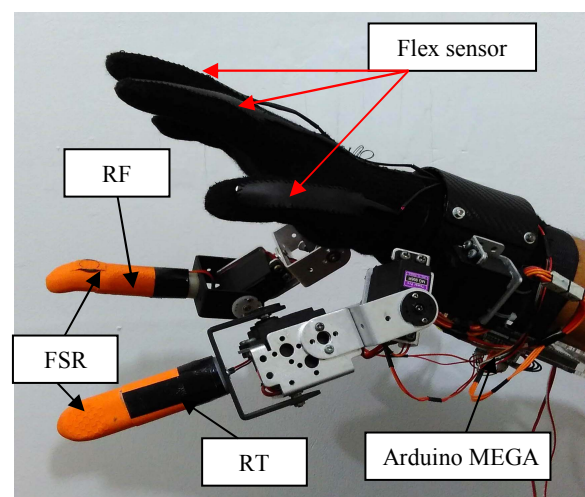


Fig. 4. Prototype of the resulted six DOF SRF

B. RT and RF Kinematics

To study the kinematics of RT and RF, Denavit-Hartenberg (DH) parameter is utilized to model forward kinematics from each joint input to the fingertip position of RT and RF. RoboAnalyzer is employed to verify the results from forward kinematics calculation using D-H parameter. Each of RT and RF has three link and three revolute joints. The general transformation matrix for D-H parameter of can be expressed in equation (1) as follows

$${}^{i-1}T_i = \begin{bmatrix} \cos \theta_i & -\sin \theta_i \cdot \cos \alpha_i & \sin \theta_i \cdot \sin \alpha_i & a_i \cos \theta_i \\ \sin \theta_i & \cos \theta_i \cdot \cos \alpha_i & -\cos \theta_i \cdot \sin \alpha_i & a_i \sin \theta_i \\ 0 & \sin \alpha_i & \cos \alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

For forward kinematics of RT, the coordinate and initial position is shown in Fig. 5. To find the fingertip position, D-H parameter is constructed based on the Fig. 5. The initial position and D-H parameter for RT can be summarized in Table I.

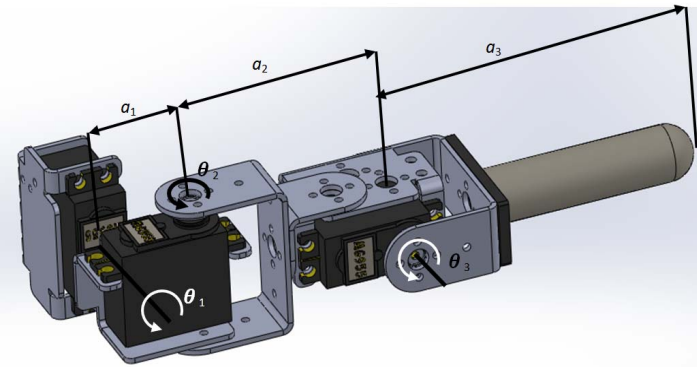


Fig. 5. Initial position of robotic thumb

TABLE I. D-H PARAMETER OF ROBOTIC THUMB

Link	$a_i$ (mm)	$\alpha_i$ (degree)	$d_i$ (mm)	$\theta_i$ (degree)
1	25	90°	0	$\theta_1$
2	75	90°	0	$\theta_2$
3	116	0°	0	$\theta_3$

The relationship of joint angle input in RT with fingertip position in X, Y, and Z axis can be determined as in equation (1), (2), and (3)

$$X = a_1 \cos \theta_1 + a_2 \cos \theta_1 \cos \theta_2 + \dots + a_3 \sin \theta_1 \sin \theta_3 + a_3 \cos \theta_1 \cos \theta_2 \cos \theta_3 \quad (2)$$

$$Y = a_1 \sin \theta_1 + a_2 \sin \theta_1 \cos \theta_2 - \dots + a_3 \cos \theta_1 \sin \theta_3 + a_3 \sin \theta_1 \cos \theta_2 \cos \theta_3 \quad (3)$$

$$Z = a_2 \sin \theta_2 + a_3 \sin \theta_2 \cos \theta_3 \quad (4)$$

The joint angle inputs are  $\theta_1=10^0$ ,  $\theta_2=40^0$ , and  $\theta_3=45^0$ . The computation results from D-H parameter and simulation using RoboAnalyzer software for RT can be seen in Fig. 6. Based on the Fig. 6, the fingertip position of RT shows the same result both on D-H parameter and RoboAnalyzer. The blue graph indicates D-H parameter results and the red one indicates RoboAnalyzer results.

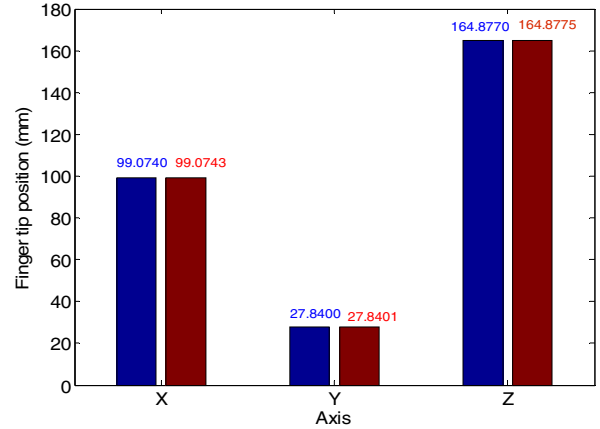


Fig. 6. End effector position of robotic thumb

For forward kinematics of RFT, to find the fingertip position of RF, D-H parameter is constructed based on the Fig. 7. The initial position and the D-H parameter for RF are shown in Table II. The relationship of the joint angle input  $\theta_1$ ,  $\theta_2$ , and  $\theta_3$  with the fingertip position in X, Y, and Z axis can be calculated as expressed in equation (5), (6), and (7).

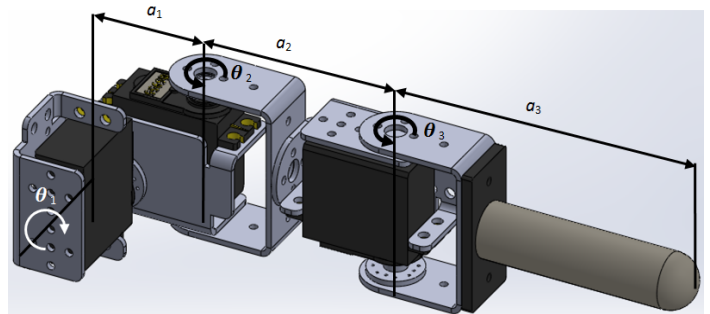


Fig. 7. Initial position of robotic finger

TABLE II. D-H PARAMETER OF ROBOTIC FINGER

Link	$a_i$ (mm)	$\alpha_i$ (degree)	$d_i$ (mm)	$\theta_i$ (degree)
1	25	90°	0	$\theta_1$
2	75	0°	0	$\theta_2$
3	116	0°	0	$\theta_3$

$$X = a_1 \cos \theta_1 + a_2 \cos \theta_1 \cos \theta_2 + \dots + a_3 \cos \theta_1 \cos \theta_2 \cos \theta_3 - a_3 \cos \theta_1 \sin \theta_2 \sin \theta_3 \quad (5)$$

$$Y = a_1 \sin \theta_1 + a_2 \sin \theta_1 \cos \theta_2 + \dots \quad (6)$$

$$a_3 \sin \theta_1 \cos \theta_2 \cos \theta_3 - a_3 \sin \theta_1 \sin \theta_2 \sin \theta_3$$

$$Z = a_2 \sin \theta_3 + a_3 \cos \theta_2 \sin \theta_3 + a_3 \sin \theta_2 \cos \theta_3 \quad (7)$$

The computation results of D-H parameter and RoboAnalyzer can be summarized in Fig. 8. The blue graph denotes D-H parameter results and the red one denotes RoboAnalyzer results. Using same joint angle inputs for RT as shown in previous computation, Fig. 8 shows the same results both for D-H parameter and RoboAnalyzer. Based on the forward kinematics results on RT and RF, it can be concluded that to increase the workspace of grasping, the joint angle  $\theta_3$  must be increased. The joint angle  $\theta_3$  must be large enough if the object that must be grasped is big and long.

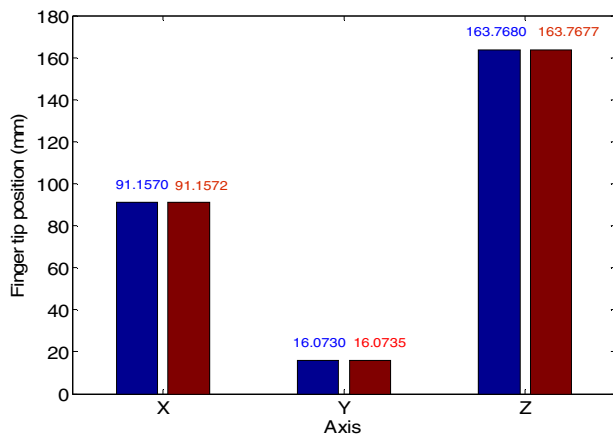


Fig. 8. End effector position of robotic finger

### III. SOFTWARE AND CONTROL STRATEGY

This section will discuss control strategy to regulate the motion of RT and RF in order to collaborate with human fingers. The finger of SRF can be controlled using five signals from the motion of human finger. Based on the previous research [9], RT and RF can be controlled using three finger input signals: index, middle, and ring. The bending angles of the fingers are measured by using three stretch sensors. The research also has shown successfully in developing SRF to assist human to perform bimanual tasks by using one healthy hand assisted by SRF.

In this research, three 2.2 inch flex sensors are employed to measure the bending angle of thumb, index, and, middle. To perform hold and manipulate task in object grasping, the input from thumb bending angle ( $x_1$ ) measured by flex sensor is used to drive the motion of RT, the input from index bending angle ( $x_2$ ) is employed to drive the motion of RF. Finally, the bending angle of middle finger ( $x_3$ ) is utilized to hold the posture of RT and RF when the value of bending angle in the middle finger reaches threshold value. User or wearer can hold the motion of both RF and RT when he/she wants the SRF to grasp and hold the object while his/her fingers are manipulating the object. This scheme can give the user use his/her own fingers posture

to collaborate with SRF in order to perform bimanual tasks in ADL.

The complete system of SRF is depicted in Fig. 9. The bending angles of thumb, index, and middle are measured using three flex sensor that attached in the glove. The measured bending angles are processed by first order low pass filter to reduce noise with high frequency from flex sensor. Arduino MEGA 2560 is used to read three flex sensors and to process the signal. The processed signal is joint angle command that is fed to servo motor and 3D Animation. The joint angle command is processed using linear equation to drive servo motors both in RT and RF. To visualize the forward kinematics and motion grasping of SRF, we develop 3D Animation of SRF that is built in SimMechanics environment. 3D animation of SRF runs on computer with baud rate 115.200 bit/s. The 3D CAD model as shown in Fig. 2 is exported from SolidWorks software to SimMechanics First Generation using SimMechanics Link that available freely on website. To Hold the posture of the SRF when perform object manipulation, it can be done by flexing the middle index. In the future research, haptic system will be incorporated in SRF by using Force Sensitive Resistor (FSR) in order to perform object grasping manipulation with soft object.

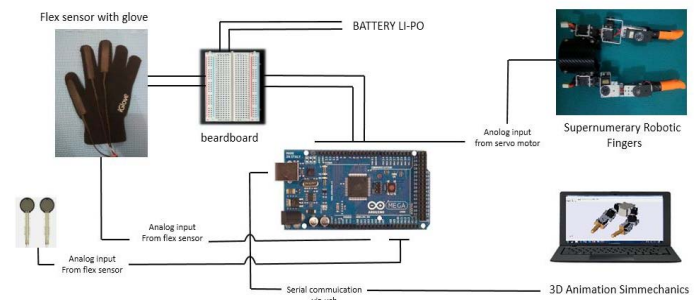


Fig. 9. Hardware system of proposed SRF

Measured thumb bending angle ( $x_1$ ) is employed to control the joint angle in RT. The joint angle command  $\theta_1$ ,  $\theta_2$ , and  $\theta_3$  of RT is processed by gain  $K_i$  as with the input  $x_1$  of shown in equation (8). While the measured index bending angle ( $x_2$ ) is used to control the joint angles in RF by using gain  $K_i$  as expressed in equation 9. The linear equation of (8) and (9) can give the user control the RT and RF independently with using his/her thumb and index. The block diagram of signal processing and control of SRF are embedded into Arduino MEGA using Simulink Support Package for Arduino. The embedded block diagram of SRF is depicted in Fig. 10.

$$\begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} = \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix} [x_1] \quad (8)$$

$$\begin{bmatrix} \theta_4 \\ \theta_5 \\ \theta_6 \end{bmatrix} = \begin{bmatrix} K_4 \\ K_5 \\ K_6 \end{bmatrix} [x_2] \quad (9)$$

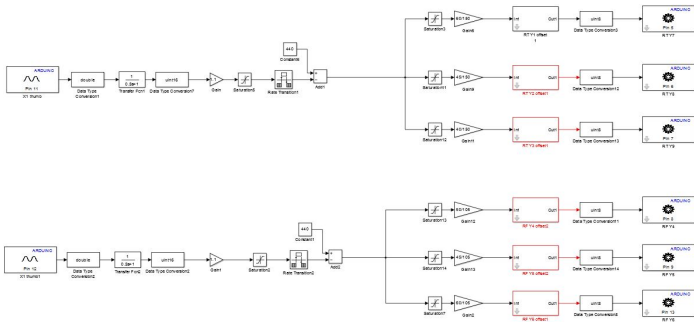


Fig. 10. Embedded control in SRF

IV. EXPERIMENTAL WORK AND RESULTS

The built prototype of SRF are tested experimentally to perform four bimanual object grasping tasks as mentioned in section I. The four tasks commonly will be difficult to perform with single hand. In this test, the four object grasping tasks are conducted by one person with healthy and normal hand. The SRF is mounted on the wrist of healthy right hand.

In the first object grasping manipulation task, the successful rate of this task reaches 50 %. RT and RF reach and grasp the object before the human fingers. The posture of SRF can be held when lifting the bottle. When the human fingers try to open the cap of the bottle, the bottle slips and goes down.

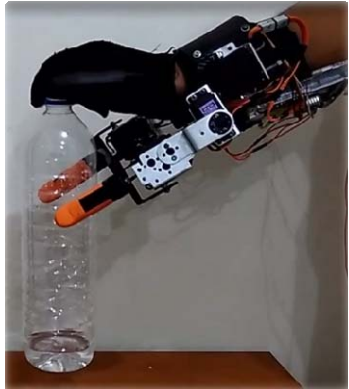
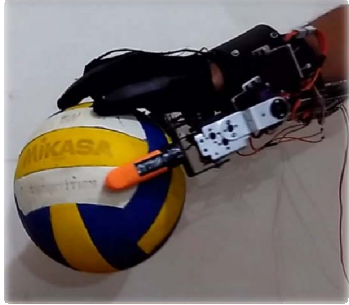
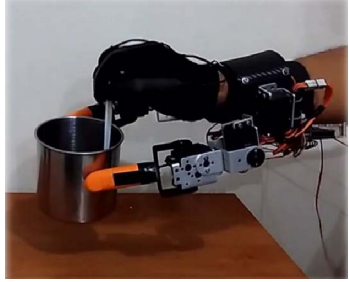

For the second task, the SRF can assist human finger to grasp, lift, and hold a large volleyball with the accuracy reaches 75 %. The difficulty of this task is to hold the object when the middle finger almost reaches volleyball surface.

In the third task, the object grasping task difficulty is almost the same with the first task. The SRF must reach the surface of object first and lift the glass, then following by human finger takes a spoon and stirs the water. The common failure of this task is similar with the first task.

For the last task, it is easier to operate the 8 inch tablet using the human index finger while RT and RF hold the tablet. The grasping accuracy for this task can reach 100 %. The results of four object manipulation tasks can be summarized in Table III and Table IV.

The highest grasping accuracy can be achieved for grasping and manipulating object while the part of object is not moving. When the human finger reaches surface of object before the SRF, it will be difficult to control hold and manipulate tasks. The coordination of human fingers and the SRF need more training in order to it can grasp successfully object. The proposed control strategy does not guarantee the fingertips of both RT and RF will always contact with the object. SRF sometimes fails to grasp the object. In this test, it cannot be implemented in object which has soft structure because the haptic algorithm has not been developed yet.

TABLE III. OBJECT MANIPULATION RESULTS

Object Manipulation	Result
Hold the bottle and open the bottle cap	
Grasp and lift a volley ball	
Lift and hold the glass while stirring with a spoon	
Hold and operate 8" tablet	

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TABLE IV. EXPERIMENTAL WORK FOR OBJECT MANIPULATION RESULTS

Objects Manipulation	Trial	Success	Percentage of Success
Grasp, hold the bottle, and open the bottle cap	8	4	50%
Grasp and lift a volley ball	8	6	75%
Lift and hold the glass while stirring with a spoon	8	5	62.5%
Hold and operate 8" tablet	8	8	100%

## V. CONCLUSION AND FUTURE RESEARCH

In this research, the proposed of SRF successfully assists four tasks in object manipulation. With the assistance of this robot, the user/wearer can perform object manipulation tasks in ADL with single hand. Based on the experimental results, object manipulation tasks for "hold and operate 8 inch tablet" get the highest accuracy of all object manipulation tasks. Object manipulation task for "Grasp, hold the bottle, and open the bottle cap" get the lowest accuracy because it is difficult to coordinate the motion of human finger with the SRF. The proposed control scheme using three flex sensors can give the user use his/her own fingers posture to collaborate with SRF in order to perform bimanual tasks in ADL.

For healthy people, this new type of wearable robot can assist user for manipulating object while it is difficult to do using single hand. This robot can also increase the work more productively in ADL. Based on the experimental works on the person with healthy hand, SRF can be implemented for people with diminished hand function such as people with hemiplegia or hemiparesis. The robot is placed on the healthy remaining hand of people with hemiplegia or hemiparesis. This robot will enable people with diminished hand function work more independently without the assistance of another person.

For controlling the SFR more intuitive and dexterous, the posture of SFR will be controlled using artificial neural network (ANN) in the future research. The type of tasks in object manipulation will be added and explored in different shape and size of object. The mechanical and electrical design will be optimized in order to reduce the weight and size of the robot. Haptic system will be developed and incorporated for grasping soft object.

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