# Design of Multi-Grip Patterns Prosthetic Hand With Single Actuator

Panipat Wattanasiri, Pairat Tangpornprasert, and Chanyaphan Virulsri

***Abstract*— In hand prosthesis design, the important characteristics that directly affect hand performance are the ability to grasp various type of objects, grasping force that provides stability for holding objects, and cosmetic appearance that resembles the human hand. The presence of all of these characteristics is currently a challenging task for prosthesis design. This paper presents the design of a five-fingered prosthetic hand that has multiple grip patterns with the use of only one actuator in order to perform important tasks in daily life and which achieves significant grip force from the large size of the actuator. The prosthetic hand is capable of performing one neutral position and two grip patterns that are dominant in daily life tasks. Different move patterns are achieved through the use of multiple sets of rigid four-bar linkages which provide different motions to fingers and thumb when the mechanism is actuated to the opposite direction. This paper describes the design of the prosthesis, mechanism synthesis, and achieved performance. The prosthetic hand developed here, having one degree of freedom, is an improvement from conventional single-actuator hands, which can only perform open/close motion. Whereas achieved grip force (34.5 N) is higher than multiple-actuator hands in market. Thus, this design could be an alternative answer of improvement between conventional and multiple degree of freedom prosthetic hands.**

***Index Terms*— Artificial limbs, dwell mechanism, prosthetic hand, prosthetics, single actuator, terminal device, upper limb prosthesis.**

## I. Introduction

THE loss of hand or upper limb extremities would cause hardship for any individual in two major aspects, one of which is the loss of ability to grasp objects in activities of daily living (ADLs). Another is the loss of cosmetic appearance to let individuals blend in with society, thus causing anxiety for amputees. Prostheses have always aimed to answer these two problems to provide better experience for users. For prosthetic hand function to be adequate for ADLs usage, important topics such as grip patterns and grip forces are usually critical in many designs.

There are 2 types of power sources available for prosthetic hands, which are body-powered and externally powered. Body-powered prosthetic hands operated by body movement through wires or cables, often have one degree of freedom with only a single grip pattern. To achieve desired functions, they often have a non-human shape, such as split hook, and prioritize functionality over cosmetic appearance [1].

The grip force of body-powered type is enough for ADLs, but requires exerted force from user to operate either continuously in voluntary close condition or momentary in voluntary open condition. Moreover, some designs can also switch between both conditions to support user's needs. There is a body-powered prosthetic research that aims to increase the grip force while reduce amount of exerted force from user with the use of alternate transmission system, such as hydraulics [2]. However, body-powered prosthetics still have single grip pattern due to the limited amount of input body movement from users.

On the other hand, externally-powered prosthetic hands operated by received muscle signals from the user and actuated with a wide range of actuators, such as electrical motor, pneumatic [3], hydraulics [4], shape memory alloy [5]–[7], or ultrasonic motor [8], [9] often have multiple degrees of freedom and are capable of performing various grip patterns. For commercial prosthetic hands, many use electricity as power source with DC motors as actuators, as they are widely used in many applications and have high reliability. Conventional electrical hands use a single motor to open/close hand like a gripper [1], whereas other recent designs use multiple motors as actuators which could perform multiple grip patterns while retaining a human-like shape, thus answering the problem of cosmetic appearance.

Many prosthetic hands have implemented different designs to improve functions in both grip patterns and grip force. Commercially available, the iLimb hand from touch bionics and Bebionic hand from RSLSteeper use 5 actuators which are individually coupled with each digit to provide a wide range of grip patterns [10], [11]. The Michelangelo hand by Ottobock uses only 2 actuators: one for thumb adduction/abduction and another for open/close grasp [12]. For prosthetic hand outside market, many improve function with the use of various transmissions and mechanisms. The SSSA-MyHand [13] uses 3 actuators and the Geneva drive

Manuscript received July 8, 2017; revised January 30, 2018 and March 19, 2018; accepted April 12, 2018. Date of publication April 23, 2018; date of current version June 6, 2018. This work was supported by Chulalongkorn University through Chulalongkorn Academic Advancement into its 2nd Century Project (Smart Medical Device). *(Corresponding author: Pairat Tangpornprasert.)*

The authors are with the Center of Excellence for Prosthetic and Orthopedic Implant, Mechanical Engineering Department, Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand (e-mail: panipat.w@gmail.com; pairat.t@chula.ac.th; chanyaphan.v@gmail.com).

Digital Object Identifier 10.1109/TNSRE.2018.2829152

transmission to perform various grip patterns, the Pisa/IIT SoftHand [14], [15] uses adaptive synergies design and friction based transmission in the underactuated hand design, whereas the SmartHand [16], DLR hand [17]–[19], MANUS hand [20], and TUAT/Karlsruhe humanoid hand [21] use differential mechanisms to reduce the number of actuators. There are other methods, such as continuum differential mechanism [22], spring-like mechanism [23]–[25], or compliant structure [26] that have been implemented to improve grip ability and reduce the number of actuators. Some research attempt to improve individually actuated digits by reducing weight and have released their designs to the public [27]. Recent studies have shown that with a higher number of actuators used inside a single hand, the number of grip patterns would be increased, whereas grip force tends to decrease due to the smaller size of actuators that have to be placed within limited space [12].

Considering the above concerns and other various designs, this research proposes a prosthetic hand design aiming for adequate grip patterns and grip force. We developed a single actuator prosthetic hand capable of performing multiple grip patterns more than those of conventional single actuator prosthetic hand, whereas significant grip force higher than many multiple-actuator prosthetic designs is achieved. Multiple sets of four-bar mechanisms are devised to provide different hand patterns at difference actuator positions. With this approach, the hand can also have a human-like shape providing a satisfactory cosmetic appearance to the prosthesis.

## II. Design Specifications & Conceptual Design

### A. Grasps Clarification & Usage

To clarify hand grasp types, there are various ways developed through time with the use of multiple parameters such as grasp function [28], fingers motion [29], [30], or skeleton position [31]. In this research, we use classic grasp clarification, which has been used for a long time in the prosthesis field. Keller et al. adapted six grasp patterns based on functionality (Tripod, Tip, Lateral, Cylindrical, Spherical, and Hook) [28]. These patterns could be categorized into smaller group by describing tripod, tip, and lateral grip as precision grips, whereas spherical and cylindrical grip are described as power grips [29]. Iberall simplified these patterns by considering which parts of the hand that the fingers and thumb tip opposed [30]. Precision grip is when finger tips oppose the thumb tip, whereas a power grip is when finger tips oppose the palm, and a lateral grip is when the thumb tip opposes the side of the index finger. To achieve the patterns above, fingers and thumb must have the ability to flex separately as fingers need to oppose both thumb and palm; thumb orientation should be rotatable to both opposed and lateral positions with palm.

Usage of each grasp type depends on the activities of users, such as household activities or machine shop activities [32]. We design prosthetic hand's grasp functions for the purpose of household daily life activities (ADLs) usage, whereas precision grip, power grip, and lateral grip usage are 35 percent, 35 percent, and 20 percent respectively [33], [34]. The prosthetic hand is driven by one actuator and has one degree of freedom. Precision grip and power grip are chosen as desired hand patterns due to their significantly usage (70 percent in ADLs) and both patterns have identical thumb orientation (opposed to palm). Open hand position, which is used around 40 percent during daytime to support small or flat objects [32], is also chosen to be the intermediate position between both grips. Lateral grip is not selected as one of the objective hand patterns because this grip requires thumb orientation to be perpendicular to the index finger, thus demanding a higher degree of freedom and complexity from the design to justify achieved functions.

### B. Grip Force & Speed

In prosthetic hand designs, increases in the number of actuators usually lead to multiple grip patterns and decreased grip force. This is due to the nature of limited space and weight requirement of prosthetics. A study has shown that a pinch force of 68 N is enough to be used in ADLs [1], but many commercial hands with multiple actuators could achieve less than the mentioned value, varying from 10.8 N to 29.5 N [12].

We propose a design using a single actuator driving through a rigid mechanism that could produce multiple grip patterns. With this approach, the actuator size could be expanded to fit within the limited space of a prosthetic and could efficiently provide more torque than multiple smaller actuators with equivalent space. This method could improve prosthetic grip force to be more than that of many available commercial multiple-actuator hands and would still be able to perform multiple grip patterns that are considered major parts of ADLs.

Another important function of prosthetic hand is grasp speed, which needs to be quick enough to operate smoothly by the user. For everyday pick-and-place tasks, finger flexion speed has been found to be between 170 to 200 degree/second [1]. But for commercial hands, this value is between 60 – 103 degree/second [12]. Finger flexion speed could also be expressed in term of required time for hand to be closed. In this research, hand closing time of 1.0 – 1.5 seconds which is equivalent to commercial hands flexion speed is chosen to be one of the design inputs for the prosthetic hand.

### C. Weight, Size, and Hand Autonomy

Prosthetic weight, size, and hand autonomy are other design specifications that have crucial role on prosthetic usages. These specifications have less impact on hand function than grasp type, force, and speed, but nevertheless need to be addressed to prevent impractical design issue and provide further development possibility after the mechanism design is implemented.

Firstly, for prosthetic weight, human hand average weight is 400 g, whereas prosthetic hand weights are varying between 350 to 615 g and 350 to 2,200 g in commercial and research-based hands, respectively [12]. These weights are usually perceived from users as too heavy because, unlike natural human hand, prosthetic socket applies force onto muscle instead of skeleton. Moreover, the suspending prosthetic weight can easily cause discomfort to user during usage hours [1]. This research aims to develop a design as light as possible with the use of available components and manufacturing method.


Fig. 1. Hand grip patterns. (a) Precision grip, four fingers and thumb are flex simultaneously, (b) Power grip, thumb flexion is delayed to allow fingers to flex first.

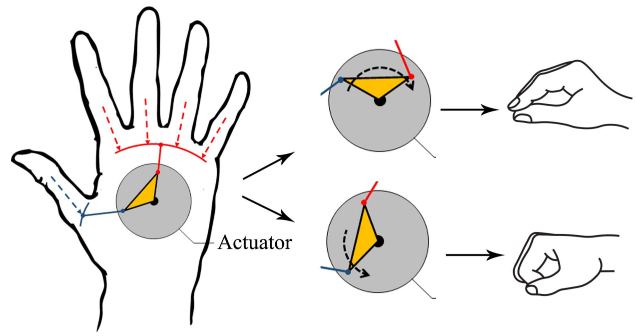


Fig. 2. Prosthetic hand mechanism concept. An actuator is placed within palm. The mechanism connects to four fingers and separately to thumb. Precision grip and power grip would occur when mechanism is actuated in different directions.

Secondly, prosthetic size normally conforms to users' anatomy. Thais are the prospect users of this design, thus the average Thai male hand size is selected as the reference size of the hand [35]. The average length from middle fingertip to wrist, hand width, and hand circumference are 195, 98, and 207 mm, respectively.

Lastly, for prosthetic hand autonomy, the hand electrical circuit and controller should be self-contained and capable of standalone operation. The design has to provide space in wrist section to accommodate standalone electronic board and battery in future development.

All of these design inputs are important for development of practical prosthetic hand. However, the main objective of this research is to present a new concept of transmission mechanism that improves grasp function while minimizes number of actuators. The prosthetic weight, size, and hand autonomy aspects are aimed and designed to be as practical as possible, while some lack of these aspects could be improved further in the future development.

### D. Hand Mechanism Concept

For precision grip and power grip, thumb closure has an important role in both patterns. If fingers and thumb flex simultaneously and the tips touch with each other, precision grip occurs as in Fig. 1a. In contrast, if thumb closure is delayed, which allow fingers to flex in first then followed by thumb flexion, power grip occurs as in Fig. 1b. The thumb tip would touch the back side of the index and middle fingers to provide more grip stability.

In this research, we propose a new concept of mechanism that uses the ability to actuate in both directions of electrical motor to provide different hand motion outputs. An actuator is placed inside the hand with rotational axis perpendicular to the palm, and this mechanism connects to four fingers and separately to thumb as in Fig. 2. Precision grip occurs when the mechanism is actuated in one direction and power grip occurs when the mechanism is actuated in the opposite direction. With this design, the prosthetic hand would be able to perform a precision grip, power grip, and open hand position (neutral position) with only a single actuator, unlike conventional single actuator prosthetic hand that has only simple open/close motion.

## III. Prosthetic Hand Design

### A. Fingers & Thumb Mechanism Design

Human fingers have three joints, whereas thumb has two joints outside the palm. This allows fingers to curl and wrap around objects with stability. In prosthetic hands design, fingers with three separate rigid linkages like human fingers may not have satisfying functions that justify with the complexity. Fewer joints and less degrees of freedom are more practical and feasible. One degree of freedom prosthetic fingers with two joints coupled together have been used for a long time because they could provide adequate function and cosmetic appearance. For example, the Bebionic hand uses four-bar linkage with a linear motion plastic rod connected to distal link, and the iLimb hand uses two rigid linkages connected by a tendon driven through bearing surface [12].

There are certain similarities in finger mechanisms found throughout many prosthetic hands. Joseph T. Belter measured the angle ratio between the Metacarpophalangeal joint (MCP) and the Proximal interphalangeal joint (PIP) of commercial prosthetic fingers to be between 1.09 and 1.27 [12]. This research designs one degree of freedom prosthetic fingers and thumb with MCP and PIP as the rotating joint. Distal interphalangeal joint (DIP) is fixed with intermediate phalange at 40 degree angle. The MCP/PIP angle ratio is 1.15, which allows fingers and thumb to perform both precision and power grips. Each finger and thumb contains 3 rigid links in the form of four-bar linkage with an additional drive link connected from distal link to move on a prismatic joint as in Fig. 3. Prismatic joint position of fingers and thumb are used as indicators of each grasp pattern. That is, fingers and thumb prismatic joints would be at F0 and T0 positions when in the open hand position as in Fig. 3a, at the F1 and T1 positions for precision grip position as in Fig. 3b, and at the F2 and T2 positions for open hand position as in Fig. 3c, respectively. All four fingers (index, middle, ring, and little finger) have identical dimensions for the purpose of less design complexity. Index and middle finger tips would touch the thumb tip if both fingers and thumb are flexed simultaneously as in Fig. 4a, whereas the finger tips would touch the inside of the palm if fingers flexion occur earlier than thumb flexion as in Fig. 4b.

### B. Hand Mechanism Design

This research proposes a design of hand mechanism which could provide different motions of fingers and thumb when actuated in each direction, with a mechanism comprised of 2 sets of rigid linkages separately connected to four fingers

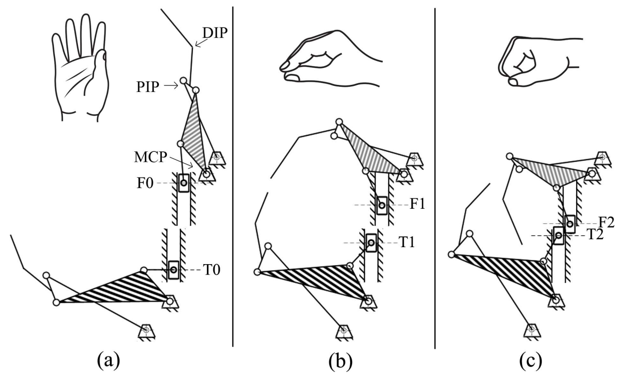


Fig. 3. Kinematic diagram of fingers and thumb mechanism. (a) Open hand position, (b) Precision grip position, (c) Power grip position.

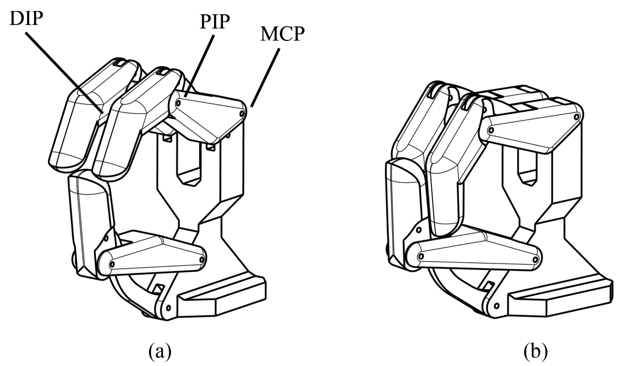


Fig. 4. Index, middle, and thumb mechanisms. Each finger is a four-bar linkage which has PIP and MCP as rotating joints. (a) Precision grip position, (b) Power grip position.

and thumb. The first set of mechanisms connected to all four fingers provides simultaneous motion for the four fingers. This is a crank-slider mechanism which has identical output profiles for both directions of actuation. The second set of mechanisms connected to the thumb is a dwell mechanism inspired by single-dwell six-bar mechanism [36] which uses coupler point of four-bar mechanism as the moving path of a drive link connected to the thumb as in Fig. 5. This dwell mechanism output motion is similar to a camshaft but consists of only rigid linkages and joints which have less wear from friction than camshaft design.

From Fig. 5, Line F0, F1, and F2 represent finger prismatic joint positions corresponding to each grip pattern, which is open hand, precision grip, and power grip, respectively, whereas line T0, T1, and T2 represent thumb prismatic joint positions of each grip pattern in the same manner. These lines are objective positions when the mechanism performs each grip pattern; the mechanism would start from F0 and T0 positions then move simultaneously to F1 and T1 positions to perform a precision grip or move to F2 and T2 positions with delayed thumb motion to perform a power grip.

### C. Hand Mechanism Synthesis

After the mechanism concept is decided, mechanism synthesis process is required to determine the dimensions of mechanism with desired motion. This synthesis process starts

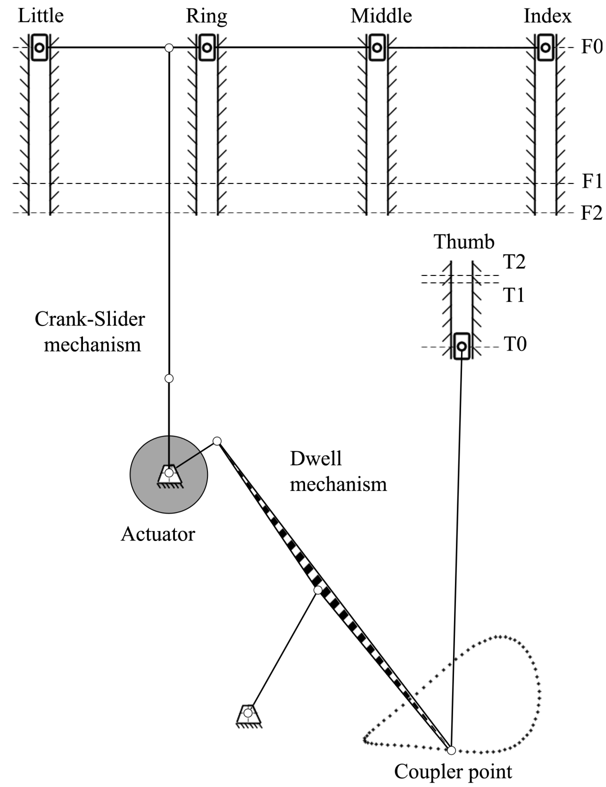


Fig. 5. Hand mechanism consists of two major mechanisms: crank-slider mechanism connected to four fingers and dwell four-bar mechanism connected to thumb. Coupler point of thumb mechanism is used to provide different motions when moved along opposite directions.

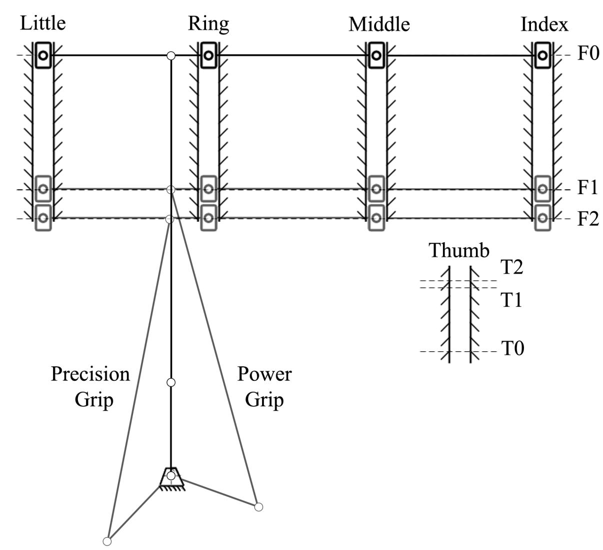


Fig. 6. Fingers mechanism connected to four fingers. This mechanism provides identical motions for each actuated direction. Line F0, F1, and F2 are positions of prismatic joint of mechanism at each grip pattern.

with the first set of mechanisms connected to four fingers which must have identical output motion for both actuated directions; this type of motion could be achieved by a simple crank-slider mechanism. The mechanism which could fit into hand space and have high mechanical advantage is designed as in Fig. 6.

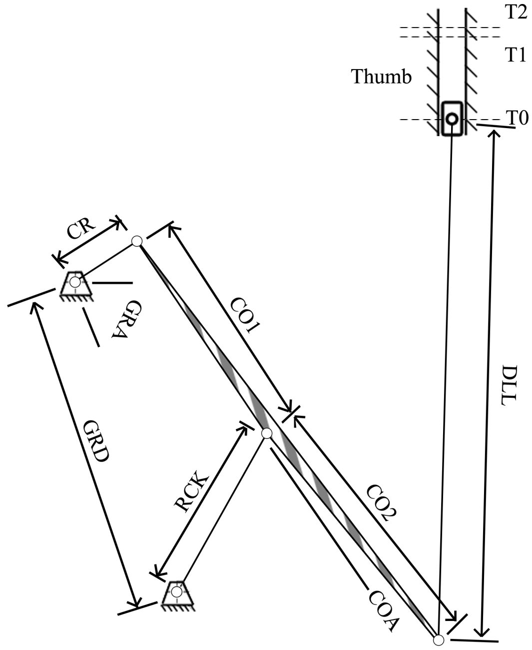


Fig. 7. Design parameters such as link lengths, positions, and angles are defined on thumb mechanism.

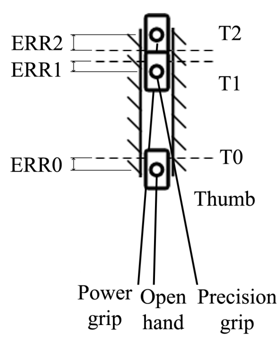


Fig. 8. Position error is the distance between desired and actual prismatic joint position at each grip pattern.

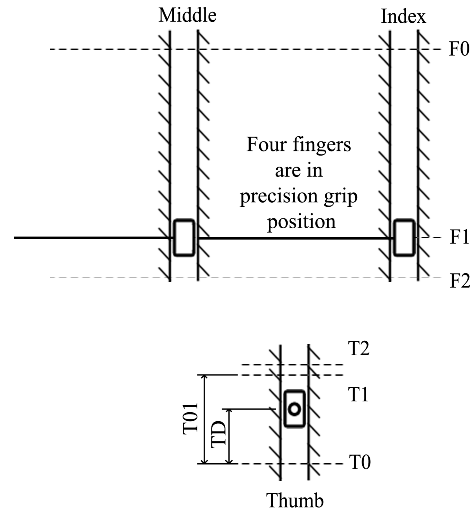


Fig. 9. Thumb delay value is computed from thumb travel distance (TD) divided by T0 to T1 distance (T01) when the fingers mechanism reaches the F1 position during power grip execution.

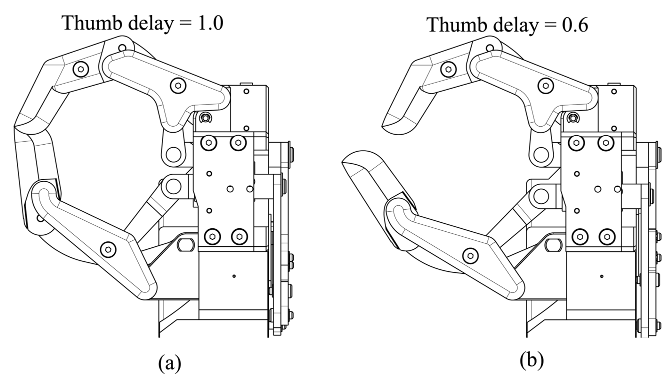


Fig. 10. Thumb delay value. (a) Value of 1.0 - finger tips touch with thumb tip, (b) Value of 0.6 provides a gap for fingers to flex in to perform a power grip.

The second set of mechanisms is the thumb mechanism which uses coupler point of four-bar linkage mechanism to achieve different outputs for each actuated direction. The dimensions of this mechanism must be computed to achieve desired performance. In this computation process, design parameters which have important effect on mechanism motions are required to be computed for the best possible outcome. These parameters, such as linkage lengths, positions, and angles are defined as in Fig. 7. MATLAB Computational program was used to compute these design parameters under constraints to achieve optimum objective function value.

Objective functions which are target parameters of this synthesis are defined into 2 parameters that reflect important characteristics of the mechanism. First, *PositionError,* represents the accuracy of the mechanism when each grip pattern is performed. This parameter is defined by the distance between computed position of thumb's prismatic joint and desired position (T0, T1, and T2) at each grip pattern as shown in Fig. 8. Position error is computed by root mean square of error distance of each grip pattern (*ERR0*, *ERR1*, and *ERR2*) as in (1).

$$PositionError = \sqrt{ERR0^2 + ERR1^2 + ERR2^2} \quad (1)$$

The second objective function is *ThumbDelay,* which represents the delay in motion of the thumb to let finger flexion to occur first without contact between thumb and fingers during power grip pattern. This parameter is defined by the travel distance of thumb mechanism at instance when fingers mechanism reaches F1 position during power grip execution. In this instance, if the thumb mechanism reaches the T1 position, both fingers and thumb would touch each other, thus it would be impossible to perform power grip. As shown in Fig. 9, the thumb delay value is computed by dividing traveled distance (*TD*) by total distance (*T01*) as in (2). With this definition, a thumb delay value of 1.0 means that fingers and thumb tips would collide with each other and perform a precision grip instead of a power grip as in Fig. 10a, whereas a value of 0.6 means that the thumb would dwell and let fingers flex in first, as in Fig. 10b.

$$ThumbDelay = \frac{TD}{T01} \quad (2)$$

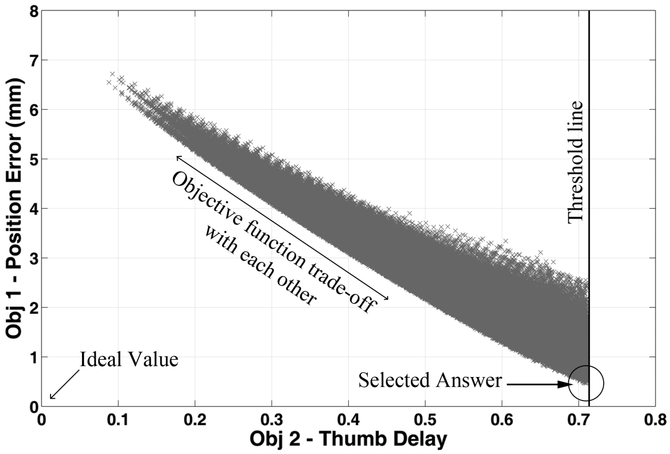


Fig. 11. Mechanism synthesis results by comparing the objective functions of each mechanism. Both objective functions appear to trade-off with each other. Answers with thumb delay values more than the threshold line were cut off.

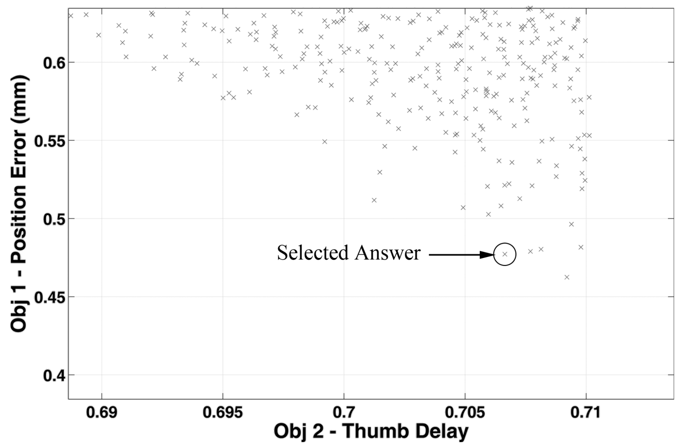


Fig. 12. The answer with the second least position error value is chosen because it has a significantly lower thumb delay value than the first answer.

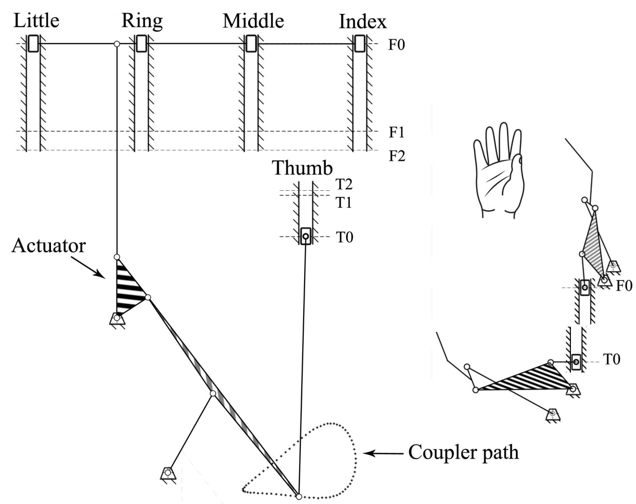


Fig. 13. Hand mechanism at open hand position. Actuator position is between precision grip and power grip.

Finally, constraints such as hand space and mechanical advantage were used in mechanism synthesis in order to obtain suitable mechanism size and force transmission ratio.

With all parameters defined, the computational process starts with the selection of design parameters from a range of possible solutions; and mechanisms which pass constraints are selected and computed for both objective functions of each mechanism. A range of parameters with the best results is then chosen to be used in next iteration with higher resolution. The result of this iteration process is displayed by comparing two objective functions of each mechanism as in Fig. 11. The ideal answer of these mechanisms is for both objective functions to be zeroes, but the results show that it is likely to be traded-off with each other. When comparing between both objective functions, position error would have a bigger impact on the design than thumb delay because the hand would not be able to perform both desired grip patterns at all if the mechanism cannot travel close to desired position. On the other hand, the hand could perform power grip with a thumb delay value of less than the certain threshold; and further lower values would only effect the gap between thumb and fingers during power grip pattern. Thus, we choose to cut off all other results with thumb delay value more than the threshold of 0.71; this is the largest value that the hand could perform a power grip without collision. The answer with second least position error value is chosen because it has a significantly lower thumb delay value compared to other answers as in Fig. 12. with a position error of 0.47 mm and thumb delay value of 0.707.

The selected thumb mechanism is combined with the fingers mechanism to become the hand mechanism that is connected to all fingers and thumb as in Fig. 13. The coupler path of this mechanism could provide different thumb motions when moved along different paths with each actuated direction. For precision grip, the mechanism is actuated to the clockwise direction. Both sets of mechanisms then move fingers and thumb linkages toward the F1 and T1 positions simultaneously, in which the index, middle and thumb tips would touch each other, as in Fig. 14. For a power grip, the mechanism is actuated to the opposite direction of precision grip (counter-clockwise). The fingers mechanism motion is identical to precision grip, whereas the thumb mechanism motion is different because the coupler point is moved along a different path with longer distance, thus causing delayed motion to thumb closure and allowing fingers to flex in first. Fingers prismatic joint is moved toward the F2 position, then the thumb prismatic joint is moved toward the T2 position in which the thumb tip would touch with the back of the index and middle fingers, as in Fig. 15.

### *D. Actuator, Transmission, and Electrical Components Selection*

To reduce manufacturing complexity, off-the-shelf components such as electrical motor and gearbox were chosen. Torque and speed of these components have to be

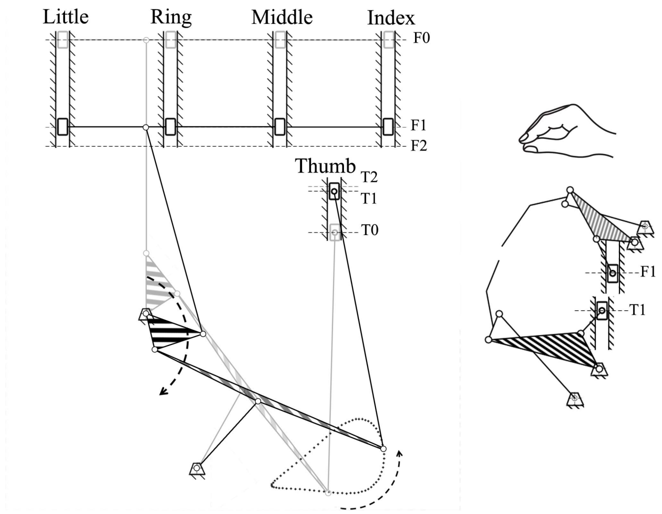


Fig. 14. Hand mechanism when performing precision grip. Fingers and thumb flex simultaneously to touch each other's tips.

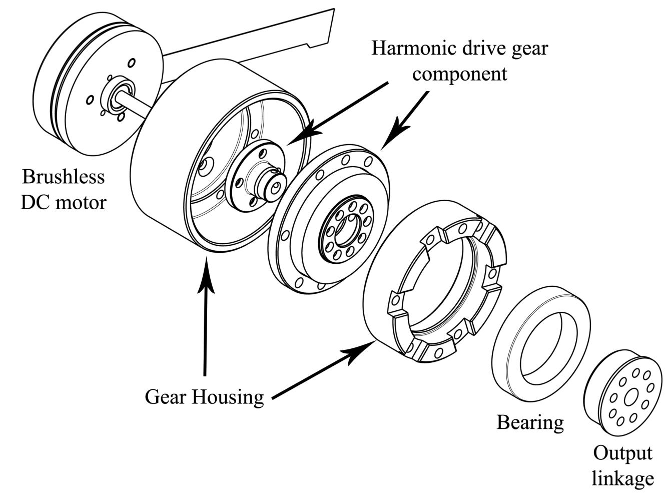


Fig. 16. Gear housing was designed and manufactured to assemble DC motor and Harmonic drive gear components together. These components could be placed within the prosthetic hand.

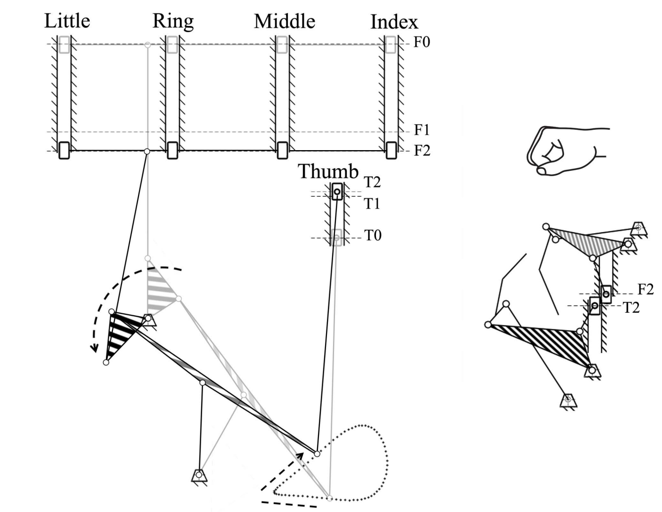


Fig. 15. Hand mechanism when performing power grip. Thumb mechanism flexion is delayed due to longer travel distance of coupler path; fingers flex in first then followed by thumb flexion touching with the back of the index & middle fingers to provide stability.

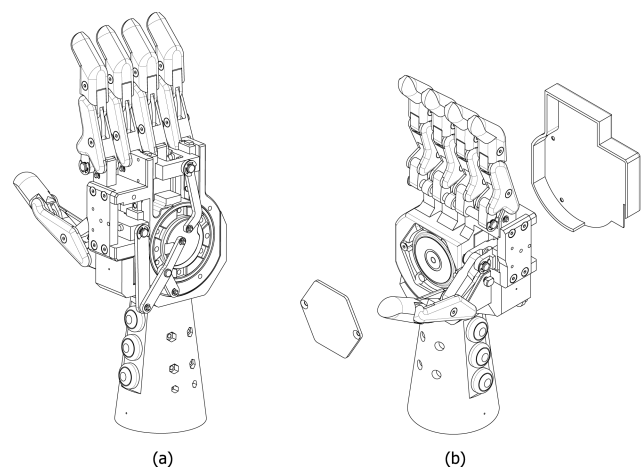


Fig. 17. Prosthetic hand design in open hand position. (a) Back of the hand with mechanism, (b) The hand with front and back cover.

considered for the hand performance to be adequate for ADLs, with a desired pinch force of at least 30 N and hand closing time of 1.0 to 1.5 second set as the objectives. Brushless DC motor (Maxon EC45-30W) with stall torque of 0.239 N-m and Strain wave gear (Harmonic drive gear CSD-14-100-2A-R) with a gear ratio of 100:1 were chosen as the actuator and transmission component. The gear housing was designed and manufactured to be compatible with the motor and could be assembled within the prosthesis, as in Fig. 16. With this configuration, all mechanisms and components should be able to provide the desired torque and speed, while also capable to be placed within the prosthesis limited space.

For electronic board, BLDC controller (Copley Accelnet Micro Module) is chosen as motor controller. The controller have function to operate both with CAN network and stand-alone operation which is suitable for experiment and ADLs usage. The board size is $64 \times 41 \times 21$ mm which is small enough to be assembled in the wrist section. In this research, external DC power supply is used instead of battery during hand experiment phase.

## E. CAD Design & Manufacturing

The prosthetic hand was designed from fingertips to wrist with CAD program as in Fig. 17. The hand has 38 revolute joints (6 in each finger & 8 in hand mechanism) and 2 prismatic joints each for the four fingers and thumb. The hand mechanism which connects the actuator to fingers and thumb has one degree of freedom and is detailed as in Fig. 18. Off-the-shelf linear guide components are used to provide the linear motion of fingers and thumb prismatic joints. Fingers and thumb coupler links are placed in the same plane of motion which could move to the limited position of each grip pattern without collision, as in Fig. 19.

The main body, fingers mechanism, and thumb mechanism are machined from aluminum alloys to provide rigid and

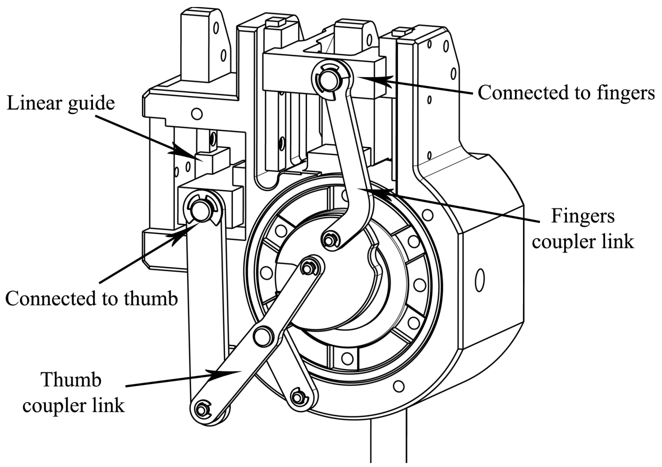


Fig. 18. Hand mechanism connecting actuator and both fingers and thumb mechanism. Linear guide components were used to provide prismatic motion of fingers and thumb drive links.

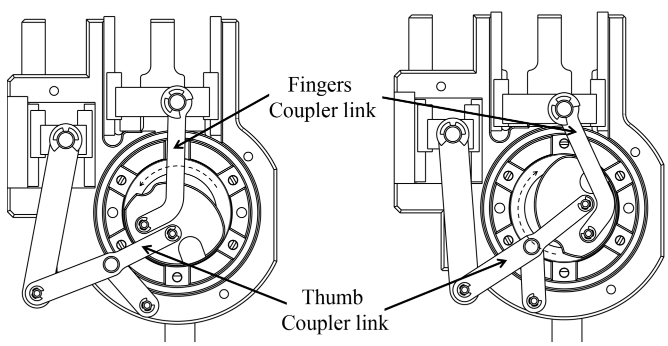


Fig. 19. Hand mechanism. Fingers and thumb coupler link could move to the limited position of each pattern without collision. (a) precision grip position, (b) power grip position.

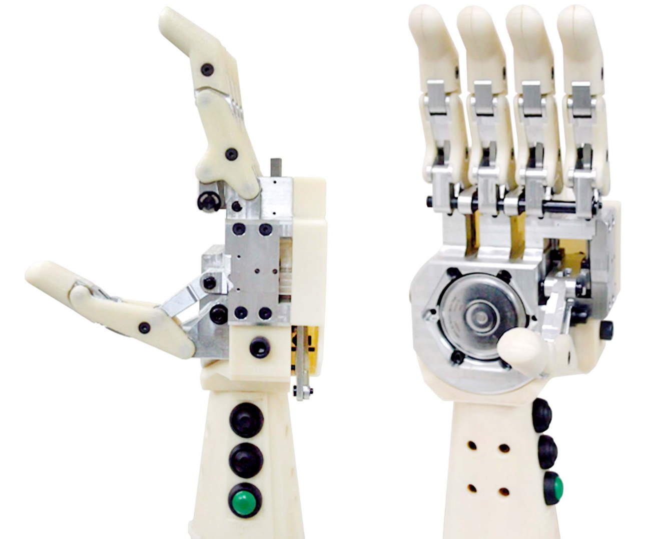


Fig. 20. The prosthetic hand. Aluminum alloy are used as body and finger skeletons, whereas ABS plastic is used as finger covers and handle to provide a natural look. (a) side view, (b) front view.

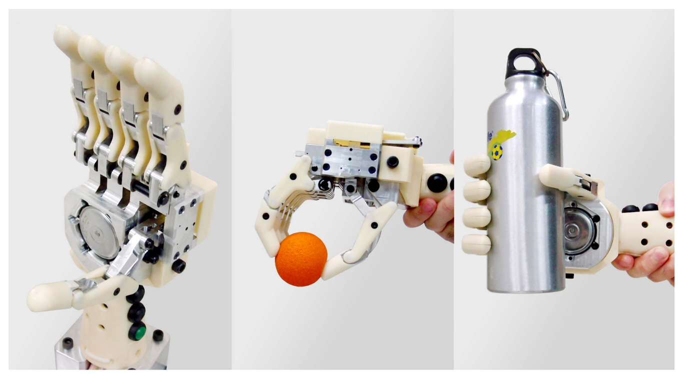


Fig. 21. The prosthetic hand. (a) open hand position, (b) precision grip, (c) power grip

lightweight body. Fingers and thumb are covered with ABS plastic (Acrylonitrile Butadiene Styrene) which has curved surface shape to provide more natural look as shown in Fig. 20. Three tactile switches are placed at the handle next to the wrist of the prosthetic hand to use as input triggers to perform each grip pattern. The prosthetic hand could perform three desired patterns, which are open hand, precision grip, and power grip as in Fig. 21. Overall size of the hand is $189 \times 97 \times 295$ mm (length $\times$ width $\times$ hand circumference) which is close to the average Thai male hand size. The prosthetic thickness is 57.7 mm. The space in wrist section is 45 mm in diameter which is enough to accommodate selected controller. Fig. 22. shows a prosthetic hand in open hand position compared with an adult male hand. Total weight from fingertip to wrist is 980 gram. Although this weight is within the range of research hands with the heaviest went up to 2,200 gram, it is about 2.5 times of average human hand and 1.5 times of heaviest commercial hand in the market, thus considered too heavy for daily life usage. This is due to the design constraints such as availability of components and manufacturing method. Comparing to commercial hands, some designs use customized actuator to optimize grasp force and space usage [12], whereas some designs use fabricated carbon fiber to increase strength per weight ratio and provide cosmetic appearance [10].

Thumb orientation is opposed to the palm which is required to perform precision grip and power grip. Thumb position is in the middle between index finger and middle finger to provide tripod function in precision grip.

## IV. Performance Experiment of Prosthetic Hand

To determine the capability of this single actuator prosthetic hand for daily life activities, multiple performance experiments, such as pinch force, hand closing time, and grasp range, were conducted and described in the following sections.

### A. Pinch Force

To measure pinch force, which is an essential function of a prosthetic hand, a compression load cell (LMB-A-100N, Kyowa Co.,Ltd, Japan) with accuracy of +- 0.5 N is placed inside a housing to prevent rotating motion and sense only compression force. This load cell is placed between the index finger, middle finger, and thumb when the hand performs precision grip as in Fig. 23. The hand is placed on a rigid base to provide stability.

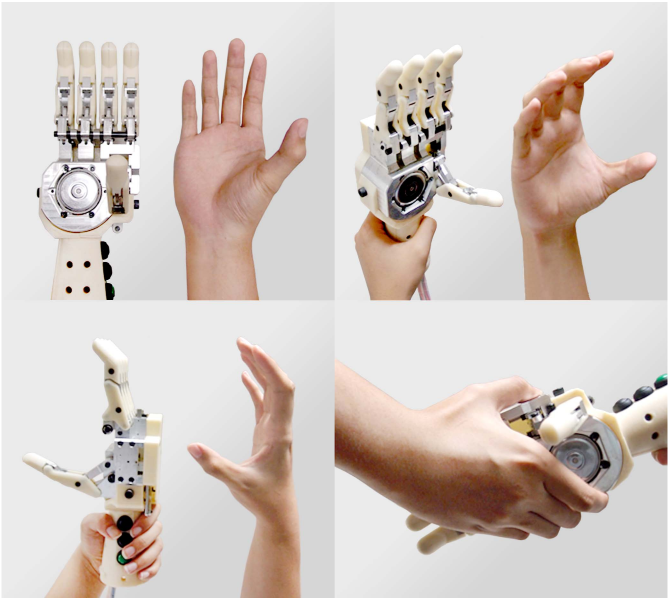

Fig. 22. The prosthetic hand compared to an adult male hand.

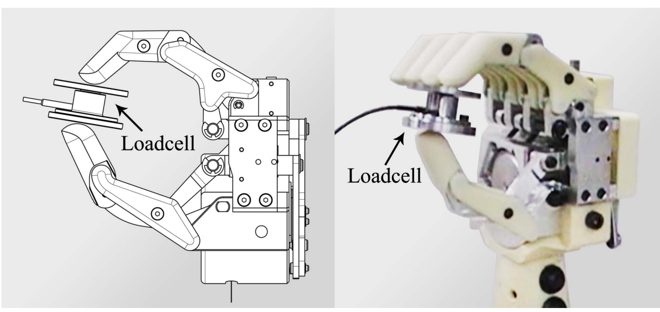


Fig. 23. Pinch force experiment. Compression load cell is placed between three fingers.

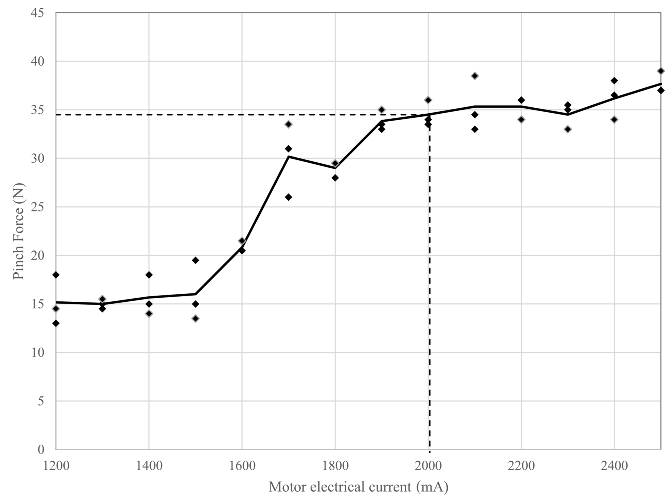


Fig. 24. Pinch force compared to motor electrical current.

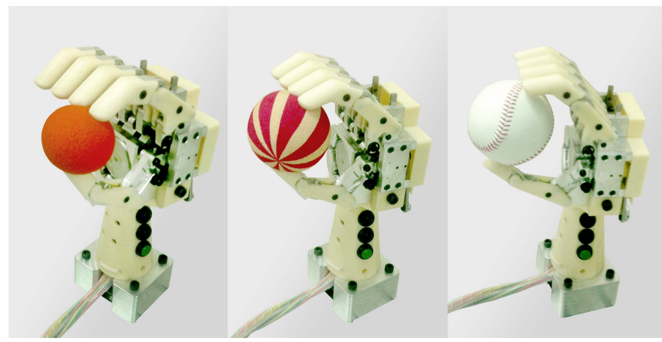

Fig. 25. Grasp range experiment with various sizes of spherical objects.

The resulting pinch force is proportional to the electrical current of the motor as shown in Fig. 24. It could reach 34.5 N at 2000 mA, which is the nominal current of the motor, but further increases in current above this value do not increase pinch force, as the mechanism does not have enough rigidity to withstand the load. The design uses the nominal current and torque of the motor as parameters for component selection; therefore, raising motor current above this value results in the start of deformation of mechanisms and linear guide components. Higher force could be exerted if the motor current up to stall current (5A) were used; but many components would need to be improved to withstand the mentioned force. In this research, we decided to use this grip force value as prosthetic performance, whereas further improvements of rigidity were left for future work.

## B. Hand Closing Time

Grasp speed could be expressed in term of hand closing time. Recommended hand closing time [1] should be between 1.0 and 1.5 seconds. In this research, hand closing time was measured experimentally by issuing grasp commands from the open hand position to perform both precision and power grips until the mechanism reached the limited position of each pattern. The result of closing time is 1.4 and 1.7 seconds for precision grip and power grip respectively, due to differences of mechanism travel length when actuated in different directions.

## C. Grasp Range

The experiment to determine the grasp range of the hand was conducted by performing a grasp with multiple sizes of spherically shaped objects, as in Fig. 25. The hand could grasp an object with diameter of up to 96 mm, whereas conventional single actuator prostheses could have a maximum grasp range of up to 100 mm [1]. The hand could perform grasp on daily life objects such as a remote controller, mobile phone, pill bottle, cup, book, towel, glasses, spoon, or shoe with the use of both grip patterns as in Fig. 26. This shows that the hand has the capabilities to be used in ADLs, which is one of the objectives of the design.

## D. Design Result and Discussion

The hand is developed from the design specifications mentioned in section II. With grasp function, force, and speed as the main objectives, hand performances are evaluated with experiments in the previous section. Table I shows the overview of the design specifications, together with the design result.

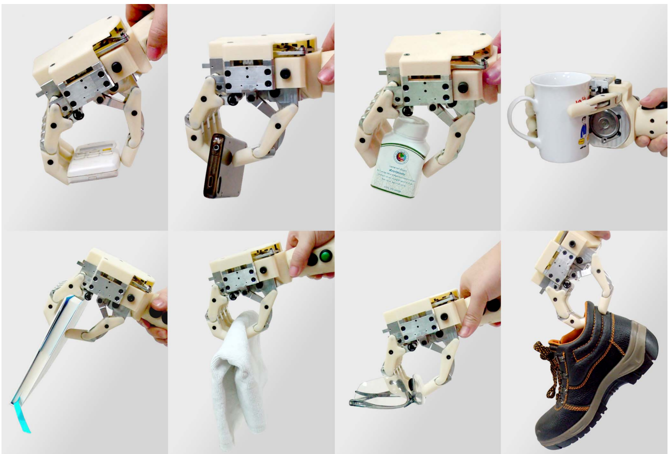

Fig. 26. Prosthetic hand performing grasps on common objects in daily life.

TABLE I
DESIGN SPECIFICATIONS, COMPARED TO THE PROSTHETIC HAND PERFORMANCE

| | Design specifications | Prosthetic hand performance | Achievement* |
|---|---|---|---|
| **Grasp patterns** | Precision grip and power grip | Acquired both patterns with different actuated direction | Good |
| **Grasp force** | > 29.5N (commercial multiple-actuator prosthetic) | 34.5 N | Good |
| **Hand closing time (speed)** | 1.0 – 1.5 s for ADLs | 1.4-1.7 s | Fair |
| **Grasp range** | 100 mm (conventional electric hand) | 96 mm | Fair |
| **Weight** | 350 – 615 g (commercial), 350 – 2,200 g (research base) | 980 g | Poor, Fair |
| **Size** | Average Thai male hand size 195 x 98 x 207 mm (length x width x circumference) | 189 x 97 x 295 mm Thickness 57.7 mm | Poor |
| **Controller and power supply** | - Capable of standalone operation - Smaller than wrist section (45 mm diameter) | Standalone BLDC controller, size 64x41x21 mm with 12V DC PSU | Fair |

* Good = fully achieved
Fair = partially achieved, at acceptable range compared to the design specs
Poor = not at practical level, requires further improvement

Evaluating the result, grasp function and force are achieved compared to the design specifications, whereas grasp speed and grasp range are at acceptable range. Two grasp patterns are acquired along with pinch force higher than that of multiple-actuator hands. The grasp speed is close to desired range. Both force and speed can be increased if the rigidity of mechanism is improved in future work. The other specifications such as weight, size, controller, and power supply are also close to desired specifications, but still not at practical level due to the nature of being in development stage and design constraints such as available components and manufacturing method. Thus, there are many rooms of improvement in the future development.

For grasp function, this research omits the lateral grasp from the design to reduce design complexity. Aside from the decrease in percentage of ADLs usage, the omitted presence of lateral posture would affect hand usage on flat objects such as key, name card, or utensils. However, these functions can also be achieved in precision grip with help of additional user's movement or auxiliary wrist rotation mechanism, which can be trained or devised in the future design. Thus, we evaluate the benefits of reduced degree of freedom and complexity of this decision to be justified with the missing function.

This research's design objective is to improve hand functions over conventional electric hand which can only perform open/close motion. The additional power grip position acquired from invented mechanism would provide multiple beneficial functions to the hand. First, the hook function, which is not presented in conventional hand, is achievable from power grip position. This function is used to hold cylindrical objects such as pole to provide stability or carry luggage handle. Second, although the conventional hand can grasp on cylindrical and spherical objects like this design does, the four fingers in power grip position of this design have higher range of motion when flexed because the opposed thumb does not obstruct with the fingers motion. Thus, the hand grasp is tightened and able to hold smaller diameter objects than both hands' pinch motion can normally achieve. With these reasons, having power grip position is beneficial to the design compared with conventional hand while the design retains a single actuator for the same force and complexity level.

## V. CONCLUSIONS

This research presents a design of a five-fingered prosthetic hand that can perform three hand configurations (open hand position, precision grip, and power grip) that are used for more than 70 percent of ADLs with only a single actuator. The design uses the concept of single-dwell six-bar mechanism to achieve different motions of thumb when the mechanism actuated in different directions: one is normal flexion for precision grip, and another is dwell motion for power grip, whereas the motion of four fingers (index, middle, ring, and little finger) is identical for both grip patterns. Open hand position is performed when the mechanism is at the neutral position, which acts as an intermediate position between both grip patterns. These functions are contained in the prosthetic hand which has a regular size when compared to commercial prosthetic hands.

This design is an improvement of a number of grip patterns from conventional single actuator prostheses which are only able to perform open/close grasp. The achieved pinch force of 34.5 N is higher than many other multiple-actuator commercial hands [12] due to the utilization of a single actuator fitted within the hand's limited space instead of multiple small actuators. Maximum grasp range is up to 96 mm and hand closing time is within 1.4 seconds. The design also has possibility for the improvement of mechanism rigidity to exert higher grasp force received from the actuator. The weight is 980 g. The hand size is 189 $\times$ 97 $\times$ 295 mm (length $\times$ width $\times$ hand circumference), with thickness of 57.7 mm. The hand is still too heavy and larger than desired specifications due to constraints in available components and manufacturing method. The controller is chosen for its standalone operation capability and miniature size which can be accommodated in wrist section.

In this research, we designed a prosthetic hand that improved grip patterns and cosmetic appearance of conventional single actuator prosthetic hand, whereas significant grip force, more than that of multiple-actuator prosthetic hands, could be achieved. The ability to perform three hand configurations with only one actuator has satisfactory functionality in both grip force and grip patterns.

While this research aims to explore the possibility of new mechanism to improve hand functions, other design aspects are also necessary for fully functional prosthetic hand. One of the important topics of improvement is the non-backdrivable mechanism which is crucial to hand function. Non-backdrivable mechanism can help holding object without continuous load of actuator [37]. With less energy consumption, we can improve various design specifications such as smaller actuator, lighter, and smaller hand design. Although it is not yet implemented into the design, we plan to accommodate the mechanism inside each finger to prevent reaction force from the object to return to the actuator. This beneficial function will be designed and implemented in the future phase of the research. Other topics of future improvement are adaptive grasp mechanism to provide grasp stability, and implementation of prosthetic to be used with battery and signal receiver from users.

## References


[1] R. F. F. Weir, "Design of artificial arms and hands for prosthetic applications," in *Standard Handbook of Biomedical Engineering Design*, 1st ed. New York, NY, USA: McGraw-Hill, 2003, ch. 32, pp. 32.1–32.61.

[2] G. Smit, D. H. Plettenburg, and F. C. T. van der Helm, "The lightweight delft cylinder hand: First multi-articulating hand that meets the basic user requirements," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 23, no. 3, pp. 431–440, May 2015.

[3] H. Takeda, N. Tsujiuchi, T. Koizumi, H. Kan, M. Hirano, and Y. Nakamura, "Development of prosthetic arm with pneumatic prosthetic hand and tendon-driven wrist," in *Proc. 31st Annu. Int. Conf. IEEE EMBS*, Minneapolis, MN, USA, Sep. 2009, pp. 5048–5051.

[4] A. Kargov, T. Werner, C. Pylatiuk, and S. Schulz, "Development of a miniaturised hydraulic actuation system for artificial hands," *Sens. Actuators A, Phys.*, vol. 141, no. 2, pp. 548–557, Feb. 2008.

[5] J. H. Lee, S. Okamoto, and S. Matsubara, "Development of multi-fingered prosthetic hand using shape memory alloy type artificial muscle," *Comput. Technol. Appl.*, vol. 3, pp. 477–484, Jul. 2012.

[6] F. Gao, H. Deng, and Y. Zhang, "Hybrid actuator combining shape memory alloy with DC motor for prosthetic fingers," *Sens. Actuators A, Phys.*, vol. 223, pp. 40–48, Mar. 2015.

[7] A. M. El Kady, A. E. Mahfouz, and M. F. Taher, "Mechanical design of an anthropomorphic prosthetic hand for shape memory alloy actuation," in *Proc. 5th Cairo Int. Biomed. Eng. Conf. (CIBEC)*, Cairo, Egypt, Dec. 2010, pp. 86–89.

[8] I. Yamano, K. Takemura, and T. Maeno, "Development of a robot finger for five-fingered hand using ultrasonic motors," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Las Vegas, NV, USA, Oct. 2003, pp. 2648–2653.

[9] I. Yamano and T. Maeno, "Five-fingered robot hand using ultrasonic motors and elastic elements," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Bacelona, Spain, Apr. 2005, pp. 2673–2678.

[10] C. Medynski and B. Rattray, "Bebionic prosthetic design," in *Proc. MEC Conf.*, Fredericton, NB, Canada, Aug. 2011, pp. 1–4.

[11] B. Waryck, "Comparison of two myoelectric multi-articulating prosthetic hands," in *Proc. MEC Conf.*, Fredericton, NB, Canada, Aug. 2011, pp. 1–4.

[12] J. T. Belter, J. L. Segil, A. M. Dollar, and R. F. Weir, "Mechanical design and performance specifications of anthropomorphic prosthetic hands: A review," *J. Rehabil. Res. Develop.*, vol. 50, no. 5, pp. 599–618, 2013.

[13] M. Controzzi, F. Clemente, D. Barone, A. Ghionzoli, and C. Cipriani, "The SSSA-MyHand: A dexterous lightweight myoelectric hand prosthesis," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 5, pp. 459–468, May 2017.

[14] M. G. Catalano, G. Grioli, E. Farnioli, A. Serio, C. Piazza, and A. Bicchi, "Adaptive synergies for the design and control of the pisa/IIT SoftHand," *Int. J. Robot. Res.*, vol. 33, no. 5, pp. 768–782, Apr. 2014.

[15] C. D. Santina, G. Grioli, M. Catalano, A. Brando, and A. Bicchi, "Dexterity augmentation on a synergistic hand: The Pisa/IIT SoftHand+," in *Proc. IEEE-RAS 15th Int. Conf. Humanoid Robots (Humanoids)*, Seoul, South Korea, Nov. 2015, pp. 497–503.

[16] C. Cipriani, M. Controzzi, and M. C. Carrozza, "The SmartHand transradial prosthesis," *J. NeuroEng. Rehabil.*, vol. 8, p. 29, May 2011.

[17] D. W. Zhao, L. Jiang, H. Huang, M. H. Jin, H. G. Cai, and H. Liu, "Development of a multi-DOF anthropomorphic prosthetic hand," in *Proc. IEEE Int. Conf. Robot. Biomimetics*, Kunming, China, Dec. 2006, pp. 878–883.

[18] J. Zhao, L. Jiang, S. Shi, H. Cai, H. Liu, and G. Hirzinger, "A five-fingered underactuated prosthetic hand system," in *Proc. Int. Conf. Mechatronics Autom.*, Luoyang, China, Jun. 2006, pp. 1453–1458.

[19] H. Liu *et al.*, "Multisensory five-finger dexterous hand: The DLR/HIT Hand II," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Nice, France, Sep. 2008, pp. 3692–3697.

[20] J. L. Pons *et al.*, "The MANUS-HAND dextrous robotics upper limb prosthesis: Mechanical and manipulation aspects," *Auto. Robots*, vol. 16, no. 2, pp. 143–163, 2004.

[21] N. Fukaya, S. Toyama, T. Asfour, and R. Dillmann, "Design of the TUAT/Karlsruhe humanoid hand," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Takamatsu, Japan, Oct./Nov. 2000, pp. 1754–1759.

[22] K. Xu, H. Liu, Z. Liu, Y. Du, and X. Zhu, "A single-actuator prosthetic hand using a continuum differential mechanism," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Seattle, WA, USA, May 2015, pp. 6457–6462.

[23] L. Wu, G. Carbone, and M. Ceccarelli, "Designing an underactuated mechanism for a 1 active DOF finger operation," *Mech. Mach. Theory*, vol. 44, no. 2, pp. 336–348, 2009.

[24] J. Yang, E. P. Pitarch, K. Abdel-Malek, A. Patrick, and L. Lindkvist, "A multi-fingered hand prosthesis," *Mech. Mach. Theory*, vol. 39, no. 6, pp. 555–581, 2004.

[25] N. Dechev, W. L. Cleghorn, and S. Naumann, "Multiple finger, passive adaptive grasp prosthetic hand," *Mech. Mach. Theory*, vol. 36, no. 10, pp. 1157–1173, 2001.

[26] F. Lotti, P. Tiezzi, G. Vassura, L. Biagiotti, G. Palli, and C. Melchiorri, "Development of UB hand 3: Early results," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Barcelona, Spain, Apr. 2005, pp. 4488–4493.

[27] N. E. Krausz, R. A. L. Rorrer, and R. F. F. Weir, "Design and Fabrication of a six degree-of-freedom open source hand," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 24, no. 5, pp. 562–572, May 2016.

[28] A. D. Keller, C. L. Taylor, and V. Zahm, "Studies to determine the functional requirements for hand and arm prosthesis," Dept. Eng., Univ. California, Los Angeles, Los Angeles, CA, USA, Tech. Rep., 1947.

[29] J. R. Napier, "The prehensile movements of the human hand," *J. Bone Joint Surgery*, vol. 38, no. 4, pp. 902–913, 1956.

[30] T. Iberall, "The nature of human prehension: Three dextrous hands in one," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA).*, Mar. 1987, pp. 396–401.

[31] X. Liu and Q. Zhan, "Description of the human hand grasp using graph theory," *Med. Eng. Phys.*, vol. 35, no. 7, pp. 1020–1027, 2013.

[32] J. Z. Zheng, S. De La Rosa, and A. M. Dollar, "An investigation of grasp type and frequency in daily household and machine shop tasks," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Shanghai, China, May 2011, pp. 4169–4175.

[33] C. M. Light, P. H. Chappell, and P. J. Kyberd, "Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity," *Arch. Phys. Med. Rehabil.*, vol. 83, no. 6, pp. 776–783, Jun. 2002.

[34] C. Cipriani, F. Zaccone, S. Micera, and M. C. Carrozza, "On the shared control of an EMG-controlled prosthetic hand: Analysis of user–prosthesis interaction," *IEEE Trans. Robot.*, vol. 24, no. 1, pp. 170–184, Feb. 2008.

[35] "Adult thai male anatomy," in *Thais Anatomy Statistic Report: 2000–2001*, 4th ed. Bangkok, Thailand: TISI, 2002, pp. 52–74.

[36] R. L. Norton, "Graphical linkage synthesis," in *Design of Machinery: An Introduction to the Synthesis and Analysis of Mechanisms and Machines*, 2nd ed. New York, NY, USA: McGraw-Hill, 1992, pp. 76–143.

[37] M. Controzzi, L. B. Luciani, and F. Montagnani, "Unified approach to bi-directional non-back drivable roller clutch design," *Mech. Mach. Theory*, vol. 116, pp. 433–450, Oct. 2017.