Design of a Single-DoF Prosthetic Hand With Practical Maximum Grip Force and Grasp Speed for ADLs Using Dual-Motor Actuator

Phakawat Vanich, Pairat Tangpornprasert, and Chanyaphan Virulsri

***Abstract*—Sufficient grip force and appropriate grasp speed provided by a prosthetic hand are essential for daily use. However, due to limitations in size and weight, it is very challenging to select motors that can generate enough power to provide sufficient grip force and high grasp speed. Accordingly, this research proposes a new prosthetic hand design using a dual-motor actuator as an actuation strategy, which consists of two motors separated by a differential mechanism to operate at the load (high force) and no-load (high speed) conditions individually. One motor is used for creating a high torque and the other for creating a high speed, so the prosthetic hand can operate at the loads without using a high-power motor with excessive size and weight. The developed prosthetic hand can perform grasping motions with the following achievements: It can provide a maximum grip force of 80.2 N and maintain a maximum of 62 N with non-backdrivable mechanisms, and provide an average closing time of 1.2 s. Furthermore, the design can provide more grip force than research prosthetic hands using a single motor.**

***Index Terms*—Actuation and joint mechanisms, mechanism design, prosthetics and exoskeletons.**

I. INTRODUCTION

DISABILITIES in the upper limb affect activities of daily living (ADL), especially the ability for prehensile movements. For this reason, prosthetic hands are essential for upper-limb amputees. There are two necessary functions, including grip strength and grasp speed, in order to conduct ADLs. Improvements in both grip force and grasp speed will lead to better functionality [1]. Amputees prefer higher grip strength [2] and grasp speed [3] which are essential to perform ADLs. A prosthetic hand that cannot provide sufficient grip force may be unable to perform all tasks [1]. Likewise, a prosthetic hand that cannot provide appropriate grasp speed will be inadequate for conducting ADLs [4]. In general, if a prosthetic hand is designed to produce sufficient grip force and speed, High power motors are required. As a result, the prosthetic hand's overall weight will become excessive. Biddiss et al. [5] found that the excessive weight of a prosthetic hand can affect the comfort of use, which is as important as the main functions mentioned above.

In current technology, prosthetic hands have been categorized into two main types according to their power source, namely, body-powered and externally powered prosthetic hands. The body-powered prosthetic hands are actuated by physical forces created by amputee movements, such as the movements of shoulders. The externally-powered prosthetic hands are driven by actuators that create mechanical power from an external power source, typically batteries. Mechanical power can be created by many types of actuators, e.g., direct current motor (DC motor), hydraulic, pneumatic, and ultrasonic motor. DC motors have been widely used in prosthetic hands [1]. The key benefit of these actuators is that their electrical energy can be stored in compact batteries [6]. Although the motors can provide the lowest power with respect to their weight in terms of power density, the motors are reasonably efficient and accurate [6]. However, these prosthetic hands have disadvantages as they have to bear the power source's weight and require more space to fit in.

Many researchers have proposed different designs with user needs and requirements, such as weight, size, appearance, grasp pattern, grip force, grasp speed, and usage time. Current design challenges, especially grip force and grasp speed [1], are the bases of prehensile movements for ADLs. The grasp speed of electrical prosthetic hands has been commonly designed to be sufficient for ADLs [4], [1]. However, according to the weight comparison of research and commercial prosthetic hands [7], precision grip forces were obtained by the prosthetic hands with an appropriate weight of less than 500 g [8]. As a result, most prosthetic hands are incapable of providing precision grip force more than a minimum requirement of 45 N for practical use [8]. For instance, the TBM Hand, is a single-degree-of-freedom (DoF) prosthetic hand, was actuated by a single DC motor with a linear ball screw. The pinch force was still only 14 N, compared to the minimum requirement [8]. The other multi-DoF prosthetic

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hands, e.g., Southampton-Remedi hand, i-Limb, and BeBionic, also had the same issue. However, the issue of these prosthetic hands can be compromised by the ability to accomplish more achievable grasp patterns, which is also an important aspect of performing ADLs. The improvement of grip force provided by a prosthetic hand is significantly challenging. In general, most prosthetic hands typically have appropriate grasp speed. Nevertheless, they cannot provide sufficient grip force due to weight limits imposed by the actuator's power density and efficiency. Since actuators in these prosthetic hands are DC motors, their torque and speed are inversely proportional. Consequently, it is necessary to compromise between both the grip force and grasp speed of the motors within the limitations of their power outputs [2]. However, there are commercial prosthetic hands that have addressed this issue, the Ottobock Sensor Hand, Ottobock DMC Hand, and Motion Control Hand, which use a single motor with a clutch module [9], [22] to enhance their grip force when their fingertips are in contact with an object, the NU-VA Synergetic Prehensor, RSLSteeper Powered Gripper, which use the principle of synergetic prehension [9] to switch between multiple motors to operate in their operating points to boost overall performance. Consequently, these prosthetic hands can operate two-speed loads like those mentioned above. However, the clutch module is mechanically complex [9] due to noncommercial components and is cost-prohibitive for developing countries.

During each grasp cycle, a prosthetic hand is required to move with a high fingertip speed until its fingertips make contact with an object's surface. Then, the grip force of the prosthetic hand increases to hold the object. The load characteristics of the two situations appear to be completely different. Due to the DC motor characteristics, designing a prosthetic hand that requires high grasp speed and high grip strength has been challenging. This research proposes a new prosthetic hand design using an actuation strategy composed of available components to achieve the minimum grip force and grasp speed adequate for ADLs. Therefore, we applied the dual-motor actuator configuration to the prosthetic hand mechanism [10], [11], [12], [13], [14]. The mechanism includes a differential mechanism that allows the operation of two motors to be separated independently. One of the motors operates at high speeds and the other at high loads. With this approach, the prosthetic hand can enhance the sufficient grip force and adequate grasp speed for ADLs.

II. DESIGN SPECIFICATION AND CONCEPTUAL DESIGN

A. Achievable Grasp

A prosthetic hand that can accomplish many grasp patterns can perform functions similar to those of an actual hand and expand the number of daily activities. However, Belter et al. [7] demonstrated that in a mechanism with many joints, the mechanism weight would be increased, and a mechanism with many actuators tends to provide lower strength within the size and weight constraints. Furthermore, amputees with higher upper limb levels have lost the ability to command their muscles for complex myoelectric control because the number of available inputs from users is limited by their disabilities, which are usually less than the number of a prosthetic hand's required outputs [9]. Therefore, the design of a prosthetic hand with many grasp patterns should not be more complicated than the user's ability to control the prosthetic hand. Many researchers have developed underactuated prosthetic hands as an option to reduce their complexity, weight, and number of control inputs. The prosthetic hands have the ability to adapt their fingers to conform to an object's shape passively. However, previous research [15] showed that an underactuated prosthesis's grip force and grip function test score was significantly lower than those of a comparable nonadaptive prosthesis.

In order to achieve a simple and lightweight prosthetic hand, this research designed a single-DoF prosthetic hand that can only perform a precision grasp pattern, which covers 30% of ADL usage [16]. It can be controlled by the amputee in two states: closing and opening. Furthermore, the prosthetic hand was designed to grasp an object with a maximum size of 10 cm, aiming to cover a wide range of object sizes [9].

B. Grip Force and Grasp Speed

The grasp speed of a prosthetic hand must be within the appropriate range. If the grasp speed is too low, it will affect ability to perform ADLs. Meanwhile, an amputee has difficulty focusing on where fingertips will be in contact with an object when the grasp speed is too fast [7]. The grasp speed of prosthetic hands is measured in several ways. The most common measurement metric is the closing time in terms of a finger's closing period. Dechev et al. [4] suggested that the 1.0–1.5 s closing period is sufficient for ADLs.

Although the grip force provided by a normal human hand can reach 95.5 N for precision grasp [9], previous research claimed that a prehension force of 0 - 66.7 N is sufficient for carrying out most ADLs [17] and a grip force of 45 N is a minimum requirement for practical use [8].

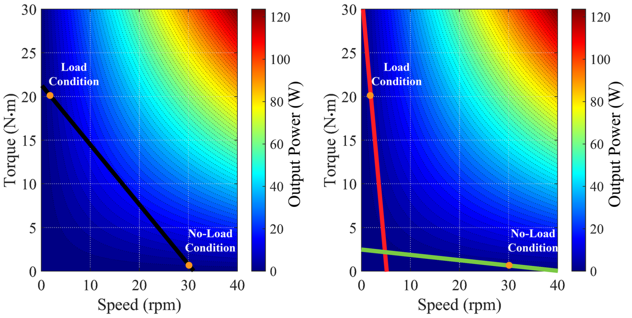
C. Weight and Size

The weight of a prosthetic hand is a significant factor affecting a user's comfort and wearing [5]. Controzzi et al. [6] demonstrated that a prosthetic hand with a high number of actuators is commonly heavy. In particular, a prosthetic hand using motors with a high-torque capacity is generally heavy. Belter et al. [7] suggested that the overall weight of a prosthetic hand, including the mechanism, prosthetic glove, and electrical components, should not exceed 500 g.

The overall size and shape of a single-DoF prosthetic hand should be similar to the anthropomorphic dimensions of the average human hand [1] to provide anthropomorphic similarity for the prosthetic hand. Therefore, space management inside a prosthetic hand is a significant challenge in designing the hand mechanism.

D. Conceptual Design

Considering object grasping in daily life, two load conditions can occur in object grasping. First, the no-load condition occurs when a prosthetic hand's fingers freely move before making



(a) (b)

Fig. 1. Concept of the output speed–torque curve of a finger mechanism that is actuated by (a) a single motor or (b) dual-motor mechanisms compared to their iso output power contour.

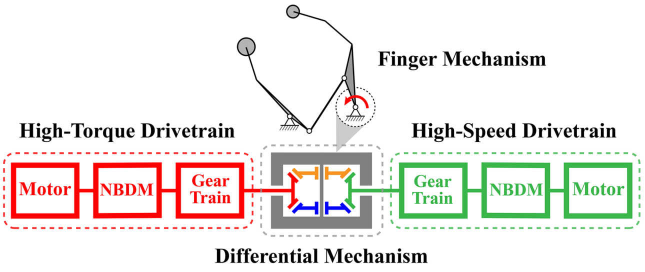


Fig. 2. Concept of the dual motor actuator is applied to a prosthetic hand.

contact with an object. Second, the load condition occurs when a prosthetic hand's fingers make contact with an object. A prosthetic hand typically operates at two completely different operating points. In the current technology, a DC motor with a wide-enough operating range to cover these operating points can be chosen. The output speed–torque curve of the selected DC motor (black) can operate in both load and no-load conditions, as shown in Fig. 1(a). However, although selecting a DC motor that can operate in these operating points is possible, the selection must require a DC motor with a high nominal power, which becomes large and heavy [6], [18].

This research proposes the dual-motor actuator concept to the prosthetic hand mechanism aiming to operate each motor independently to drive the output at its operating points [10]. This design concept mainly comprises a differential mechanism with two different motor drivetrains as inputs and a finger mechanism as the output, as illustrated in Fig. 2. The motor drivetrains are coupled to the two inputs of the differential mechanism. When one of the motors is activated, a motor torque can directly deliver to the output. In other words, the differential mechanism allows each motor to operate in its operating points to drive the same finger mechanism. Therefore, a prosthetic hand can be implemented with two smaller motors. The torque-speed curves of each motor (red and green) can also operate in the same load and no-load conditions, as shown in Fig. 1(b). For this concept, the motors of the prosthetic hand can be seamlessly switched to operate at loads during object grasping. In this case, the high-torque motor can drive the finger mechanism to produce a strong grip force, whereas the high-speed motor can drive the finger mechanism to move fast.

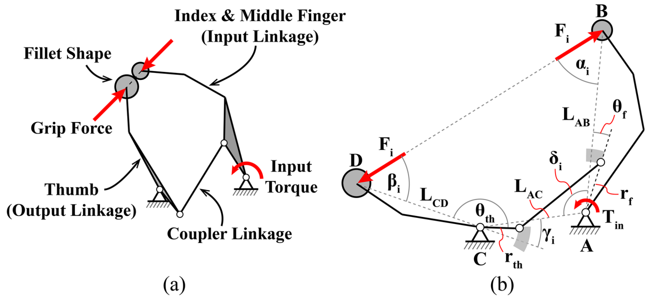


Fig. 3. Four-bar linkage diagram of the finger mechanism and a grip force reacting on its fingertips at (a) the fully close position and (b) fully open position along with the parameters for linkage optimization.

III. PROSTHETIC HAND DESIGN

A. Finger Mechanism Design

A finger mechanism was designed to be an output for the dual-motor mechanism of this design. The finger mechanism is a four-bar linkage with a single-DoF. In Fig. 3(a), the four-bar linkage consists of an input linkage that contains the index and middle fingers fixed together, an output linkage that acts as a thumb, and a coupler linkage that connects the two linkages. The mechanism functions as a tripod gripper, with their fingertips being designed to be fillet shapes. This shape allows a reaction force to be always directed toward the center of the fingertips to grip an object and form a static equilibrium at any surface of the fingertips, as illustrated in Fig. 3(a). Note that the behavior of the reaction force can be determined only with rigid objects. In daily use, objects may have properties such as deformable, floppy [19], and uncertain surface. The result of reaction force would be different in term of magnitude and direction. Furthermore, the lengths of each phalange were designed to match the average lengths of bone phalanges in order to be as close to the human fingers as possible [20].

A linkage optimization is required in the design of the finger mechanism. The four-bar linkage was optimized to determine a set of design parameters, such as the coupler linkage's length and joint positions. The linkage optimization allows the mechanism to produce the maximum grip force while any constant input torque drives its input linkage. However, to ensure that the actuators operate as close to the designed operating point as possible in varying object sizes, the differences in grip forces between the fully close and fully open positions, as shown in Fig. 3, should be minimized. The objective functions of the linkage optimization including grip force per input torque $\left(\frac{F_c}{T_{in}}\right)$ and grip force variation factor $\left(\frac{F_o}{F_c}\right)$ can be expressed in (1). The parameters used in the equation, such as design parameter boundaries (grey area) and constant parameters, are displayed in Fig. 3(b), and the design parameter boundaries used for the optimization $(r_f,\ \theta_f,\ r_{th},\ \theta_{\text{th}})$ were scoped as $r_f \in [20,\ 25]$ mm, $\theta_f \in [-5,\ 12]$ deg, $r_{th} \in [15,\ 20]$ mm, $\theta_{\text{th}} \in [160,\ 190]$ deg, respectively, in order to comply with the designed finger.

$$\frac{F_i}{T_{in}} = \left(L_{AB}\sin(\alpha_i) + L_{CD}\sin(\beta_i)\cdot\frac{r_f\sin(\delta_i+\theta_f+\varepsilon_i)}{r_{th}\sin(\gamma_i-\theta_{th}+\varepsilon_i)}\right)^{-1}.$$

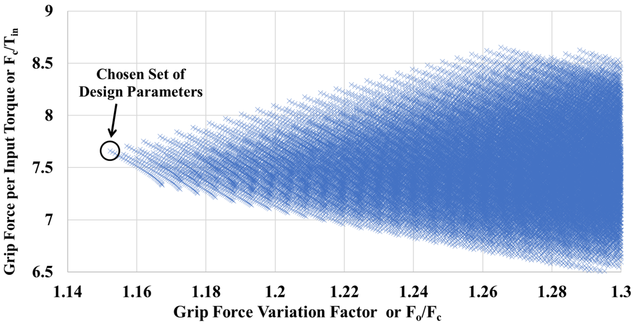


Fig. 4. Sets of design parameters used for the finger mechanism design that provides grip forces and their variations. A set of design parameters that can provide a minimum grip force variation is chosen.

$$\varepsilon_i = \tan^{-1}\left(\frac{r_f \sin(\delta_i + \theta_f) + r_{th} \sin(\gamma_i - \theta_{th})}{L_{AC} - r_f \cos(\delta_i + \theta_f) - r_{th} \cos(\gamma_i - \theta_{th})}\right).$$

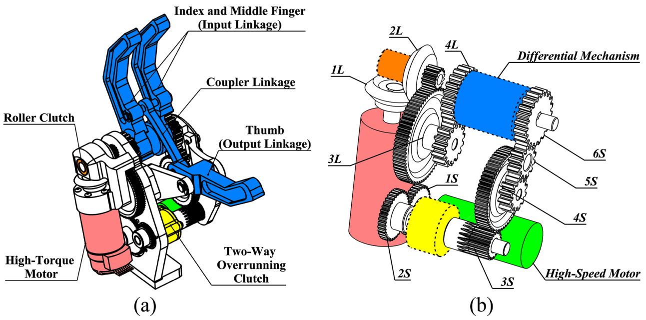
$$\frac{F_c}{T_{in}} = \left.\frac{F_i}{T_{in}}\right|_{i=c}, \frac{F_o}{F_c} = \left(\left.\frac{F_i}{T_{in}}\right|_{i=o}\right) \Big/ \left(\left.\frac{F_i}{T_{in}}\right|_{i=c}\right). \quad (1)$$

Where the subscript o and c indicate constant parameters in those fully open and close positions, respectively. Coordinate $(r_f,\ \theta_f)$ and $(r_{th},\ \theta_{th})$ are polar coordinates of the coupler linkage's joints located on the index & middle finger and thumb, respectively.

As a result of the linkage optimization from (1), there are trade-offs between two objective functions resulting from many sets of design parameters, as shown in Fig. 4. If the grip force variation from different object's sizes is considered more significant, the grip force variation factor should be minimized. Therefore, a chosen set of design parameters, which achieved the maximum grip force at the minimum variation factor of approximately 1.15, was obtained. Hence, the grip forces at the fully open position (F_o) are 15% higher than those at the fully close position (F_c), with the ratio of the grip force and provided input torque $\left(\frac{F_c}{T_{in}}\right)$ equal to 7.74 N/N·m.

B. Drive Mechanism Design

The drive mechanism should have sufficient reduction ratios so that the selected motors are not too heavy and oversized. In this research, the drive mechanism consists of gear trains and a differential mechanism. In Fig. 5, the gear trains are responsible for transmitting power from each motor to the differential mechanism, which was connected as an input for the finger mechanism. In Fig. 5(b), the gear trains were divided into two sides according to the transmitting path of each motor: the high-torque-side gear train (1L-4L) and the high-speed-side gear train (1S-6S). The gear trains compose of designed gears (1L-4L, 4S-6S) and purchased gears (1S-3S). Their materials and bending strengths used for designed and purchased gears are nitrided through-hardened steel (AISI 4140 grade 2, 213 MPa [21]) with bending strength and through-hardened steel (AISI 4140 grade 1, 409 MPa [21]), respectively. Although most designed gears were designed as compound gears, they were a combination of various modules or gear types to minimize the overall size of gear trains. Spur gears and bevel gears were used in the gear trains to avoid low-efficiency gears such as worm drive and lead screws to maximize the mechanism's force and speed capabilities. In order to achieve the desired loads, each gear train has a reduction ratio corresponding to its input motor, and the gears of the gear trains were considered in the failure of the bending strength according to the American Gear Manufacturers Association, which followed Shigley's handbook [21].



(a) (b)

Fig. 5. Overall components of the prosthetic hand, including (a) the finger mechanism, drive mechanism, non-backdrivable mechanisms (NBDMs), and actuators, (b) the positions of each gear in the gear trains and their connection.

The differential mechanism used in the drive mechanism consists of two inputs, which were connected to their gear trains, and an output, which was mounted with the input linkage of the finger mechanism, as shown in Fig. 5(a). The type of differential mechanism used in this design is a crown differential, which has a reduction ratio of 2:1 defined from either input to the output. Although the crown differential commonly has a reduction ratio less than a planetary differential, their elements can be designed in a compact size and are simple and easy to manufacture.

In previous research, locking mechanisms have been required to be used with a dual-motor mechanism [10], [11], [14] to prevent undesirable rotary motions of a motor, which has a lower load capacity than another while the mechanism is on a high load. Therefore, this research found that a non-backdrivable mechanism (NBDM) can be used as a locking mechanism for the drive mechanism using a dual-motor configuration, as illustrated in Fig. 2. Two types of NBDM were inserted in each gear train, as shown in Fig. 5(a). The type of NBDM used in the high-speed-side gear train was a two-way overrunning clutch. The two-way overrunning clutch was designed and manufactured using a concept developed by Controzzi et al. [22] because of its small size and ease of manufacture. The type of NBDM used in the high-torque-side gear train was a one-way overrunning clutch (roller clutch) to maintain the load after the active motor was powered off, resulting in battery savings and grasp stability at the desired position [26].

A prosthetic hand's mechanism with the dual-motor configuration was obtained. It can operate alternately between desired loads and maintain the load without power consumption.

C. Actuators and Electrical Component Selection

The motors used to drive the drive mechanism should be as small and light as possible. The high-torque motor requires

TABLE I
DESIGN PARAMETERS OF THE MOTORS FOR THE ACTUATOR SELECTIONS OF THIS DESIGN

Motor	Motor & Gearhead Output	Gearhead Ratio	Gear Train's Reduction Ratio	Desired Output
High-speed motor	168 rpm (No-load speed)	69:1	10	16.8 rpm
High-torque motor	1.6 N·m (Rated continuous torque)	196:1	12.4	20.1 N·m

transmitting power through its gear train, resulting in a torque of 20.1 N·m at the input linkage, to generate the desired grip force of more than 45 N at any position of the fingers. Moreover, the high-speed motor requires transmitting power through the gear train, resulting in a speed of 16.8 rpm at the input linkage, to achieve the desired closing time of 1.0 s. Therefore, the high-torque and high-speed motors selected in this design were DC motors with the following gearhead characteristics: 9 W/12 V FAULHABER brushless DC-Flat Motors series 2214 + 196:1 gearhead and 5 W/6 V FAULHABER DC-Micromotor series 1717 + 69:1 Gearhead, respectively. The design parameters of the motors are summarized in Table I.

The electrical components used for the performance testing in this research were selected based on the following criteria: their sizes having to fit in a prosthetic socket with a diameter of 45 mm and their weights being as light as possible. Three main electrical components are selected: First, a motor controller for the high-torque motor is a brushless DC motor controller (Maxon ESCON Module 24/2) used to control the current outputs of the motor in order to meet the desired grip forces. The current outputs were simply controlled with closed-loop current control by setting to Current Controller Mode in ESCON Studio program. Second, a motor driver for the high-speed motor is a DC motor driver (Pololu: MC33926) used to drive the motor and detect a transition between the no-load and load conditions by sensing a change in the feedback current. Lastly, the motor controller and driver collaborated with a stand-alone microcontroller (ATtiny84A) to receive closing and opening commands from a user, communicate between the electrical components, and control grasping states.

IV. PERFORMANCE TEST OF THE PROSTHETIC HAND

A. Enhancing Grip Force

In an experimental setup, the grip forces at the fingertips were measured by a compression load cell (LMB-A-100N, Kyowa Co., Ltd, Japan, with an accuracy of ±0.5 N) assembled with a 22 mm rigid housing.

All experiments for measuring grip forces were performed by recording grip forces over time. In each experiment, the currents of the high-torque motor were set between 0.12 A and 1.14 A with three sample sizes ($n = 3$). Each measurement was started with the high-speed motor rotating at a full speed at 100% pulse-width modulation (PWM) until the fingertips made contact with the load cell for 1.5 s. Then, the motor was turned off while the high-torque motor was turned on for 3 s. Meanwhile, the current would reach the preset value. Afterward, the motor was turned off. The measurement was continuously recorded until the recording time reached the 10th second.

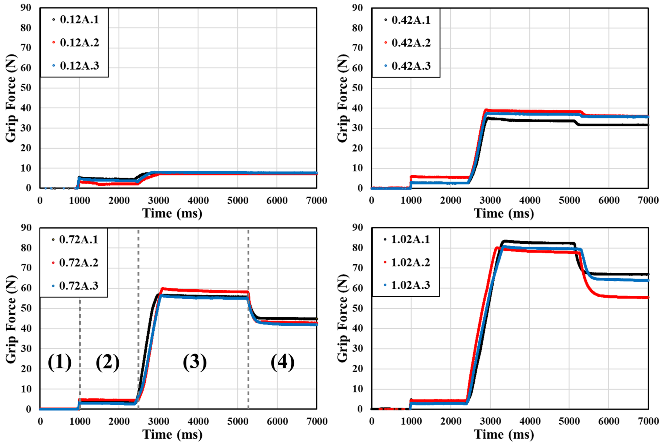


Fig. 6. Examples of the grip forces over time recorded by the load cell at currents of 0.12, 0.42, 0.72, and 1.02 A. The time axis was divided into 4 zones. Zone (1): High-speed motor is powered on with no-load condition, Zone (2): High-speed motor is powered on with load condition, Zone (3): High-torque motor is powered on with load condition, and Zone (4): High-torque motor is powered off and the loads are maintained by NBDM.

The measured data can be analyzed in two ways: First, the grip force over time was analyzed to study the grip force characteristics over time while a prosthetic hand performs grasping. Second, the grip force was compared to the high-torque motor currents to determine a maximum grip force that the mechanism could generate within the motor current limit.

The grip force was analyzed over time. The grip forces can be shown as examples with the varying motor current in Fig. 6. The fingertips had made contact with the load cell (zone (2)) before the high-torque motor enhanced the higher grip force (zone (3)). The amplitude of the grip force at zone (2) was found to be approximately 2–6 N. The grip forces in the transition zone (between zone (2) and zone (3)) were seamlessly increased because there was no force drop in that zone, in contrast to a general gearshift mechanism where the force drop always occurs when the load was momentarily disappeared during a gearshift transition [11], [23]. After the motor was turned off (zone (4)), both NBDMs responded to maintain the loads. The grip forces dropped from their maximum values. The percentages of the dropped grip forces compared to their maximum grip force are displayed in Fig. 7. The results showed that the higher the grip force, the larger the grip force drops. The drops in grip forces may be caused by a combination of the overall mechanism's deformation after the load from the motor was removed and uncertain clearances of each roller contact between its lock and unlock phases. The deformation increased in relation to the load of the overall mechanism, which corresponded to the above results. Consequently, a maximum drop could reach 31.3% of the grip force.

The analysis of grip forces was performed by comparing the grip forces to high-torque motor currents to determine the maximum grip force that the mechanism can provide according

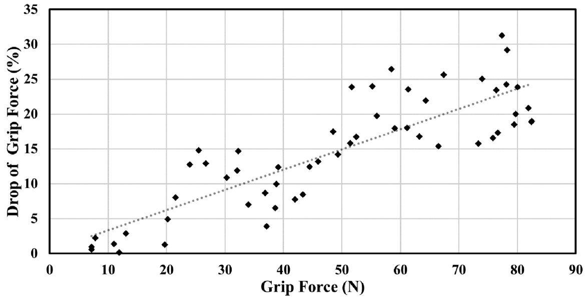


Fig. 7. Percentages of the grip force drop compared to their maximum value of grip forces ($R^2 = 0.7149$).

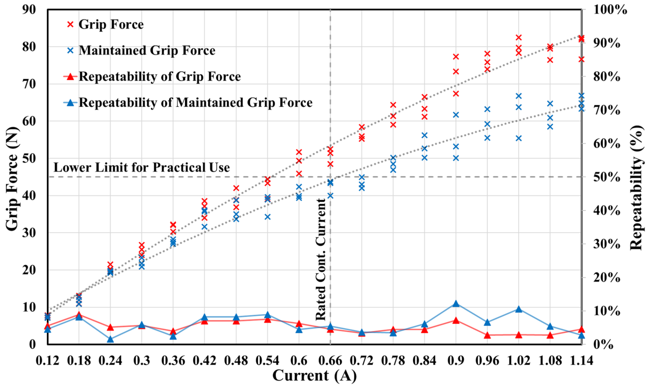


Fig. 8. Results of the grip forces ($R^2 = 0.9857$), maintained grip forces ($R^2 = 0.9706$), and their repeatabilities of this prosthetic hand at motor currents between 0.12 A and 1.14 A.

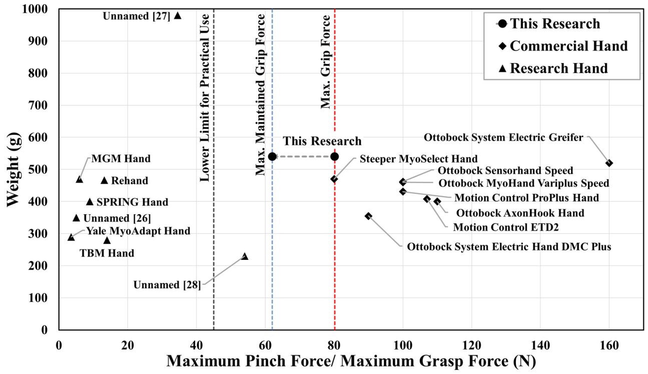


Fig. 9. Grip force comparison of the prosthetic hand with other research (named and unnamed [26], [27], [28]) and commercial prosthetic hands using single motor.

to the motor's specifications, i.e., 12 V and 0.66 A rated continuous current. The results are shown in Fig. 8, where a positive correlation between grip forces and currents is revealed. The grip force provided by the prosthetic hand at the rated continuous current was approximately 50.8 N, which is sufficient to cover the minimum grip force for practical use of 45 N. However, the grip forces provided by the motor with continuous operation constantly consume energy affecting the usage time of batteries. At high currents, the motor can also generate high grip forces but only in transient operations. Therefore, the NBDMs were used to the maintained grip forces. The results showed that the maintained grip forces at 0.78 A in the transient operation were greater than the minimum grip force for practical use. The current was approximately 18% larger than the rated continuous current. Therefore, in practical use, we recommend setting an upper limit current at least at the value to minimize energy consumption. Finally, for currents greater than 0.78 A, the grip forces and their maintained grip forces were steadily increased until they remained constant, averaging at 80.2 and 62.0 N, respectively. In addition, the maximum grip force can cover the range of 0 – 67 N for conducting most ADLs. However, there is a limitation regarding the repeatability of grip force while the prosthetic hand is gripping a fragile object. The repeatabilities of the grip forces and maintained grip forces at each current can be defined as percentages of their maximum derivation divided by their average force. As shown in Fig. 8, The results showed that the repeatabilities of both forces at all currents are approximately less than 10%. Regarding safety, if the critical grip force of the fragile object can be determined, the applied force should be set below 90% of the threshold force that critical failure will occur to ensure that the prosthetic hand grips a fragile object without failure.

This design can be compared with research and commercial prosthetic hands using a single motor in the research of Damerla et al. [1] and other commercial hands [24], [25] regardless of their method of transmission and their weights of wrist or forearm are excluded, as shown in Fig. 9. The developed prosthetic hand can create the maximum pinch force remarkably higher than research prosthetic hands with comparable weight and maintain its grip force without energy consumption. Although those prosthetic hands can provide less grip force, they can provide other abilities. For instance, adaptive prosthetic hands such as TBM Hand, Yale MyoAdapt Hand, unnamed [26], SPRING Hand, and MGM Hand have passive adaptability in grasping objects. The research prosthetic hands that can achieve many grasp patterns such as unnamed [26], MGM Hand, and unnamed [27]. Moreover, the research prosthetic hands such as Yale MyoAdapt Hand and unnamed [26] have non-backdrivability by using worm gears to maintain loads without consuming energy from their motors. However, most commercial prosthetic hands can provide higher grip force, including single-DoF greifer type (2 digits) and tripod gripper (3 digits). Note that there are many commercial prosthetics hand, such as Ottobock Sensor Hand, Ottobock DMC Hand, and Motion Control Hand, published their performance when their motor was overvoltage [9] where their maximum grip force and grasp speed were increased from their normal operating condition. In addition, there are many advantages of using the dual motor configuration. The grip force and grasp speed can be independently operated because its output torque can be regulated without affecting output speed and vice versa. Consequently, the motors can be selected in a way that both outputs can be operated in their optimum ranges to maximize their efficiencies. Therefore, the dual motor configuration can be an alternative solution for operating at extremum torque-speed conditions [11] especially object grasping, because the configuration is simple for implementation and requires commercially available components.

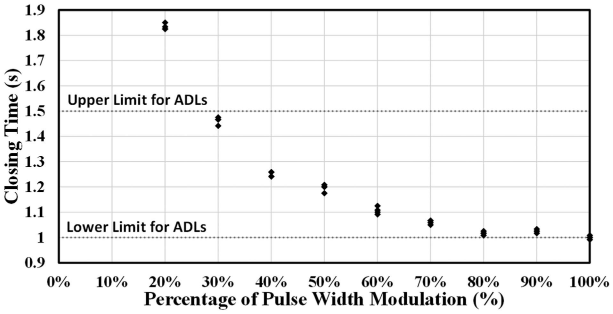


Fig. 10. Result of the closing times as compared to the pulse-width modulation (PWM) percentages of the high-speed motor.

TABLE II
ANTHROPOMORPHIC COMPARISON OF THE PROSTHETIC HAND'S DIMENSIONS

Hand Dimension	Average Men Hand [1] (mm)	This Research (mm)
Hand Length	191.7	174.3 (b + c + d + e)
Hand Width	88.2	75.7 (a)
Palm Length	108.9	101.5 (b + f)
Index Finger Length	75.3	70.5 (c + d + e - f)

B. Grasp Speed

The grasp speed of the prosthetic hand is defined as the closing time, which is the time it takes to close from the fully open position to the fully close position. The closing times were measured by capturing the timestamps on the recorded videos of the two positions to obtain periods of the hand closing. The videos were captured with a digital camera set to 120 frames per second and a resolution of 60 megapixels. The results of measuring the closing times were processed and compared to their PWM percentages of the high-speed motor, as shown in Fig. 10. The results showed that by regulating the percentages of the PWM from 100% to 20%, the closing times could be adjusted between 0.99 and 1.85 s. The closing times generated by the PWM between 30% and 100% are located in the desirable range of 1–1.5 s, which is adequate for ADLs. For practical use, we recommend setting the PWM percentage at 50% to generate approximately 1.2 s of the closing time, which is in the middle of the appropriate range. However, after using the prosthetic hand for a long time, the friction in the mechanism may increase. This friction may cause closing times to exceed the upper limit for ADLs. Therefore, the percentage of the PWM can be adjusted to compensate for the increased friction and keep closing times within the range.

C. Size and Weight

The prosthetic hand was designed by considering the average hand size. Its appearance was compared to a real human hand, as displayed in Fig. 11. The results of the qualitative comparison of the prosthetic hand's dimensions can be obtained, as detailed in Table II. Since the developed hand was intended to use with a prosthetic glove to improve the cosmetic appearance in the future, all dimensions were designed to be smaller than average men's hand dimensions [1].

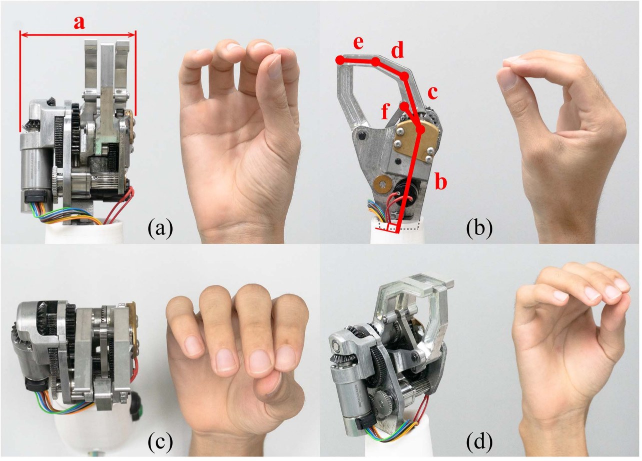


Fig. 11. Views of the prosthetic hand as compared to a normal human hand: (a) front view, (b) side view, (c) top view, and (d) isometric view.

TABLE III
WEIGHTS OF THE COMPONENT GROUPS OF THE PROSTHETIC HAND

Component Group	Weight (g)	Weight (%)
Frames and rotating supports	160	29.6
Motors	130	24.1
Gear trains	130	24.1
Finger and differential mechanism	90	16.7
NBDMs	30	5.5

The overall weight from the fingertips to the wrist connector is 540 g, which can be subdivided into component groups, as detailed in Table III. The weight of the prosthetic hand is dominated by frames, rotating supports, motors, and gear trains. The combined weight of the high-speed motor (5 W) and high-torque motor (9 W) is 130 g. Based on the comparison of the combined weight and the weight of an equivalent single motor (30 W/12 V FAULHABER Brushless DC-Flat Motors series 3216 + 44:1 Gearhead) that can operate at the same operating points, the weight is up to 298 g (2.3 times). This result is consistent with researches [10], [11] that a dual-motor tends to have a significantly lower weight than a single-motor. Furthermore, the equivalent single motor has a large diameter and requires twice the input power of the dual-motor.

V. CONCLUSION

In this research, a conventional single-DoF prosthetic hand using the dual-motor configuration which is capable of closing and opening motions was developed. The design of the prosthetic hand improves the grip force and grasp speed. The prosthetic hand can provide a maximum grip force of 80.2 N for carrying out most ADLs and also maintain without power consumption of 62.0 N, which exceeds the minimum requirement for practical use. Moreover, the prosthetic hand can generate a greater maximum grip force than other research prosthetic hands that use a single motor. The average grasp speed of 1.2 s also achieves the speed requirement, which can be adjusted to match the range of the allowable speed for ADLs. Moreover, because the grip force and grasp speed generated by this design are independently controllable without affecting one other, the design is flexible and can easily control the grip force and grasp speed compared to other prosthetic hands. Finally, the overall weight of the prosthetic hand is 540 g. Furthermore, the size and appearance of the design can be anthropomorphically compared to those of the average human hand.

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