การออกแบบและพัฒนาอุปกรณ์มือสำหรับให้ความช่วยเหลือเพื่อเพิ่มความสบายและทำให้ใช้งานร่วมกับมือมนุษย์ได้ดีขึ้น

นายศิวกร ตู้จินดา

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
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Design and Development of an Assistive Hand Device for Enhancing Compatibility and Comfortability

Mr. Siwakorn Toochinda

A Thesis Submitted in Partial Fulfillment of the Requirements

for the Degree of Master of Engineering Program in Mechanical Engineering

Department of Mechanical Engineering

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ศิวกร ตู้จินดา : การออกแบบและพัฒนาอุปกรณ์มือสำหรับให้ความช่วยเหลือเพื่อเพิ่มความสบายและทำให้ใช้งานร่วมกับมือมนุษย์ได้ดีขึ้น (Design and Development of an Assistive Hand Device for Enhancing Compatibility and Comfortability) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ. ดร.วิทยา วัณณสุโภประสิทธิ์, 100 หน้า.

ในปัจจุบัน มีหุ่นยนต์โครงร่างภายนอกส่วนมือถูกพัฒนาและนำเสนอ ทั้งในเชิงกายภาพบำบัดและให้ความช่วยเหลือ ซึ่งอุปกรณ์เหล่านี้ถูกออกแบบมาเพื่อใช้งานร่วมกับมือมนุษย์ โดยสามารถขยับนิ้วของผู้ป่วยให้ทำกิจกรรมต่างๆ ได้ด้วยตัวเอง ซึ่งเป็นการช่วยลดงานของนักกายภาพบำบัด และเป็นอีกหนึ่งทางเลือกในการทำกิจกรรมบำบัด แต่อย่างไรก็ตาม ยังมีผู้ป่วยโรคหลอดเลือดสมอง ที่ไม่สามารถฟื้นฟูกล้ามเนื้อของพวกเขาได้ เนื่องจากเลยระยะ 6 เดือนแรก ของการฟื้นตัวของเซลล์สมอง ส่งผลให้การกายภาพ ไม่สามารถบำบัดให้กล้ามเนื้อทำงานได้ดีขึ้นอีก ซึ่งถ้ามีอุปกรณ์สำหรับให้ความช่วยเหลือ ที่สามารถเติมเต็มหน้าที่การทำงานของมือ ที่ขาดหายไปของผู้ที่สูญเสียการควบคุมกล้ามเนื้อก็จะเป็นประโยชน์อย่างมาก แต่อุปกรณ์เหล่านั้น ยังไม่ได้มีการพัฒนาไปถึงขั้นที่สามารถนำมาใช้ในชีวิตได้จริง โดยหุ่นยนต์โครงร่างมือแบบอ่อนที่มีน้ำหนักเบาและขนาดที่เล็กซึ่งเหมาะสำหรับการพกพาไปใช้ในชีวิตประจำวัน กลับยังไม่สามารถสร้างการเคลื่อนที่ของนิ้วได้ใกล้เคียงกับการกำมือตามธรรมชาติของมนุษย์ ดังนั้น งานวิทยานิพนธ์ฉบับนี้จะมุ่งเน้นไปที่การพัฒนาระบบส่งกำลังผ่านเส้นเอ็น (tendon-driven mechanism) ของหุ่นยนต์โครงร่างมือแบบอ่อน เพื่อเพิ่มทำให้อุปกรณ์สามารถใช้งานร่วมกับมือมนุษย์ได้ดีขึ้น โดยที่อุปกรณ์สามารถขยับนิ้วของผู้ใช้งานให้สามารถทำกิจกรรมต่างได้อย่างเป็นธรรมชาติ ผลการทดสอบอุปกรณ์ได้บ่งชี้ว่า ระบบส่งกำลังที่นำเสนอสามารถจำลองการกำมือและหยิบจับสิ่งของได้อย่างใกล้เคียงกับการกำมือโดยธรรมชาติของมนุษย์ ทั้งเส้นทางการเคลื่อนที่ของปลายนิ้ว และองศาการกำของข้อนิ้วมือทั้ง 3 ข้อ ที่มีลักษณะสอดคล้องกัน

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ลายมือชื่อนิสิต ....

ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

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Currently, there are plenty of hand exoskeletons for rehabilitation and assistive purpose that have been developed. They have been designed for working with patient's limbs and can be used for hand positioning and executing task which help reduce therapist's workload and gives them an alternative way to rehabilitate patients. However, there are some patients with permanent impairment which cannot improve from rehabilitation further. Thus, portable assistive devices could greatly help them performing simple activities of daily living (ADL), but such device has not been fully explored yet, the present design of tendon routing cannot closely replicate finger orientation and motion during grasping. Improving the flexion tendon would increase the possibility of grasping for patients with hand disability. This research aims to develop a tendon routing design of soft exoskeleton to increase compatibility with human hand, while it can execute tasks and exercises more naturally compared to normal limbs to help stroke patients to live independently. Results convince that the proposed flexion routing can closely replicate human grasping motion with sufficient fingertip force to perform daily activities.

Department:	Mechanical Engineering	Student's Signature	....
Field of Study:	Mechanical Engineering	Advisor's Signature	....
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Introduction

1.1 Statement of Problem

Stroke kills millions of people each year while leaving many survivors with motor impairment. Losing hand function affects those survivors tremendously. Especially for doing activities of daily living (ADL) such as taking a bath, eating and grasping. Many of them suffer difficulty in life and cannot live life independently. In Thailand, there are 154,200 new patients each year and 12,600 dies [1].

The statistics from National Stroke Association reveals that only 10 percent of stroke patients fully recovered and more than 75 percent suffer from limb disability, while approximately 10 percent died after stroke as illustrated in Fig.1.1 [2]. Note that the impaired limbs take life dependency from the patients especially, hand, because it is the toughest limb to recover due to its complicated tendon and muscle system. Hand impairment usually be the main organ that the stroke patients cannot fully recover, while it is the most crucial limb of human as almost manipulative and precise tasks require proper hand functions.

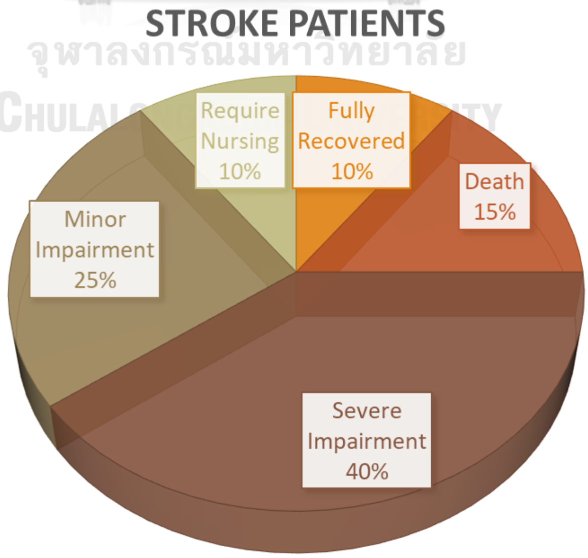

Figure 1.1 Proportion of stroke patients after stroke

To recover hand functions, the treatment has to be early as possible in order to have a chance to fully recover impaired hands [3], the golden period of rehabilitation is only six months after stroke. After that, the recovery of limbs function will drastically decrease.

In the first stage of rehabilitation, therapists help patients positioning their hands and do the passive range of motion exercise to reduce the chance of joints and muscles stiffness from spasticity [4]. When the spastic muscle has been recovered, therapists help patients performing daily activities until the hand function is fully recovered.

As mentioned above, the rate of successful recovery is quite low because the good mentality of the patient also being an important role in rehabilitation process as it takes long time before noticing the desirable result and it is also tedious, thus a lot of patients have given up. Moreover, spasticity, which is muscle stiffness disorder causes pain and muscle fatigue, it makes patients rehabilitate harder and unwilling to rehabilitate. Especially in Thailand, there is only few rehabilitation centers and it is not enough for current patients. Long travelling time to the rehabilitation center is another reason why they gave up. Thus, the aforementioned issues above are the important reasons that more than 75 percent of stroke patient are left disabled.

Currently, there are a plenty of hand exoskeletons for rehabilitation purpose that have been developed. They have been designed for working with patient's limbs and can be used for hand positioning and executing task which reduces therapist workload. However, there are a lot of patients suffer from muscle impairment that rehabilitation does not provide much. Thus, portable assistive devices could greatly help those performing simple ADLs to give them an independent life, but such device has not been fully explored yet. Thus, this research aims to develop a tendon routing design of soft exoskeleton to increase compatibility with human hand and wearability, this means that the exoskeleton can execute tasks and exercises more naturally compared to normal hand to help stroke patients live independently.

1.2 Objectives

1. To design an assistive hand device which can operate with human hands.
2. To manufacture an assistive hand device which can manipulate human hand.
3. To perform assistive tasks with the device which are range of motion grasping and power grasping objects.

1.3 Research Scopes

1. Designing and manufacturing an assistive hand device with an actuation unit and a control unit.
2. Evaluating the design concepts.
3. Implementing the hand functions with the device by performing range of motion (ROM) grasping and object grasping.

1.4 Approaches

1. Studying biomechanics of human hand and fingers.
2. Reviewing hand exoskeletons and related works.
3. Analyzing and summarizing the current problems.
4. Specifying design requirements.
5. Working on the conceptual designs.
6. Implementing a prototype based on the conceptual designs.
7. Evaluating and Re-designing the prototype and manufacture the actuation and the control unit.
8. Testing the assistive hand device and the actuation system

1.5 Benefits

1. Introducing the new concept design of an assistive hand device.
2. Being an assistive device for people who have problem with impaired hand.
3. Being a novel design for making a practical assistive hand device.

Chapter 2
Literature Review

This literature review will provide necessary knowledge and insight about hand exoskeletons and their purpose in the field of rehabilitation and assistance. The content includes elementary knowledge of stroke recovery, biomechanical model of human hand, and the review of related hand and finger devices.

2.1 Stroke Recovery

After stroke, the brain has a mechanism called neuroplasticity, this allow the brain to recovery itself by rewiring neural pathways of the damaged neuron to the healthy brain areas. Thus, purpose of rehabilitation is to encourage neuroplasticity. Rehabilitation should start as early as possible because patients have only 6 months until neuroplasticity stops working. Recent studies suggest that rehabilitation with repetitive motion enhances neuroplasticity and lead to the recovery of motor function in stroke patients [5]. Not only physical rehabilitation but mental rehabilitation like imagine about him/herself performing motor function also enhances neuroplasticity [6]. In recent years, there are plenty of robotics devices which have been proposed in rehabilitation program, since it has the potential to execute rehabilitation task automatically and it can be used to monitor the result of the sessions as well as home rehabilitation [7].

However, after six months of rehabilitation if patients cannot fully recover, their chances decrease drastically. Their hand function remains as it is for the rest of their lives or it could get slightly better with daily rehabilitation. Since there are more than 75 percent of post stroke patients who live with muscle impairment [2]. Well-performed assistive hand devices will match the need of patients or people who have impaired hand function.

2.2 Biomechanics of human hand

Human hand consists of four fingers and one thumb. Each finger except thumb has three phalanges: Distal Phalange, Middle Phalange, and Proximal Phalange, while thumb has only two phalanges: Distal and Proximal as shown in Fig. 2.1. All the proximal phalanges are connected to the bones which is called metacarpals. Those phalanges are connected by joints called Metacarpophalangeal (MCP) joint, Proximal Interphalangeal (PIP) joint, and Distal Interphalangeal (DIP) joint.

DIP, PIP, and MCP joints have range of motion (ROM) of 0 - 85°, 0 – 105°, and 0 – 100°, respectively [8]. The critical issue in designing hand devices is that human joints are not perfect revolute joints, their center of rotation slightly translate during flexion.

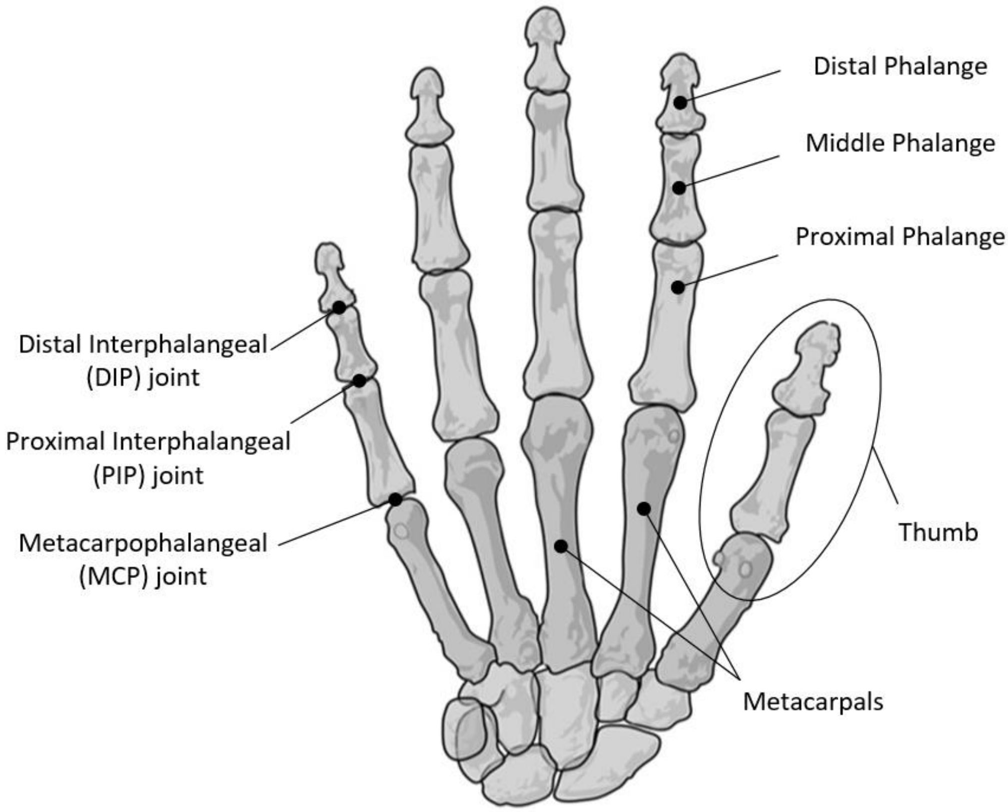

Figure 2.1 Biomechanical model of human hand

2.3 Activities of Daily Living (ADLs)

In daily life, human encounter routines and unexpected daily tasks which called activities of daily living (ADLs), most of the tasks do involve interaction with objects. To accomplish those tasks, we use both hands as the main tool to manipulate objects. As there are various tasks in daily life, Matheus et al. have categorized ADLs into 3 main groups [9], which are: Domestic Activities of Daily living (DADLs) which involve housekeeping and food preparing tasks, Extra domestic Activities of Daily living (EADLs) which are outside-of-the-home tasks, and Physical Self-Maintenance (PSM) which are feeding, bathing, grooming, etc.

2.3.1 Hand functions

Human hand has 2 roles in daily life, the first one is for prehension or object manipulation, another is for sensing. To manipulate different objects, the hand has plenty of gripping gesture as distinguished into power grip or gross hand function and precision grip or fine hand function [10].

2.3.1.1 Power grip

Power grip or gross function has been used when we need to perform forceful tasks and do not need precision such as holding, squeezing or pulling objects. Three types of power grip have been characterized by hand gestures which are hook grip, cylindrical grip and spherical grip. Design of the assistive hand device in this research will focus on performing power grip with grasping motion, since power grip is the simplest hand function to be executed.

Hook grip has been used for pulling or holding bags with every finger flexes and maintains the shape of hook as shown in Fig. 2.2a. While cylindrical grip is for holding cylindrical objects with the thumb and index finger form a circle loop to maintain the force output (see Fig. 2.2b). Lastly, spherical grip has been used for holding or manipulating round or ball-shaped objects with the hand gesture similar to cylindrical grip, but it more flexion angle as shown in Fig. 2.2c.

Figure 2.2 (a) hook grip, (b) cylindrical grip, (c) spherical grip

2.3.1.2 Precision grip

Human use precision grip when the task needs precision or fine movement such as manipulating small object. Precision grip can be separated into three types which are pad-to-pad prehension or pulp pinch, tip-to-tip prehension or tip pinch and pad-to-side prehension or key pinch.

Pad-to-pad prehension or pulp pinch is performed by using volar side of the thumb to touch volar side (or pulp) of others finger to form a loop. For example, using volar side of thumb to perform fine gripping with index or middle finger or both as shown in Fig. 2.3a and Fig. 2.3b.

Tip-to-tip prehension or tip pinch has been used for manipulating miniature objects such as needle or pin. It is performed by using thumb fingertip to form a circle loop with others finger as illustrated in Fig. 2.3c.

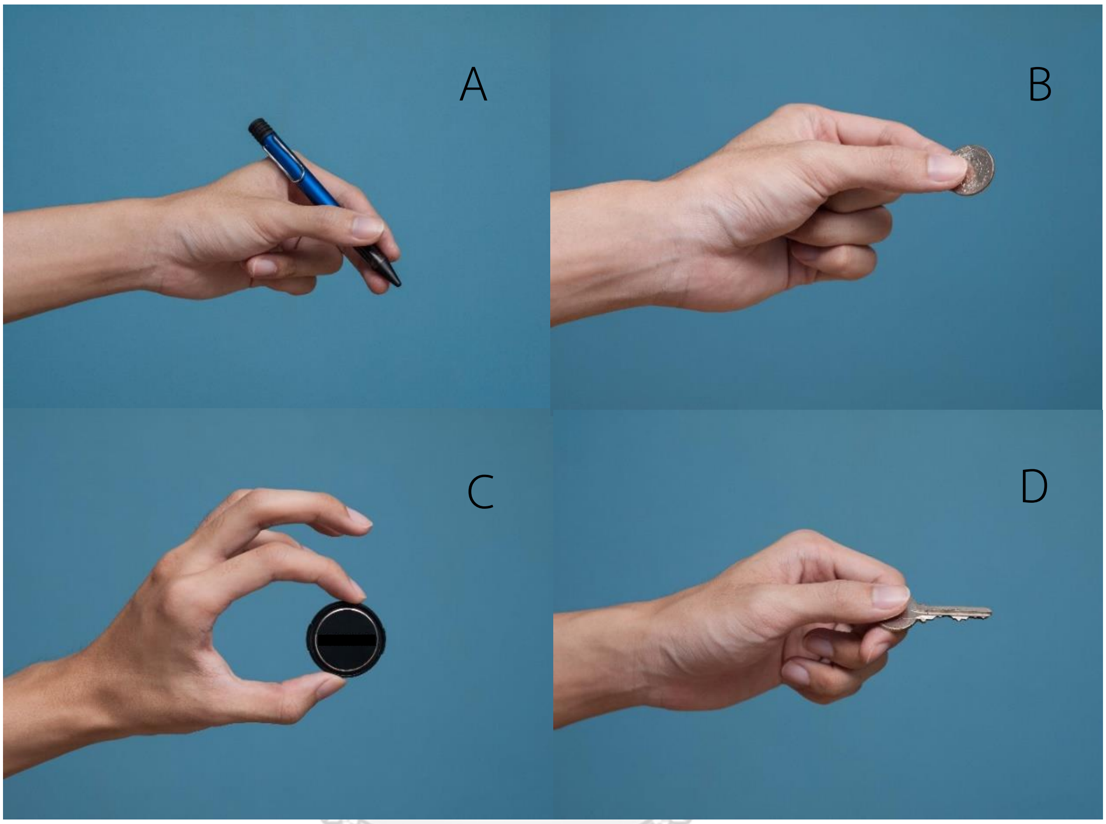

Figure 2.3 (a) 3-point pulp pinch, (b) 2-point pulp pinch, (c) tip pinch, (d) key pinch

Lastly, the pad-to-side prehension or key pinch is named according to the way human manipulate a key, with pulp of the thumb connects with the lateral side of index finger which stabilizes an object during hand rotation. Although the human hand has various ways to manipulate object, this work will focus on power grasping since it is the simplest hand gesture and it is one of the most tasks performed in daily life.

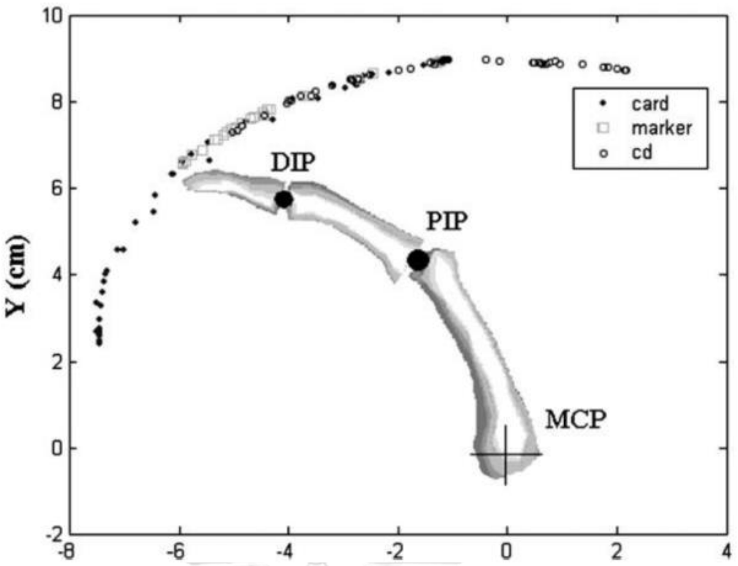

Figure 2.4 Fingertip trajectories from Kamper et al. experiments [11]

However, in attempt to perform whether precision or power grip, human fingers flex in the same pattern independent of its profile. Kamper et al. conducted an experiment on 10 healthy subjects. The subjects performed 20 trials of reach-to-grasp motion with various objects, such as different size of plastic cups, a CD, a card, a softball, and a marker. The result shows that fingertips were moved in curved paths and their profile are quite consistent across subjects even though the grasped objects' profile are completely different as shown in Fig. 2.4 [11].

Moreover, the result of 20 trials grasping one subject fingertip positions is shown in a logarithmic spiral plot (Fig. 2.5) to give another aspect of fingertip trajectory compared to its workspace. Radius = 0, denotes the MCP joint and at 90° is the index fingertip neutral position, while radius is a distance from the MCP joint to the subject's fingertip. Dense black areas are the actual fingertip positions during experiments and the grey points are the actual fingertip workspaces.

From the logarithmic plot below, the fingertip positions show the remarkable result that human fingertips are curved paths and repetitive. The black areas started from 75°, where the subject extends his/her fingers out before grasping, then, flexed his/her to 150° approximately. Note that the black area that indicates the actual fingertip positions is a small portion compared to the fingertip possible workspace. In addition, the radius change is below 2 centimeters during grasping period but information of each joint angular displacement cannot be seen from this plot.

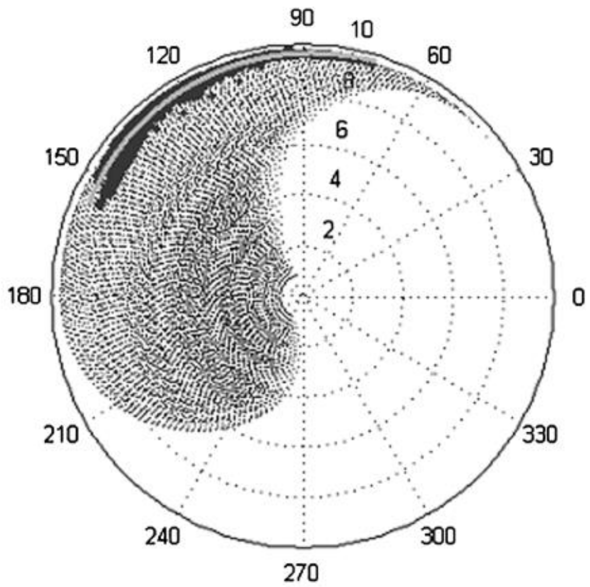

Figure 2.5 Polar plot of fingertip trajectory from Kamper et al.'s experiments [11]

Further analysis from Kamper et al. attempted to give deeper insight from the experiments by relating MCP, PIP and DIP angular displacement with linear relationship. Subjects' joint angles through the grasping phase were used to compute ratio between PIP-MCP angle and DIP-PIP angle (except thumb) as shown in Table 2.1 [11]. The linear regression was used to define relationship between joint angles, to compare the result in an easier manner.

The averaged ratios of PIP-MCP of every finger are all less than 1, which indicates that the MCP flexion angle was significantly greater than PIP flexion angle. While DIP-PIP ratio also has the same trend, which means that DIP joint has the slightest movement in all joints.

Table 2.1 The averaged ratio between PIP-MCP angle and DIP-PIP angle of the healthy subjects across Kamper et al.'s experiment trials [11].

	PIP-MCP		DIP-PIP	
Finger	Slope	R^2	Slope	R^2
Index	0.26	0.31	0.32	0.65
Middle	0.37	0.36	0.36	0.71
Ring	0.72	0.46	0.16	0.51
Little	0.70	0.47	0.25	0.59

Thus, this result brings an excellent insight in human object grasping. The subjects tend to repeat their natural fingertip trajectories instead of creating new finger orientation in every object interaction. In addition, MCP joint is the main executor of the grasping, subjects move every digit to move the fingertips and wrap their fingers around objects rather than rely on moving PIP or DIP joint only. This fact points out that an assistive exoskeleton does not need complex mechanism to provide same trajectories over grasping period. The mechanism with an underactuated mechanism is also possible for this requirement.

Besides trajectory of the exoskeleton, force output requirement generated by an assistive device has to be determined, daily life objects weight range and friction coefficient between hand and objects have to be specified. Fortunately, Matheus et al. have conducted the experiments to find friction coefficient of various daily household objects and 6 common surfaces in household which are granite, furniture linoleum, glass, unfinished wood, stainless steel and birch wood veneer [9].

Sixty-five household objects which weigh between 10-1500 g. were tested in 6 different surfaces as described, the result shows that the data of friction coefficient has an average value of 0.300 and median of 0.255 with a lot of outlier values because of some objects have high amount of friction coefficient than any others subjects such as the objects with rubber-based which its coefficient can reach 0.8, while the others are in range of 0.15 to 0.35 as illustrated in Fig. 2.6 [9].

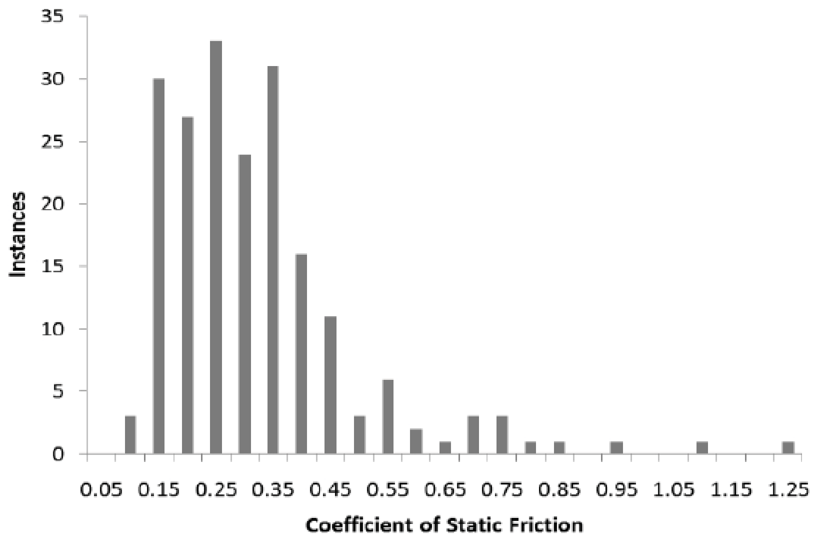

Figure 2.6 The distribution of static friction coefficient [9]

Fig 2.7 below, is only some part of 65 household objects collected by Matheus et al. [9]. Note that more than 90 percent of the objects weigh below 500 g. Thus, it is fine to use 500 g. of weight as a design specification of the assistive device force output, while the friction coefficient from the experiment is measured between surfaces and objects which is not the desired value. Therefore, the force output requirement calculation will use the friction coefficient of 0.255 (very slippery condition) to provide some safety factor.

Object	Categories	Source(s)	Mass (g)	Dims. (cm)
Food Preparation				
bag of coffee beans, paper	D1, P1	[36]	n/a	n/a
baking pan (non-stick metal)	D1, P1, D2	[34]	351.9	21x11x8
bottle cap, metal	D1, P1, D2	[24, 31]	n/a	n/a
bowl, glass	D1, P1, D2	[28, 31]	545.1	18x8
box of crackers, cardboard	D1, P1	[37]	194.6	6x13x20
eating utensil, stainless steel	D1, P1, D2	*most sources	47.6	18x4x1
can of preserved food, steel	D1, P1		473.9	7x11
bowl, ceramic	D1, P1, D2	[28, 31]	479.3	13x8
juice carton (empty), paper	D1, P1, D2	[34]	74.5	10x10x24
coffee can (full), tin	D1, P1	[24]	397.4	10x18
dinner plate, ceramic	D1, P1, D2	[28]	798	27x3
drinking straw, plastic	D1, P1	[28]	n/a	n/a
beverage bottle, glass (empty)	D1, P1	[31, 32, 36]	213.7	6x24
beverage bottle, glass (full)	D1, P1	[31, 32, 36]	597.1	6x24
jar, glass	D1, P1, D2	[25, 34]	289	7x16
jar lid, steel	D1, P1, D2	[25, 30, 34]	n/a	n/a

Figure 2.7 Example of household object [9]

2.3 Hand and finger exoskeletons

Currently, the exoskeletons have been proposed in rehabilitation field and being assistive devices, because of its repeatability, precision and robustness. Hand exoskeletons are the most complicated and challenging among all types of the exoskeleton because numerous DOF of the hand and limited usable mounting space.

Generally, an exoskeleton exerts force on each finger phalanges, making joints of a user rotated to perform hand gestures. Early designs consist of link and joint mechanisms, Kang et al. [12] use the word “rigid frame exoskeleton” to call this kind of exoskeleton [13-15] as shown in Fig. 2.8b [12]. They are driven by actuator mounted on the hand. The mechanism can control position and generate force at finger phalanges to interact with daily-life objects. But it has drawback such as, high amount of weight that burdened wearer, misalignment of the mechanism joints and finger joints which causes interference while operating and leads to the undesirable translational force exerted on the phalanges.

Cempini et al. suggest that these problems bring up the compatibility and wearability issues. To increase the physical human-robot interaction (pHRI) of the exoskeletons [16], the mechanism with redundant DOF has been proposed [16-19] to provide translation motion between MCP-PIP and DIP-PIP joint for reducing undesired force. While the remotely transmission using Bowden cables to transmit force became an extensive choice because it can tremendously reduce weight of the exoskeleton. Instead of inventing portable exoskeleton, some propose station-like designs that the mechanism is attached on a frame or platform [18]. This removes load and inertia on wearer’s hand while trading off with restricted arm movement and no regulation of the hand.

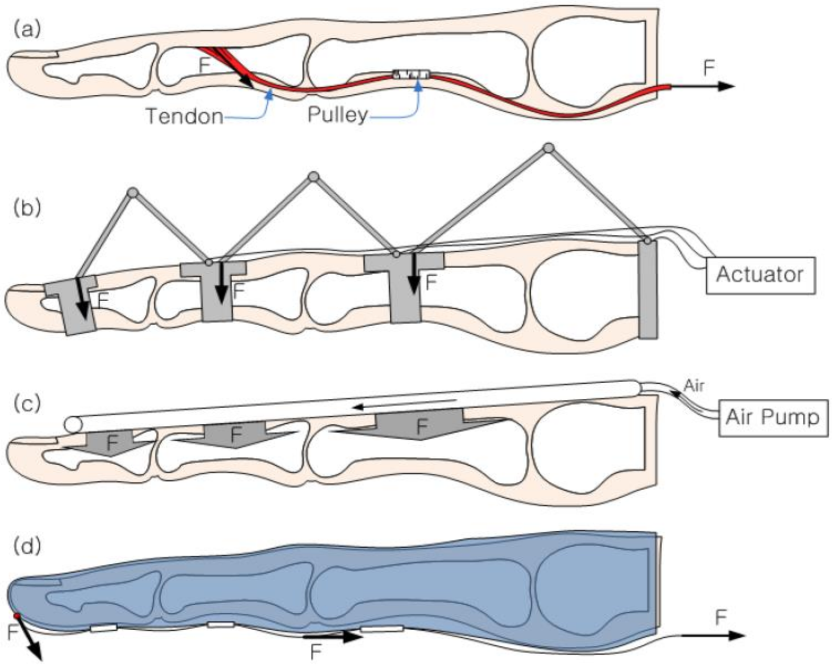

Figure 2.8 (a) musculoskeletal model of human finger,

(b) joint and link mechanism,

(c) polymer-based pneumatic actuation,

(d) tendon driven mechanism [12]

However, the aforementioned mechanism still does not compact enough, the soft exoskeletons have been invented to increase wearability and compatibility by using fabric glove or polymer as its body [12, 20, 21] and tendon routes to remotely transmit force (Fig. 2.8d). The soft mechanism with tendon routing has a very low-profile but trading off with some non-linearity in actuation and weaker force generated from this mechanism, thus, the soft exoskeleton purpose is aiming to assist weakened or impaired hand patients more than stroke patients with increased muscle tone.

The state-of-the-art mechanisms such as exoskeletons with soft actuator [22] as illustrated in Fig. 2.8c. and multi-layered spring mechanism [23, 24] have been proposed for being alternative choices to integrate human with robotics system. The reviews of the related hand exoskeleton work have been summarized in the next section which include rigid frame exoskeletons as well as soft exoskeletons.

2.3.1 Rigid frame exoskeletons

The link-based rigid frame exoskeletons use joint and link mechanism to control finger joints. The transmission links usually located on the dorsal side of the fingers because there is not enough space to place it between fingers and at the palm of the hand will be used to manipulate objects. Some are based on platform to ground their operating inertia [18]. The link-based exoskeletons are the most common frame type for exoskeletons which is good in case of position control and the variety of mechanism designs, but the greatest advantage of link and joint mechanism is the force exerted on the tip of the mechanism or on each joint can be monitored and controlled by closed-loop controlling.

There are 2 major kinds of mechanism, which are closed kinematic chain and open kinematic chain mechanism. The first one is similar to the 3 actuated joints robot attached to user’s fingers to generate force at finger phalanges [16, 25, 26]. While the latter one takes the user’s fingers as its own linkage while operating [18, 26] with the ability to self-form remote center of motion to coincide user’s joints. The closed- chain mechanism usually takes lateral finger space with its lateral joints, while the open chain mechanism usually relies on chain of four-bar or three-bar linkages at the upper side of the fingers.

However, the design faced some problems as joint misalignments when finger joints and exoskeleton joints do not coincide along their workspace which cause by anatomical of human joints, which are not perfect revolute joints. This leads to another issue that is interference of the device and fingers which cause uncomfortable due to exertion of undesired force on phalanges. While minor problems are the appearance of rigid frame exoskeleton that its weight burdens wearer and its profile looks threat to use in daily activities.

The early design of a finger exoskeleton with 4 DOFs has been proposed by Wege et al. [14] as shown in Fig. 2.9. The linkage has been used to transmit forces from pulleys to each phalange. Two Bowden cables can actuate the pulley in bi-directional movements. The design is a wearable exoskeleton which allows open palm to interact with objects while provide almost full ROM for gripping. Rotational joints of the exoskeleton have been placed on the side of DIP and PIP joint which cause no misalignment between human-robot joint theoretically. However, the closed-chain mechanism causes interference at every phalange. Moreover, the mechanism is considered cumbersome and complicated to be implemented on 5 fingers.

Figure 2.9 Wege's exoskeleton, 2005 [14]

In 2009, Chiri et al. [17] proposed superior design as illustrated in Fig. 2.10. The HANDEXOS is a compact design of finger exoskeleton actuated by tendon driven transmission with the closed kinematic chain. The finger exoskeleton joints have been designed to be align with the wearer's DIP and PIP joints while operating. It uses 3 actuators to control each joint flexion separately, while the extensor using one underactuated tendon driven only. Moreover, The HANDEXOS has 2 redundant DOFs for the MCP joint which makes the mechanism adaptable to joint misalignment at MCP. Thus, this mechanism reduces interference between proximal phalange and the exoskeleton because the MCP is not an ideal revolute joint.

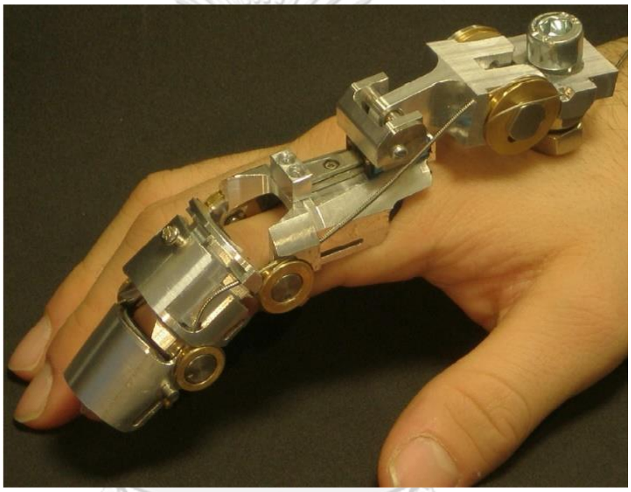

Figure 2.10 HANDEXOS, 2009 [17]

However, this design takes plenty of space between fingers, implementing this design with 5 fingers might be a problem. In addition, it is possible that interference might be occurred at distal and middle phalanges due to misalignment of exoskeleton's joint placement.

Another hand exoskeleton that has been proposed in rehabilitation field. The concept of this exoskeleton is to provide fixed finger path for each finger as shown in Fig. 2.11 (flexion-extension of MCP and PIP joint) [13]. Major advantage of this design is the remote center of rotation (RCM) is ideally aligned with each finger joint along the path, result in no misalignment of finger joint and mechanism RCM. Neglecting to control DIP joint makes the design less complicated and limits its weight to 500 g. While, the actuation part consists of five linear actuators powered by pneumatic to control each finger separately.

Even though the mechanism actuates one degree of freedom only, the design is considered a high profile one. To implement this mechanism on assistive device is quite inappropriate.

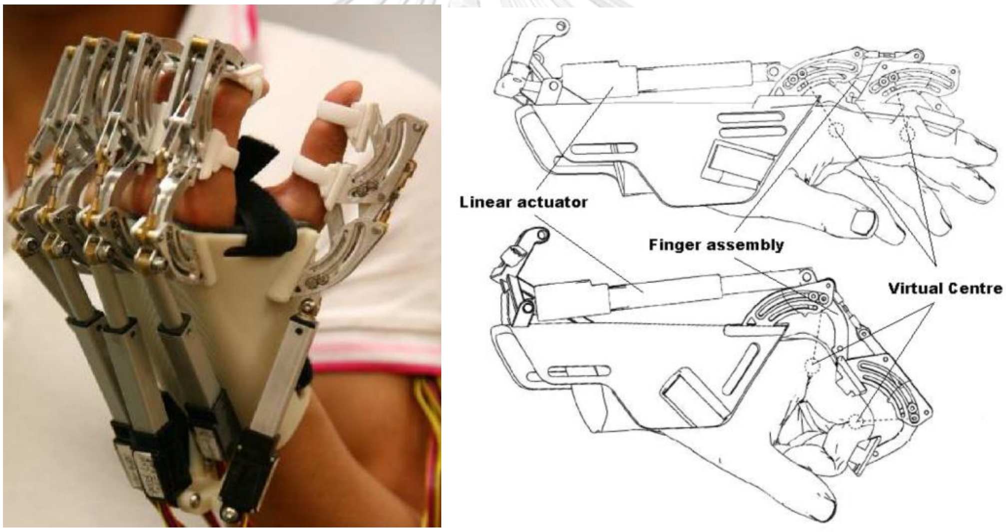

Figure 2.11 Ho et al.'s exoskeleton, 2011 [13]

The low-profile finger exoskeleton has been proposed by Burton et al. to increase wearability and comfortability [15]. The compact design has been placed on the dorsal side of the finger to minimize misalignment of joints. This design is achieved by using half round pulley to exert only perpendicular force on the proximal phalange with the help of Bowden cable transmission to actuate the system bidirectionally. While the revolute joints are meant to align with PIP and DIP joint.

This hand exoskeleton is considered a very compact one, but it takes space between lateral side of the finger which cause problem to imply this mechanism for whole hand. Moreover, the design may cause interference at the distal and middle phalange due to the closed-chain profile and the idea of half round pulley cannot be implied on those phalanges because of the space is not enough.

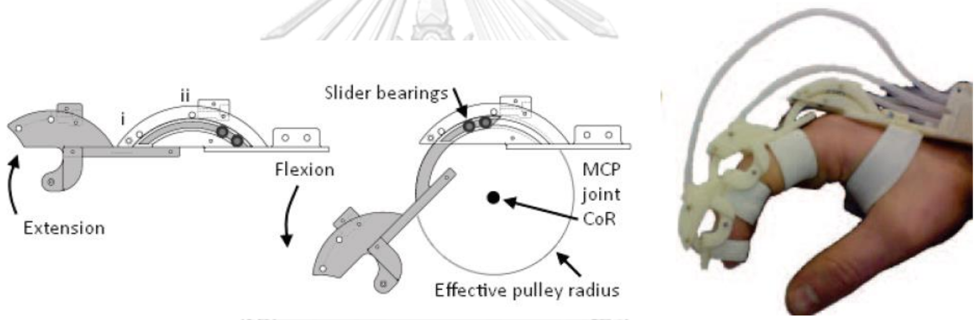

Figure 2.12 Burton et al.'s exoskeleton, 2011 [15]

Festo's proposed commercial hand exoskeleton for rehabilitation and teleoperation usage called the Exo-hand [27]. This closed-chain exoskeleton actuates each finger (3 DOF) except thumb with only one pneumatic actuator (see Fig. 2.13). While thumb has two actuators to flex and rotate for a better grasping gesture. The mechanism for each finger consists of three loops of four-bar linkage connected serially to achieve fine precision flexion path. Two revolute joints are placed aligned with PIP and DIP while operating.

However, the downside of this design with the closed kinematic chain is the interference problem at every phalange. The second issue is the range of motion, the fixed linkage limits its range of motion and it is quite difficult to exceed full ROM for gripping because the limitation of four-bar mechanism.

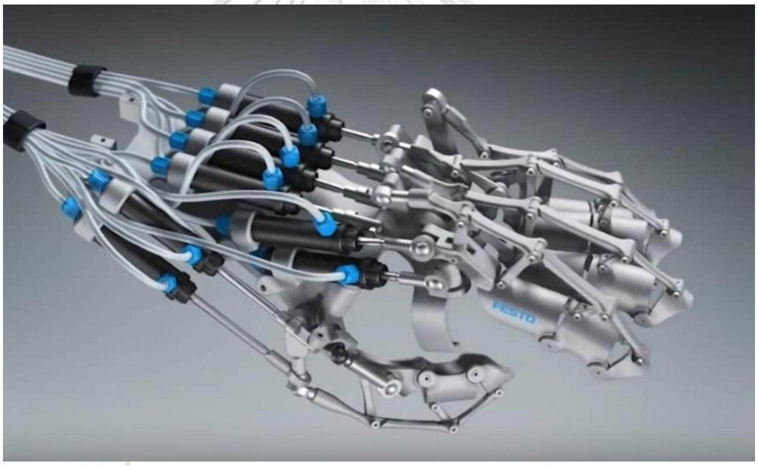

Figure 2.13 Festo's Exo-hand, 2012 [27]

Another low-profile exoskeleton has been proposed by Weiss et al. [25]. A unidirectional exoskeleton for stroke rehabilitation or people with weakened extensor muscle have been proposed. The state-of-the-art of this design is to implement 3-D printed part for whole exoskeleton body with sliding pulleys at MCP joints in which its RCM is co-incident with MCP's. The rotational joints are placed aligned with DIP and PIP joint. The under-actuation with Bowden cable transmission is used to extend user hand, tendon is attached to the attachment bead as shown in Fig. 2.14, then, routed through guiding point on the middle and proximal phalange to achieve 3 actuated DOF per finger. The dimension of this hand exoskeleton parts can be customized from hand parameterization process.

Although the design has interference because it is a closed-chain mechanism, but its overall profile of this customable exoskeleton is considered low profile comparing with other design with linkage transmission.

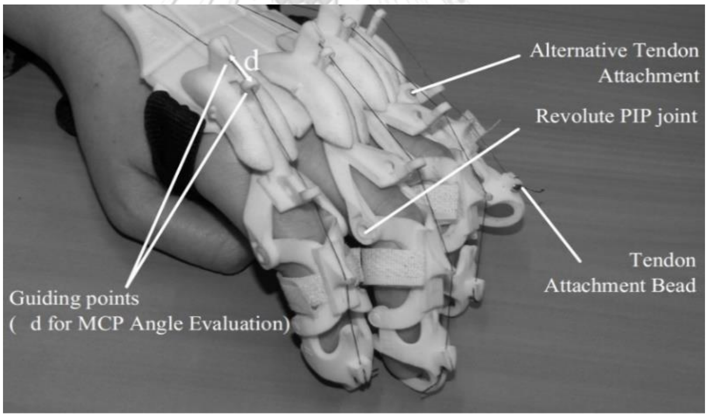

Figure 2.14 Weiss et al.'s exoskeleton, 2014 [25]

In the recent years, researchers attempt to increase the physical human-robot interaction (pHRI) of the hand exoskeletons by making the device cause less undesired force and interference and optimizing its weight. Cempini et al. proposed the design of the rigid frame exoskeleton has been actuated 3 DOF for each joint and another 2 passive DOF for MCP flexion/extension and abduct/adduction [16]. Four pulleys are placed on each finger lateral side as transmission paths for finger flexion and extension. Each pulley connects to the next one with a tendon loop. When the first one at MCP is actuated the others rotates, resulting in under-actuation of the mechanism. One side of the pulleys has been used for flexion, while another is for extension. The idea of redundant joint is also applied to the thumb to achieve lowest profile possible.

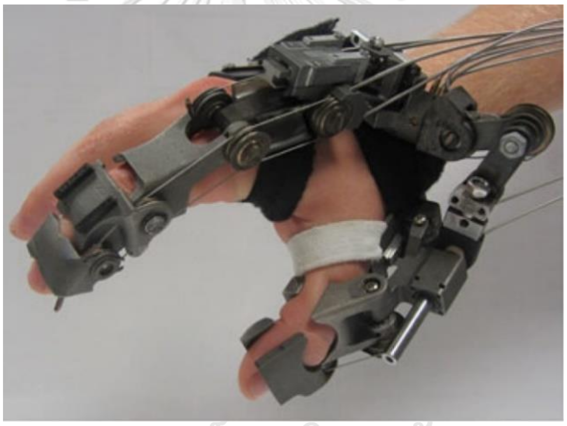

Figure 2.15 HX, 2015 [16]

On the other hand, the lateral joint design with closed-chain mechanism always suffers from insufficient space between lateral side of the fingers which makes it hard to implement the design on every finger. Thus, Surakijboworn et al. proposed a platform based tendon driven exoskeleton to solve joints misalignment and interference problem (see Fig. 2.16) [18]. The sliding joints in every phalange makes the mechanism to be able to self-form remote center of motion at finger joint along its workspace. With the six-bar mechanism, force exerted on every phalange is always perpendicular to them. Theoretically, there is no translational force occurred on user's finger which is perfect for ROM rehabilitation (the force which is act on phalanges in its axis, it causes uncomfortable feeling and is considered inappropriate to be exerted on phalanges continuously).

However, the design is considered high profile for being an assistive device's mechanism and it is quite difficult to optimize size of the six-bar mechanism to achieve full-hand exoskeleton.

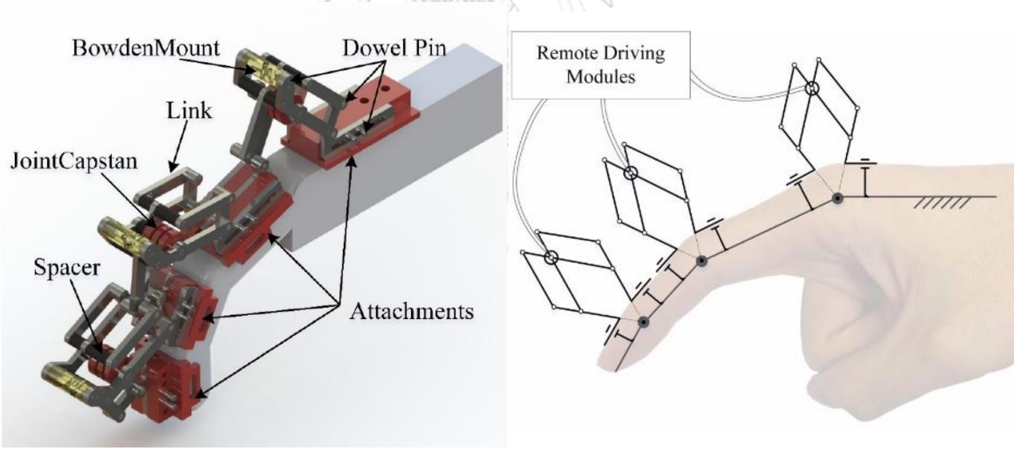

Figure 2.16 Surakijboworn et al.'s exoskeleton, 2015 [18]

An open-chain exoskeleton has been developed by Youngmok Yun et al [19, 26] to achieve more comfortable in rehabilitation session .Three four bar loops with sliding joints allow the mechanism to locate at the upper side of phalanges, result in zero interference because linear motion allow the finger to move freely without hindrance. While the upper joint can self-form four bar loop with the finger joints, so the misalignment of joint is not to be concerned. In the other hand, this result in high profile mechanism and transmission, but the developers claim that UT hand weighs below 200 g.

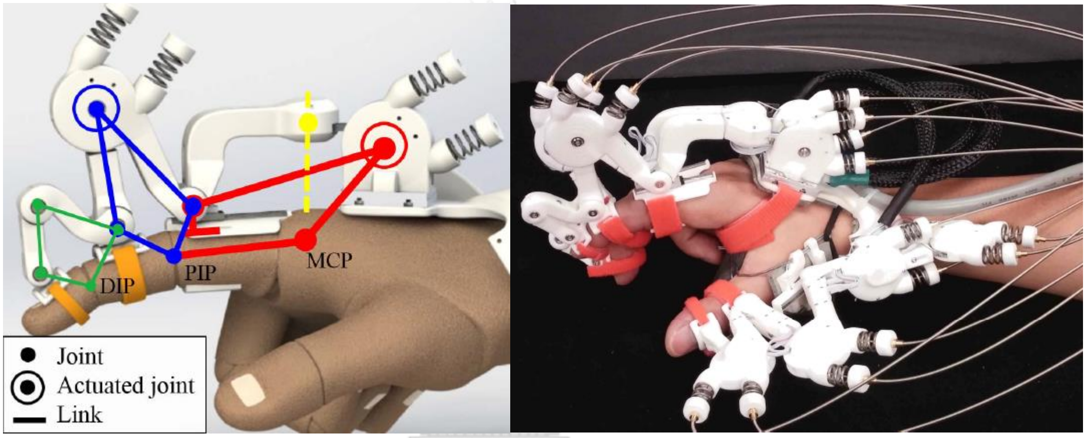

Figure 2.17 UT hand, 2016 [26]

In conclusion, the currently design of rigid frame exoskeleton aim to optimize its compactness and appearance to improve pHRI. The Bowden cable transmission has been used widespread because its advantage of remotely actuation which reduces overall exoskeleton weight drastically. Furthermore, many designs concern about interference and joint misalignment as they provide redundant DOF to make their mechanisms operate with less or no interference. However, by implementing those mechanism, rigid frame exoskeleton became more complex, which makes it difficult to be optimized further because working space on human hand is quite limited.

Even though the ability to control each phalange or manipulate finger precisely, the rigid frame exoskeletons usually heavy and its profile is cumbersome relative to human hand, that many patients are unwilling to use it for a rehabilitation session. Due to limitations of the mechanism, soft exoskeleton has been proposed.

2.3.2 Soft exoskeleton

To make exoskeletons practical in daily use, plenty of fabric-based tendon driven exoskeletons or soft exoskeletons have been developed because they are compatible and light-weight because their body are based on soft materials such as fabric or rubber gloves. While the transmission was designed based on the tendon and muscle system in human hand by routing tendon paths on the glove, when the tendon is actuated, tendon will exert force on phalanges, providing desired movement of finger. For example, the fabric straps act as mechanical pulleys between each joint as illustrated in Fig 2.18 [20]. Pulling the tendon on one finger can achieve 3 DOFs (flexion of MCP, DIP and PIP joint) as the tendon between finger joint has been shortened.

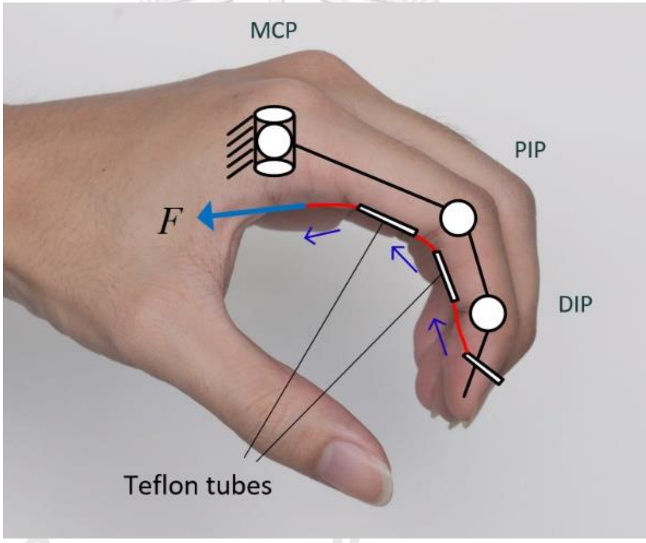

Figure 2.18 Tendon routing transmission in soft exoskeleton

Furthermore, the soft exoskeletons utilize benefits of the underactuated tendon routing mechanism to reduce number of actuators. Moreover, the tendon driven can be remotely operated from a distance. It makes the exoskeleton and the actuator separable and reduces exoskeleton's weight tremendously.

However, this type of exoskeleton encounters non-linearity of the system because the fabric glove is a stretchable material which makes it difficult to control the finger trajectory accurately. In addition, its force transmission has a lot of friction in the tendon routing paths. Thus, it provides weaker force compared to the link and joint mechanism.

To develop the assistive hand device, the related soft hand and finger exoskeleton designs have been reviewed and analyzed.

The first one is a commercial soft exoskeleton from Bioservo called SEM glove. It was released in 2012 [28]. The SEM glove is a 3 fingers exoskeleton along with a portable power unit which can be separated as shown in Fig.2.19b. This hand exoskeleton has been developed to help those who have weakened hand muscles to gripping objects in daily life. It will provide extra force at middle finger, ring finger and thumb. The force is transmitted by tendon route actuated from linear actuator located at forearm. The tendon paths are routed underneath the glove, it starts from palm of the hand to both side of each finger and meets at the fingernail. Thus, each finger has its own loop which is driven by single actuator. While actuated, tension in the tendon paths will make user's fingers flexed with 3 DOF and increase their gripping force. The SEM glove has to trade-off between the maximum force generated and the safety of the wearer because the tension in tendon may harm user. Thus, force in tendon is limited to 20 N which generates 3-4 N at the fingertips. Note that this exoskeleton only provides enough force for performing ADLs and aims to reduce its weight as much as possible while keeping it simple for practical use.

Figure 2.19 (a) the SEM glove and the actuator (left),
(b) separately power unit (right), 2012 [28]

In 2013, Delph II et al. proposed the design of a portable soft exoskeleton which attempt to integrate soft robotics with daily usage. Developers proposed separable tendon driven of each finger, while the transmission were routed and systemized with a control unit in a backpack as shown in Fig. 2.20 [21].

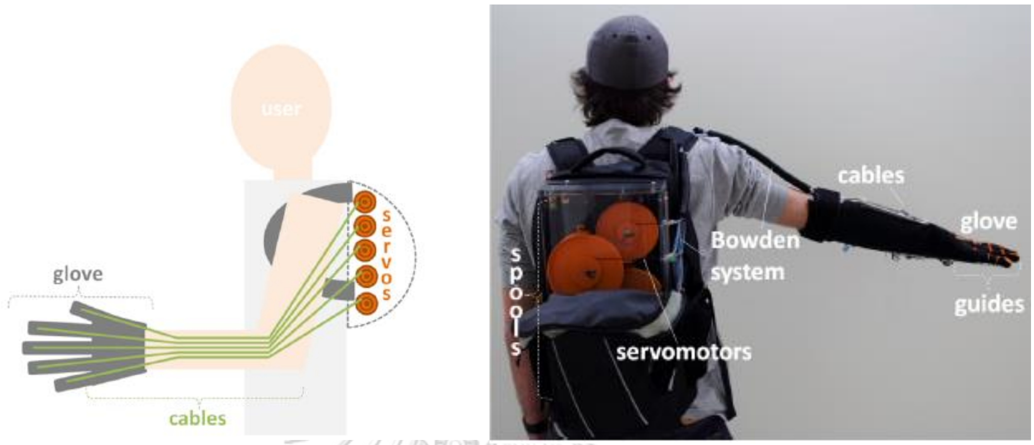

Figure 2.20 Delph II et al.'s exoskeleton, 2013 [21]

The state-of-the-art of this exoskeleton is its flexion and extension can be achieved by using two-level spool with only one actuator. Two level spools have been used to hold the tendon as shown in Fig. 2.21. The flexion tendon is attached to the outer side of spool because flexion tendon distance used is 2 times longer than the extension distance. Thus, the extensor tendon is fixed with the inner level of the spool and the flexion is attached with the outer level because when the spool rotates, it winds tendon distance more than the opposite. Well-calculated tendon fixation and spool dimension can achieve flexion before the extensor tendon has been winded in other direction. Meanwhile in the extension driven, the tendon makes fingers opened before the flexor starts to rewind in the opposite direction (On the right of Fig. 2.21).

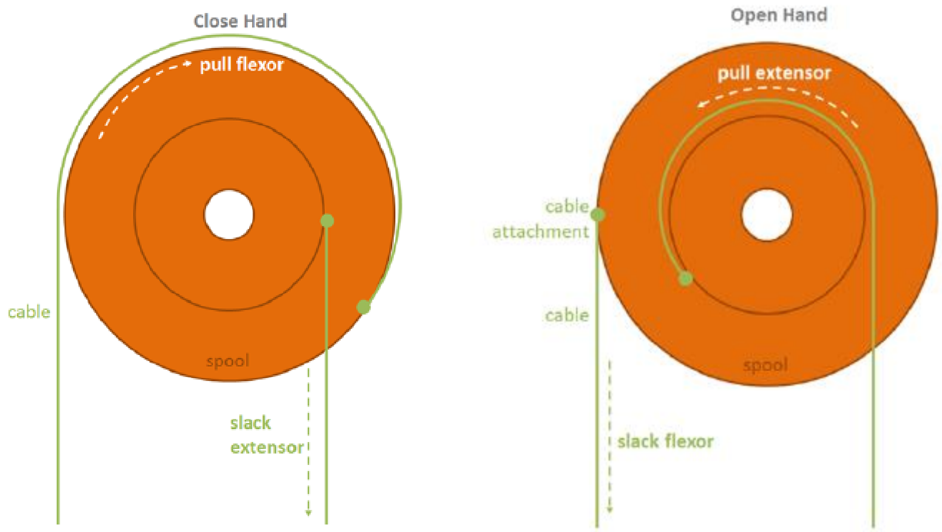

Figure 2.21 Two level spool mechanism [21]

The next soft exoskeleton has been proposed by In et al. The Exo-glove is a three-finger soft exoskeleton which is actuated by tendon driven transmission (see Fig. 2.22) [12, 20]. Developers proposed the idea of implanting Teflon tube, which is a low friction material when using as paths in tendon driven mechanism. While operating, the motor winds the flexion tendon into the spool, shortening overall distance of the flexion tendon. Resulting in movement of flexion of the thumb, index, and middle finger by using only one actuator. This concept is also applied to the extension tendon path as well.

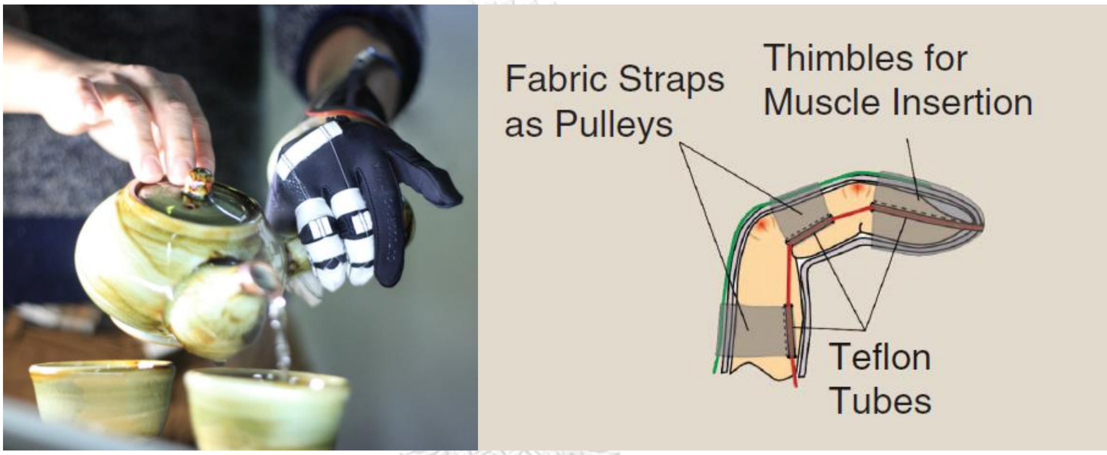

Figure 2.22 The Exo-glove with its tendon routing mechanism, 2012 [20]

The flexion tendon of index and middle finger has been routed as one loop as shown in Fig. 2.23. While operating, if one finger stuck, another can move freely. The performance of transmission is relying on low friction of cable routing. This concept is very useful for adaptive grasping when the object has complicated profile and the under-actuation mechanism in the Exo-glove also benefits from using less actuator compared to the rigid frame exoskeleton.

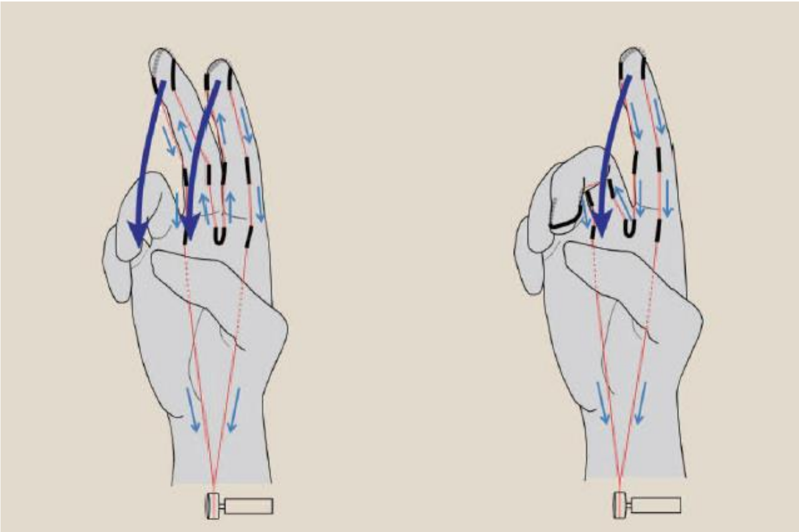

Figure 2.24 The Exo-glove's cable routing [20]

Later, Kang et al. proposed novel idea of using fabricated polymer as its body with the Exo-glove's tendon routing [29]. Because of the compliance of fabric glove that it cannot maintain its shape, causing errors in position and force control. The tendon routing path is routed in one loop on the palmar side through index and middle finger for the flexion motion, while using one tendon line each for under-actuation finger extension. Another advantages of using polymer is, it can be fabricated by molding process which is easy to customize all the parts and polymer glove is also washable.

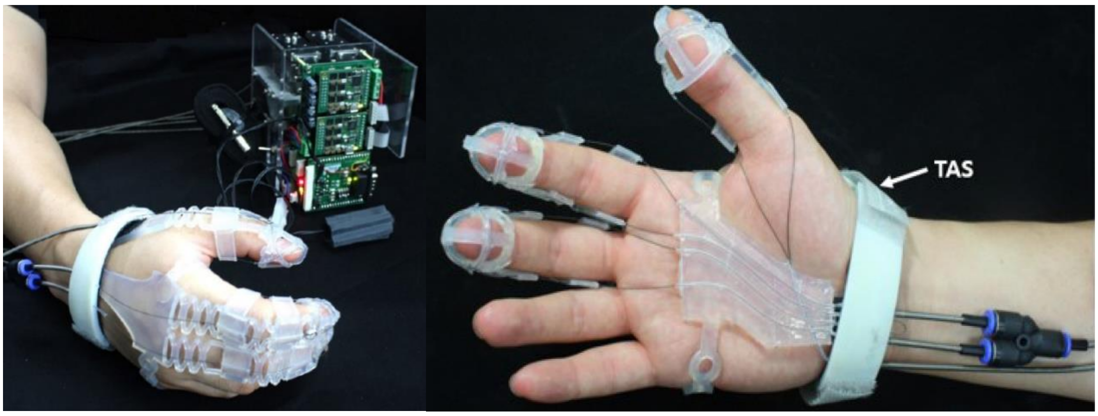

Figure 2.23 the Exo-glove poly, 2016 [29]

The tendon routing path is similar to the Exo-glove which uses a differential mechanism as shown in Fig. 2.25. When one of the finger stops, another can operate normally. This exoskeleton actuates only 2 fingers while the thumb will be fixed in the appropriate position while operating, to perform grasping with index and middle finger to reduce the device's profile and maintain easiness to wear this exoskeleton.

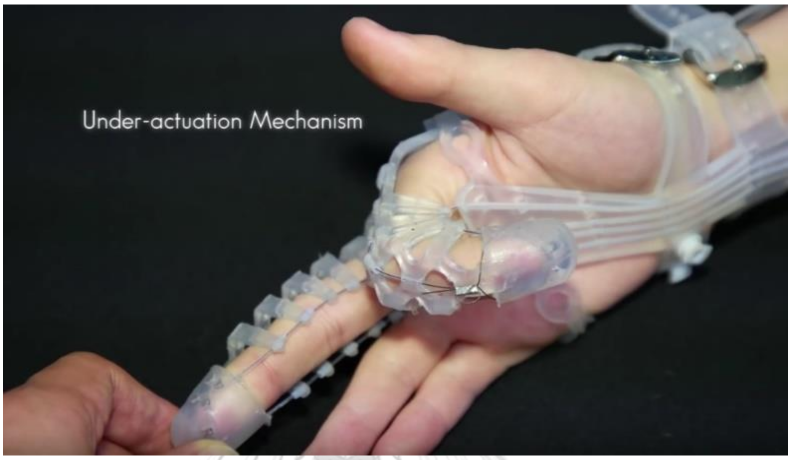

Figure 2.25 Under-actuation mechanism [29]

The last one is called Roboglove [30]. It is a portable soft hand exoskeleton has been developed by NASA and General motors for supporting hand function in factory use. The device was designed to provide workers extra gripping force which increases their working limitation and reduces muscle fatigue in long working day.

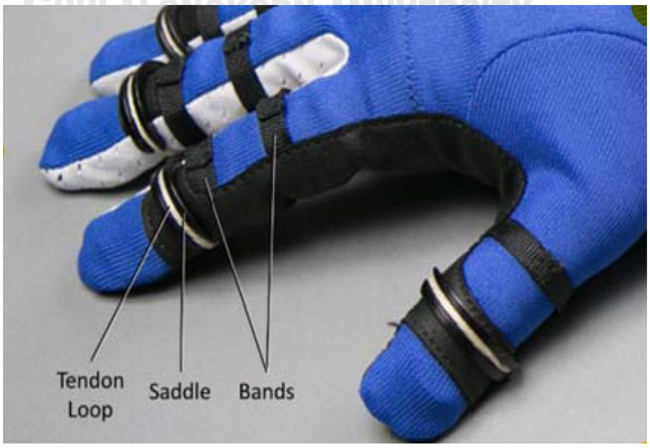

Figure 2.26 Roboglove [30]

Transmission path has been routed beneath the glove and hooked on a saddle on the middle phalange as shown in Fig. 2.26. While operating, force exerted on the middle phalanges help user to maintain grasping load easily. The developers claim that working range of force generated is around 15-20 lbs. Thus, the glove has to be thicker than normal glove to protect user from cable tension while operating.

Each finger has separated tendon loop which is driven by linear actuator located on user's forearm along with batteries and controllers which have been integrated into portable forearm strap with overall weight below 1 kg (see Fig. 2.27).

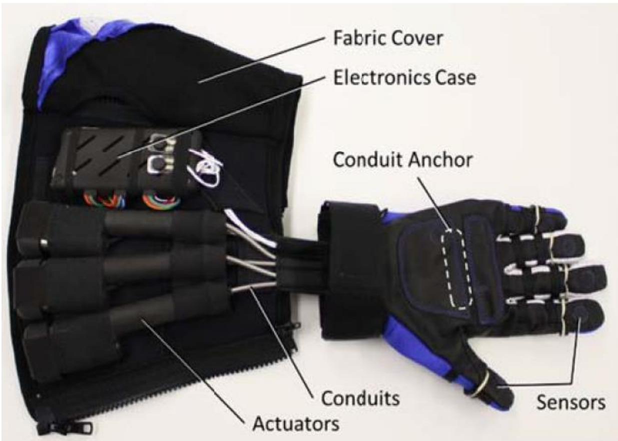

Figure 2.27 roboglove with actuation unit [30]

2.3.3. Other type of exoskeletons

Besides rigid frame and soft exoskeleton, some researchers proposed the novel mechanism to increase portability while also reduce exoskeleton's profile. Even though numerous amount of hand exoskeletons have been proposed but most of them cannot be portable in daily usage. Thus, Arata et al. propose three-layer springs mechanism with portable actuation unit of overall weight below 1 kg as shown in Fig. 2.28 [23, 24].

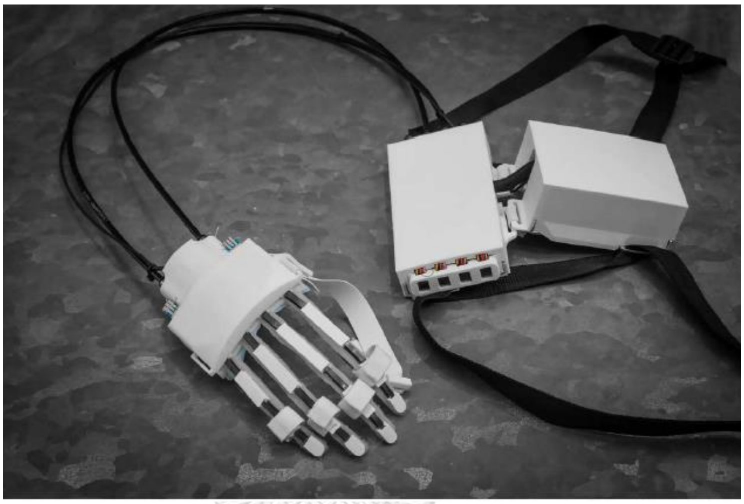

Figure 2.28 Arata et al.'s exoskeleton, 2016 [24]

Teflon wire has been used to transmit force from linear actuators to the sliding spring by pushing and pulling the Teflon wire. The mechanism contains three spring layers (see Fig. 2.29), the lowest spring has been fixed with the 3D printed parts, while the middle spring is an activation spring. Lastly, passively sliding spring can move freely which makes the mechanism to be able to self-form joint center depends on wearer's finger. By the way, the range of motion of this mechanism is quite limited due to the mechanical property of the spring sheets and the transmission also suffers from cable buckling when it is pushed at high amount of force.

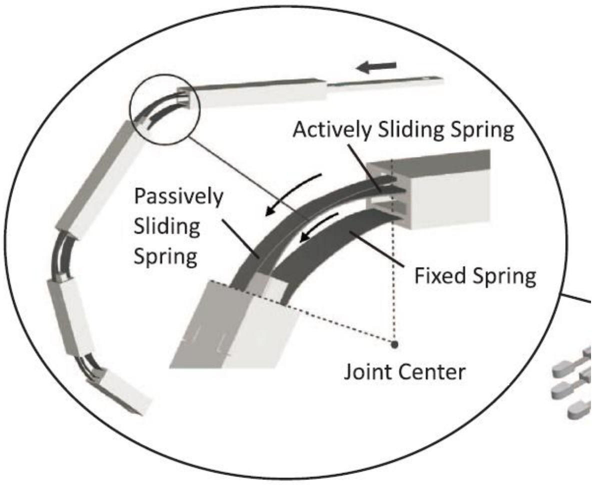

Figure 2.29 Arata et al., 2016 [24]

There is another type of exoskeleton that use pneumatic actuation. It uses fabricated polymer tubes with air channels inside to control hand motion (see Fig. 2.30) [22]. The stiffness of the tube varies along the tube to provide flexion and it can be customized for different hand size. When air is filled in the air channels, the tube extends and forced the fingers to flex. This polymer tube technology has been used in adaptable gripper for grasping various shapes, it called soft actuator and it can be fabricated by pouring fluid silicone into a customized mold. This design is similar to the soft exoskeleton because the light-weight and low profile with a glove-based body.

However, the downside of the polymer tube is, it is unidirectional actuated (flexion) and it provides limited range of motion due to the silicone property.

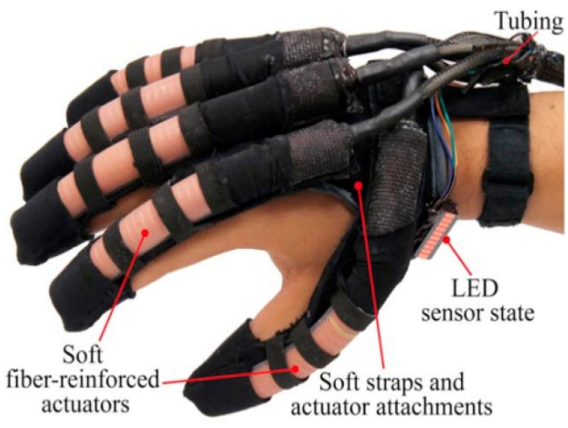

Figure 2.30 Walsh et al.'s exoskeleton [22]

All of pros and cons of each type of exoskeletons can be listed for analyzing and choosing appropriate design for assistance purposes as shown in Table 2.2.

Table 2.2 Advantages and disadvantages of different kinds of exoskeleton as being an assistive device

Type of Exoskeletons	Advantages	Disadvantages
Rigid exoskeletons • Platform-based • Portable type	• Accurate trajectory control and transmit sufficient force • No load received while operating (Platform-based) • More actuated DOF (usually 3 DOF per finger)	• High profile, inertia, and taken a lot of space on hands • No hand orientation (Platform-based) • Misalignment of joints
Soft exoskeletons • Tendon-driven • Polymer-based	• More adaptable to user's hand (compared to link-based) • Compact and low profile • Under-actuation mechanism	• Non-linearity of the system • Weaker force transmitted to the fingertips (compared to rigid exoskeletons) • Hard to wear (especially in patients with spasticity)

In conclusion, wearability and compatibility of the device with user's hand are the most crucial factors for increasing pHRI. Assistive devices should have high wearability, it should be worn on hand within few seconds and its profile and weight should not let users think that it will affect their mobility when using it in daily life. Thus, the assistive devices should be compact and comfortable to wear and carry around on the hand. Even though the rigid frame exoskeleton gives accurate performance in phalanges manipulation, it takes up a lot of space on the affected limbs with its bulky and cumbersome profile.

Moreover, the separable joint control is not necessary for daily activities as we mostly perform gross hand function. While complicated tasks, which require complex phalange orientation, can be performed by unaffected hand of the patients. Thus, high-profile mechanisms must be replaced by other mechanisms with lower profile material to make the exoskeleton practical in daily life. The size of the link and joint mechanism is difficult to be decreased and its performance is over necessity for being assistive device.

Another huge drawback of rigid frame exoskeleton is it also generate undesired force (from interference of mechanism and hand) which is considered incompatible with human hand. Hence, soft exoskeleton's mechanism is incomparably suitable for designing compact, lightweight, and user-friendly device, because underactuated mechanism reduces complexity of the exoskeleton while it can provide enough DOF for rehabilitation and performing ADLs without joint misalignment problem.

Furthermore, body of the soft exoskeleton is fabric-based which enhances compatibility of the device with user's hand, since it causes no interference between fingers and the device and it is also light-weight and adaptable on different hand profiles. As the polymer-based pneumatic actuation can only actuate fingers in one direction, it will not meet the design specification. Besides, the model in Fig. 2.8d shows that the tendon driven mechanism is similar to tendon and joint in muscular system of the human hand (Fig. 2.8a) and it is the most compact one compared to the others.

Thus, the soft exoskeleton with tendon driven transmission is the appropriate design for a compact rehabilitation or daily use device and it resembles to the transmission in our fingers, which is the most optimized transmission for hands. In the near future, improvement of tendon routing mechanism will be the beginning design of a practical hand exoskeleton which affordable for stroke and other patients who require hand motion assistance. This research will be conducted on developing the design of a soft hand exoskeleton with tendon driven transmission.

After reviewing the related works of soft exoskeletons, the design will be focused on the tendon routing transmission to achieve acceptable performance to execute hand gestures naturally, efficiency in force transmission.

2.4 Challenges and problems in design

From the problems of conventional wearable robotics hand, the soft exoskeletons have been proposed as rehabilitation and assistive device. However, the new issues occur which are: non-linearity of the mechanism, the efficiency of transmission and the gesture which exoskeleton performs.

The non-linearity of the system causes inaccuracy in motion and trajectory control because gloves are an elastic material, stretchable materials cause the misalignment of the tendon paths, which sometimes changes direction of exerted force on phalanges, causing the exoskeleton performs poor hand gestures. Moreover, the force transmission model and force exerted to phalanges is very difficult to achieve because there is no rigid body in the mechanism.

The tendon driven mechanism of soft exoskeleton has an advantage in compactness, but it has a lot of friction in transmission routes. As the tendon routing usually have many curvatures, since it is implied along the hand surface. But for safety of the user, maximum tension in the tendon has to be restricted. This makes the exoskeleton generates lower force at the fingertips compared to the rigid-frame exoskeleton at the same mechanical power actuator. This issue also leads to the non-compactness of actuation unit.

The joint angle performed by under-actuation mechanism is not precise because of the aforementioned issues. Which means the path of motion of every phalange must be close to human natural grasping path as much as possible to be able to manipulate objects and positioning fingers effectively. However, tendon routing system is a very low-profile mechanism which has various ways to route the path on a finger to achieve proximately natural hand gesture.

Compactness and compatibility are the most important factor for making exoskeleton friendly to use. The hand device must be compatible with user's hand not only it can operate on user's hand but also cause no interference and uncomfortable issues. While compactness of the device decides whether it can be used as an assistive device or not.

Chapter 3
The design of tendon driven mechanism for the soft exoskeleton

3.1 Conceptual Design

3.1.1 Design requirements

This research is focused on developing the design of a soft exoskeleton which assists patients to perform DADLs because it is the less complicated type of daily activities which can be achieved by gross hand function such as hook grip or cylindrical grip. Design of the soft exoskeleton has to be compatible with human hands, which means that the exoskeleton has to be compact and comfortable to wear. Not only physical interaction properties that refer to the compatibility, but it also means that the exoskeleton must perform grasping closely to the human natural grasping without having undesired force exerted on phalanges.

To make the design less complicated, the thumb will be fixed in ready-to-grasp position due to complexity in its workspace. In addition, thumb muscles will be used as a grasping support produced by other fingers when the rest of the fingers are actuated to grasp the object into the palm of the hand.

The exoskeleton must provide enough force at the fingertips to grasp daily objects with gross hand function. The amount of force is calculated by the daily objects maximum weight of 0.5 kg. (90 % of household objects weigh below 0.5 kg.). While, the static friction coefficient has been determined by the median of static friction coefficient between household objects and surfaces because friction coefficient between the device and objects has not been determined yet. However, the device can be made to reach more friction coefficient by using non-slippery surface, but in this calculation the friction coefficient of 0.255 (very slippery condition) will be used in force calculation to make sure that the soft exoskeleton will produce enough force for lifting at least 0.5 kg. objects. From the friction equation

$$f = \mu_s N$$

Every finger must produce roughly 4.9 N to be able to grasp, hold and lifting objects. Normally, weight of the soft exoskeleton is considered lightweight. Thus, the primary focus of this work is to develop tendon routing of the soft exoskeleton to achieve better fingertip force and hand grasping gesture, the design specification can be divided into several points.

1. The soft exoskeleton must perform finger flexion and extension with 10 - 90 degrees of MCP joint, 10 – 100 degrees of PIP joint and 10 – 80 degrees of DIP joint.
2. The soft exoskeleton must provide more than 4.9 N per finger for manipulating daily objects with gross hand functions.
3. Covering all fingers except thumb.

3.2 Soft Hand Exoskeleton Mechanism

The main idea of hand exoskeleton is to exert force on user's phalanges to generate desired movement of fingers. Soft exoskeletons utilize an advantage from compliance of materials such as fabric gloves and polymers combined with tendon-driven transmission to significantly reduce its weight with remotely actuation via Bowden cable. Tendon-driven transmission also an under-actuated mechanism which reduces number of actuators and complexity of the exoskeleton. While it also provides adequate fingertip forces for grasping. To transmit actuation force, flexion and extension tendon paths are routed to each finger of the glove except thumb (4 lines of Bowden cable each). Then, each tendon passes through a Bowden cable which is mounted with the actuation unit as illustrated in Fig. 3.1. To be able to operate the exoskeleton, tendon length between the glove and the actuation unit must be fixed. Otherwise, it will be the hand that is pulled towards the actuation unit.

In this case, the Bowden cable acts as flexible tube that maintains the same tendon length between exoskeleton and the actuation unit, while motor is pulling tendons. As a result, tendon at the exoskeleton side is being shortened, providing finger movements.

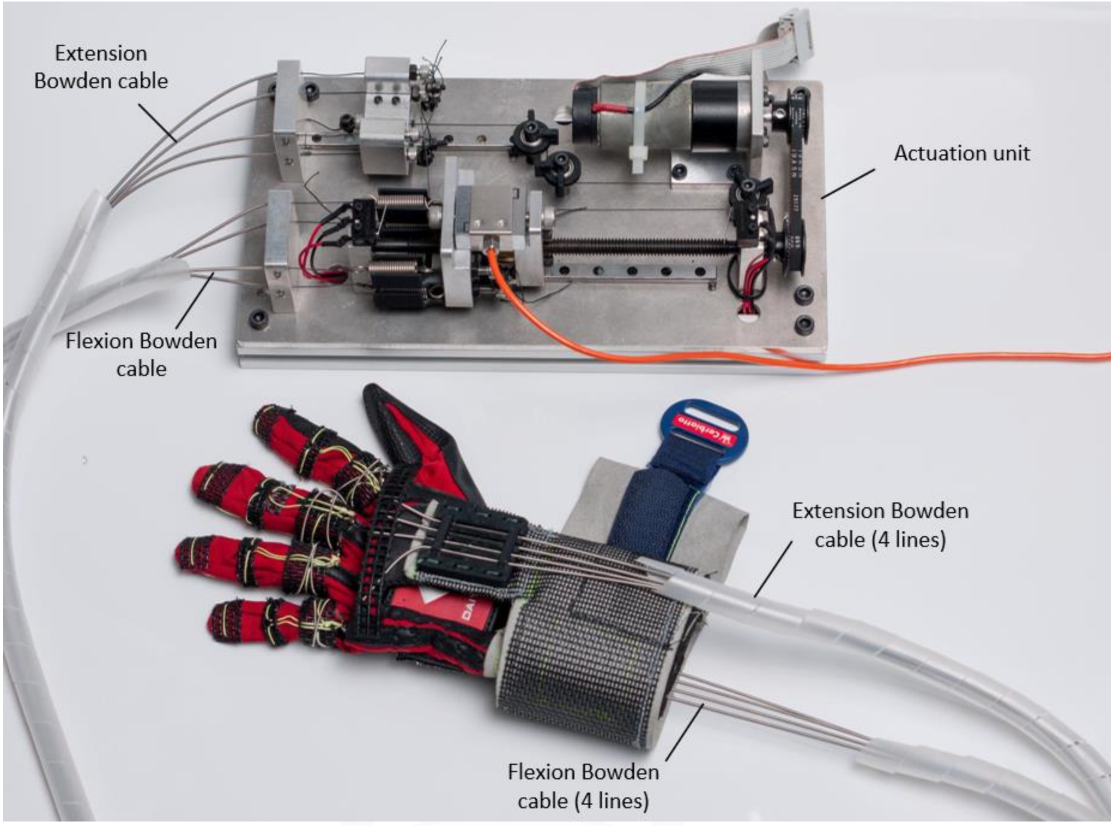

Figure 3.1 The soft exoskeleton with actuation unit

However, the actuation will cause Bowden attacher movement by the reaction of the tension pulled by the motor, resulting in loss of tendon pulling length and poor hand gesture. Thus, supports for the Bowden attacher is also be a crucial part that affects performance of the soft hand exoskeleton. The details of the flexion-extension tendon routing and the Bowden attachers will be explained in next sections.

3.2.1 Flexion Tendon Driven Mechanism

The tendon routing model of several soft hand exoskeletons have been analyzed and illustrated in Fig. 3.1 (left). In this chapter, for the simplicity of free body diagram, phalange will be considered as rigid links. While wrist joint will not be considered in the soft routing model which will be taken as static joint. In this model, MCP joint has 2 DOF, which is adduction/abduction of joint around y-axis and rotational of joint around z-axis, while others have only rotational around z-axis. But with force applied to the model in Fig. 3.2, motions will only occur by rotation of finger joints. From the Exo-glove tendon routing model [20, 29], tendon is routed to a glove as one loop per finger. Tendon routing starts from palm of the hand to lateral side of the finger, then, crosses over the fingernail, then it is routed through another lateral side through the palm. The Teflon tubes act as low friction pulleys for the tendon to slide through.

When tension is being applied to a pair of tendons of each finger (the system is considered frictionless), the force exerted on distal phalange creates movement of joint and also generates moment for other finger joints. While the position of Teflon tubes will guide direction of force exerted on the phalanges. The free body diagram in the right side of Fig. 3.2 shows that force exerted on distal phalange only.

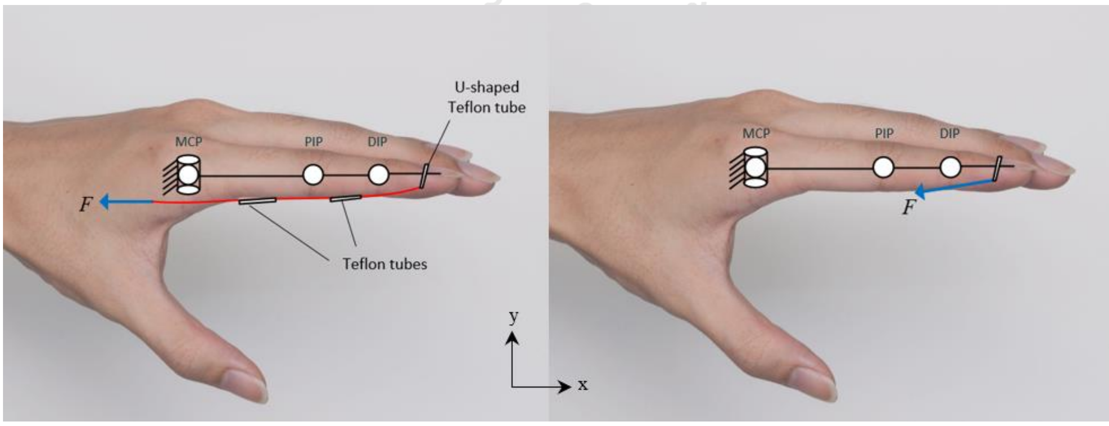

Figure 3.2 (Left) Conventional routing model

(Right) Free Body Diagram of the model

The joint motion of this model depends on direction of Teflon tubes that guide the tendon. As illustrated in Fig. 3.3, when the tendon is being pulled, the distance between tubes has been gradually shortened. Tension will gradually rotate fingertip toward the palm of the hand, flexing every joint all together. Teflon tubes also act as mechanical limit that stop the motion when the Teflon tubes between each phalange collide.

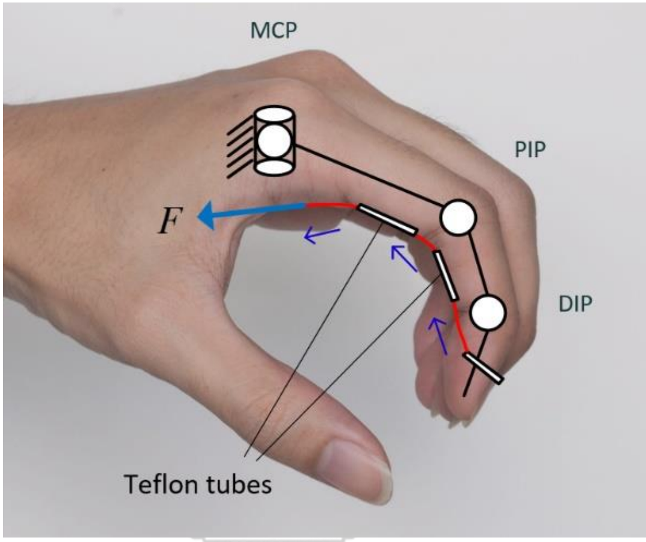

Figure 3.3 Convention routing model

From the Exo-glove result of bare-hand grasping, the result in Fig. 3.3 shows that the MCP and PIP angle is around 46 degree which is smaller than voluntary grasping range of motion.

Even though the researchers have claimed that the Exo-glove range of motion is sufficient for grasping several objects. But from the experiment of Kamper et al., human grasp objects with the help of every joint. Especially the ratio of PIP-MCP is very low (0.26 for the index finger), which indicates that MCP should be the dominant joint in object grasping. But in this case the MCP joint flex as much as the PIP joint.

Moreover, this model will reduce grasping working space because the DIP and PIP joint are the first to rotate as seen in the free body diagram in Fig. 3.2, narrowing the gripping loop and cause problem when user attempts to grasp bulky objects respect to their hands as the sequence of joint flexion is unnatural.

Table 1. The joint angles during tripod grasping. The metacarpophalangeal (MCP) joint angles of fingers at extension phase are regarded as 0°. The thumb anteposition angle represents how much the thumb flexes in front of the palm.

	Extension Phase	Flexion Phase
Index finger MCP	0°	46°
Index finger proximal interphalangeal (PIP) joints	4°	48°
Index finger distal interphalangeal (DIP) joints	5°	12°
Middle finger MCP	0°	46°
Middle finger PIP joints	6°	54°
Middle finger DIP joints	4°	12°
Thumb anteposition	64°	51°
Thumb abduction	31°	0°
Thumb interphalangeal joints	0°	27°

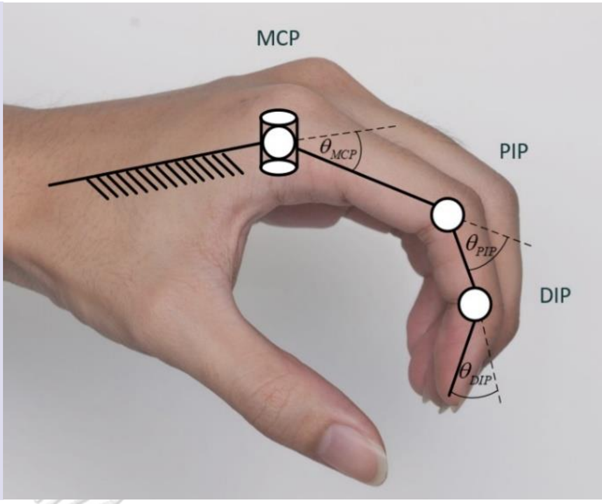

Figure 3.5 (Left) Conventional routing model [20]

(Right) Schematic diagram of joint angle measuring

To develop tendon driven soft exoskeleton, the model of soft tendon routing has been proposed as illustrated in Fig. 3.5. The routing path is similar to the conventional path except the proximal phalange area. The x-crossed path of Bowden cable starts from lateral side of proximal phalange. Fixation points are positioning tips of Bowden cable to make the tips stay below PIP and MCP joint to make it generates moment for flexion. Glove tunnels are the area that tendon passes through the inner side of the glove, doing the same purpose as Teflon tubes.

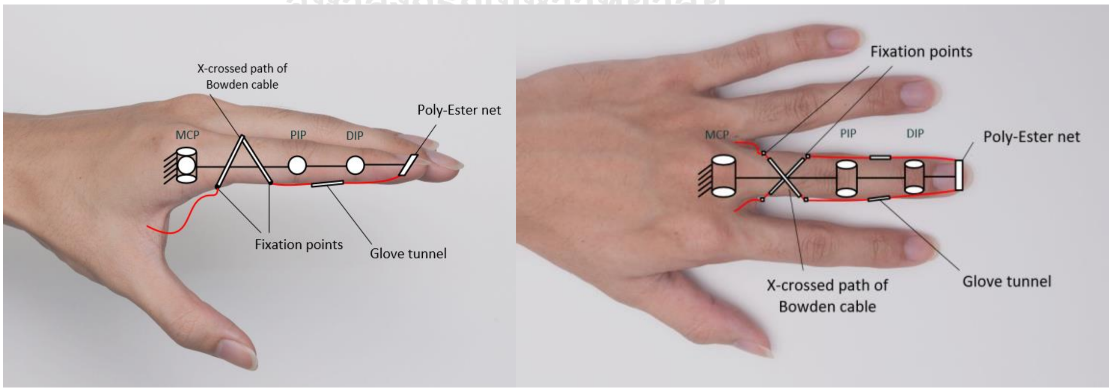

Figure 3.4 (Left) Side view of the proposed flexion tendon routing model

(Right) Top view of the proposed flexion tendon routing model

From the free body diagram in Fig. 3.6, $l_1, l_2,\ l_3$ are the length of proximal, middle and distal phalange respectively. x is the length from MCP to x-crossed path and d is the length from Teflon tubes to the middle of the joint. By applying tension in the route, the x-crossed path of Bowden cable exerts force on distal phalange, force also will be occurred at distal phalange as shown in the free body diagram in Fig. 3.6 (right). Note that force exerted on both phalanges have the same magnitudes, but they point in different directions. Force on proximal phalange generates moment around MCP joint more than F_{tips} on distal phalange because the moment arm x is larger than d.

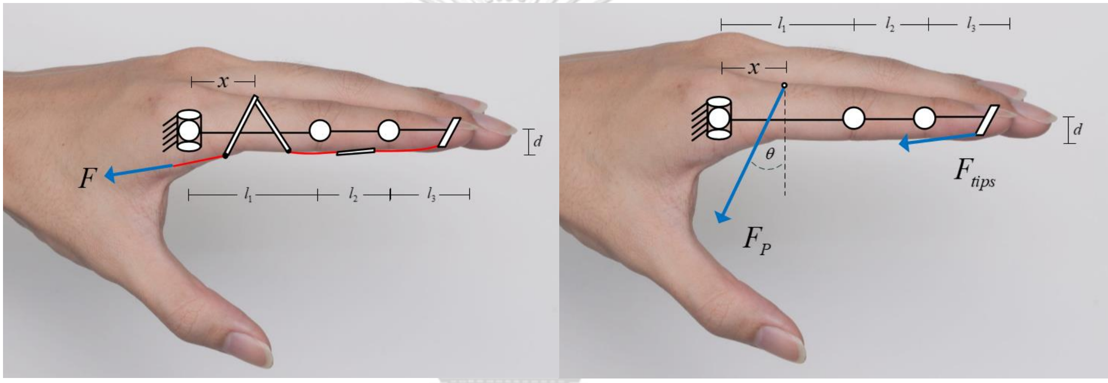

Figure 3.6 (Left) Proposed flexion tendon routing model with the applied force (Right) Free body diagram of the proposed model when applying the force

The x-crossed path solves the problem of under flexed MCP joint, by crossing the tendon around upper side of the proximal phalange, when tension is applied to the routing, force will exert on proximal phalange, rotating MCP joint more than other joints with its superior moment arm. While F_{tips} will pull fingertip into the palm of the hand which cause movement of PIP and DIP both. The distance x can be adjusted to vary the moment generated at MCP. The most important components in this model are the fixation points of the x-crossed path. The fixation points must be located below finger joints in the horizontal plane to generate clockwise moment for flexion of each joint.

3.2.2 Extension Tendon Routing Mechanism

Main purpose of extension actuation for soft hand exoskeleton is to release an object after the exoskeleton performed grasping or to initialize user's hand gesture. Extension tendon paths are started beneath the proximal and middle phalange, threaded through poly-ester net to the upper side of the finger as shown in Fig. 3.7., and then integrated into one line of tendon for actuation. The distal phalange has no routing because DIP movement contribute less than other joints in the extension process and to reduce complexity of the routing as well.

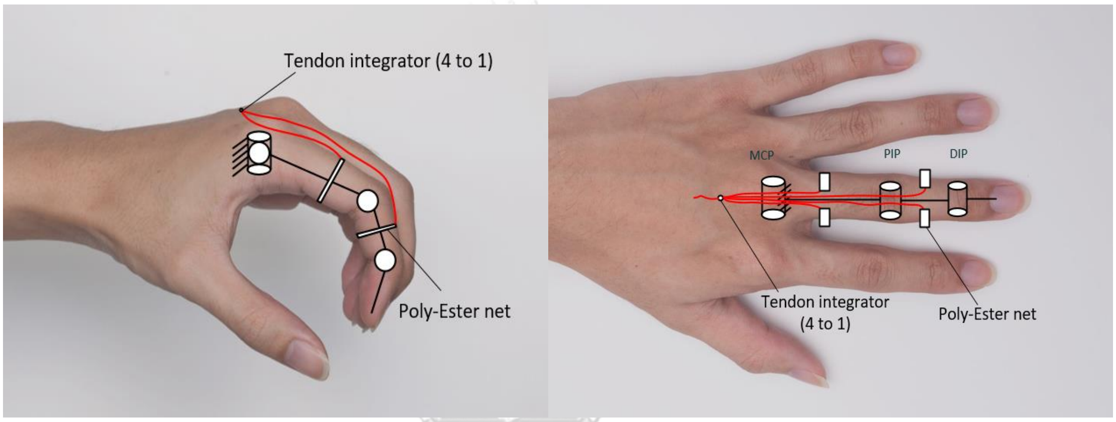

Figure 3.7 (Left) Side view of the proposed extension tendon routing model (Right) Top view of the proposed extension tendon routing model

From the model in Fig. 3.8, by applying tension in the routing, force will be exerted on proximal and middle phalange and it is always perpendicular to the phalanges. In addition, tensions in these phalanges are distributed equal ($F_1 = F_2$) because each tendon line are integrated and pulled as a group.

The motives of designing this routing is to prevent unexpected digit orientation by the conventional model, where its routing starts from upper side of the fingertips, then passes over the DIP, PIP, and MCP joint respectively. The conventional extension routing exerts force on the fingers in the routing direction, causing interference force in joints. Especially, exerting force on fingertip of human finger that has 3 DOFs will obtain an unpredictable result, depending on various disturbances such as initial condition of each joint before getting initiated and the tendon route positioning respect to the hand.

Aforementioned conditions can occur more frequently in the soft exoskeleton, where the actuation of tendon routing model is non-linear and its body not a rigid structure as the rigid frame exoskeleton. With the proposed model, proximal and middle phalange will receive force with same magnitude, by applying tendon limit, the joint will not exceed over-extension phase.

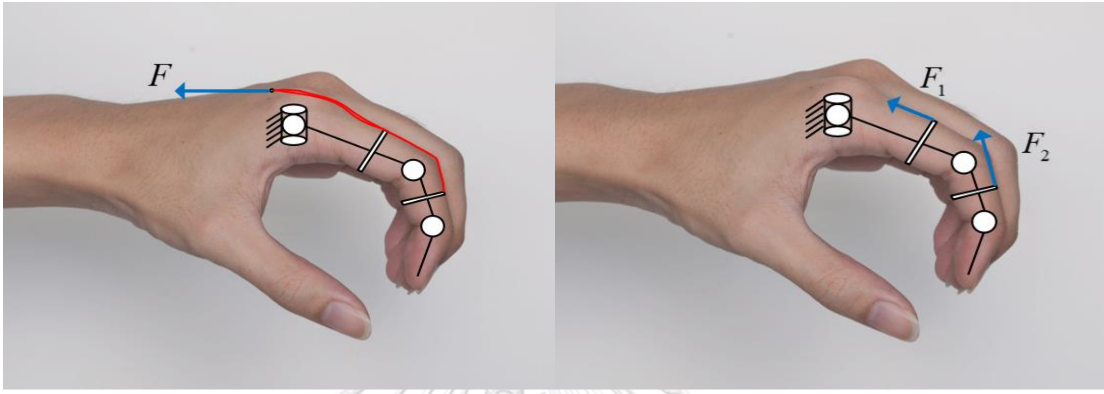

Figure 3.8 (Left) Proposed extension tendon routing model with the applied force (Right) Free body diagram of the proposed model when applied the force

Moreover, the finger will receive less total interference force compared to the conventional model at the same tension input by excluding DIP joint from the routing.

The final prototype has both flexion and extension routed together as illustrated in Fig. 3.9. Poly-ester nets are threaded to every phalange as base structures to reinforce the glove to support reaction from actuation and to distribute tendon force on the finger into larger areas. The poly-ester is compliance and has low profile while it does not deform much when received the actuation load.

The exoskeleton can operate even though the x-crossed path and the extension route are crossing because tension is applied on one route at a time.

Figure 3.10 Top view of the exoskeleton with flexion and extension tendon routing

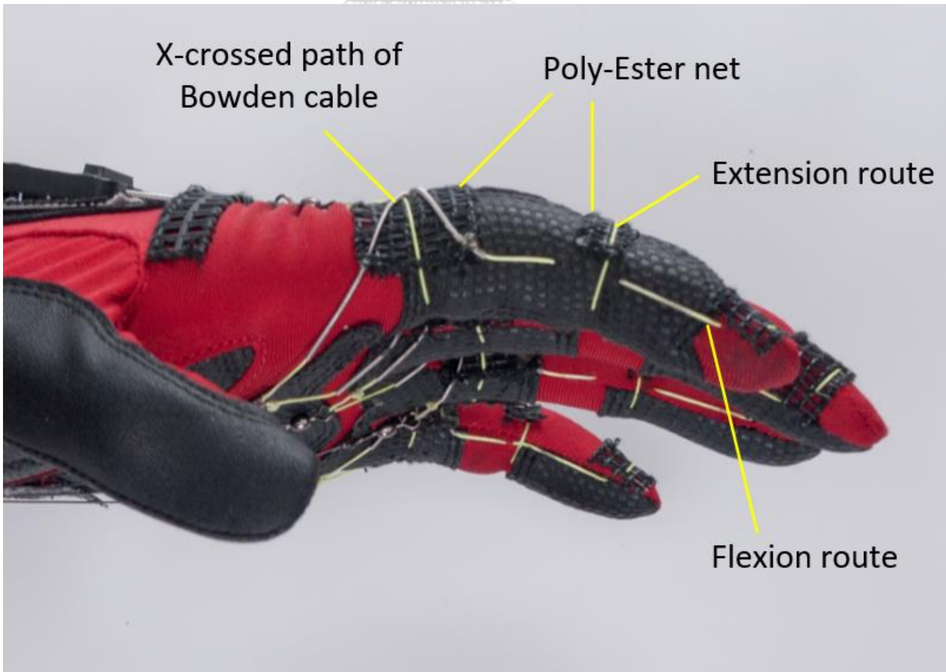

Figure 3.9 Side view of the exoskeleton with flexion and extension tendon routing

3.2.3 Tendon-driven transmission and Bowden attacher support

Tendon-driven transmission of the exoskeleton is operated pass through Bowden cables as shown in Fig. 3.11. Bowden cable is a flexible tube that can stretch in its longitudinal axis but cannot be compressed, it resists the compression force and maintains the distance between the actuation unit and the glove when the tendon is being pulled by the actuation unit and make the system viable.

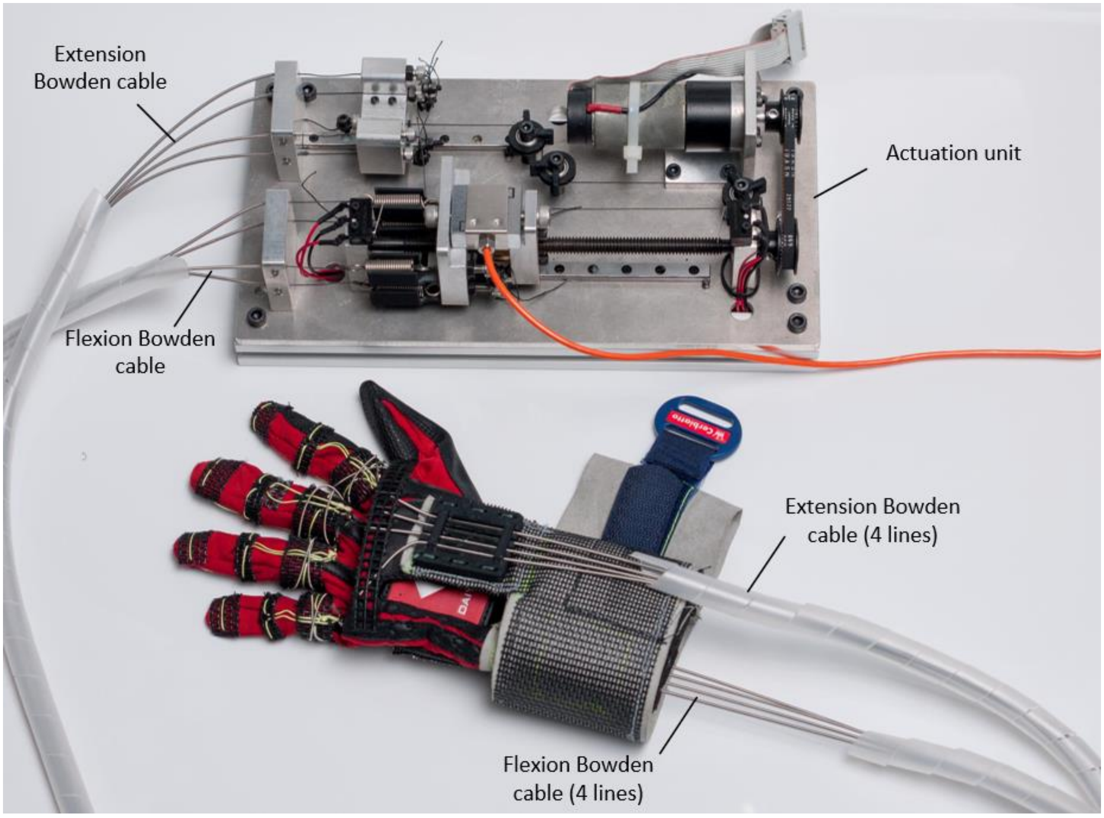

Figure 3.11 The proposed soft exoskeleton with actuation unit

Four lines of each flexion and extension Bowden cables connect the exoskeleton with the actuation unit. Both flexion and extension cable are routed through the inner side of Bowden cables, connecting tendon with the actuation unit.

In the remotely tendon-driven system, there are two main parts which are: actuation unit and actuated mechanism. With no Bowden cable between two systems, actuating tendon will pull whole limb that wear the exoskeleton instead of moving the desired limbs. The Bowden cable solves this problem by maintaining distance between two systems, only tendon at the exoskeleton side will be shortened. For example, if attached one tip of the Bowden cable above the wrist, tension will pull only targeted finger.

As mentioned in the earlier section, there is a problem which reaction force occurs on the Bowden fixation point at the exoskeleton when tension is applied to the flexion tendons, causing upward movement of Bowden fixation point which is an actuation movement loss. Because Bowden cable connects the actuation frame with the Bowden fixation point on the exoskeleton. Thus, it will receive same reaction force together.

As shown in the diagram in Fig. 3.12. When the tendons are being actuated with force from DC motor (F_{motor}) via Bowden cable, the reaction force (F_A) of the pulling force will react on the actuator frame which also reacts on the Flexion Bowden attacher. Thus, F_A will pull the Bowden attacher up toward the fingertips which causes movement loss instead of pure flexion motion.

However, size and position of the Bowden attacher are also crucial factors which limits design workspace because it should be located above the wrist to be independent from wrist motion that can change tension in the system.

After few prototypes, it is clearly that placing flexion Bowden attacher above the wrist is not compatible with human hand. Because the attacher should not interfere with palmar and thumb muscles during grasping. Which is difficult to design due to limited space of palmar side of the hand and it also interferes with the grasping objects. In addition, locating the attacher above the wrist is difficult to provide any supports to hold it in place.

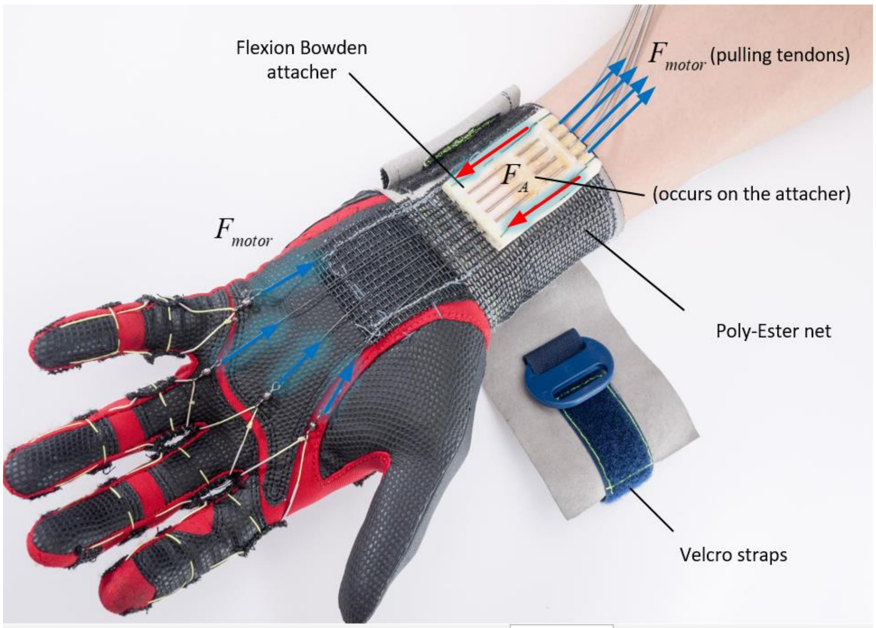

Figure 3.12 The force diagram of the exoskeleton while actuated

Thus, the flexion Bowden attacher is located below the wrist on a fabric strap where it holds 4 tendons from each finger except thumb. The fabric strap can wrap around itself with Velcro to help fixing the attacher in place. The strap is reinforced with polyester fiber net to help distributing reaction force from the actuation along the strap to minimize movement of the attacher as much as possible.

In the other hand, the extension Bowden attacher is comfortable to place at dorsal side of the hand as shown in Fig. 3.13. Thus, the flexion tension does not get affected by wrist motion. The extension Bowden attacher holds 4 Bowden cables from each finger. The poly-ester net has been also implemented on the extension side to minimize the attacher movement as well.

Figure 3.13 The extension Bowden attacher

3.5 Actuation Unit

3.5.1 Flexion and Extension driving unit

According to Fig. 3.14 (upper), both ends of the Bowden cable are attached to the exoskeleton and the actuation unit to fix the tendon length between them. As informed in the earlier section that Bowden cable maintains distance between the actuation unit and the glove. Moreover, it also protects inner tendon from being cut and prevent tendon winding along the line.

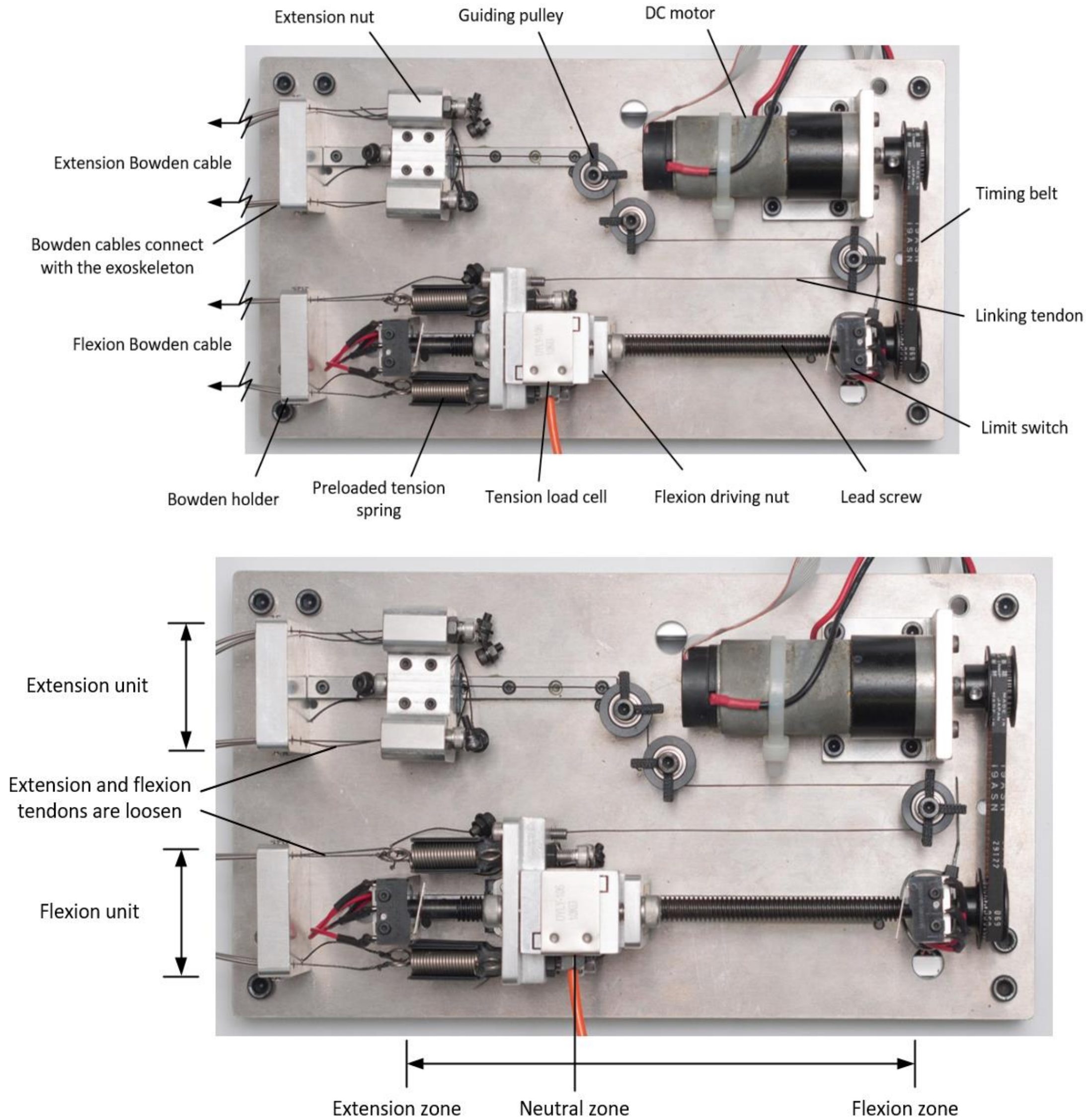

Figure 3.14 Schematic diagram of the actuation unit's top view

The actuation system consists of two sections which are: flexion unit and extension unit (Fig. 3.14 lower). The flexion unit, which is a lead screw and driving nut mechanism, has the flexion tendons attached on its driving nut. DC motor has been used to operate system via timing belt to translate the nut to the right-hand side of the figure.

As each finger has different length, pulling distance to achieve full flexion motion of each finger is not equal (little finger has the shortest distance). Preloaded tensional spring has been used in each flexion tendon. Stretching length of the spring allows each finger to move separately when interact with non-smooth surface objects or one of them is already in the full flexed position.

For example, when actuated tendons, the little finger will be pulled to the full flexed position first. If there is no tensional spring in the system, the other fingers will not be moved unless the little finger flex more. This situation will obstruct the actuation and could harm the little finger if tendon does not tear first. The preload in tensional spring keeps the spring unstretched at low tension to prevent tendon slackening. Moreover, to control the grasping force of the exoskeleton. The tension load cell is attached serially between the driving nut and flexion tendon fixation points as shown in the Fig. 3.14 to measure the input tension for feedback control.

Extension unit has the extension nut, which fixes the extension tendon, mounted on a linear guide. Activation of this unit occurred by linking tendon which is routed from the flexion nut to the extension nut as shown in Fig. 3.14 The tendon is guided by three pulleys to rearrange direction of the tendon and make both ends of it parallel to each other, to synchronize flexion and extension unit as an on-off mechanism.

Synchronization of the mechanism is shown in Fig. 3.15-3.17. After user put the exoskeleton on, user can set initial position of the hand while the mechanism is at neutral position by adjusting tension in each tendon line on both flexion and extension nut to make exoskeleton compatible with each user at this phase hand does not receive tension from any tendon as illustrated in Fig. 3.15.

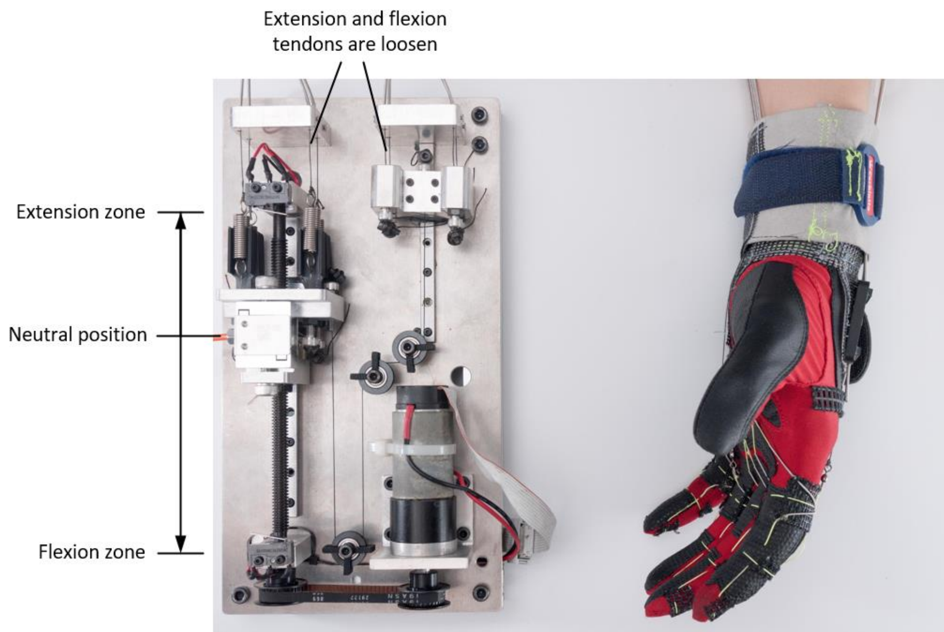

Figure 3.15 The actuation unit's mechanism at neutral position

For example, little finger has the shortest actuating distance. Thus, it flexion tendon should be slacker than other fingers to make all fingers flexed simultaneously. In the other case, users' phalanges have different size and length, adjusting tendon length in the system will make the exoskeleton relatively suitable for any user.

To perform flexion motion, the nut is driven towards lead screw to the flexion zone (Fig. 3.16). Shortened tendon length creates tension in the flexion tendon, generating flexion motion equal to the distance pulled. While at the extension unit, the linking tendon is loosened and allowed to move freely which creates no tension at extension side. Thus, the flexion actuation works with no interference between flexion and extension unit.

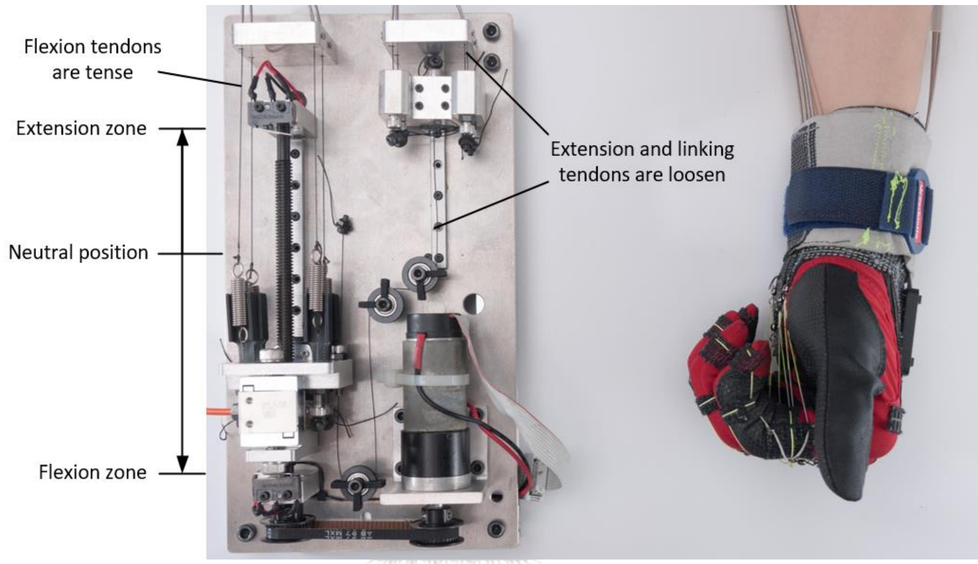

Figure 3.16 The actuation unit's mechanism when reached flexion zone

In the same manner with flexion motion, the extension motion can be achieved by driven the flexion nut towards lead screw to the extension zone. After it went beyond the neutral position, tension is gradually developed in the extension tendon via linking tendon as the flexion nut is moving towards extension zone of the lead screw. The tension pulls extension tendons and generates extension motion from the distance pulled. There are two limit switches at both ends of the lead screw rack to limit the motion of the nut.

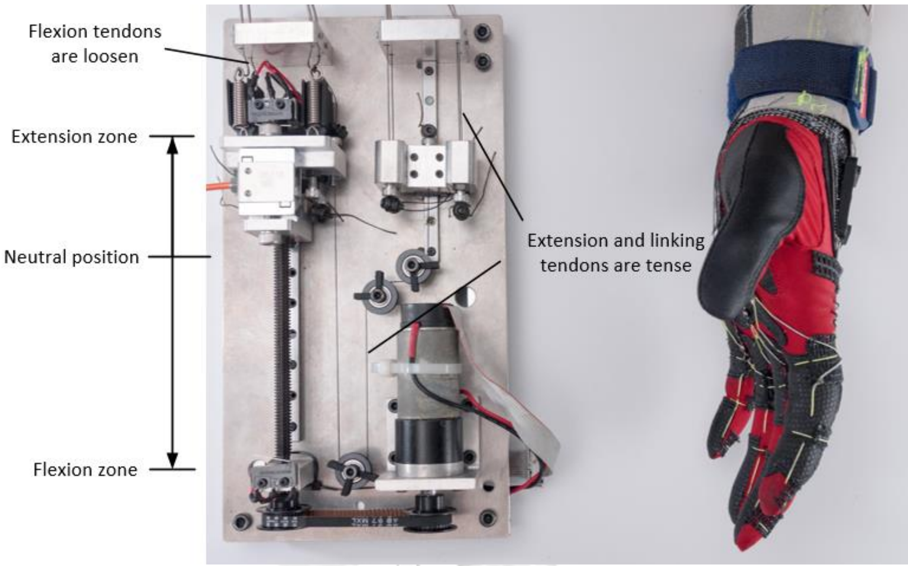

Figure 3.17 The actuation unit's mechanism when reached extension zone

3.5.2 Electronics and Control Instruments

The control unit consist of four main parts which are: a micro-controller, a digital motor amplifier (Copley Controls' Accelus), a load cell amplifier, and 24 V switching power supply (Maxwell). The micro-controller is FiO-2 board with ARM cortex-M4 CPU which receives encoder and load cell inputs from both amplifiers and sends PWM voltage command to the Copley Controls' Accelus motor amplifier. Both motor amplifier and load cell amplifier receive power source from the Accelus and load cell amplifier. The system electronics input-output diagram is shown in Fig. 3.17.

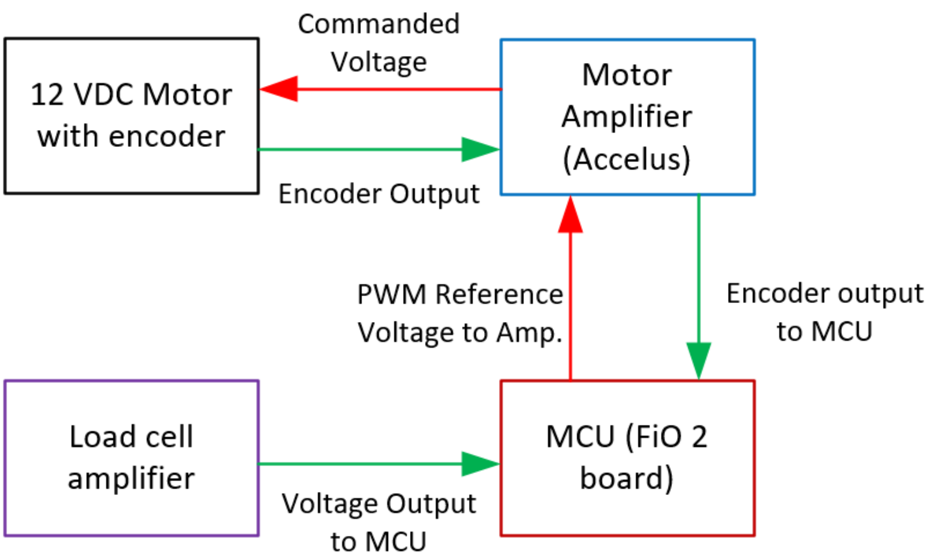

Figure 3.18 The system's input-output diagram

Chapter 4
Evaluation

To evaluate performance of the soft exoskeleton, the design specification in chapter 3 has been used as criterions. Experiments on important matters such as range of motion, fingertips force, and fingertip trajectories of the exoskeleton were conducted, analyzed, and illustrated in this section.

4.1 Trajectory Evaluation

To verify force diagram of the proposed flexion model and to find its range of motion compared to natural hand grasping, thus, the ROM grasping was demonstrated. The trajectory evaluation consists of two experiments. First, a subject performed range of motion grasping 5 trials with his hand with no interaction with any object (bare hand grasping). Each time, subject started to grasp from the neutral position of his hand.

Figure 4.1 Trajectory evaluation experiment

Then, same subject performs another 5 trials using the exoskeleton with no assistance from his hand muscles. Index finger motion was captured perpendicular to palm of the hand planar and analyzed by using Kinovea experimental version. The experimental footage is shown in Fig. 4.1.

Coordinates in the captured plane of every digit were tracked and used to calculate index joint angle. The motion generated by exoskeleton can be divided into 2 phase as shown in Fig. 4.2 and index MCP, PIP, and DIP angles compared with grasping cycle time are plotted as shown in Fig. 4.3 – 4.5.

The result of the natural range of motion grasping (bare hand grasping) in Fig. 4.3-4.5. (Black lines) shows that MCP joint was rotated the most in the first 1.5 s. Then, from 1.5 s. onwards, the PIP and DIP joint angular velocity were significantly increased (the slope obviously ramped up) as illustrated in Fig. 4.4 and 4.5. Note that in this phase, the MCP joint gradually slowed down and almost stopped at 75°, one second before the other joints. The result convinces that the MCP joint participate the most in the early stage of grasping, while DIP and PIP joint are slowly moving until MCP reached its destination and stopped at 75° approximately. Then, DIP and PIP flexion speed increase obviously in the second phase.

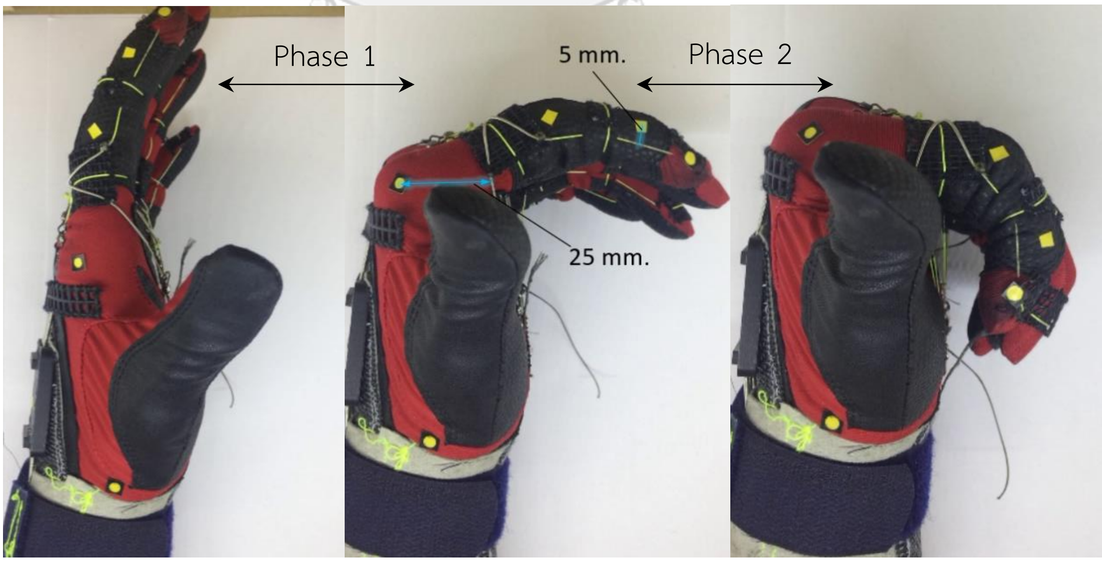

Figure 4.2 Grasping experiment using exoskeleton

The result of using the exoskeleton can also be divided into 2 phases. In the first phase, index MCP angle when using the exoskeleton rotates more than natural hand grasping from the initial position to 85° approximately as shown in Fig.4.3. In accordance with force diagram of the proposed model which has force exerted on the proximal phalange, thus, it generates significant moment for MCP joint.

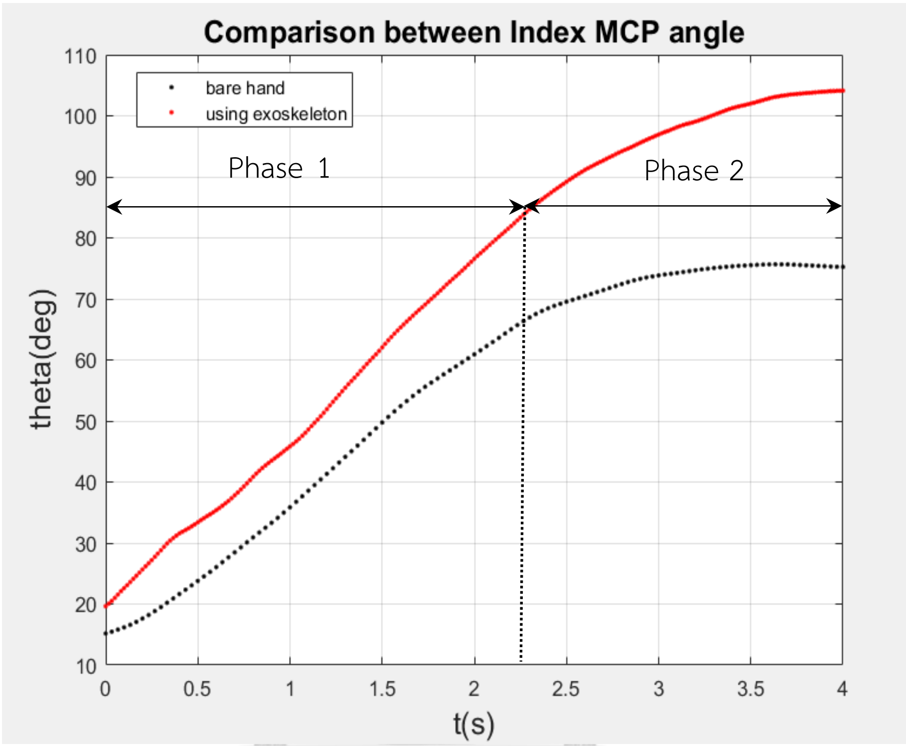

Figure 4.3 Comparison of index finger flexion MCP angle between two experiments

Even though PIP and DIP joint slowly rotate in the first stage, but their flexion angles are close to the natural grasping at the end of the first stage. In addition, the moment arm of the MCP joint (25 mm.) is remarkably larger than moment arm of the DIP joint at the index fingertip (5 mm.) as shown in Fig. 4.2 (middle).

In the second phase, MCP joint angular velocity starts to decrease until it the angle stopped around 105°. Because at high MCP flexing angle (70 – 90°), the extensor tendon in human fingers is tensed already. When MCP joint exceeds this angle, the extensor tendon will generate antagonist moment that resists proximal phalange motion.

In contrast to MCP motion, DIP angular velocity slightly increases as shown in Fig. 4.5, and it gradually curls the index fingertip inside the palm of the hand. While PIP joint also responds as same as DIP joint (Fig. 4.4), which verifies the force diagram of the proposed flexion routing. Even though PIP and DIP joint are slightly under flexed compared to the natural hand grasping, their motions represent the same behavior as the natural grasping, only slopes are different.

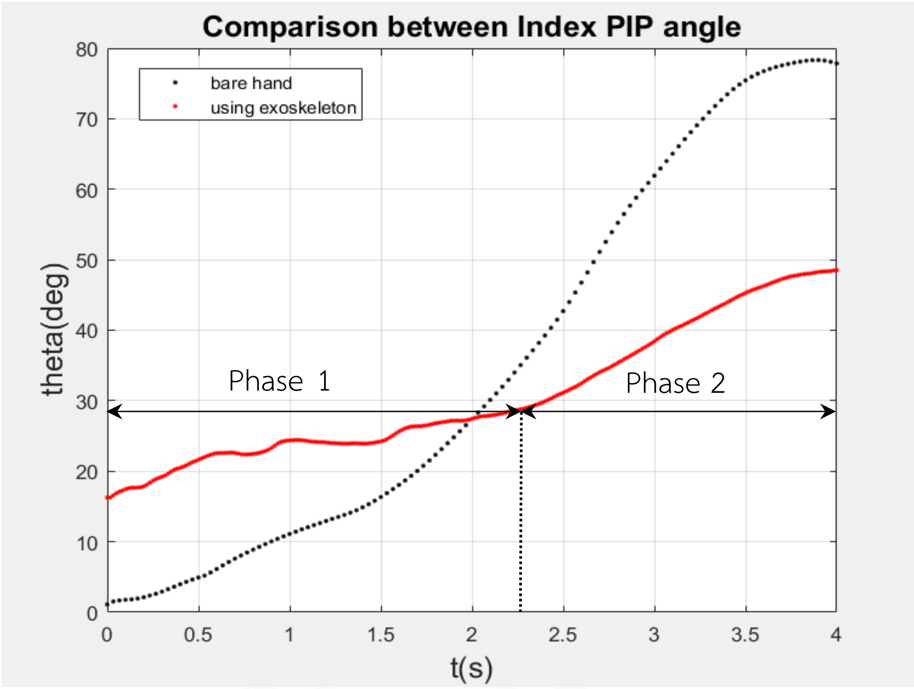

Figure 4.4 Comparison of index finger flexion PIP angle between two experiments

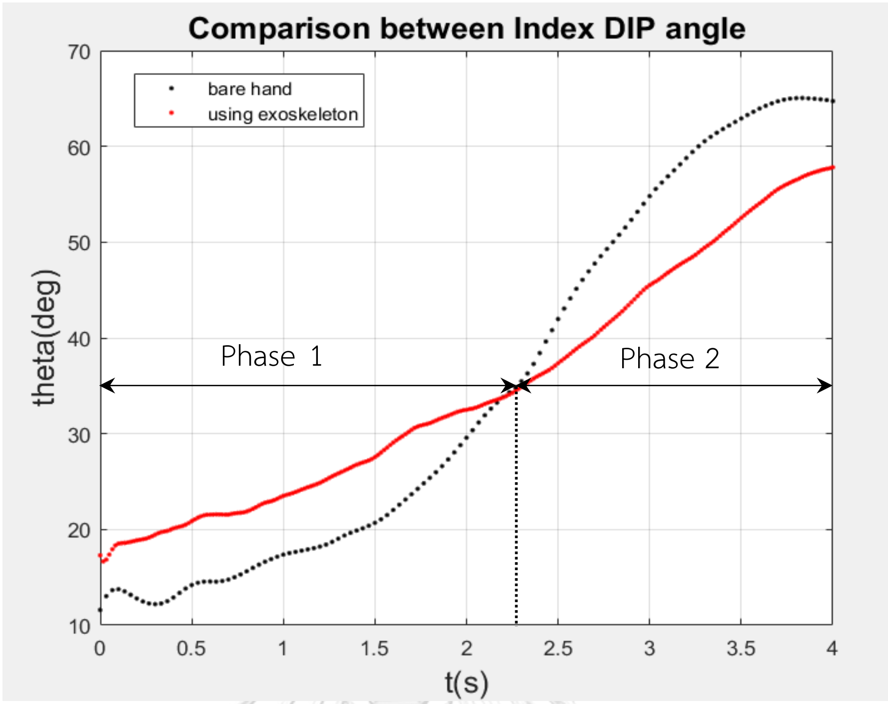

Figure 4.5 Comparison of index finger flexion DIP angle between two experiments

In conclusion, the range of motion experiment of the exoskeleton nicely demonstrates that the proposed model is reasonable for developing tendon routing mechanism in soft exoskeletons. Although the final angles are slightly off, but the result shows that exoskeleton grasping performed with the same characteristic as the intentional hand grasping The final angles of every joint are shown in Table 4.1., exoskeleton MCP angle stopped at 104.1°, it was flexed 20° more than natural hand grasping while PIP and DIP were under flexed. Increasing pulling distance to achieve more DIP and PIP angle is possible but it will also generate moment for MCP joint which is uncomfortable at high angle region and it might harm MCP joint. This result indicates that the moment arm of MCP is excessive compared to the DIP moment arm. Another reason that intercepts DIP and PIP motion is the imperfection of the fabric glove and tendon routing. It can be seen while conducting experiments that the routing is not perfectly fixed relative to the fingers and fibers of the poly-ester net are not perfectly rigid. It deforms while actuated. Especially at the x-crossed path where its right fixation points, near the PIP joint as shown in Fig. 4.2 (middle), receive reaction force in positive y-axis direction. Such reaction force tries to lift poly-ester net of the x-crossed path up, the more it goes up the less moment generated to PIP joint because the PIP moment arm decreases.

Table 4.1 The results of index finger maximum flexion angles from two experiments

	MCP angle	PIP angle	DIP angle
Bare hand	75.2°	77.8°	64.7°
Using Exo.	104.1°	48.5°	57.8°

The subject's index fingertip trajectory is plotted in the polar coordinates to give another aspect of this grasping experiment as shown in Fig. 4.6. Radius (mm) of the plot denotes index fingertip radius, MCP joint is located at r = 0 and θ (0-360°) denotes index fingertip angle, while fingertip position at neutral position is located at θ = 90° (straight finger, all joint angles are zero). Fingertip trajectory were computed by using obtained joint angles with forward kinematics.

The data of fingertip trajectory is mirrored to achieve right-hand-like result for a better understanding plot (subject is left-handed). The fingertip trajectories of both experiments are curved paths as the experiment of D.G. Kamper et al.[11]. Fingertip trajectory performed by exoskeleton is slightly off the bare hand trajectory in the first phase as shown in Fig. 4.6., because of different initial joint angles.

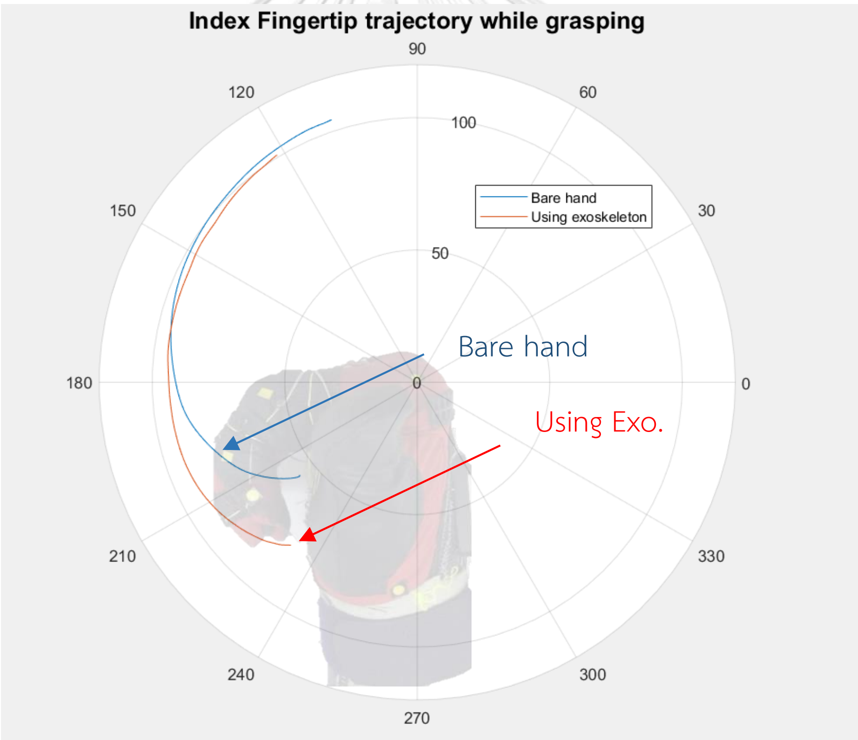

Figure 4.6 Polar plot comparison of the index fingertip trajectories between subject's bare hand and using exoskeleton

The path's trends are almost identical in the first half, then, it starts to separate from each other according to the previous experiment that DIP and PIP of natural grasping flex more than using exoskeleton.

In conclusion, the flexion routing model cannot exactly resemble fingertip trajectory of natural grasping due to the complexity of human tendon system which rotated mostly MCP joint in the first phase. Then it suddenly stopped and flexed high amount of DIP and PIP angle over the short period.

However, the idea of exerting force on proximal phalange yields a good result in term of replicating natural hand grasping with only 1 DOF of actuation. Without proximal phalange force, the fingertip path would have been extremely different from natural grasping. Major movement would occur from DIP and PIP joint from the beginning with minor amount of MCP angle, cause unnatural movement of the fingers.

4.2 Grasping object trajectory evaluation

To assure that the proposed flexion tendon routing can perform with objects, a subject intentionally performs 5 trials of a 50 mm cylindrical object grasping and another 5 trials using exoskeleton without his effort to grasp. Subject's thumb was fixed in the grasping position as illustrated in Fig. 4.7. The cylindrical bottle was fixed to the ground which parallels with the camera frame. Motions were captured, and all index joint angles were analyzed by Kinovea experimental version. The experiment footage is shown in Fig. 4.7 and the averaged maximum joint angles are shown in Table 4.2.

Figure 4.7 Grasping object trajectory evaluation experiment

Table 4.2 The results of index finger averaged maximum flexion angles while grasping from two experiments

	MCP angle	PIP angle	DIP angle
Bare hand	47.9°	67.2°	17.3°
Using Exoskeleton	41.1°	43.1°	39.4°

The index finger motions from two experiments are identical, as the motions can be distinguished into 3 phases even when using the exoskeleton as shown in Fig. 4.8 – 4.9. First, MCP joint gradually rotates until it touched the object and stopped, then, middle and distal phalange also rotate to wrap the object respectively.

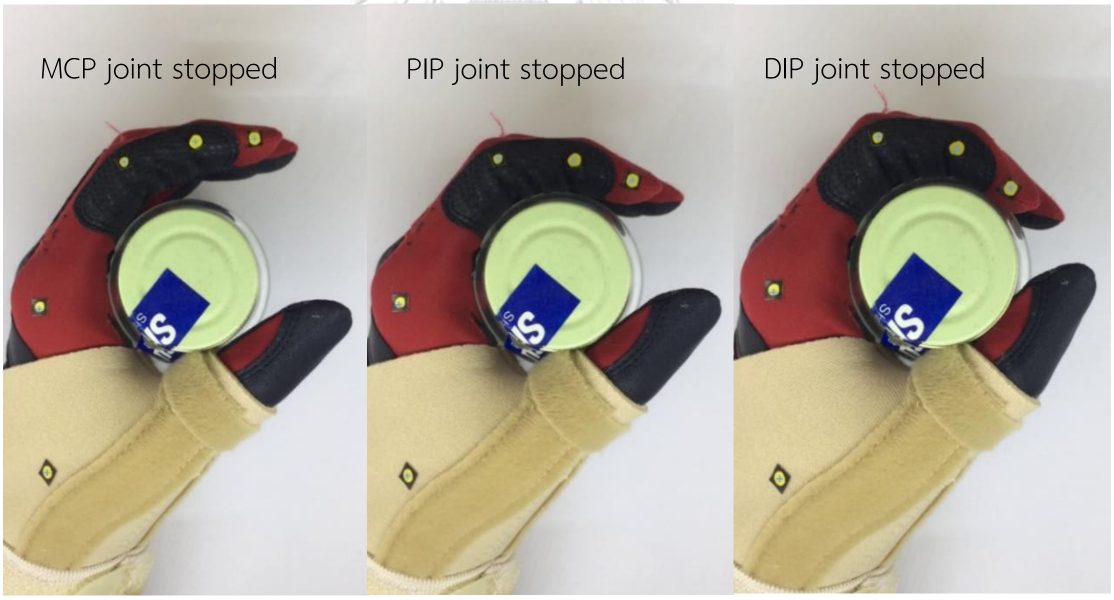

Figure 4.8 Three phases of the bare hand object grasping experiment

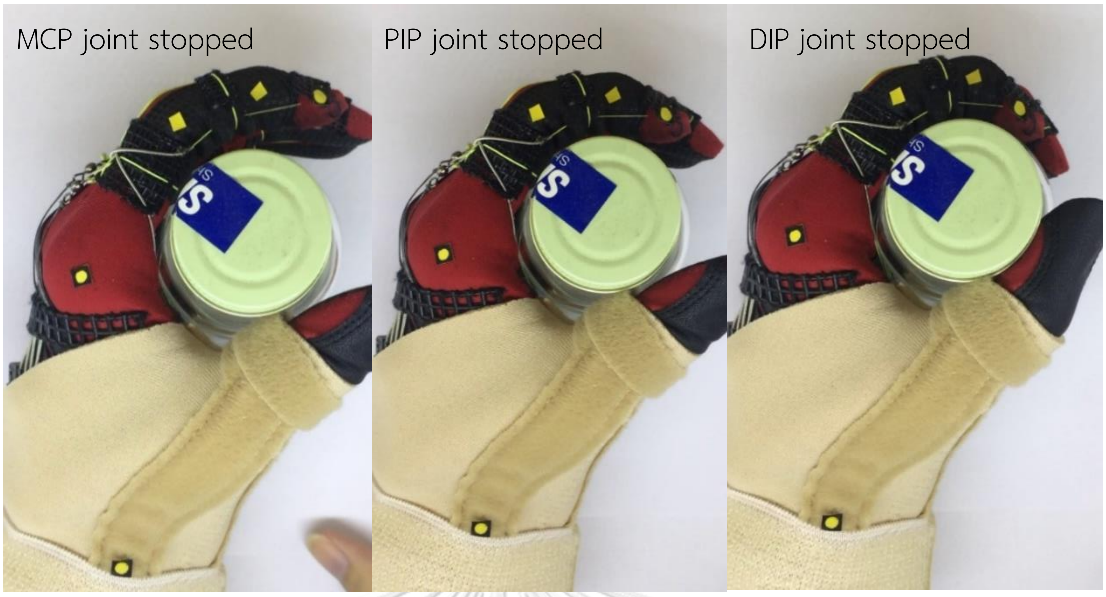

Figure 4.9 Three phases of the exoskeleton object grasping experiment

The index finger motion was captured, and joint angles are plotted against grasping cycle time as shown in Fig. 4.10 – 4.12. The results show that all joint angles intentionally performed by subject’s bare hand are increasing linearly during grasping. MCP joint stopped rotating when proximal phalange touched the object, at this phase, there is a small angular displacement of PIP and DIP joint. MCP joint rotates with the highest angular velocity among these joints (highest slope) which means that subject tries to wrap around the object by mainly rotating MCP joint followed by PIP joint. After that, PIP joint rotates until middle phalange touched the object. Lastly, DIP joint was gradually flexed at the end to help stabilizing the object in the palm by providing fingertips force.

On the other hand, MCP angle performed by exoskeleton is slightly less than the natural grasping of the same subject. Note that MCP joint is starting to rotate at 0.4 seconds, slightly before the other joints at 0.7 seconds time because MCP moment arm is a lot bigger than DIP's and the friction in the x-crossed path also delays its motion as mentioned in earlier section. When the proximal phalange touched the object, the MCP joint stops. At that time, the PIP and DIP angle is gradually rotating until middle phalange reached the object, leaving distal phalange rotates only (at 1.4 s.). Lastly, the DIP angle stopped rotating when subject's index fingertip touched the cylinder, successfully securing object in his palm of the hand.

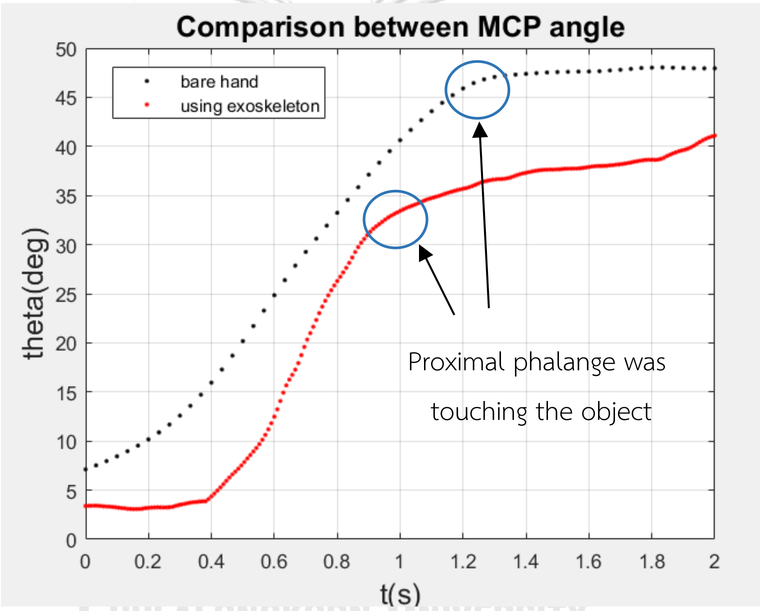

Figure 4.10 Comparison of index finger flexion MCP angle between two experiments

In addition, with the proposed tendon routing, DIP and PIP joint barely moved in the first 1 seconds of the experiment as same as the range of motion grasping experiment. But after proximal phalange touched the object, PIP and DIP angular velocity drastically increase and exceed the slopes of natural grasping as illustrated in Fig. 4.11-4.12. Especially the slope of DIP angle, since proximal phalange motion was restrained. The actuating force is affected on distal phalange, resulting in major movement of DIP joint and lower angular velocity of PIP joint.

In conclusion, the proposed tendon routing can replicate natural sequence of grasping. Both natural and exoskeleton grasping have same 3 phases of grasping. Firstly, MCP rotates until proximal phalange was touching the object and suddenly stopped. Then, PIP flexes until it touched the object and lastly, the DIP joint. Exoskeleton MCP joint slightly flexed less than natural grasping because when human perform grasping, we know that where our palm should touch the objects by seeing its profile. By knowing this, human adjust finger and palm orientation to match with the grasped object profile, but this is difficult during the actuation, resulting in slightly under flexed MCP joint.

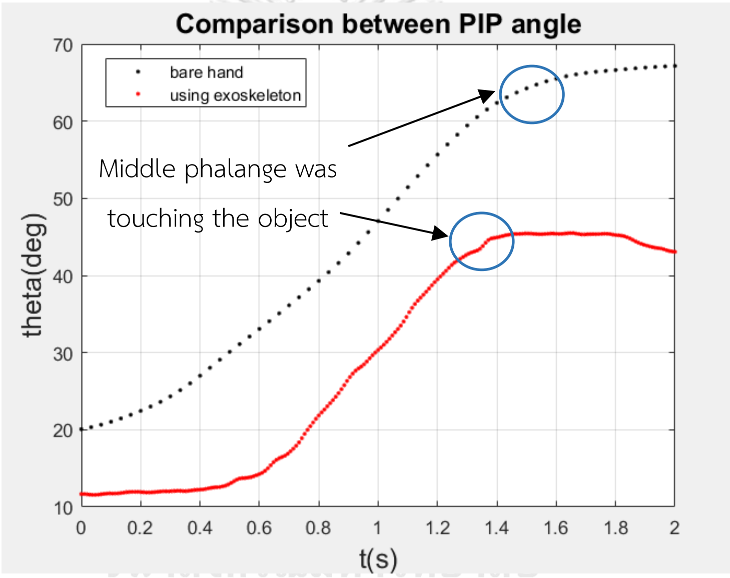

Figure 4.11 Comparison of index finger flexion PIP angle between two experiments

While PIP joint is also under-flexed compared to the natural PIP grasping because the middle phalange has no force exerted on, PIP motion occurred by the effect of fingertip force on distal phalange only. Thus, PIP joint flexed less than natural grasping. In the other hand, DIP joint barely moves in the early grasping stage, even though the fingertip affected directly by the actuation force. But after proximal phalange touched the object the tension affects only the fingertip; the joint velocity has been increased drastically.

However, the proposed tendon routing also has limitation, the underactuated routing rotates both DIP and PIP simultaneously with the greater DIP angle which is unnatural. The PIP should rotate before and rotate more than DIP joint in grasping period.

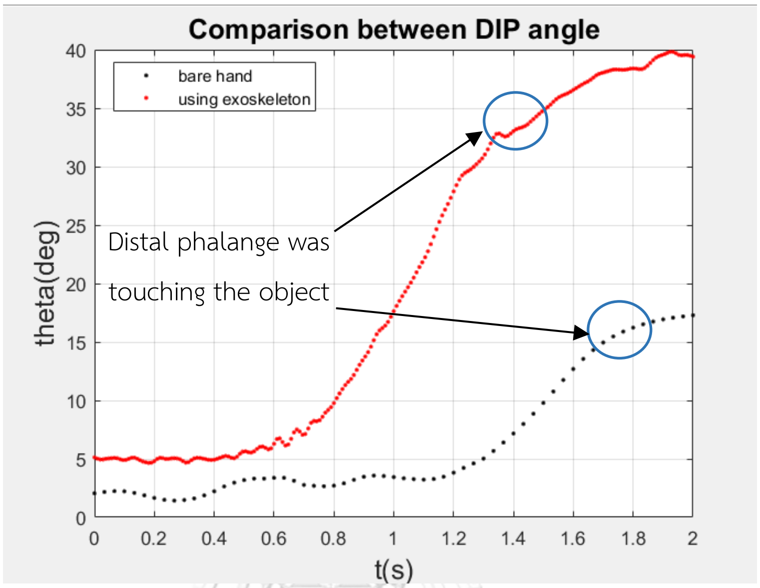

Figure 4.12 Comparison of index finger flexion DIP angle between two experiments

The subject's index fingertip trajectory is plotted in the polar coordinates as shown in Fig. 4.13. Radius (mm) of the plot denotes index fingertip radius, MCP joint is located at r = 0 and θ (0-360°) denotes index fingertip angle, while fingertip position at neutral position is located at θ = 90° (straight finger, all joint angles are zero). Fingertip trajectory were computed by using obtained joint angles with forward kinematics.

The data of fingertip trajectory is mirrored to achieve right-hand-like result for a better understanding plot (subject is left-handed) as same as the previous experiments. The result shows that two trajectories are almost identical during θ between 100 – 160°. After that phase, the paths begin to separate, as the exoskeleton exerts force on the subject's fingertip, causing DIP to flex towards the palm earlier than intentional grasping. While the natural grasping does not have constant force that

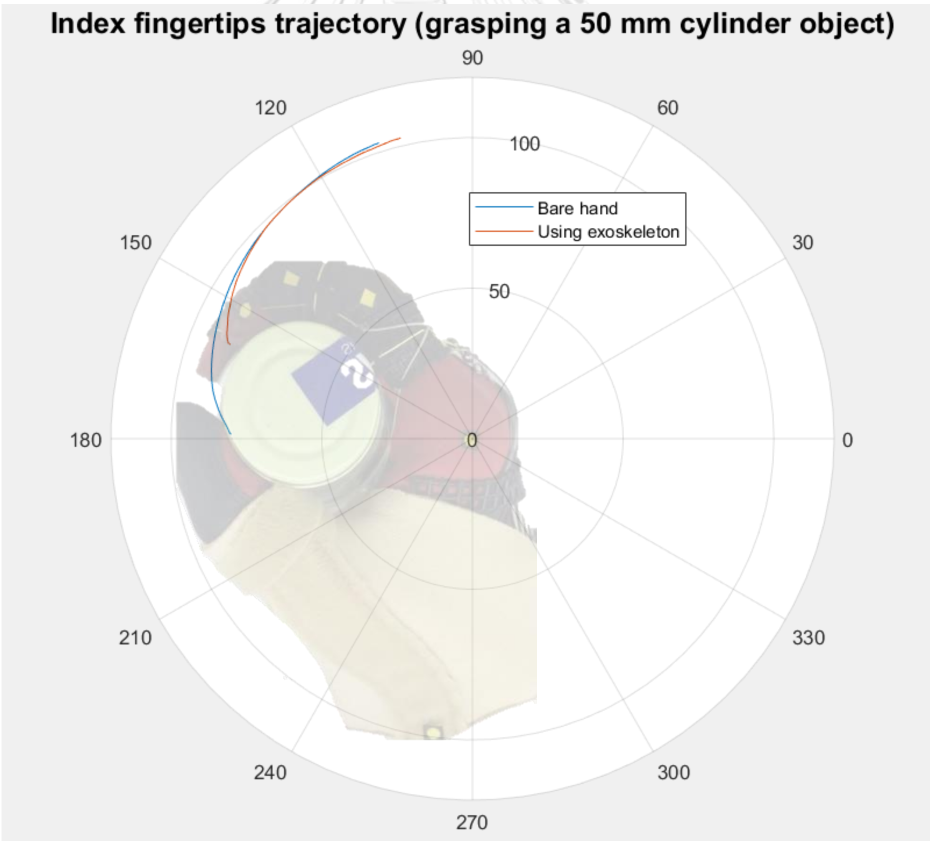

Figure 4.13 Polar plot of the index fingertip trajectories between subject's bare hand and using exoskeleton

pushes the fingertip inside before middle phalange touched the object, resulting in longer distance wrapped around the cylinder.

In conclusion, the index fingertip trajectories of both experiments are identical before the proximal phalange touched the object. After that, force exerted on index fingertip flexed distal and middle phalange which makes a difference in two plots as shown in Fig. 4.13. because natural object grasping will lastly rotate DIP joint after proximal and middle phalange touched the object resulting in more distance covered in the trajectory plot. Lastly, exact trajectory as the natural grasping is difficult to achieve by 1 DOF of actuation that the actuation unit provides because the tendon routing has to exert force on the fingertip to be able to flex every joint of the finger, but by doing this, DIP joint will flex earlier than the natural object grasping.

4.3 Fingertips force Evaluation

To evaluate fingertips force, calibrated pressure sensors were used to measure exoskeleton fingertip force. Calibrated round-type pressure sensors were used to measure each fingertip force separately. Pressure sensors were attached to pressing buttons, then the button will be mounted on a cylindrical testing rig as shown in Fig. 4.14 (right).

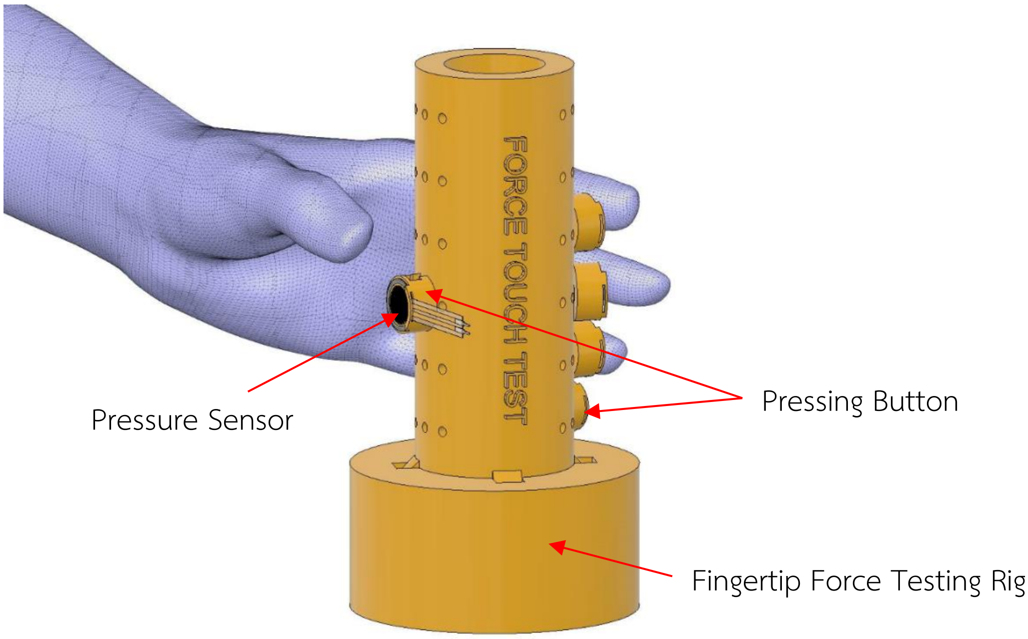

Figure 4.14 Fingertip force testing rig and pressure sensors

The testing rig has multiple holes on the lateral side to make the buttons compatible with any subject. Orientation of the hand were fixed relative to the testing rig during the experiment to achieve the best possible result. The fingertip force measurement of each finger was conducted separately (Index, middle, ring, little finger one at a time) with 5 trials each. While the actuation unit was pulling a tendon, the input tension and fingertip force were recorded until the tension input reached 30 N. Then, the actuator loosened the tendon and the process was repeated for every finger.

Average value of every fingertip force is plotted with input tension in x-axis and fingertip force in y-axis as illustrated in Fig. 4.15. Linear relationship fits the graph very well with slope of 0.36 (r-squared of 0.98). Other fingers also have the same trend as the index finger as shown in Fig. 4.15 – 4.18.

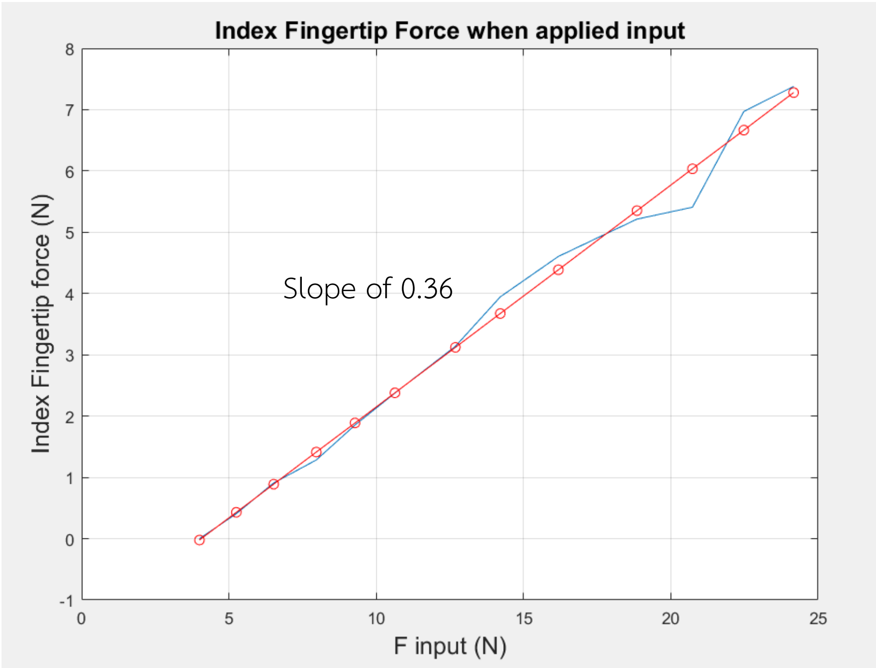

Figure 4.15 Index fingertip force compared with tension input

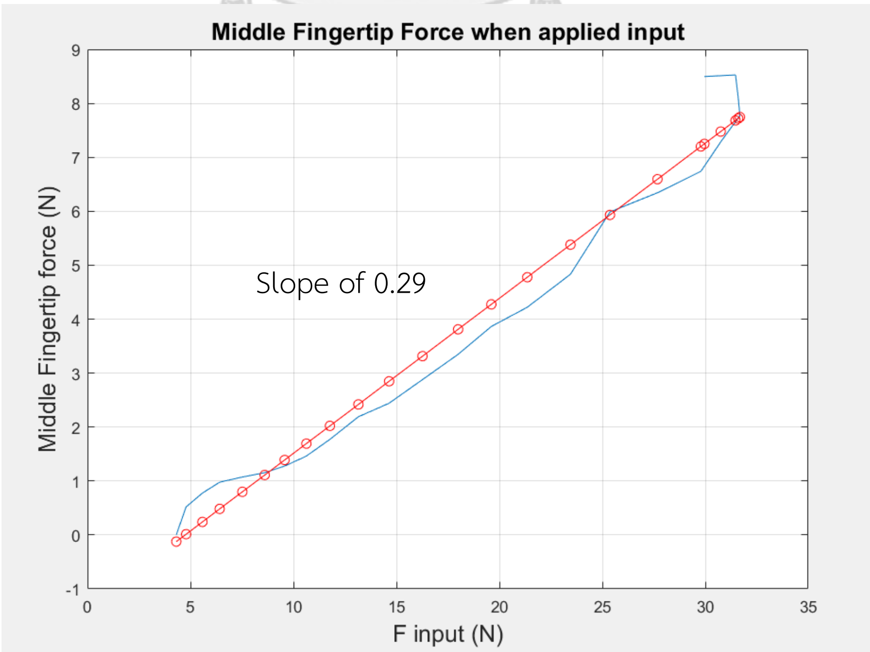

Figure 4.16 Middle fingertip force compared with tension input

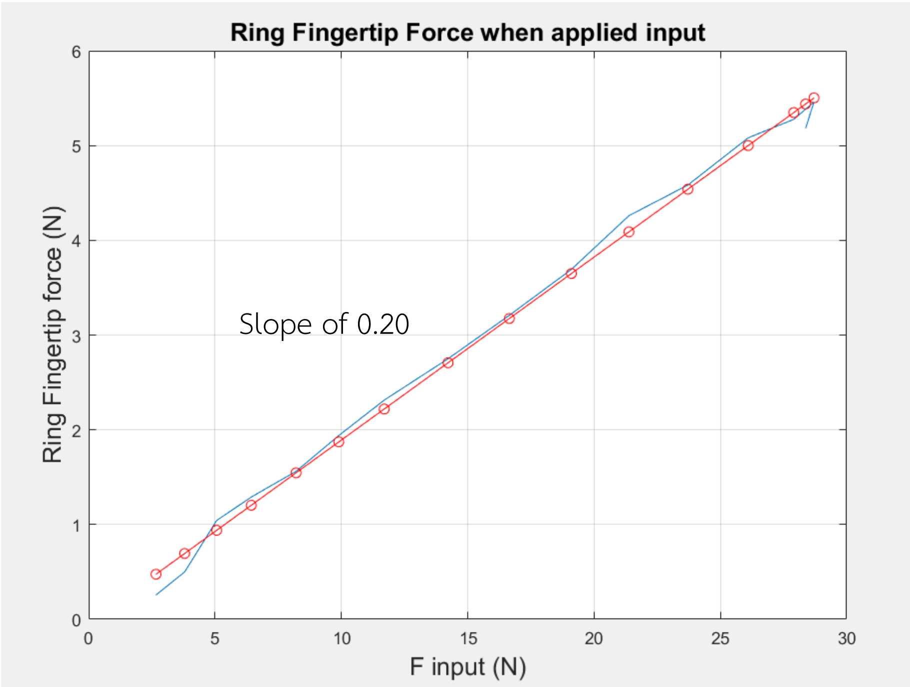

Figure 4.17 Ring fingertip force compared with tension input

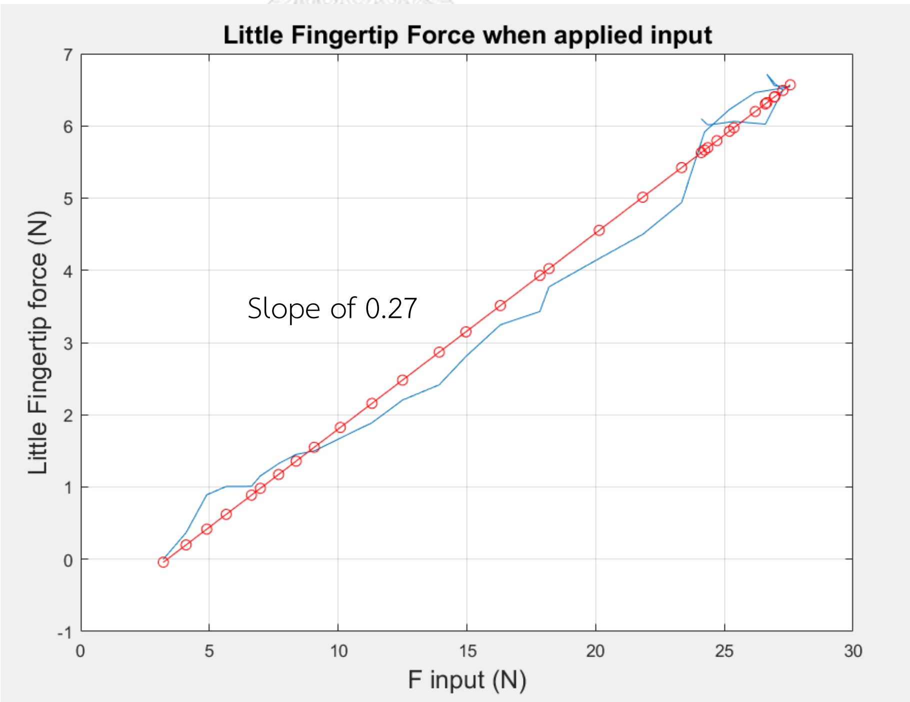

Figure 4.18 Little fingertip force compared with tension input

The averaged fingertip force is approximately 30 % of the input. Due to the flexion tendon path that create fingertip force in a direction as shown in Fig. 4.19. (left), but the collected value is the normal force in the direction which perpendicular with the object curvature as shown in Fig. 4.19. (right). The averaged θ from the experiment is about 30 degrees. Thus, the main reason of low percentage force output is the tension direction, another cause is the friction in the flexion path, especially the x-crossed path that has sharp edges and curvatures. Besides that, the friction between Bowden cable and tendon is a minor factor compared to those aforementioned issues.

In conclusion, the average fingertip force is approximately 30 % of the tension input and it passes the criteria of producing 4.9 N of fingertip force for each finger by using 16 – 17 N. The major loss for this transmission is its direction that creates low normal force. This limitation is difficult to avoid in the soft tendon routing transmission, but it has advantages being a simple with under-actuation mechanism instead. However, friction reduction in the transmission is still possible with material with slippery surfaces attached along sharp edges of routing paths.

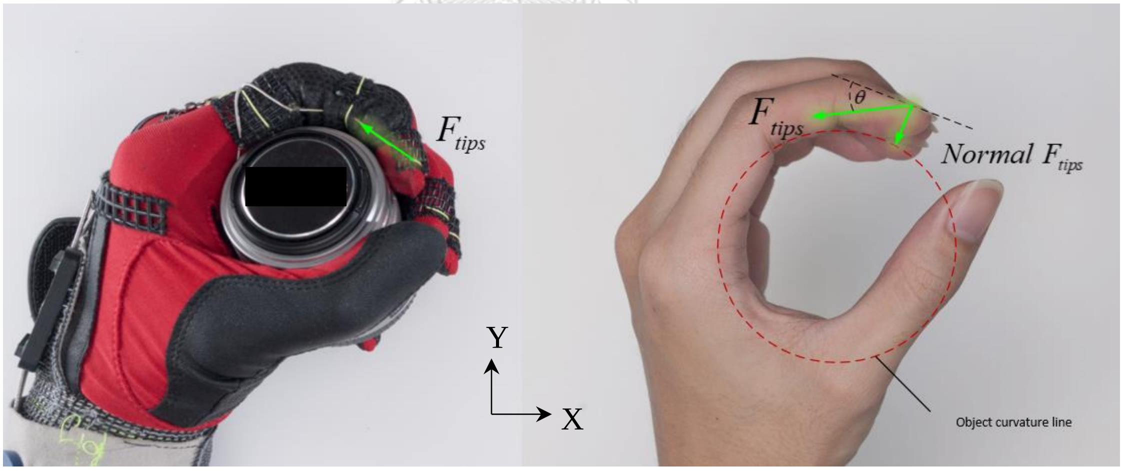

Figure 4.19 (left) Direction of the tension at index fingertip

(right) Fingertip force schematic while grasping an object

Chapter 5
Conclusion

The proposed soft exoskeleton has a low-profile body which weigh only 80 g. While the Exo-glove [20] weigh 194 g., and the three-layered sliding spring exoskeleton [24] weigh 113 g. Thus, the proposed soft-exoskeleton can be considered light-weight. The light-weight profile is achieved by overlaying tendon routing mechanism on a DAIYA golf GL model. It is a standard free-size golfing glove and it also has sweat ventilation technology for the sanitary issue. With its glove-like body, users are able to wear the exoskeleton using only 15 – 20 seconds. Besides the glove, the actuation unit can actuate both flexion and extension of all fingers except thumb with only one actuator. While other soft exoskeleton works using at least 2 actuators. Total weight of the actuation unit is 1.80 kg. (the Exo-glove poly's [29] weigh 1.63 kg), which is unable to carry around in daily life, but it is light enough to be moved and operated in anyplace or even distributing to patient's home to conduct rehabilitation sessions.

Moreover, the flexion routing performed well in both range of motion grasping and object grasping. Even though the range of motion is slightly less than the requirement for PIP and DIP joint, but overall range of motion is extensive and sufficient for object grasping as seen from the previous experiment. The fingertip trajectory performed by the soft exoskeleton also displays a close result compared to the natural grasping in the early stage, but the difference occurs in the late stage of grasping because the proposed flexion tendon routing exerts force on fingertips. Such fingertips force flexes both DIP and PIP joint, while the natural object grasping sequentially flexes MCP, PIP, and DIP respectively.

Furthermore, the PIP and DIP angles performed by the exoskeleton are slightly less than intentional grasping because the maximum moment arm at DIP and PIP joints that can achieve by underactuated tendon routing are still comparatively small, about 5 mm. or less, which is one of the limitation of an underactuated tendon routing. However, the motion generated by the exoskeleton is achieve with only one DOF of actuation by one DC motor, while human hand has more than one DOF of actuation.

Despite of small moment arm, the fingertip forces comfortably achieve the design requirement of 4.9 N with the 30 % output (using 16 – 17 N. of input). The transmission loss mainly occurs by direction of force exerted on fingertips. However, the soft exoskeleton will be able to hold and lift any object that weighs equal or below 500 g. at least, even in a slippery condition (μ below 0.3).

5.1 Challenges and Problems

Main problems that affect performance of the exoskeleton are bended wrist and movement of the flexion Bowden attacher. Bended wrist is caused by high amount of tension in flexion routing combined when user grasps an object as shown in Fig. 5.1 (left). Because of the flexion Bowden attacher is located below the wrist and high amount of tension will cause wrist moment as mentioned in earlier section.

There are two possible solutions, first, design a small sized Bowden attacher that does not interfere with the grasping if it is placed above the wrist. Second solution is to reduce number of actuated fingers to reduce overall tension as two or three fingers might be enough to grasp and stabilize objects, with this solution, the Bowden attacher movement is also reduced.

Second problem is flexion Bowden attacher movement, force that occurs on the attacher is the reaction force of the actuation force. The solution is quite the same as bended wrist problem that is trying to reduce actuation force while keeping the same performance or revising the attacher design to achieve a better force distribution surface. In addition, manufacturing process of the soft exoskeleton is quite laborious because small parts have to be sewed on the glove such as poly-ester net, Bowden cable, and tendon. Moreover, the x-crossed paths are also difficult to manufacture, and its fixation point is being the weakest point in tendon routing as it is damaged after numerous times of usage.

Another issue is to conceal the flexion tendons at the palm of the hand. Flexion routes are routed from the Bowden attacher to the x-crossed paths across the palm.

From the observation during testing, this issue does not interfere with object grasping but it might cause higher friction along the route and cause unattractive appearance.

Figure 5.1 (left) Bended wrist when grasping object,

(right) Upward Bowden attacher movement

5.2 Future works

In the near future, we hope that this soft exoskeleton could be used as a portable assistive device that people can use in daily life. Thus, all the future works are selected towards practical usage issues to help the people in need.

Further works can be divided in 3 matters, developing the flexion Bowden attacher, optimization of the actuation unit, and improving the soft exoskeleton’s appearance. First, design of the flexion Bowden attacher has to be revised to minimize its movement during actuation. Secondly, there is a plenty of parts that can be revised to reduce the actuation unit’s weight and size as much as possible. Lastly, appearance of the exoskeleton must be improved to make it looks friendlier to user.

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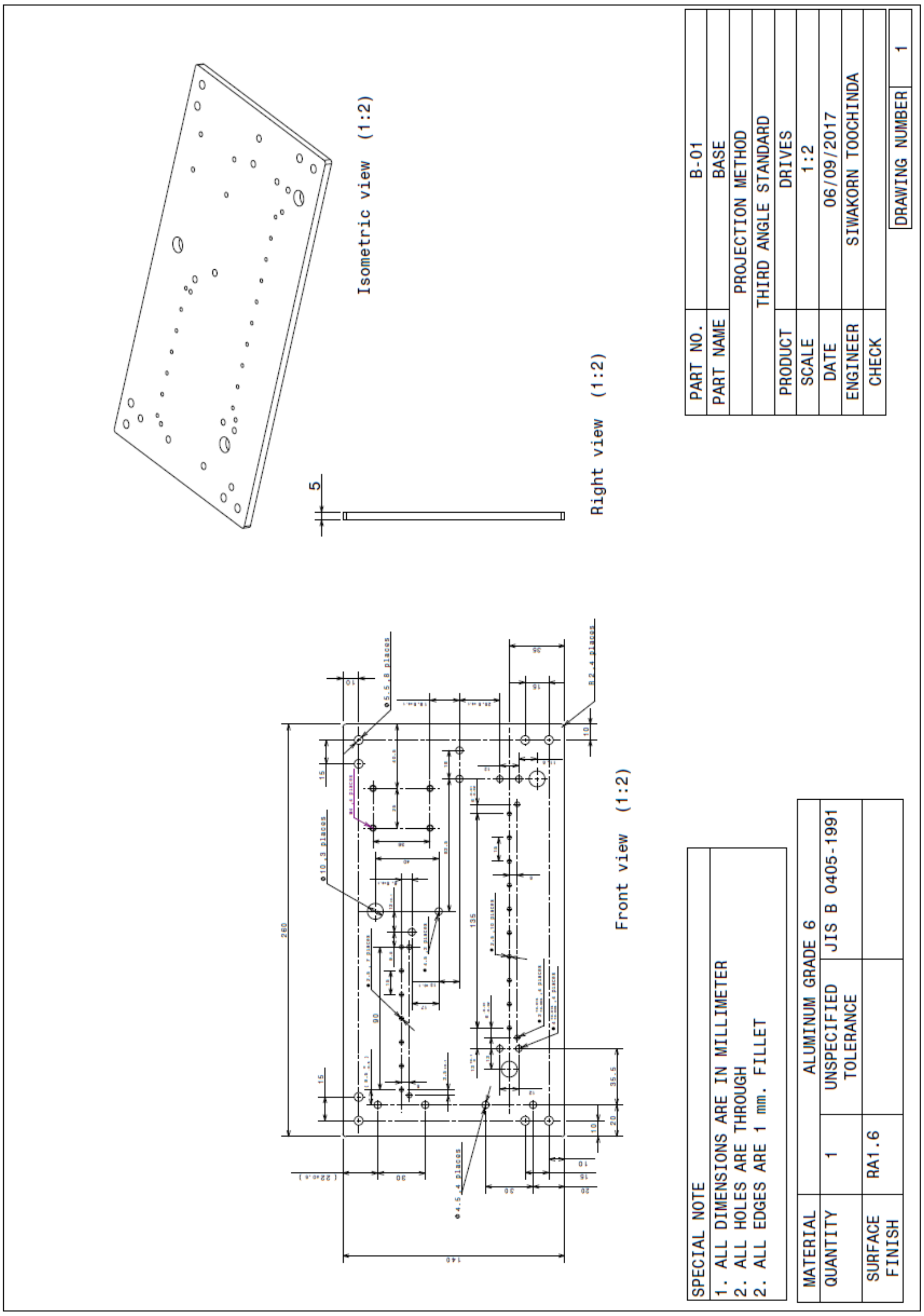
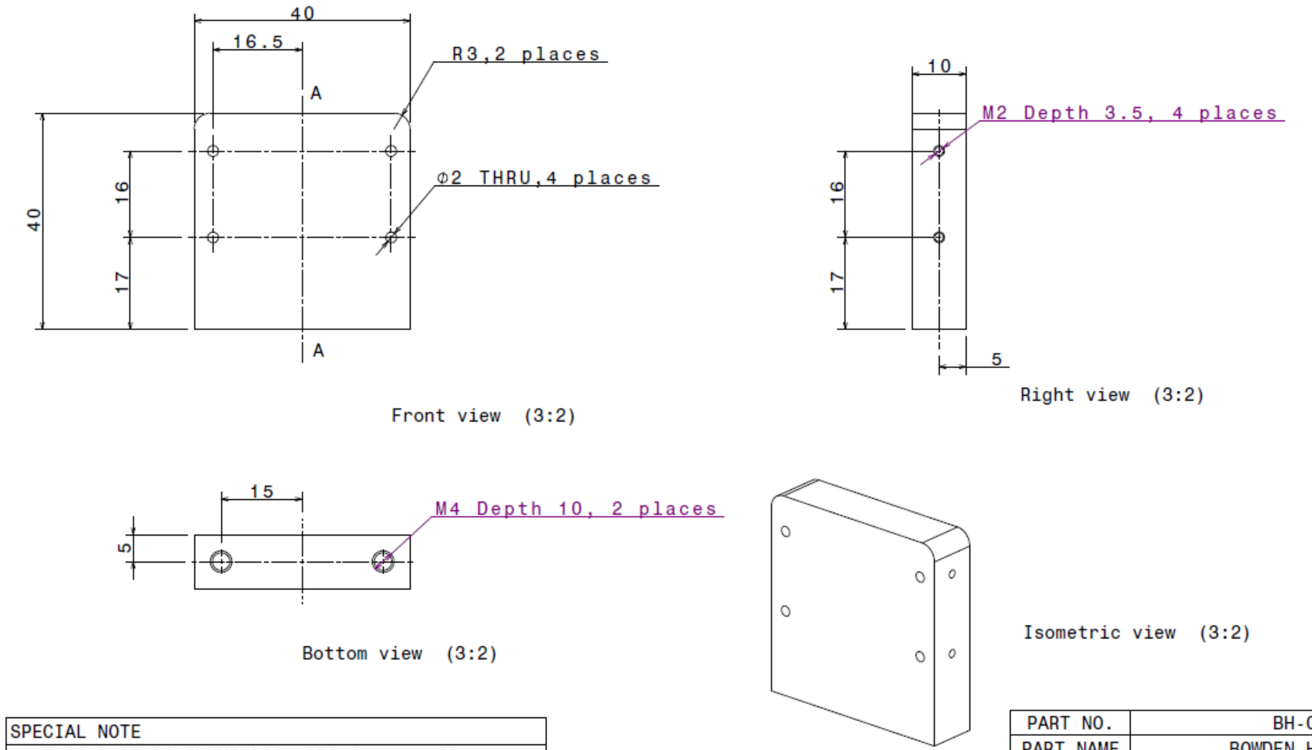
APPENDIX A

FABRICATED PARTS



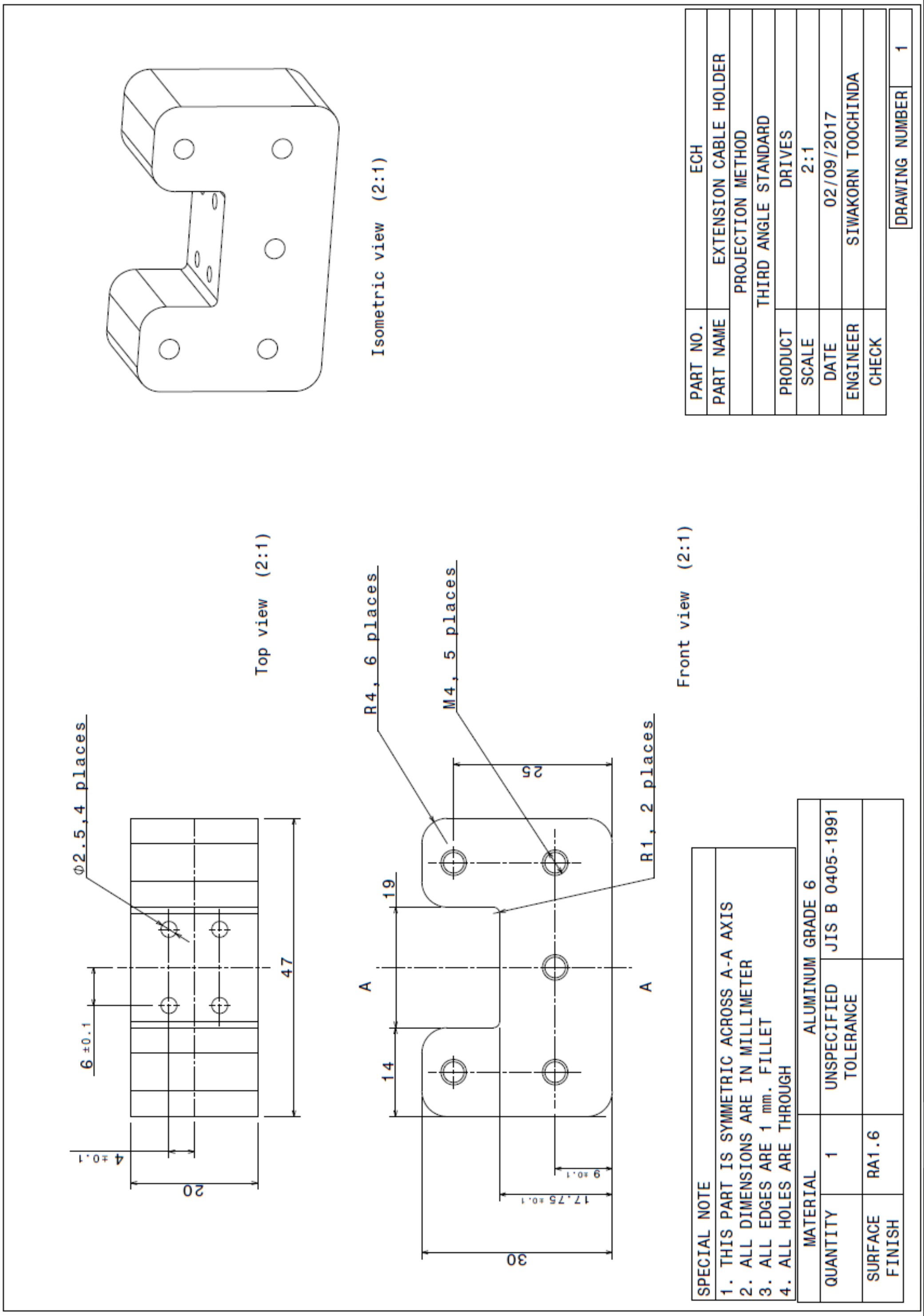


SPECIAL NOTE
1. THIS PART IS SYMMETRIC ACROSS A-A AXIS 2. ALL DIMENSIONS ARE IN MILLIMETER 3. ALL EDGES ARE 1 mm. FILLET

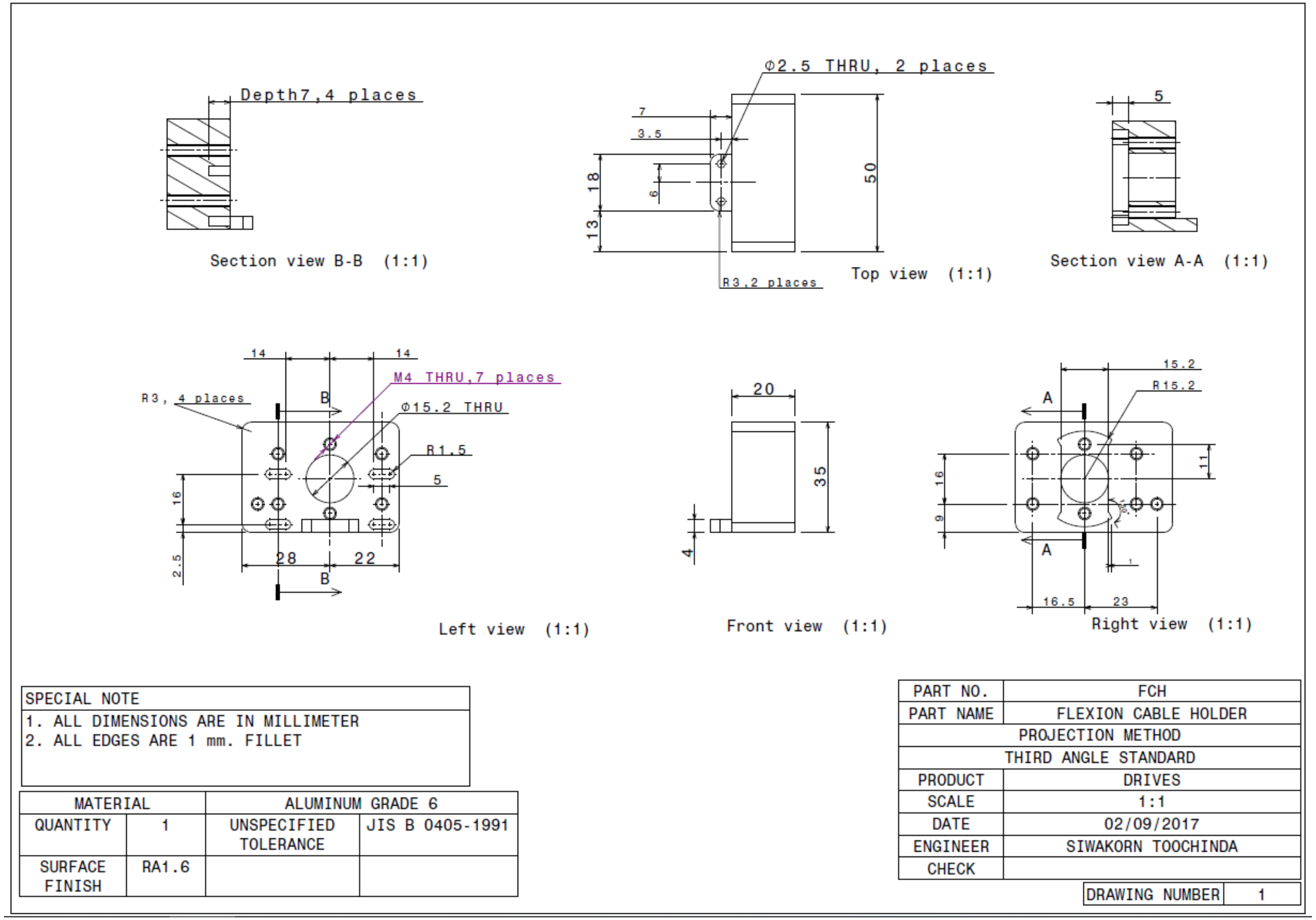
MATERIAL		ALUMINUM GRADE 6	
QUANTITY	2	UNSPECIFIED TOLERANCE	JIS B 0405-1991
SURFACE FINISH	Ra1.6		

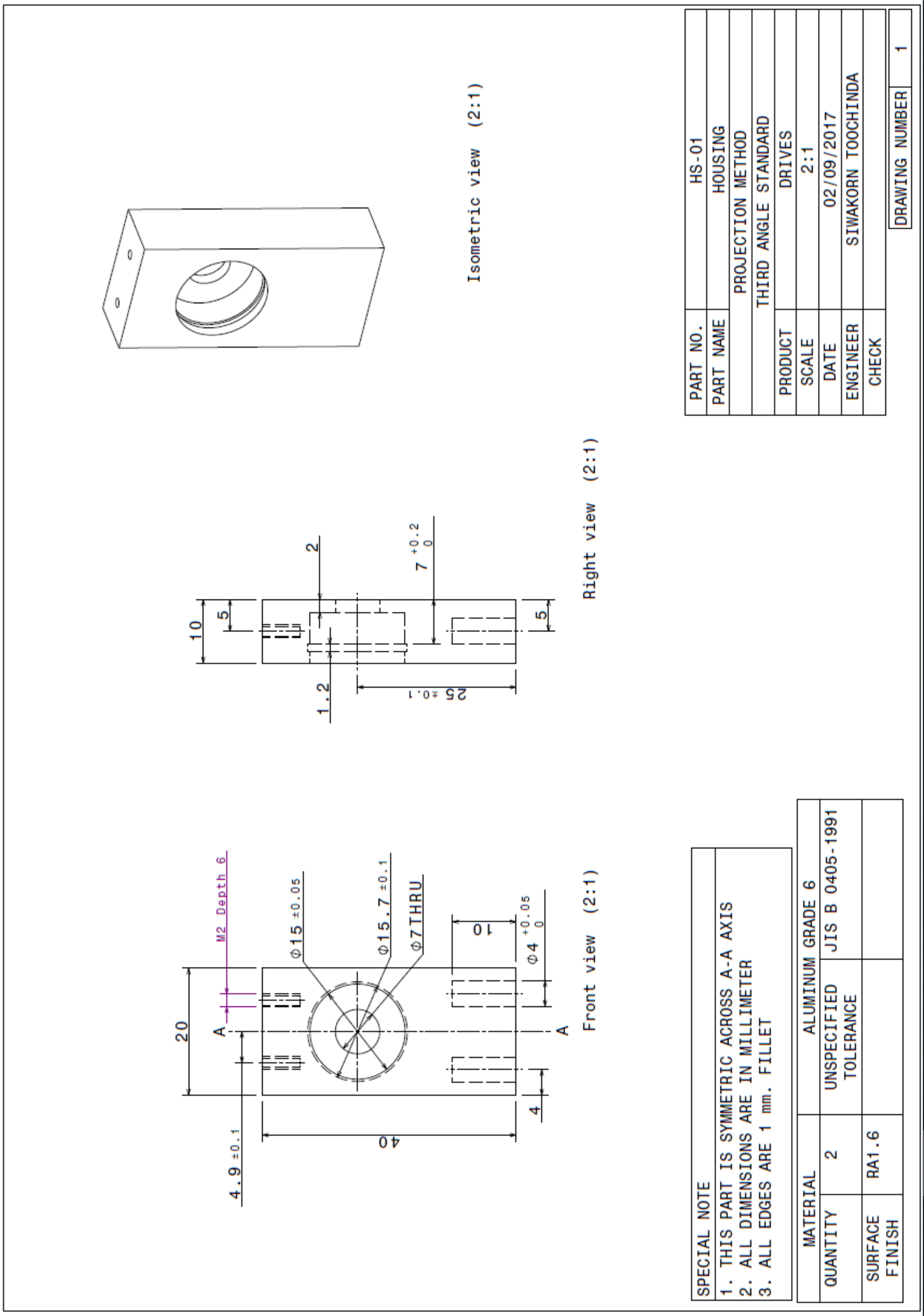
PART NO.	BH-01
PART NAME	BOWDEN HOLDER
PROJECTION METHOD	
THIRD ANGLE STANDARD	
PRODUCT	DRIVES
SCALE	3:2
DATE	02/09/2017
ENGINEER	SIWAKORN TOOCHINDA
CHECK	

DRAWING NUMBER	1

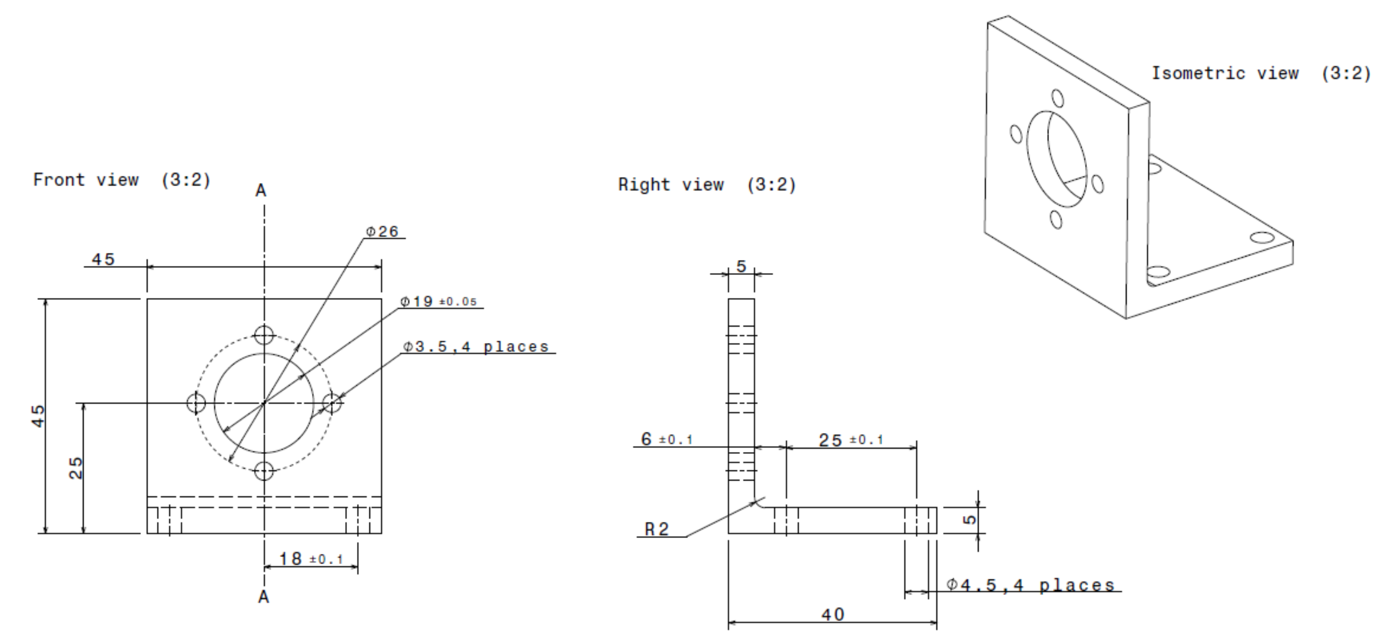


Isometric view (2:1)
Top view (2:1)
Front view (2:1)
Φ2.5,4 places
6 ±0.1
4 ±0.1
20
47
R4, 6 places
M4, 5 places
R1, 2 places
25
19
14
A
A
9 ±0.1
17.75 ±0.1
30
PART NO. ECH
PART NAME EXTENSION CABLE HOLDER
PROJECTION METHOD
THIRD ANGLE STANDARD
PRODUCT DRIVES
SCALE 2:1
DATE 02/09/2017
ENGINEER SIWAKORN TOOCHINDA
CHECK
DRAWING NUMBER 1
SPECIAL NOTE
1. THIS PART IS SYMMETRIC ACROSS A-A AXIS
2. ALL DIMENSIONS ARE IN MILLIMETER
3. ALL EDGES ARE 1 mm. FILLET
4. ALL HOLES ARE THROUGH
MATERIAL ALUMINUM GRADE 6
QUANTITY 1
UNSPECIFIED TOLERANCE JIS B 0405-1991
SURFACE FINISH RA1.6


Depth7,4 places
Section view B-B (1:1)
Φ2.5 THRU, 2 places
7
3.5
18
6
13
50
R3,2 places
Top view (1:1)
5
Section view A-A (1:1)
14
14
M4 THRU,7 places
R3, 4 places
B
Φ15.2 THRU
R1.5
5
16
2.5
28
22
B
Left view (1:1)
20
35
4
Front view (1:1)
15.2
R15.2
A
11
16
9
A
1
16.5
23
Right view (1:1)
SPECIAL NOTE
1. ALL DIMENSIONS ARE IN MILLIMETER
2. ALL EDGES ARE 1 mm. FILLET
MATERIAL
ALUMINUM GRADE 6
QUANTITY
1
UNSPECIFIED TOLERANCE
JIS B 0405-1991
SURFACE FINISH
RA1.6
PART NO.
FCH
PART NAME
FLEXION CABLE HOLDER
PROJECTION METHOD
THIRD ANGLE STANDARD
PRODUCT
DRIVES
SCALE
1:1
DATE
02/09/2017
ENGINEER
SIWAKORN TOOCHINDA
CHECK
DRAWING NUMBER
1



Isometric view (2:1)
Right view (2:1)
Front view (2:1)
M2 Depth 6
Φ15 ±0.05
Φ15.7 ±0.1
Φ7THRU
Φ4 +0.05 0
7 +0.2 0
25 ±0.1
4.9 ±0.1
20
40
10
5
2
1.2
4
A
PART NO. HS-01
PART NAME HOUSING
PROJECTION METHOD
THIRD ANGLE STANDARD
PRODUCT DRIVES
SCALE 2:1
DATE 02/09/2017
ENGINEER SIWAKORN TOOCHINDA
CHECK
DRAWING NUMBER 1
SPECIAL NOTE
1. THIS PART IS SYMMETRIC ACROSS A-A AXIS
2. ALL DIMENSIONS ARE IN MILLIMETER
3. ALL EDGES ARE 1 mm. FILLET
MATERIAL ALUMINUM GRADE 6
QUANTITY 2
UNSPECIFIED TOLERANCE JIS B 0405-1991
SURFACE FINISH RA1.6

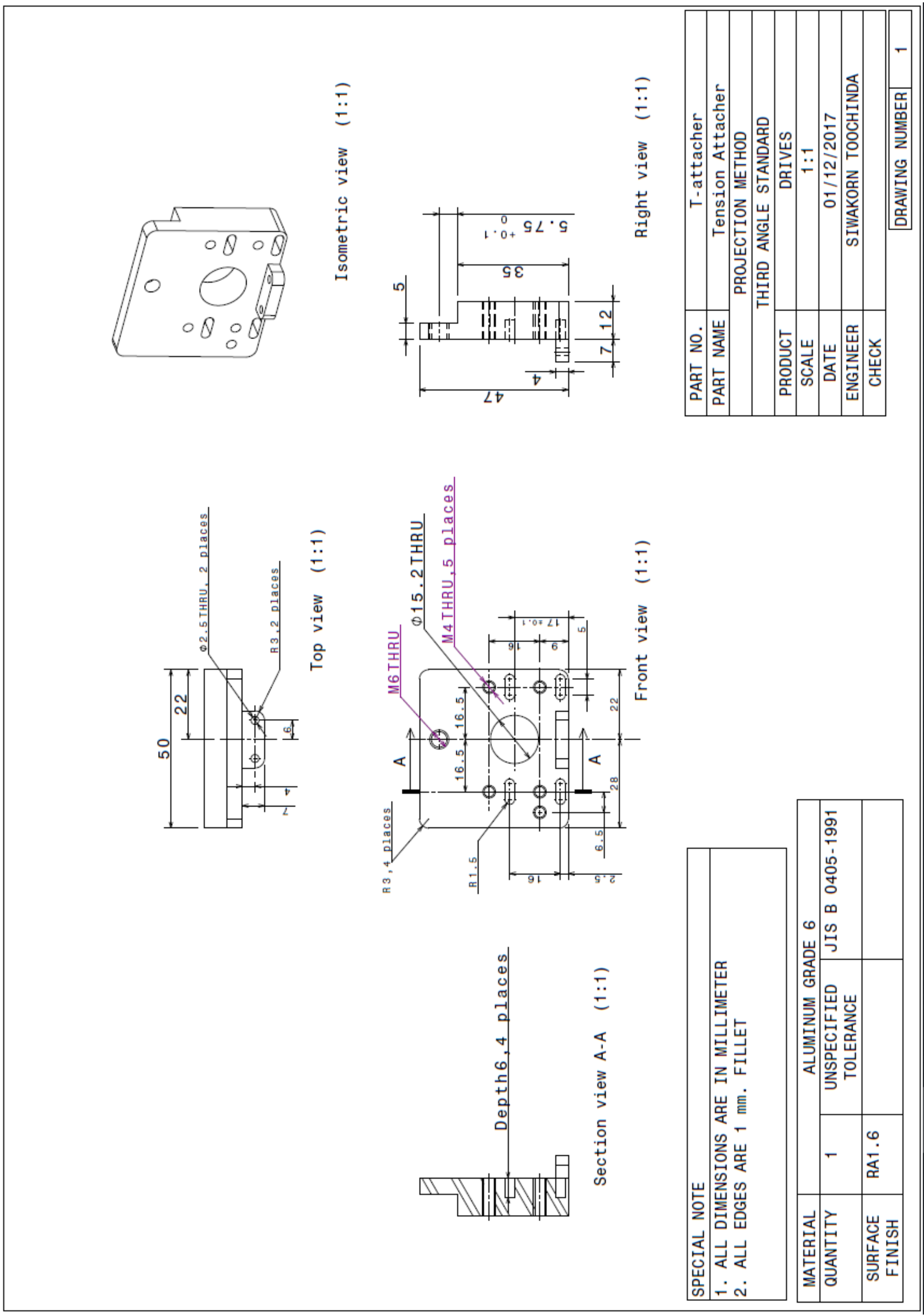


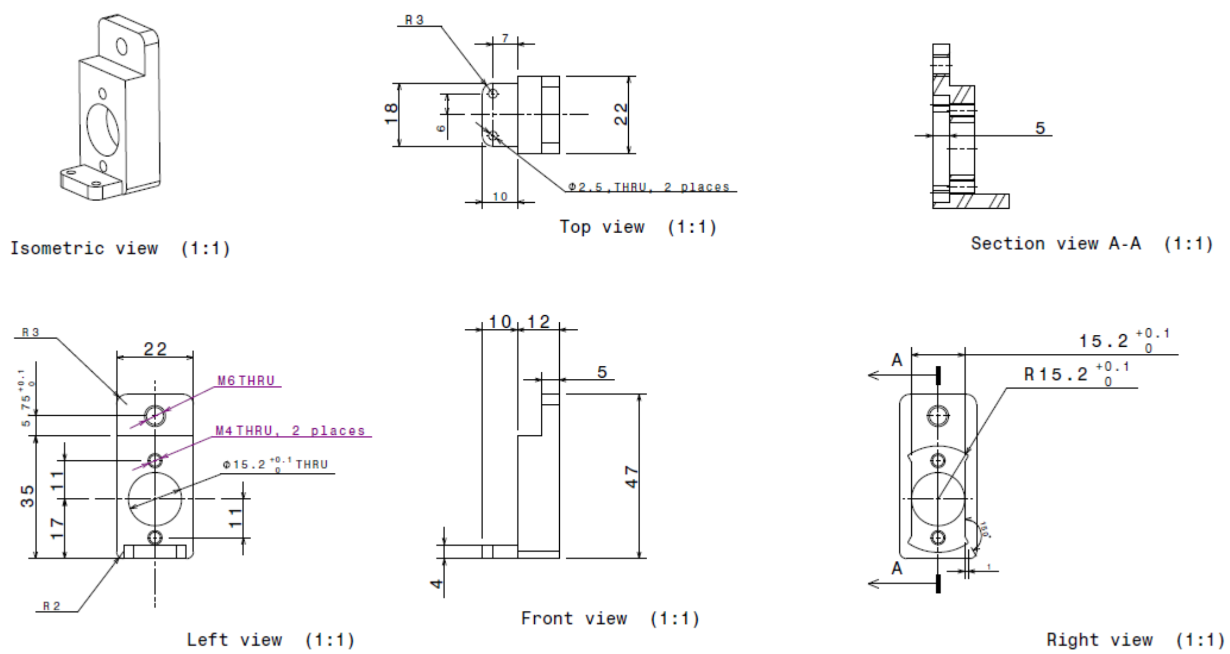
SPECIAL NOTE
1. THIS PART IS SYMMETRIC ACROSS A-A AXIS
2. ALL DIMENSIONS ARE IN MILLIMETER
3. ALL EDGES ARE 1 mm. FILLET
4. ALL HOLES ARE THROUGH

MATERIAL		ALUMINUM GRADE 6	
QUANTITY	1	UNSPECIFIED TOLERANCE	JIS B 0405-1991
SURFACE FINISH	RA1.6		

PART NO.	RE-29B
PART NAME	MOTOR BRACKET
PROJECTION METHOD	
THIRD ANGLE STANDARD	
PRODUCT	DRIVES
SCALE	3:2
DATE	02/09/2017
ENGINEER	SIWAKORN TOOCHINDA
CHECK	

DRAWING NUMBER	1


50
22
Φ2.5THRU, 2 places
R3,2 places
Top view (1:1)
Isometric view (1:1)
Depth6,4 places
Section view A-A (1:1)
R3,4 places
M6THRU
Φ15.2THRU
M4THRU,5 places
R1.5
16.5
Front view (1:1)
Right view (1:1)
47
35
5.75
SPECIAL NOTE
1. ALL DIMENSIONS ARE IN MILLIMETER
2. ALL EDGES ARE 1 mm. FILLET
MATERIAL ALUMINUM GRADE 6
QUANTITY 1
UNSPECIFIED TOLERANCE JIS B 0405-1991
SURFACE FINISH RA1.6
PART NO. T-attacher
PART NAME Tension Attacher
PROJECTION METHOD
THIRD ANGLE STANDARD
PRODUCT DRIVES
SCALE 1:1
DATE 01/12/2017
ENGINEER SIWAKORN TOOCHINDA
CHECK
DRAWING NUMBER 1



SPECIAL NOTE
1. ALL DIMENSIONS ARE IN MILLIMETER 2. ALL HOLES ARE THROUGH 3. ALL EDGES ARE 1 mm. FILLET

MATERIAL	ALUMINUM GRADE 6		
QUANTITY	1	UNSPECIFIED TOLERANCE	JIS B 0405-1991
SURFACE FINISH	RA1.6		

PART NO.	Tnut
PART NAME	Tension nut
PROJECTION METHOD	
THIRD ANGLE STANDARD	
PRODUCT	DRIVES
SCALE	1:1
DATE	01/12/2017
ENGINEER	SIWAKORN TOOCHINDA
CHECK	

DRAWING NUMBER	1

APPENDIX B

PARTS FROM SUPPLIERS


Copley Controls Corp.

Accelus™ Panel

DIGITAL SERVOAMPLIFIER
for BRUSHLESS or BRUSH MOTORS

RoHS

Control Modes
- Gearing, Position, Velocity, Torque

Command Interface
- Stepper commands
- ±10V velocity/torque command
- PWM velocity/torque command
- Master encoder [Gearing]

Communications
- RS232

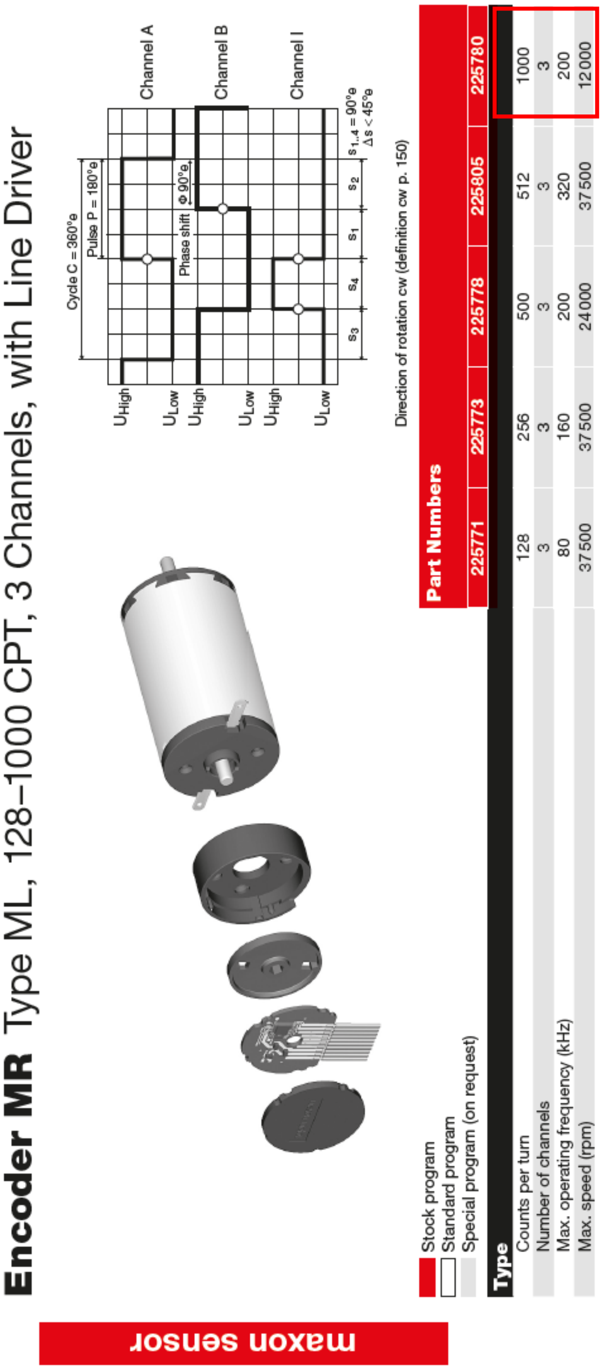
Feedback
- Digital Quad A/B encoder
- Digital Halls

I/O - Digital
- 6 inputs, 2 outputs

Dimensions: mm [in]
- 168 x 99 x 31 [6.6 x 3.9 x 1.2]

MODEL	IC	IP	VDC
ASP-055-18	6	18	55
ASP-090-09	3	9	90
ASP-090-18	6	18	90
ASP-090-36	12	36	90
ASP-180-09	3	9	180
ASP-180-18	6	18	180

Copley Control’s Accelus Servo Amplifier – ASP-055-18 (Image from Copley Controls Corporation https://www.copleycontrols.com/)


maxon sensor

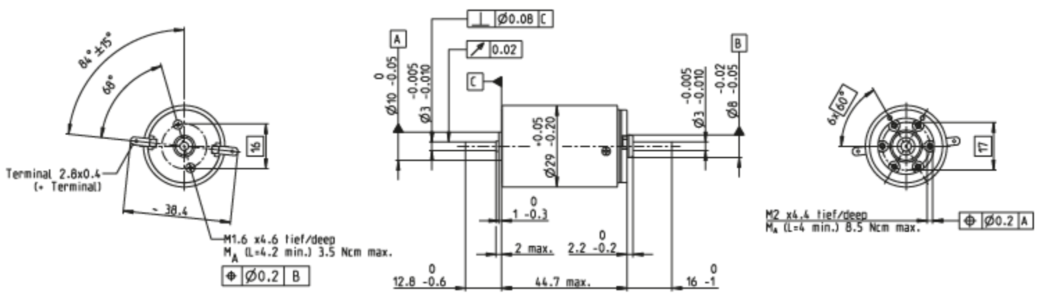
Encoder MR Type ML, 128–1000 CPT, 3 Channels, with Line Driver

Stock program
Standard program
Special program (on request)

	Part Numbers				
	225771	225773	225778	225805	225780
Type					
Counts per turn	128	256	500	512	1000
Number of channels	3	3	3	3	3
Max. operating frequency (kHz)	80	160	200	320	200
Max. speed (rpm)	37 500	37 500	24 000	37 500	12 000

Maxon 1000 ppr Encoder (Image from https://www.maxonmotor.com)

RE-max 29 ∅29 mm, Graphite Brushes, 22 Watt



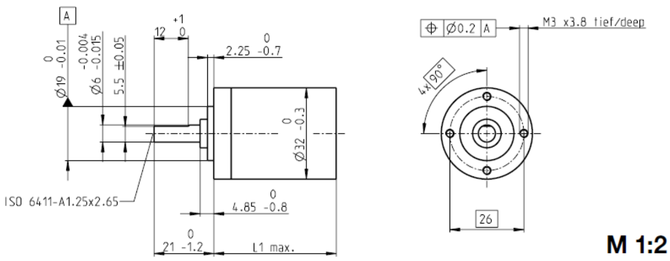
M 1:2

Stock program
Standard program
Special program (on request)

Motor Data	Unit	226801	226802	226805	226806	226807	226808	226809	226810	226811	226815	226816	226817	226818	226819	226820
Values at nominal voltage																
1 Nominal voltage	V	9	12	18	24	30	36	42	48	48	48	48	48	48	48	48
2 No load speed	rpm	7890	9350	9010	8860	9140	8700	8410	8630	7470	6110	5250	4870	4040	3250	2700
3 No load current	mA	78.2	73.7	46.8	34.2	28.6	22.3	18.3	16.5	13.7	10.5	8.7	7.93	6.33	4.9	3.96
4 Nominal speed	rpm	7580	8960	8270	8050	8200	7760	7450	7670	6450	5100	4240	3850	3000	2200	1630
5 Nominal torque (max. continuous torque)	mNm	10.9	12.3	19.7	27	30.8	31.1	30.8	30.7	29.4	30.8	31.1	31.2	30.9	30.9	30.6
6 Nominal current (max. continuous current)	A	1.08	1.08	1.08	1.08	1.01	0.811	0.666	0.595	0.495	0.423	0.366	0.34	0.28	0.225	0.186
7 Stall torque	mNm	284	299	242	299	300	287	271	277	215	188	162	150	120	95.7	77.5
8 Stall current	A	26.1	24.5	12.7	11.6	9.6	7.29	5.71	5.22	3.52	2.51	1.86	1.6	1.06	0.684	0.461
9 Max. efficiency	%	89	89	88	90	90	89	89	89	88	88	87	86	85	84	82
Characteristics																
10 Terminal resistance	Ω	0.345	0.49	1.41	2.07	3.13	4.94	7.36	9.19	13.6	19.1	25.8	30.1	45.1	70.2	104
11 Terminal inductance	mH	0.034	0.044	0.106	0.195	0.285	0.453	0.66	0.82	1.09	1.63	2.21	2.57	3.72	5.73	8.27
12 Torque constant	mNm/A	10.9	12.2	19	25.8	31.2	39.4	47.5	53	61.1	74.7	86.9	93.7	113	140	168
13 Speed constant	rpm/V	879	781	502	370	306	242	201	180	156	128	110	102	84.6	68.2	56.8
14 Speed / torque gradient	rpm/mNm	27.9	31.4	37.4	29.8	30.6	30.4	31.1	31.3	34.8	32.7	32.6	32.7	33.8	34.2	35.1
15 Mechanical time constant	ms	4.21	4.24	4.29	4.23	4.24	4.25	4.26	4.26	4.3	4.3	4.3	4.3	4.32	4.34	4.35
16 Rotor inertia	gcm^2	14.4	12.9	11	13.6	13.2	13.3	13.1	13	11.8	12.5	12.6	12.5	12.2	12.1	11.8

Maxon brush 22 W 12 V DC motor (Image from https://www.maxonmotor.com)

Planetary Gearhead GP 32 A ∅32 mm, 0.75–4.5 Nm

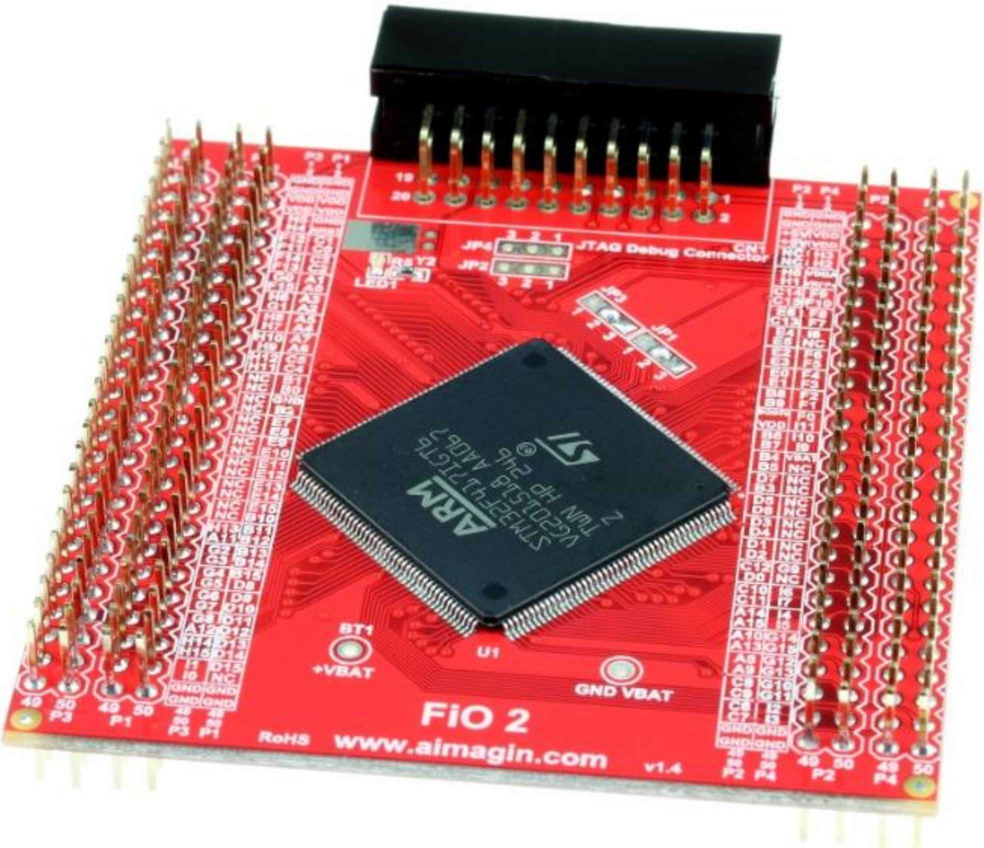


Technical Data	
Planetary Gearhead	straight teeth
Output shaft	stainless steel
Shaft diameter as option	8 mm
Bearing at output	ball bearing
Radial play, 5 mm from flange	max. 0.14 mm
Axial play	max. 0.4 mm
Max. axial load (dynamic)	120 N
Max. force for press fits	120 N
Direction of rotation, drive to output	=
Max. continuous input speed	6000 rpm
Recommended temperature range	-40…+100°C
Number of stages	1 2 3 4 5
Max. radial load, 10 mm from flange	90 N 140 N 200 N 220 N 220 N

Option: Low-noise version

	Part Numbers		166157
1	Reduction		5.8 : 1
2	Absolute reduction		$^{23}/_{4}$
3	Max. motor shaft diameter	mm	3
4	Number of stages		1
5	Max. continuous torque	Nm	0.75
6	Max. intermittent torque at gear output	Nm	1.1
7	Max. efficiency	%	80
8	Weight	g	118
9	Average backlash no load	°	0.7
10	Mass inertia	gcm²	1.5
11	Gearhead length L1	mm	26.5

Maxon 5.8:1 ratio planetary gearhead (Image from https://www.maxonmotor.com)



Aimagin Fio 2 with Arm Cortex-M4 CPU microcontroller (Image from https://www.aimagin.com/fio-2.html)

VITA

Siwakorn Toochinda was born on 12th May 1994, the eldest child of Saran Toochinda and Aim-on Toochinda. He graduated from Bodindecha (Sing Singhaseni) School. Then, he received bachelor's degree in mechanical engineering from Chulalongkorn University in 2016. To continue researching in human-robotics related field, he pursues a master's in mechanical engineering at Chulalongkorn University majoring in control and robotics.