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DESIGN AND DEVELOPMENT OF A ROBOTIC FINGER EXOSKELETON FOR REHABILITATION

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การกายภาพบำบัดแบบเรนจ์ออฟโมชั่นในปัจจุบันใช้นักกายภาพบำบัดช่วยเหลือผู้ป่วยแบบคนต่อคน งานในลักษณะนี้สามารถใช้อุปกรณ์เชิงหุ่นยนต์ทดแทนได้เป็นอย่างดี โครงการวิจัยนี้มีเป้าหมายคือการออกแบบและพัฒนาระบบหุ่นยนต์โครงร่างภายนอกของนิ้วมือในลักษณะเป็นเครื่องซีพีเอ็ม (continuous passive motion device) สำหรับการกายภาพบำบัดแบบเรนจ์ออฟโมชั่น งานวิจัยได้นำเสนอกลไกรูปแบบใหม่สำหรับการออกแบบหุ่นยนต์โครงร่างภายนอกของนิ้วมือ แนวคิดหลักของกลไกดังกล่าวคือการออกแบบให้ไม่มีการขัดแย้ง (interference) กับการเคลื่อนที่ของนิ้วมือและไม่มีแรงปฏิกริยาแนวขนานกับกระดูกของนิ้ว (translational force) กลไกหุ่นยนต์โครงร่างภายนอกของนิ้วมือประกอบด้วยกลไกขับเคลื่อนข้อต่อ (joint mechanism) ที่เหมือนกัน 3 ชุด โดยแต่ละชุดมีการใช้กลไกจำลองจุดหมุนระยะไกล (remote center of motion mechanism) ซึ่งเสมือนกับข้อต่อแบบหมุน (revolute joint) 1 จุด ประกอบกับข้อต่อแบบเลื่อนขนาน (prismatic joint) 2 จุด เมื่อรวมกับข้อต่อของมนุษย์ (anatomical joint) 1 จุด ส่วนประกอบที่กล่าวมาจะรวมตัวเป็นกลไกวงปิด (close-loop mechanism) สายเคเบิลและท่อหรือเรียกรวมกันว่าระบบส่งกำลังแบบบาวเดนเคเบิล (Bowden cable transmission) ถูกนำมาใช้เพื่อลดภาระจากน้ำหนักของระบบขับเคลื่อน ชิ้นงานต้นแบบถูกขับเคลื่อนด้วยมอเตอร์ 3 ตัวสำหรับการเคลื่อนที่แบบงอ/เหยียดของข้อต่อทั้งสามของนิ้วมือแยกกัน ได้แก่ ข้อต่อเอมซีพี (metacarpophalangeal joint) ข้อต่อพีไอพี (proximal interphalangeal joint) และ ข้อต่อดีไอพี (distal interphalangeal joint) แนวคิดของกลไกดังกล่าวถูกประเมินในขั้นต้นด้วยการจำลองการเคลื่อนที่กับข้อต่อจริงของนิ้วมือมนุษย์ ผลการจำลองแสดงให้เห็นว่ากลไกที่ออกแบบมาสามารถรองรับกระดูกของนิ้วมือได้ในทุกๆท่าทางของการเคลื่อนที่ การประเมินจากความต้องการในการออกแบบและการทดสอบเชิงความรู้สึกแสดงให้เห็นว่าอุปกรณ์สามารถขับเคลื่อนนิ้วของผู้ทดสอบได้อย่างเป็นธรรมชาติและไม่ติดขัด อุปกรณ์ได้ถูกทดสอบกับผู้ร่วมทดสอบที่มีสุขภาพแข็งแรงทั้งหมด 14 คน

ภาควิชา	วิศวกรรมเครื่องกล	ลายมือชื่อนิสิต	....
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5770273521 : MAJOR MECHANICAL ENGINEERING
KEYWORDS: EXOSKELETON / FINGER / REHABILITATION / HAND / CPM

MAHASAK SURAKIJBOWORN: DESIGN AND DEVELOPMENT OF A ROBOTIC FINGER EXOSKELETON FOR REHABILITATION. ADVISOR: ASST. PROF. WITAYA WANNASUPHOPRASIT, Ph.D., 84 pp.

Current ROM (range of motion) rehabilitation is done by a therapist helping each patient individually, which can be done more effectively and efficiently by robotic devices. The goal of this work is to design and develop a robotic finger exoskeleton system as a CPM device for finger ROM rehabilitation. The research introduces a novel mechanism for finger exoskeleton design. The main concepts of the proposed design are having no interference and no translational forces on phalanges. The finger exoskeleton consists of 3 identical joint mechanisms which, for each, adopt a six-bar RCM as an equivalent revolute joint incorporating with 2 prismatic joints to form a close-loop mechanism with one anatomical joint. Cable and hose, known as Bowden cable transmission, is adopted to reduce burden from weight of driving modules. The prototype is driven by 3 motors moving flexion/extension of each joint individually, i.e. an MCP (metacarpophalangeal) joint, a PIP (proximal interphalangeal) joint and a DIP (distal interphalangeal) joint. The mechanism concept is preliminarily evaluated by simulation with the real anatomical joint trajectory. The simulation result shows that the mechanism can accommodate 2 adjacent phalanges at all configurations. The requirement based evaluation and the subjective test show that the device can move a subject’s finger with quite natural and unimpeded motion along the predefined path. The device is successfully tested with 14 healthy subjects.

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

Adaptability	This term is used as a quality measure of an ability to be used with variety of finger sizes.
Anatomical joint	In this research the terms refers to a human joint that is not assumed as a revolute joint as usual in the field of robotics.
Backdrivability	The terms refers to the property of transmission system that allows downstream action to move back to upstream actuators.
Bowden cable	Bowden cable is one type of cable transmission system that has a connecting hose between 2 reference frames and an inner transmitting cable. The merit of this system is tension transmission between moving frames.
CPM device	The device is used for ROM exercise, which can move a human joint back and forth between predefined angles.
Degeneracy	In this research, the word particularly describes the situation that total degree of freedom of mechanism chain is nearly reduced to zero because of the collinearity of 2 prismatic joints.
Interference	In this work, the word means internal obstruction of a mechanical system. More precisely, this term particularly means *interference* between a finger and the attached mechanical linkage.
Misalignment	In the research field of exoskeleton robotics, this term is widely used to describe the situation that the rotational axis of the attached mechanism is not corresponding to the anatomical joint axis.
Phalanx	The term refers to a finger bone.
RCM mechanism	The set of mechanism that has a virtual center of rotation at the point where a mechanical part is not required.
ROM	The word stands for *Range of Motion* which means the range that human joint can move properly. In this research, the particular meaning is the available workspace of each finger joint.

ROM exercise The term is widely used in the field of physical therapy. There are 3 types of exercises, i.e., passive ROM, assistive ROM and active ROM. Passive ROM means an exercise to move a patient's joint by the external assistance, e.g. from therapist or from the other hand, etc. Assistive ROM is the exercise that incorporates patient's efforts and therapist's assistance. On the contrary, Active ROM is the exercise which patient move a joint by his or her effort without external assistance.

Translational force In this work, when the exoskeleton exerts effort onto a finger, translational force is addressed as the undesirable component of reaction forces on phalanges, which is parallel to the finger bone.

CHAPTER 1
INTRODUCTION

1.1 Statement of Problem

Hand function is crucial in ADL (daily-living activities). This capability might be deteriorated by many incidents such as accidents, surgeries, diseases, stroke [1, 2], etc. Thankfully, hand disability can be recovered by many means of therapy. In a conventional way, a therapist helps each patient individually to move their hand or fingers. This therapeutic training is repetitive and patterned, which is an appropriate task for a robot. Recently, robotic exoskeletons have shown effectiveness in hand rehabilitation [3, 4].

At the early stage of rehabilitation process, most patients require ROM (range of motion) exercise to prevent or recover from a stiff joint as illustrated in Figure 1.1. Each joint of each finger needs correct prescribed ROM exercises otherwise a secondary injury occurs. These types of rehabilitation can be done by a CPM (continuous passive motion) device which is device that helps patients move their limbs along prescribed ROM exercise. In this research, we propose a novel CPM device for an individual finger which can move each finger joint individually.

In essence, a finger is the most basic functional component of a hand, and should be fundamental investigation of a further hand exoskeleton design. This research leads design and construction of a robotic finger exoskeleton system. The focus point lies on how to design a proper mechanism which can operate with a real human finger. Also, constructions of the prototype and mechatronic system are clearly illustrated. The evaluation of the prototype is conducted to verify important concepts.

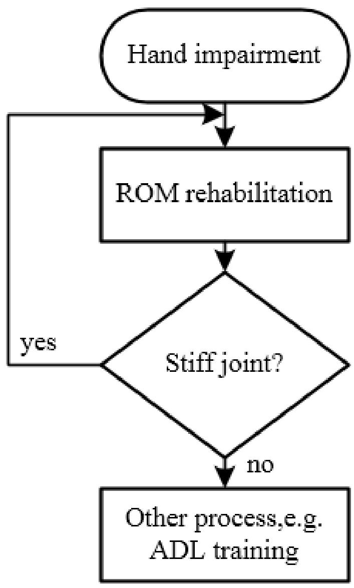


Figure 1.1 Most hand impairment requires ROM rehabilitation.

1.2 Objectives

1) To design a mechanism for a finger exoskeleton which can operate with a real human finger.
2) To construct a finger exoskeleton system which can control each finger joint independently.
3) To achieve the basic rehabilitation mode: moving a finger along the specified trajectories.

1.3 Research Scope

1) Reviewing finger biomechanics and related works.
2) Designing and constructing a finger exoskeleton system.
3) Evaluating design concepts.
4) Implementing the basic rehabilitation mode by specified trajectories.

1.4 Approach

1) Studying biomechanics of a finger.
2) Reviewing the related works on hand and finger exoskeletons.
3) Summarizing previous problems and specifying the design requirements.
4) Synthesizing the conceptual design and fabricate a plastic prototype.
5) Testing the basic concepts using the plastic prototype: corresponding movement, range of motion, finger attachment and manual actuation.
6) Redesigning the prototype, designing the actuation system and the control system.
7) Constructing the prototype, the actuation system and the control system.
8) Evaluating: range of motion, interference, independent actuation, backdrivability.
9) Implementing the basic rehabilitation mode: moving by specified trajectories

1.5 Benefits

1) Being the therapeutic device for an individual-finger CMP device.
2) Being the prototype to test the concepts for the further design, e.g., corresponding movements, force transmission, effectiveness for level of control independency, etc.
3) Introducing the novel design of a joint mechanism for a wearable robot
4) Being the initiative research contributing to the future project on hand exoskeleton.
5) Understanding and being able to apply mechanics between 2 attaching systems, i.e., mechanical structure and human limbs.

CHAPTER 2
LITERATURE REVIEW

Many incidents can cause finger or hand impairment, e.g., stroke, surgery, accident, age, etc. Different types of disability may require different modes of rehabilitation. Moreover, there are huge arrays of techniques to regain motor functions. However, the first step is to recover from stiff joint by ROM rehabilitation which is the exercise to move patient's joints back and forth to the prescribed ROM. The basic idea is that a therapist help patients do exercise which can be active, assistive or passive depending on a stage of a patient and a purpose of training [5]. Opposite from robotics, active mode in rehabilitation is the mode that patient's limbs are moved by their effort only. Assistive mode is the mode that patient's limbs are moved by their effort and assistance from a therapist. Passive mode is the mode that patient's limbs are moved by therapist's assistance only. An example of passive therapeutic training is shown in Figure 2.1. For stroke rehabilitation, one challenge is how to overcome boredom of rehabilitation process such that devices should be flexible enough to provide attractive interface, or the activity itself is supposed to be enjoyable. However, the imperative priority is about safety issue. In this research, we develop the robotic finger exoskeleton system that can drive an injured finger with an idea of substituting therapist's action. To operate with vulnerable human limbs, finger structure and finger joint kinematics must be studied prior to designing the cooperating mechanism. This chapter firstly addresses the nature of finger biomechanics to explain the adopted model. The problem in mechanism design will be explained. Also, the mechanical designs of the remarkable devices in the recent decade are individually reviewed as the sample knowledge. Moreover, the essential design criteria are summarized at the final part of this chapter.

2.1 An Anatomy and a Biomechanical Model of a Finger

A hand consists of 5 digits, i.e., a thumb, an index finger, a middle finger, a ring finger and a little finger as in Figure 2.2. 4 fingers except a thumb have the same structures but different sizes. For the wrist reference, each finger has 4 phalanges and 4 joints moving flexion and extension motion at a CMC joint (very small displacement), an MCP joint, a PIP joint and a DIP joint, and abduction and adduction motion at an MCP joint. A thumb has 3 phalanges and 3 joints moving flexion and extension motion at a TMC joint, an MCP joint and an IP joint, and abduction and adduction motion at a TMC joint.

As focusing only on a sagittal plane of a finger, the morphology of human joints is not a perfect revolute joint. Thus, the motion is not pure rotation. This issue must be addressed as designing a robotic exoskeleton, especially for vulnerable human limbs. The complex motion of an anthropologic joint comes from the structure of a human joint where 2 segments (Figure 2.3) that are not rigidly and not congruously connected. In a sagittal plane, the motion of a finger joint incorporates rolling, sliding and translation [6]. The instantaneous rotational axis (IRA) is not constantly located at the center of a condyle (the distal end of the first phalanx) because joint motion incorporates complex motions between a condyle and a concave as α (the angle between the first phalanx and the adjacent one) changes as illustrated in Figure 2.3. However, the simulation result shows that the IRA will be limited in 3.5mm circle along the range of motion as in Figure 2.4. Note that the IRA of a finger joint also has small change in a frontal plane [7].

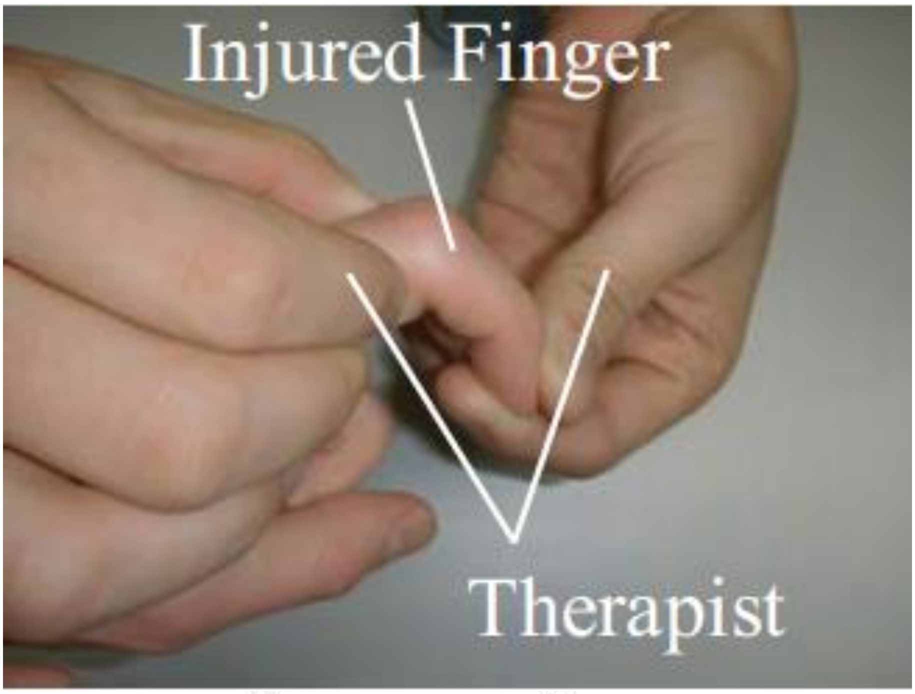


Figure 2.1 Conventional rehabilitation (picture from H. Yamaura et. al. [8]).

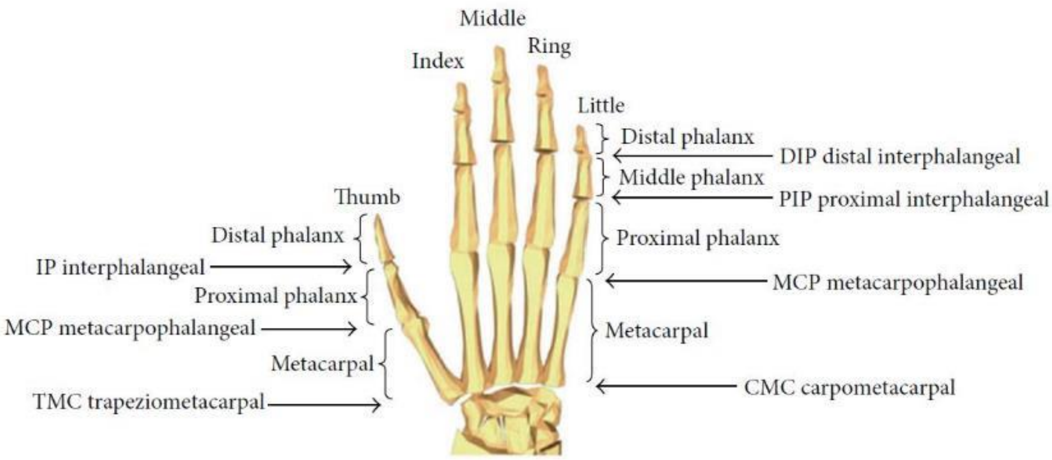


Figure 2.2 An atomy of a hand skeleton (picture from F. Chen Chen et al. [9]).

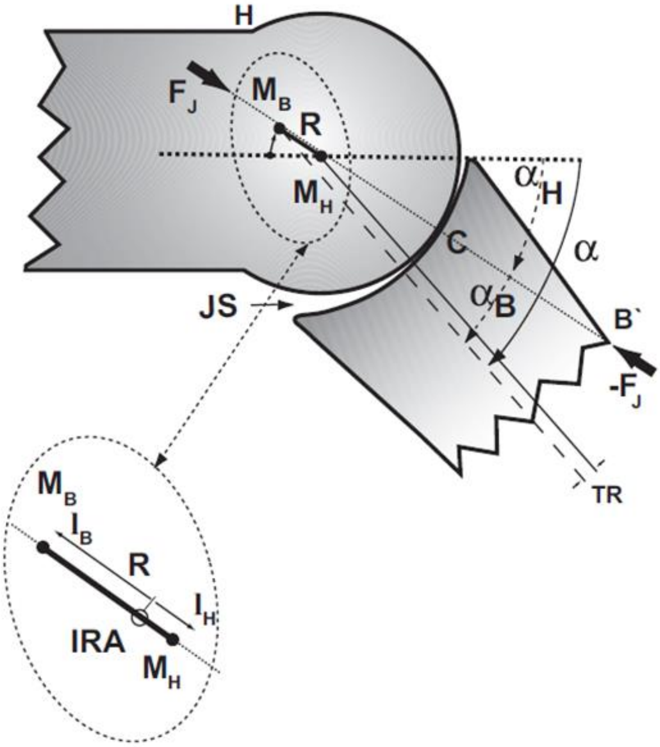


Figure 2.3 The anatomical joint model of a PIP joint (picture from C. Dumont et al. [10]).

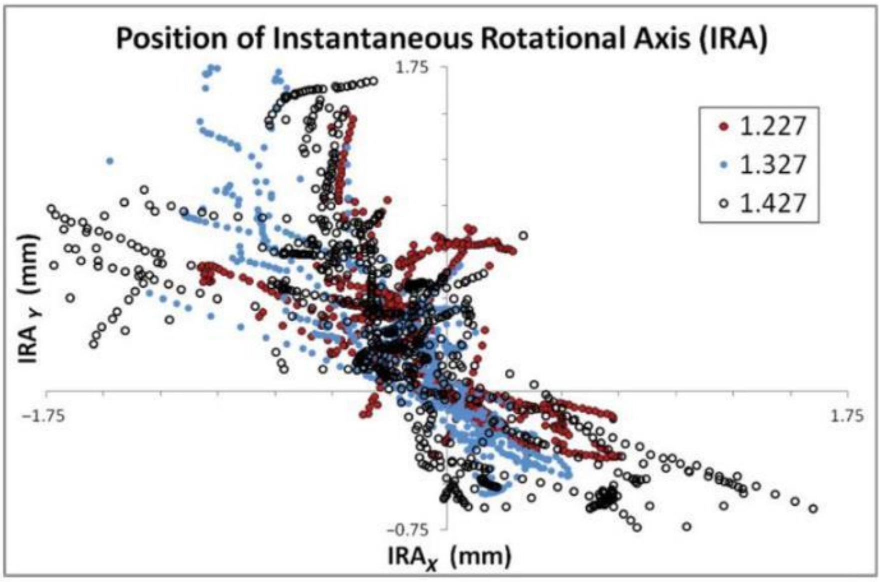


Figure 2.4 Positions of IRA of a PIP joint in the x–y coordinate plane around center of a condyle for ratios of radius of curvature of 1.227, 1.327 and 1.427. (picture from M. Mousavi et al. [6]).

To visualize the real anatomical joint motion, we extracted the sample points from [6] and simulate the motion with constant increment of the flexion angle of a PIP joint. The simulation result at each flexion angle is illustrated in Figure 2.5. Note that the via-points are not IRAs. We only show the motion of the phalanx with reference to one another in the more understandable way.

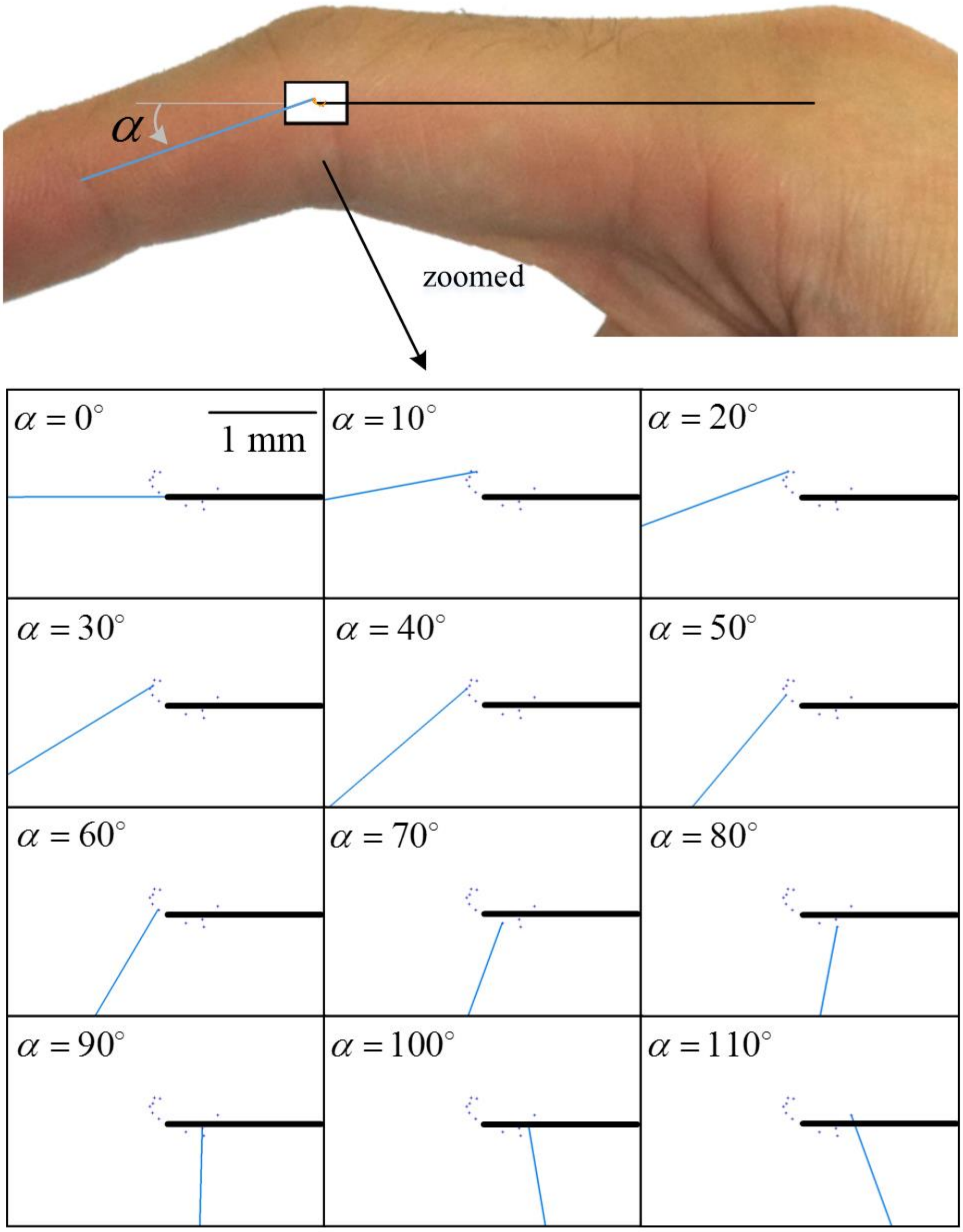


Figure 2.5 Simulation of a PIP anatomical joint motion by the data extracted from [6]. Note that α represents the angle between the 2 phalanges, and the via points in each picture represent the trajectory of point fixed on the relatively-moving phalanx.

To design a mechanical structure that works correspondingly with human motion, the researcher will consider each joint as a 1-DoF imperfect revolute joint. The device must not impede human natural motion to ensure safety of a wearer. However, the joint characteristics is very similar to a normal revolute joint as simulated by Adams/View software in [6]. The error at the fingertips between 2 models is less than 2%.

The simplified widely-used biomechanical model of a finger, presented in Figure 2.6 , consists of four serially-connected links, a metacarpal bone (assumed to be fixed as a reference base), a proximal phalanx, a middle phalanx and a distal phalanx, respectively. Each adjacent links are connected by a revolute joint, a PIP joint (flexion/extension) and a DIP joint (flexion/extension), except an MCP joint which is simply decomposed to MCP1 (flexion/extension) and MCP2 (abduction/adduction). For this model, the forgoing discussion suggests that the cooperating mechanism should have an additional DoF to compensate imperfection of the assumed model. Note that this work conducts only the development of a finger exoskeleton not for a thumb.

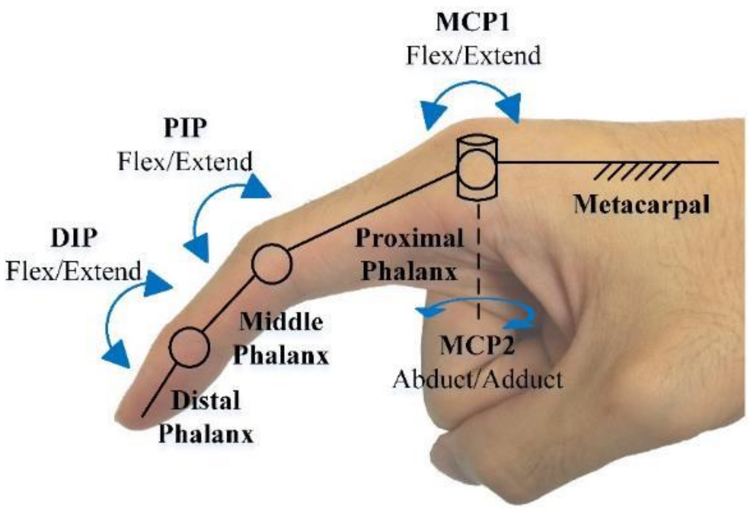


Figure 2.6 The biomechanical model of a finger.

2.2 Mechanism Design of a Finger Exoskeleton

In the sagittal plane of a finger, if misaligned mechanical structure with one revolute joint (Figure 2.7) is mounted on phalanges to drive one joint, interference will occur between the finger and the mechanism. In case of rigid attachment, the overall system will be jammed and cannot move. However, as illustrated in Figure 2.8, the loosest connection, usually at the attached area, will slip causing undesirable forces on phalanges. In comparison with the aligned joint axis, the mechanism can move correspondingly with the finger motion.

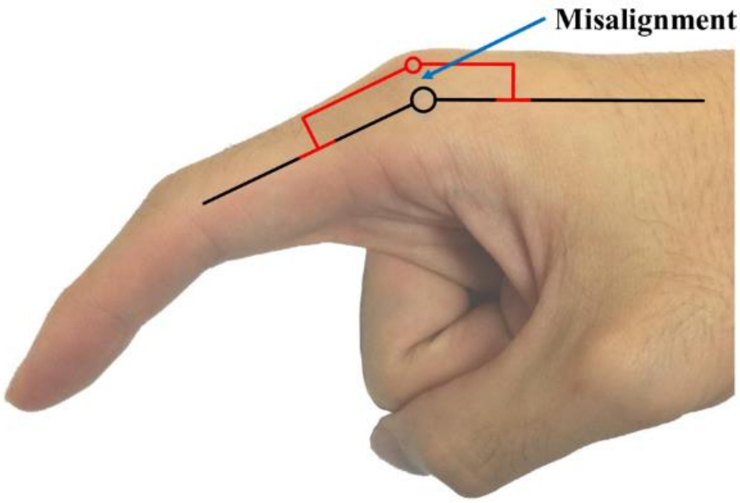


Figure 2.7 The misaligned mechanical structure mounted on phalanges.

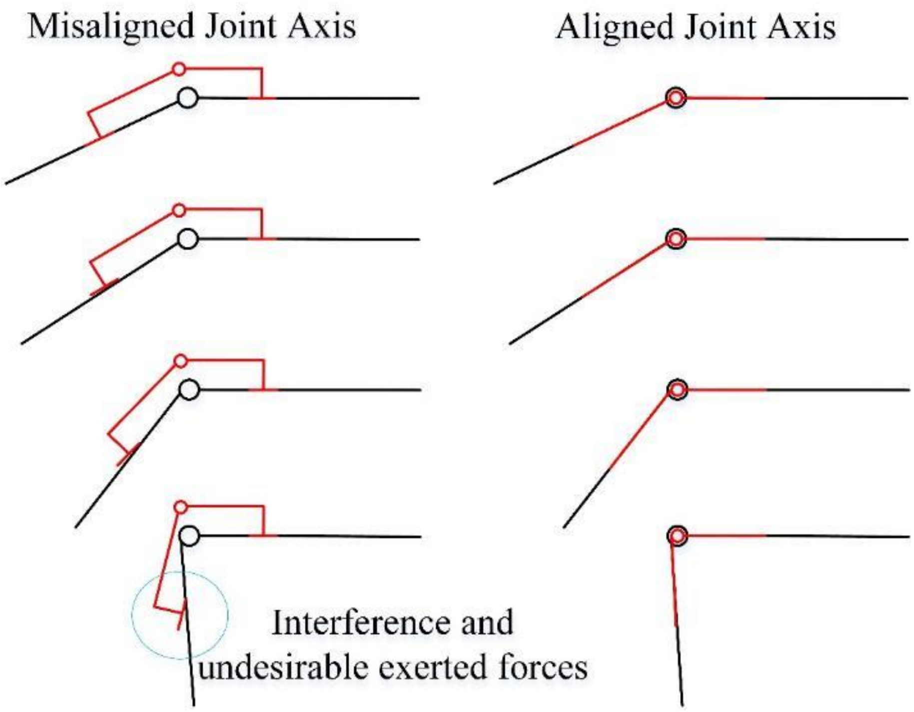


Figure 2.8 The misaligned joint mechanism and the aligned joint mechanism.

Recently, many finger exoskeletons are designed based on the idea that places the device's joints, either mechanical or virtual joints, at the anatomical joints of a finger, e.g. [4, 11-22]. Figure 2.9 shows examples that use this design concept. However, exact joint alignment is impossible because attachment is not precise and rotational axes of anatomical joints change overtime as mentioned before.

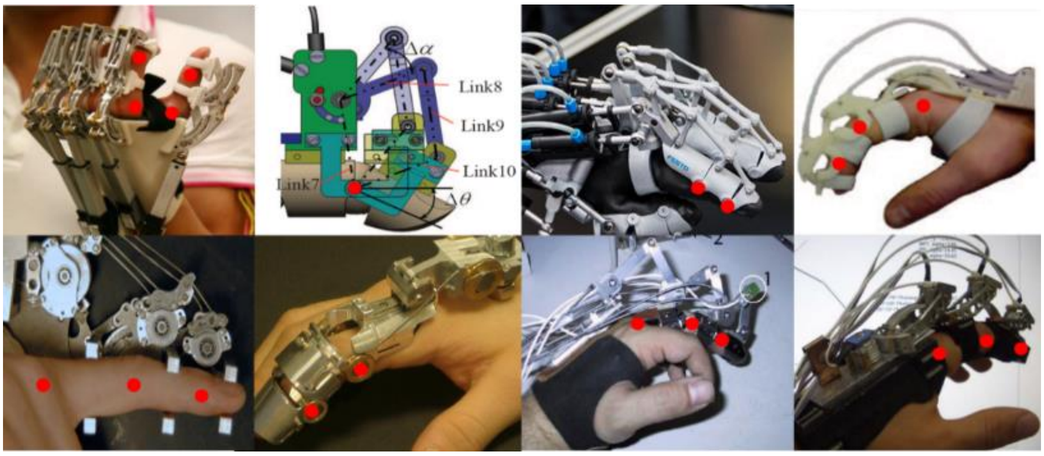


Figure 2.9 Finger exoskeletons that are designed based on idea of aligning device's joints with anatomical joint axes (pictures from K. Tong et al., FESTO, T. Burton et al., M. J. Lelieveld et al., A. Wege et al., J. Li et al., C. L. Jones, et al. and A. Chiri et al. [12-16, 18, 21, 22]).

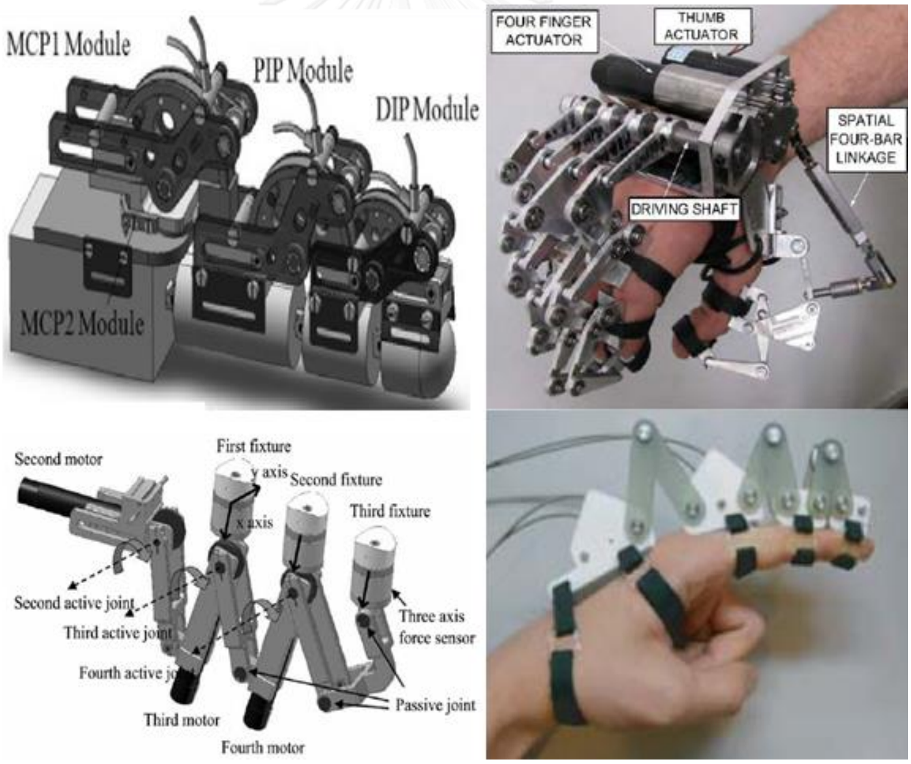


Figure 2.10 Finger exoskeletons that are designed based on idea of viewing phalanges as parts of linkage system (pictures from H. Yamaura et al., J. Wang et al., H. Kawasaki et al. and C. Loconsole et al. [8, 23-25]).

Some researchers have dealt with joint alignment problem by different approach. By this mean, an exoskeleton itself is designed as an open-loop structure that will be attached with the finger and forms a close-loop mechanism, e.g., [8, 23-

26] (Figure 2.10). With this paradigm, phalanges are viewed as parts of the linkage system. When the device cooperates with finger's structure, close-loop mechanism functions as 1 DoF four-bar linkage system (Figure 2.11(a)). This design has no interference owing to a proper DoF of the system. Moreover, the mechanism can accommodate extent of phalanges' length as the phalanges are parts of mechanism.

Open-loop exoskeletons still face translational reaction forces when a finger resists the device's motion as shown in Figure 2.11(b). The forced translation in the unmovable direction yields skin depression and axial loads in bones which may cause uncomfortable condition or an injury [27]. However, this problem can be reduced or theoretically eliminated. [23, 26, 28-30] employ prismatic connections joint to constrain reaction forces between phalanges and mechanisms. [16] implements flexible connection claimed to allow only desired perpendicular forces. [31-33] apply self-aligning and differential mechanism to mathematically eliminate translational forces at an MCP joint.

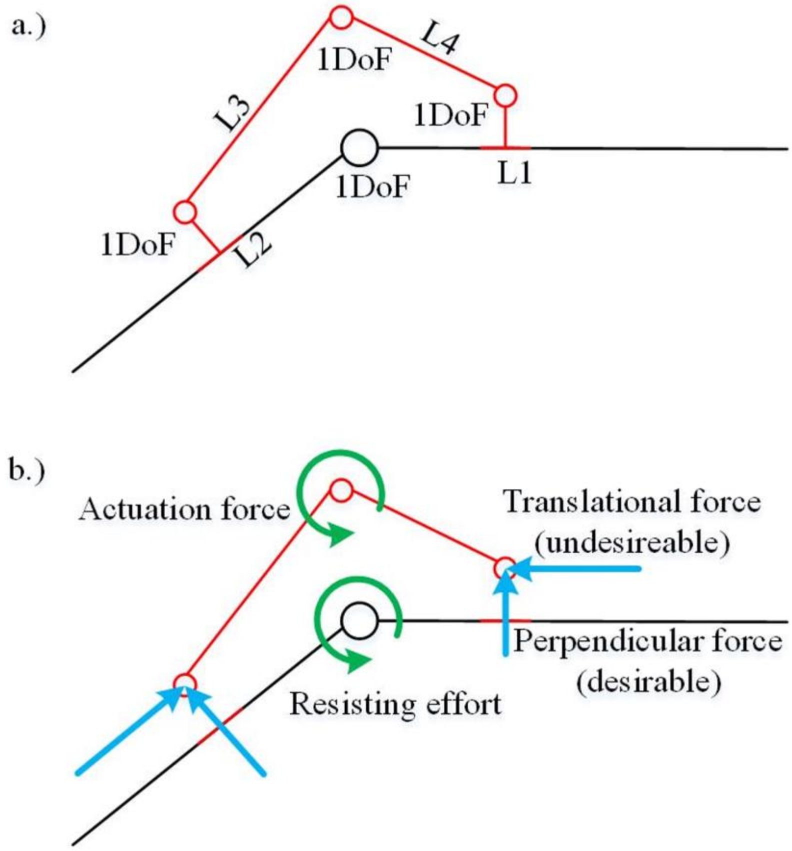


Figure 2.11 a.) A kinematics diagram of an open-loop exoskeleton which form close-loop mechanism with phalanges. b.) Reaction forces on phalanges when resisting effort is present.

Some researchers exploit advantages of differential mechanism [8, 13, 22, 31, 33-35]. Underactuation simplifies the system and works well in grasping scenario due to similarity of anatomical pulley-tendon system in vivo. It is worth to be considered in finger exoskeleton design due to a number of advantages, e.g., weight, simplicity, cost, safety, compliance. As tested in previous author's work [36], underactuation system requires additional analysis to ensure the function of the system, e.g., stability analysis for grasping an object. To implement differential mechanism in exoskeleton design, system must have additional analysis to ensure the safety of a wearer.

2.3 Development of Finger Exoskeletons

In the recent decade, the hand exoskeleton development has become more intense. There are emerging reviews on hand exoskeletons [37-39]. Novel mechanisms and innovative designs have been proposed to deal with critical design problems. [8, 23-26] are open-chained structure realized by different mechanisms as to eliminate interference between structures of a digit and a device. [16, 23, 26, 28-31] can reduce or theoretically eliminate undesirable forces, translational forces upon phalanges. [4, 14, 15, 21, 30] adopt RCM (remote center of motion) mechanism to minimize the aforementioned problems. [23, 26, 29, 33] provide ability for adapting to an extent of hand sizes. Most of the designs implement remote actuation system to reduce burden of a wearer, for example, through cable transmission [14, 16-19, 23, 26, 29-31, 34, 40], fluid transmission [13]. Each research team has different outstanding technique for their devices. To explore some of those, the author has provided short individual analysis, on perspective of mechanical design, of the remarkable finger exoskeletons in the recent decade below. Moreover, the author has extracted important data of the reviewed documents which is presented in Figure 2.25.

- A. Wege et al., 2005 [16, 17]

Figure 2.12 A finger exoskeleton developed by A. Wege et al. (picture from A. Wege et al. [16]).

Illustrated in Figure 2.12, this rehabilitative finger exoskeleton has been developed in consideration of bidirectional movement, supporting 4 DoFs of each finger and a free space on a palm. The device, integrated with orthopedic attachments, is designed as a close-chained mechanism. The flexible joints between attachments can compensate undesired translational forces. Each joint is separately actuated by mean of a Bowden cable. The joint mechanism is a 4-bar linkage which has 1 DoF.

Due to the close-chained mechanism, this exoskeleton has a good property in exerting perpendicular forces but conversely having some interference with a finger.

- T. Worsnopp et al. (AFX), 2007 [20, 21]

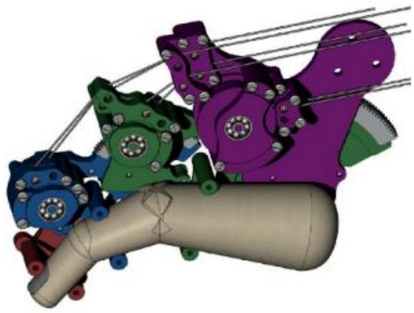


Figure 2.13 A finger exoskeleton developed by T.Worsnopp et al. (AFX) (picture from T. Worsnopp et al. [20]).

Illustrated in Figure 2.13, the exceedingly complex exoskeleton has been developed in order to assess the optimal strategy for rehabilitation. With respect to the requirement, the device must have independent and precise control of each joint. The exoskeleton is designed as a close-chained mechanism to avoid the difficulties of RCM design. The attachments are rollers which can minimize interference with a digit. The joints are driven by spur-gear mechanism, which the forces are transmitted via cable through the preceding phalanx. To achieve the precise either force or motion control, each actuated DoF is driven by 2 electric motors. Trading off with complexity, this finger exoskeleton realizes precise force and motion control. This design also has backdrivability due to gear transmission ratio. The exoskeleton is attached to each phalanx by rollers which allow small flexibility during movement. However, point contacting may cause secondary injuries. Note that this exoskeleton has been redesigned and developed the control strategy in [20], which the joint mechanisms are replaced by RCM gear segments.

- J. Wang et al., 2009 [23, 28]

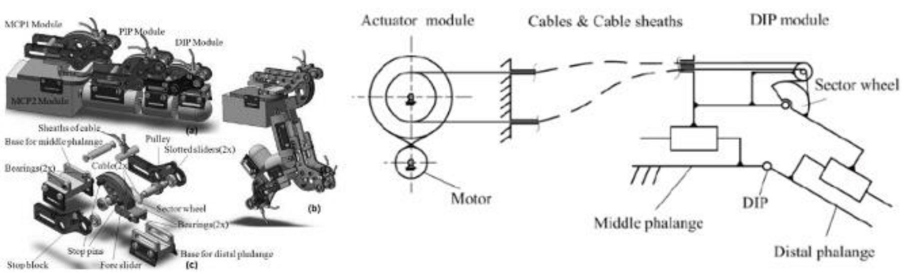


Figure 2.14 A finger exoskeleton developed by J. Wang et al. (picture from J. Wang et al. [23]).

Illustrated in Figure 2.14, the proposed exoskeleton has features of bidirectionally-independent control, adapting to variety of hand sizes, changeable ROM and sensing forces exerted on phalanges. The design is open-chained mechanism which eliminates joint misalignment. The joint mechanism consists of 1 revolute joint and 2 prismatic joints operating with 1 finger joint, as a result of which the combined mechanism forms 1 DoF closed chain. Each joint is driven by a sector wheel while force is transmitted via cables. The sector wheels have slot pins for the sake of ROM limit change. This design has preferable adaptability for extent variety of hand sizes. More importantly, exerting forces are theoretically perpendicular to phalanges. However the full ROM cannot be realized because of slider limitation.

- A. Chiri et al. (HANDEXOS), 2008 [22, 41]

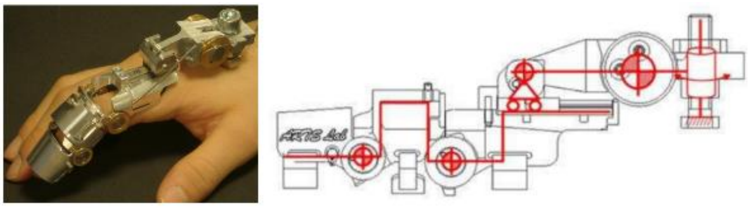


Figure 2.15 A finger exoskeleton developed by A Chiri et al. (picture from A. Chiri et al. [41]).

Illustrated in Figure 2.15, the HANDEXOS' finger is a 4-DoF exoskeleton whose purpose is functional and safe interaction with a finger. The researchers exploit underactuation in design in order to increase safety and simplicity. The joint mechanisms are a slider-crank and 2 revolute joints for an MCP1 joint, a PIP joint and a DIP joint respectively. Extension motion is realized by underactuated pulley-cable mechanisms transmitted through a preceding idle pulley via cable as shown in Figure 2.15. Flexion motion is provided by remote preloaded springs which transmit forces through cables to each opposite fixed pulley. The motion around an MCP2 joint is allowed by a passive revolute joint. The merits of the design are the sake of underactuation and that a translational force on a proximal phalanx is eliminated by slider-crank. The design has some drawbacks of interference because of joint misalignment due to a close-chained mechanism at a PIP joint and a DIP joint.

- J. Li et al. (iHandRehab), 2010 [18, 19, 42-44]

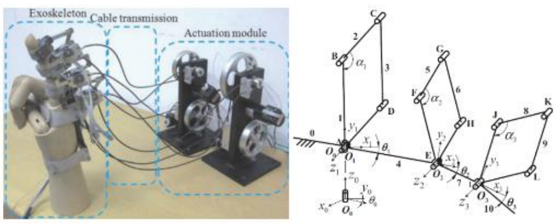


Figure 2.16 A finger exoskeleton developed by J. Li et al. (picture from J. Li et al. [18]).

Illustrated in Figure 2.16, the iHandRehab's finger is designed in order to satisfy 2 therapeutic training modes, active mode and passive mode. The device has 4 independently-controlled DoFs actuated by cable transmission. Abduction and adduction are driven through an abduction wheel located on beneath an MCP1 joint of the device. The mechanism is close-chained parallelogram which simplifies high-level control. The mechanical structure is mounted on the dorsal side of a finger where one revolute joint correspond to each finger joint. Trading with some interference from joint misalignment, the corresponding joints compensate translational forces, whereas control simplification trades with encumbrance of linkages.

- T. Burton, 2011 [14]

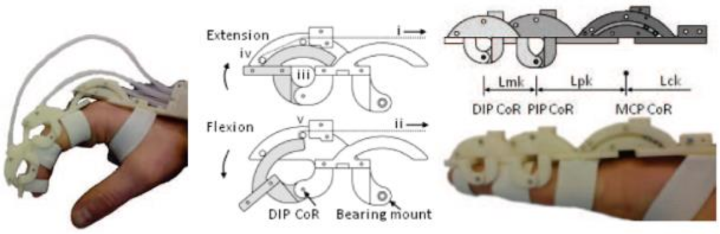


Figure 2.17 A finger exoskeleton developed by T. Burton et al., (picture from T Burton et al. [14]).

Illustrated in Figure 2.17, the T.M.W. Burton et al.'s finger is designed for purposes of being an assistive and rehabilitative device. The exoskeleton finger is 2 DoFs close-chained mechanism, where a DIP joint and a PIP joint are coupling in motion. The actuation forces are generated by 2 braided pneumatic actuators transmitting via cables to each joint. The novel joint mechanism is proposed as "open pulley" implementing with a circular segment. The revolute joints are placed aligning with a PIP joint and a DIP joint, whereas an MCP1 joint is designed as an RCM circular segment. The circular shape of the structure make the design more compact and have lower profile comparing with a linkage mechanism. Besides, an RCM mechanism at an MCP1 joint can be simply realized by mere circular segment. However, the exoskeleton has some interference with a finger due to close-chained structure.

- K. Y. Tong et al., 2010 [4, 12, 45]

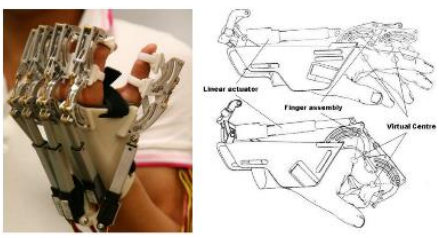


Figure 2.18 A Hand finger exoskeleton developed by K. Y. Tong et al. (picture from N. S. Ho et al. [4]).

Illustrated in Figure 2.18, the developed finger exoskeleton has been envisioned to be portable for activities of daily living. Under requirements of assisting close and open hand function, providing both passive and active motion, allowing user to feel an object and being light and portable, the 1-DoF close-chained finger exoskeleton has been designed. The mechanism is circular segment RCM located correspondingly at an MCP1 joint and a PIP joint. The mechanical structure is attached on dorsa of a metacarpal, a proximal phalanx and a middle phalanx, in which an MCP1 joint and a PIP joint are coupling in motion. The advantage of having coupling motion is that the design is simpler and lighter mainly because of actuator reduction. The main drawback of this exoskeleton is about safety because of solid transmission and coupling motion mechanism.

- FESTO (ExoHand), 2012 [13]

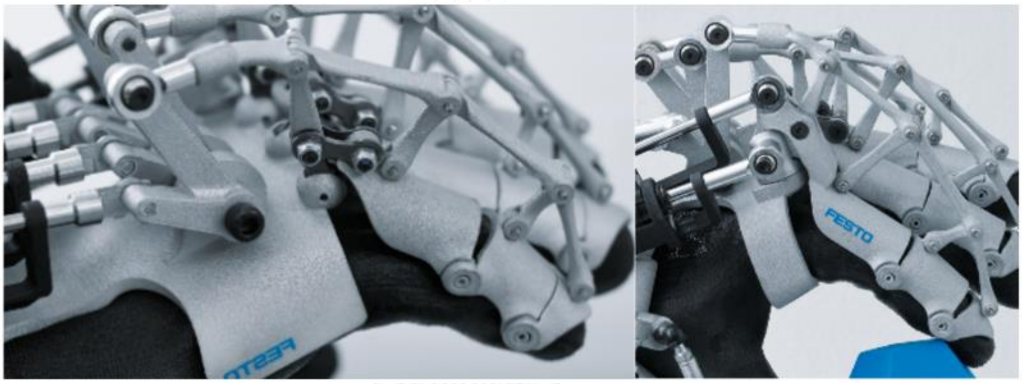


Figure 2.19 A hand exoskeleton developed by FESTO (picture from "New Scope for interaction between humans and machines" [13]).

Illustrated in Figure 2.19, the ExoHand has been developed by FESTO as a multi-purpose exoskeleton actuated by a pneumatic system. The hand exoskeleton consists of a thumb, an index finger and 3 identical fingers. Every finger is driven by linkage transmission, where the forces are transmitted through preceding phalanges via linkage. Universal joints are used to connect positioned actuation modules with the finger system. Note that this review is going to explore only mechanical structure of the 3 identical fingers and an index finger. The 3 identical fingers have 1 actuated DoF, which is underactuated between an MCP1 joint, a PIP joint and a DIP joint. Considering at an MCP1 joint, the exoskeleton forms close-chain mechanism with a human's joint, as a result of which this joint has no misalignment. The index finger has 3 actuated DoFs, one is for MCP2 motion, one is for an MCP1 joint and the last is for both a PIP joint and a DIP joint by underactuation. From the mechanical structure at an MCP1 joint, the proximal phalanx is never fully-attached with the exoskeleton yielding interference and undesirable forces upon the proximal phalanx. Despite some drawbacks of interference, the design has a precise control and very fine cosmetic appearance.

- J. Arata et al., 2013 [33]

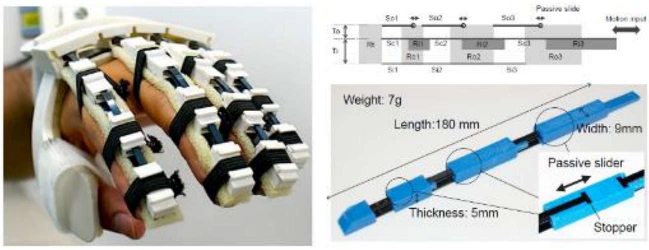


Figure 2.20 A hand exoskeleton developed by J. Arata et al. (picture from J. Arata et al. [33]).

Illustrated in Figure 2.20, this innovative finger exoskeleton has been developed for simple rehabilitation purpose. The device is an underactuated compliant mechanism which has 1 actuated DoF distributing forces to each phalanx of a finger. The researchers exploit the nature of flat springs synthesizing the novel joint mechanism, a three-layer spring. Each joint consists of 3 layers. The inner layer is a flat spring rigidly connected with adjacent phalanges. The outer layer is a flat spring which works as a mechanical limit between phalanges. The center layer is one serially connected part from flat springs and small rigid body which can move translationally in phalanges except distal one (fixed to the end of distal phalanx). When the center layer is linearly actuated, the force is distributed to each joint. Apart from simplicity and compactness, compliance makes the design safer than others. Moreover, the nature of mechanism can self-form RCM with human’s joints. In contrast, the compliance makes user less comfortable because of reacting translational force. In addition, precise control is seemingly difficult to be realized.

- M. Cempini et al. (HX), 2013 [31, 40]

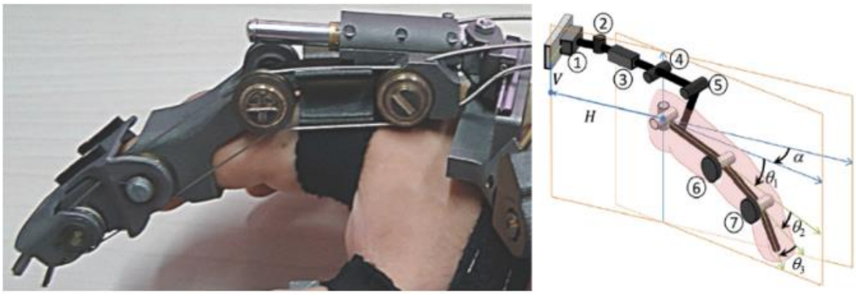


Figure 2.21 A finger exoskeleton developed by M. Cempini et al. (picture from M. Cempini et al. [31]).

Illustrated in Figure 2.21, the HX’s finger is developed to satisfy the requirements of safety, comfort and compactness. To meet these requirements, an underactuation system and a passive mechanism has been implemented. An MCP1 joint is driven by the self-aligning mechanism which consists of 1 prismatic and 2 revolute joints forming close-chain mechanism with the MCP1 revolute joint. Due to the mathematical relation, pulley-cable underactuation is implemented to compensate translational force at an MCP1 joint. MCP2 motion is provided by 1 passive prismatic and 1 revolute joint. A PIP joint and a DIP joint is driven by underactuation system transmitted through preceding idle pulleys via cable. Trading off with some mechanical complexity, advantages of underactuation apparently make the design more compact, more comfortable, lighter and safer, including theoretically, without the opposite-side pulley, eliminating translational force at an MCP1 joint.

- Y. Fu et al., 2011 [26, 29]

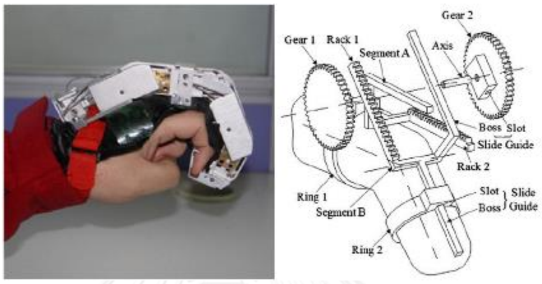


Figure 2.22 A finger exoskeleton developed by Y. Fu et al. (picture from F. Zhang et al. [26]).

Illustrated in Figure 2.22, the proposed finger exoskeleton has capabilities of operating full ROM, high adaptability, ensuring perpendicular forces on phalanges. The design has fully actuated 3 DoFs for each joint except an MCP2 joint. The mechanism is open-chained structure attached to the dorsa of phalanges. As a result, the kinematic chain requires 1 revolute joint and 2 prismatic joints to be movable DoF at each finger joint, and stretching motion is necessary to operate full ROM. The symmetrical pinion and rack mechanism, which can be rotated and translated at the same time, and sliding parallel mechanism is adopted as the design solution called “circuitous joint”. This rehabilitative exoskeleton has lot of small parts and a complex mechanical structure trading off with the aforementioned capabilities of the device.

- P. Weiss et al., 2014 [46, 47]

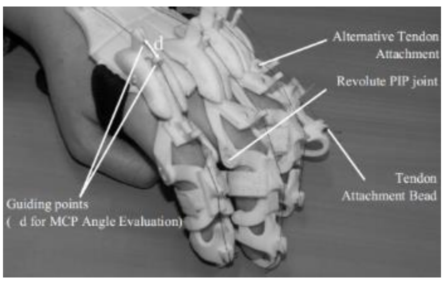


Figure 2.23 A hand exoskeleton developed by P. Weiss et al. (picture from P. Weiss et al. [47]).

Developed from the previous study [46], the rehabilitative finger exoskeleton, illustrated in Figure 2.23, is proposed based on parameterization of the particular patients. With the focus on cost-effective system, the device is 1-DoF close-chained exoskeleton which is unidirectionally underactuated by tendon-based transmission system. An MCP1 joint is an arc structure RCM articulated by revolute joints of a PIP joint and a DIP joint. An MCP2 is a passive revolute joint allowing abduction/adduction motion. Underactuation makes the design have high level of safety and comfort trading off with performance. Most importantly, the author has envisioned new term of use of exoskeleton. The device could be produced specifically for one user which reduces every effect of size variation and complexity, as a result of which the discussion issues would become parameterization and cost-effective production method.

- H. Taheri et al. (FINGER), 2014 [48, 49]

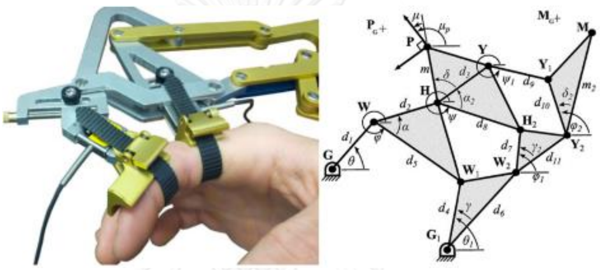


Figure 2.24 A finger exoskeleton developed by H. Taheri et al. (picture from H. Taheri et al. [48]).

Illustrated in Figure 2.24, the 1-DoF finger exoskeleton is developed to serve therapeutic hand-training by mean of musical games. As a result, the device must have precise timing and high backdrivability. The mechanism is 8-bar linkage formed by 3 loops of 4-bar linkage actuated by one linear actuator. In order not to interfere with a finger, the position and the angle of a proximal phalanx is designed in fixed trajectories and only the position for a middle phalanx. According to the researchers, the device can achieve desired aforementioned features. Apart from that, the exoskeleton ideally exerts perpendicular force upon a proximal phalanx but not for the middle one because of open-chained connection at a PIP joint. Conversely, the interference may occur at an MCP1 joint because of close-chained connection.

2.4 Suggestion Summary for Mechanism Design of a Finger Exoskeleton

The author provides suggestion summary for being the current and further criteria in finger exoskeleton design. As safety takes the imperative role in design, a mechanism must have no interference with finger natural motion. Also, the mechanism must be adaptable to different finger sizes otherwise interference will occur. Translational forces are not desired and should be minimized. Backdrivability is desired for both in aspect of safety and comfort of a user. Weight of the device must be as lightest as possible to reduce hand fatigue during exercises. The maximum

ROM should be large and have changeable limit to ensure safety of different users. The next chapter will illustrate the synthesized concepts and design realization that serves these requirements.

Year	Name(Reference Person)	Actuation	Form of Mechanism	Transmission	DOA	Active DOF	DOF
2005	A. Wege et al.	independent	close	cable	4	4	4
2007	T.T. Worsnop et al. (AFX)	independent	close	cable	3	3	3
2008	Azzura Chiri et al. (HANDEXOS)	underactuated	open, close	cable	1	3	4
2009	Ju Wang et al.	independent	open	cable	4	4	4
2010	Jiting Li et al. (iHandRehab)	independent	close	cable	4	4	4
2010	K.Y. Tong et al.	coupling	close	linkage	1	1	1
2011	T. M. W. Burton et al.	coupling-independent	close	cable	2	2	2
2011	Yili Fu et al.	independent	open	cable	3	3	3
2012	ExoHand(3 identical fingers)	underactuated	open, close	linkage	1	3	3
2012	ExoHand(index fingers)	independent-underactuated	close	linkage	3	4	4
2013	Jumpei Arata et al.	underactuated	close	flat spring	3	N/A	N/A
2013	Marco Cempini et al. (HX)	independent-underactuated	open, close	cable	2	3	4
2014	Christopher L. Jones et al. (CAFÉ)	independent	close	cable	3	3	3
2014	Patrick Weiss et al.	underactuated	close	cable	1	3	4
2014	Hossein Taheri et al. (FINGER)	coupling	open, close	linkage	1	1	1

Figure 2.25 Extrated data from the reviewed works. Note that *DOA* is degree of actuation and *Transmission* means transmission from actuators to joint mechanisms.

CHAPTER 3

DESIGN AND CONSTRUCTION OF A FINGER EXOSKELETON SYSTEM

The design problems of finger exoskeletons are clearly explained in the previous chapter. Many researchers have been proposing their ideas to overcome those issues. However, the perfect model of a finger exoskeleton remains nonexistent. This chapter proposes the novel design of a finger exoskeleton system based on the ideas of safety and flexibility of use. The author provides elaborate details of system design and system construction. The content is dividedly explained in 3 sections, i.e. finger exoskeleton design, driving system design and system construction.

3.1 Finger Exoskeleton Design

We explain the idea of the conceptual design by sequential synthesis. The design requirements are concluded from the review chapter. We use the biomechanical model of a finger on a sagittal plane with imperfect revolute anatomical joints as a basis for design. The research develops a robotic exoskeleton only for a finger, which can be used with an index finger, a middle finger, a ring finger and a little finger. A thumb exoskeleton is not in this research scope, where design methodology would be totally different. This section is presented in 3 parts, i.e. design requirement, mechanism design of a joint mechanism, a finger exoskeleton with sliding-sixbar joint mechanisms and preliminary evaluation from a plastic prototype.

3.1.1 Design Requirements

As mentioned in the previous section, we put safety of a wearer as the critical issue for design. We use terms of interference, translational forces and backdrivability to represent level of safety. Besides, we consider flexibility of use in term of operating ROM, adaptability and actuation independency. To summarize the expected specifications, this research proposes a novel design of a finger exoskeleton which meets the specified requirements:

- Having no interference with a human finger
- No translational forces exerted on phalanges
- Covering full ROM from flat palm configuration: MCP1$[0^\circ, 90^\circ]$, PIP $[0^\circ, 90^\circ]$, DIP$[0^\circ, 90^\circ]$
- Covering all sizes of a wearer's fingers
- Individual actuation for each joint
- Having backdrivability

3.1.2 Mechanism Design of a Joint Mechanism

The conceptual design adopts the ideas of open-loop structure for having no interference with phalanges during operation. In addition, prismatic connections are designed to free axial motion on both phalanges where translational forces are reduced. The joint mechanism consists of 1 revolute joint and 2 prismatic joints operating with a 1-DoF anatomical joint, as a result of which the combined mechanism forms 1-DoF close-chain as show in Figure 3.1

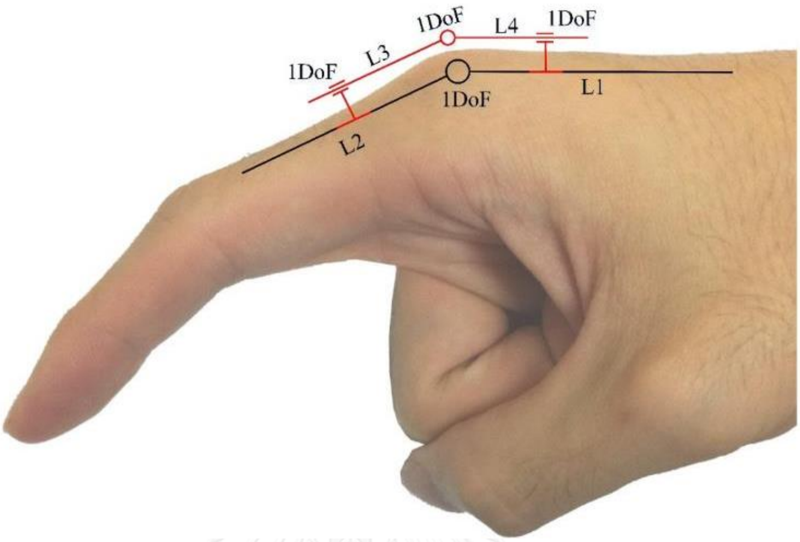


Figure 3.1 An open-loop joint mechanism with prismatic connections.

The preliminary analysis shows slider range that is required to move a finger joint in full range of motion. Illustrated in Figure 3.2, constant offset- d , since the mechanism is initially attached to a finger, enhances misalignment as θ increases. From the CAD simulation in Figure 3.3, the mechanism requires more slider range as constant offset increases because misalignment is enhanced when a joint moves. Two behaviors are studied correlated to the changing θ, i.e., misalignment- m and sliding displacement- s

The relation between misalignment and the joint angle can be expressed by

$$m = \frac{d}{\cos(\theta / 2)} \tag{3.1}$$

The equation (3.1) suggests that m non-linearly increases as θ varies. However, if the constant offset is zero, the virtual center of rotation constantly aligns with the finger joint throughout every moving angle.

At the same time, sliding displacement can be expressed as a function of θ.

$$s = d\tan(\theta / 2) \tag{3.2}$$

If the offset exists, increase in θ yields a slider to moves in order to adjust to a proper configuration. This behavior must be studied prior to design due to practical limitation of sliders.

Equation (3.1) and (3.2) can be presented by the graph in Figure 3.4(a). The lines represent the sliding displacement while the joint angle increases. Each line is for the particular constant offset. It turns out that the required slider range is very large if the constant offset is large. Conversely, the require slider range is very small of the constant offset is small.

It suggests that if the revolute joint of the mechanism is nearly corresponding to the anatomical joint, the mechanism can operate with very small sliding displacement through full range of motion. Moreover, it suggests that the same mechanism can be applied with extent variety of finger thickness.

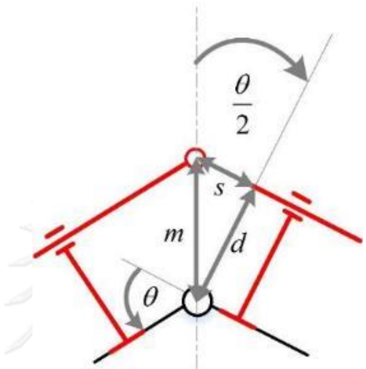


Figure 3.2 A kinematic diagram of a conceptual design of the joint mechanism.

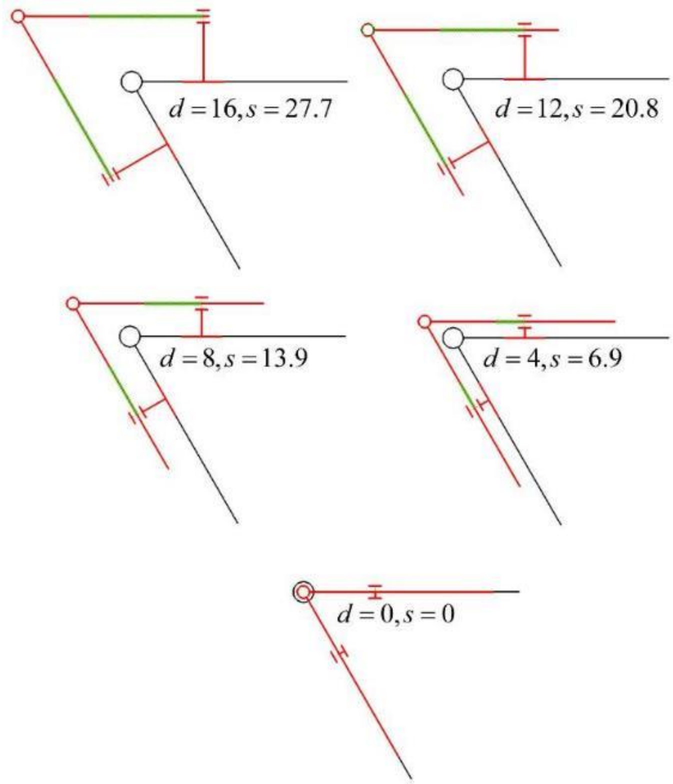
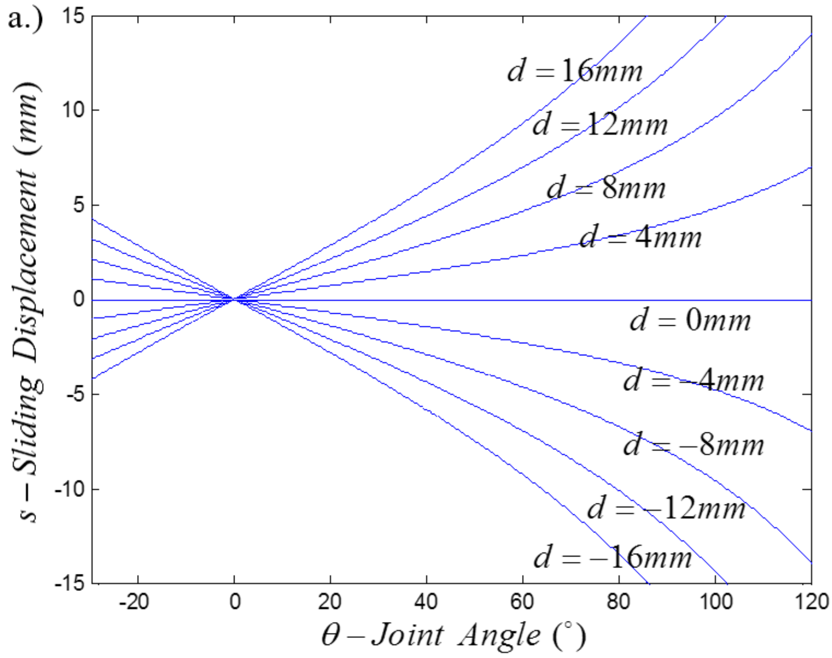


Figure 3.3 Maximum sliding displacements for different constant offsets at $\theta = 120^\circ$.



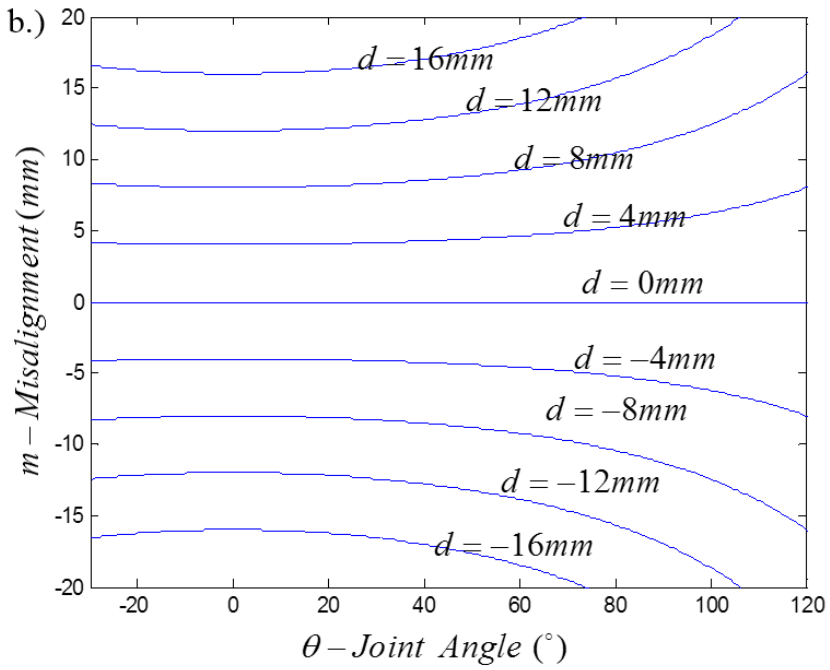


Figure 3.4 a.) Perturbation of sliding displacement on an increasing joint angle for different constant offsets. b.) Enhancing misalignment on an increasing joint angle for different constant offset.

To realize the viable design, sliding displacement must be very small such that the mechanism can sit on phalanges over full ROM, and for the mechanism to be adaptable to every finger length. In order to minimize sliding displacement, a remote center of motion (RCM) mechanism is adopted to make the virtual center of rotation very close to the finger joint axis. This allows the joint mechanism to move in full range of motion with very small sliding displacement. Moreover, the RCM mechanism allows a volar side of a finger to be free from mechanical elements where a user can feel an object. Also, free space on the lateral sides allows the mechanism to be used with a middle finger and a ring finger. The six-bar parallelogram is selected to substitute the middle revolute joint by sitting on the dorsum of a finger as illustrated in Figure 3.5.

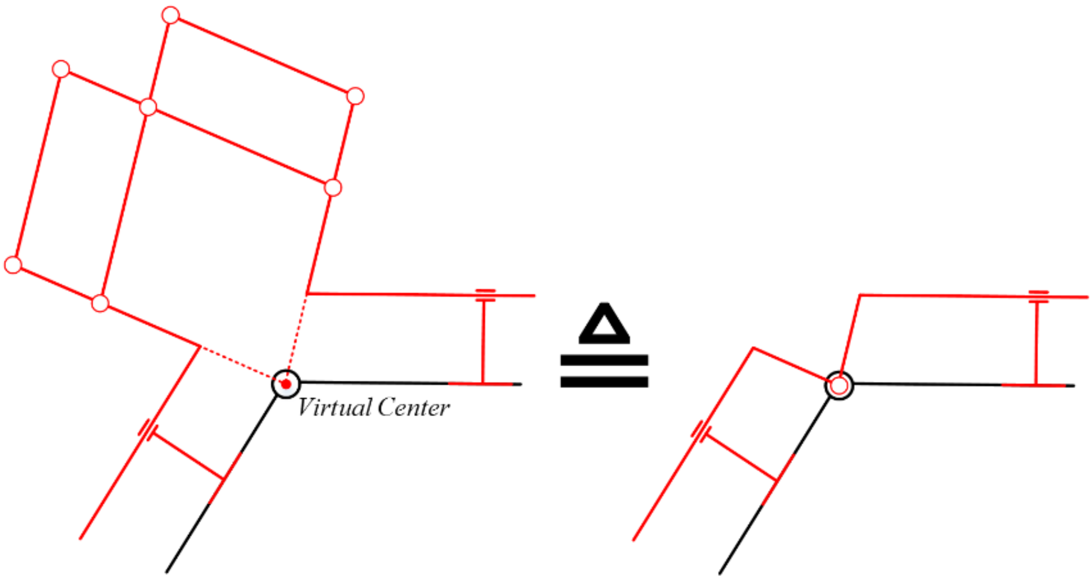


Figure 3.5 The equivalent mechanism realized by six-bar parallelogram.

This work employs static analysis for preliminary analysis when the anatomical joint resists the device's motion. The model, regardless of mass, in Figure 3.6 is the sliding six-bar joint mechanism (SSJM) attached to one joint where the virtual center of rotation does not exactly align with a finger joint. To be more understandable, phalanges (grounded link) are assumed to be a reference frame in order to do static analysis. Note that every link, including the grounded links, can move freely in an open space. T_i is an input torque transmitted by cable to the actuated joint. As a result links l_1 is driven relatively to one another. F_A, F_B, M_A, M_B are output efforts onto phalanges.

Static analysis obtains the relation between the exerting efforts and the input torque.

$$M_A = -M_B = T_i \tag{3.3}$$

$$F_A = F_B = 0 \tag{3.4}$$

The mechanism exerts only couples M_A and M_B to phalanges no matter the center of rotations are corresponding or not. This means the exerting efforts are only 2 perpendicular opposite-direction forces for each side.

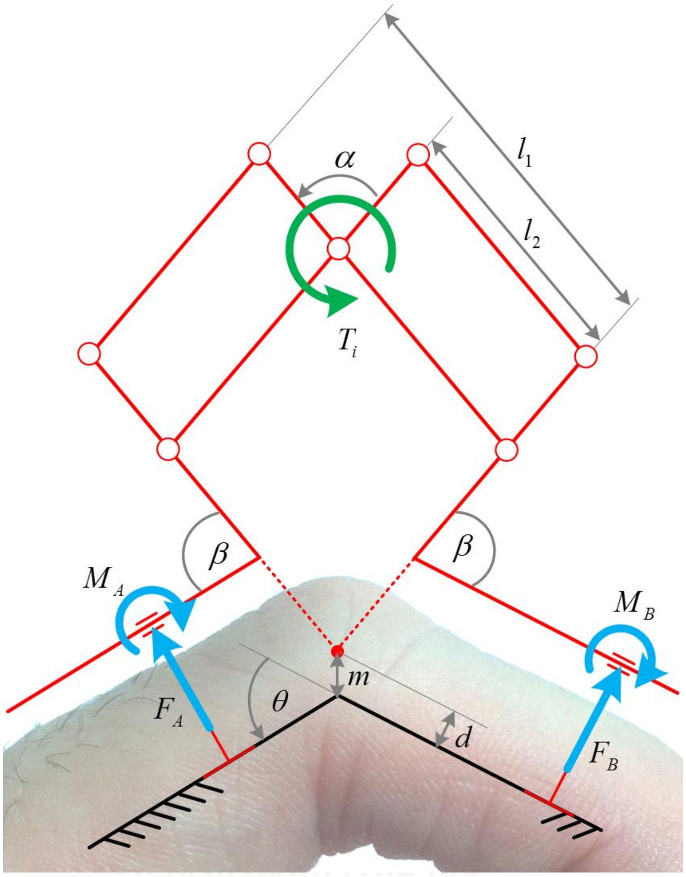


Figure 3.6 Static model of the sliding six-bar joint mechanism. Note that T_i is the driving torque which exerts to one of the middle links with reference to one another.

3.1.3 A Finger Exoskeleton with Sliding Six-bar Joint Mechanisms (SSJM)

To realize the aforementioned specifications, the proposed finger exoskeleton ([50]) has 3 identical joint mechanisms attached to a dorsum of a finger driving flex/extend motion for each joint separately, i.e., an MCP1 joint, a PIP joint and a DIP joint. Abduction/adduction motion is neglected, and one passive revolute joint is designed to give small flexibility during operation. The attachments will be attached with each phalanx by Velcro strap. The SSJM will be actuated at the interconnection of the mechanism via Bowden cable transmission which will be explained in the next section. As a result, the six-bar RCM mechanism stretches yielding the combined close-loop structure to rotate. However, the SSJM is designed ideally not to employ the function of prismatic joint but to cope with small inevitable misalignment. The schematic diagram of the finger exoskeleton is presented in Figure 3.7. The CAD simulation of the configuration of the mechanisms along flexion motion of a finger is shown in Figure 3.8.

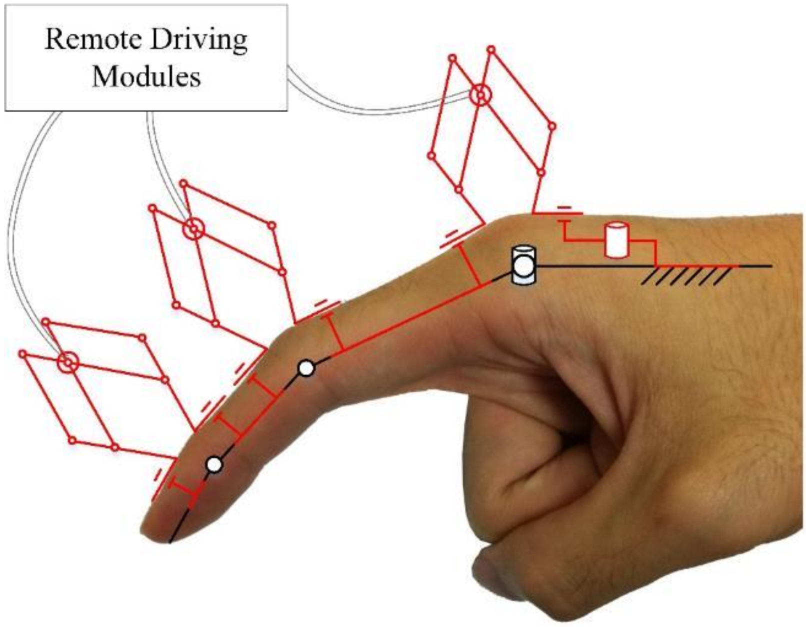


Figure 3.7 A conceptual design of a finger exoskeleton with a Sliding Six-Bar Joint Mechanism.

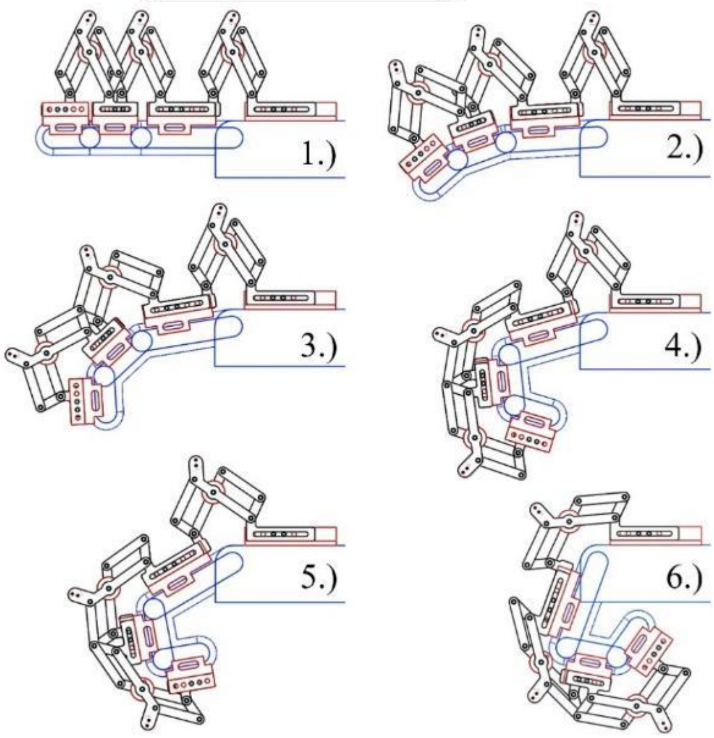


Figure 3.8 CAD simulation of finger movement throughout full ROM.

3.1.4 Preliminary Evaluation from a Plastic Prototype

With the parameter set, $l_1 = 30mm$, $l_2 = 20mm$ and $\beta = 65^\circ$, the first prototype is realized to evaluate the preliminary concept of motion and overall structure. As shown in Figure 5, the prototype is fabricated by acrylic for 2D parts and nylon for 3D parts. As a result, the design shows capability of moving following motion of a finger without any impeding configuration throughout full ROM (Figure 3.9) of every size of fingers in the laboratory.

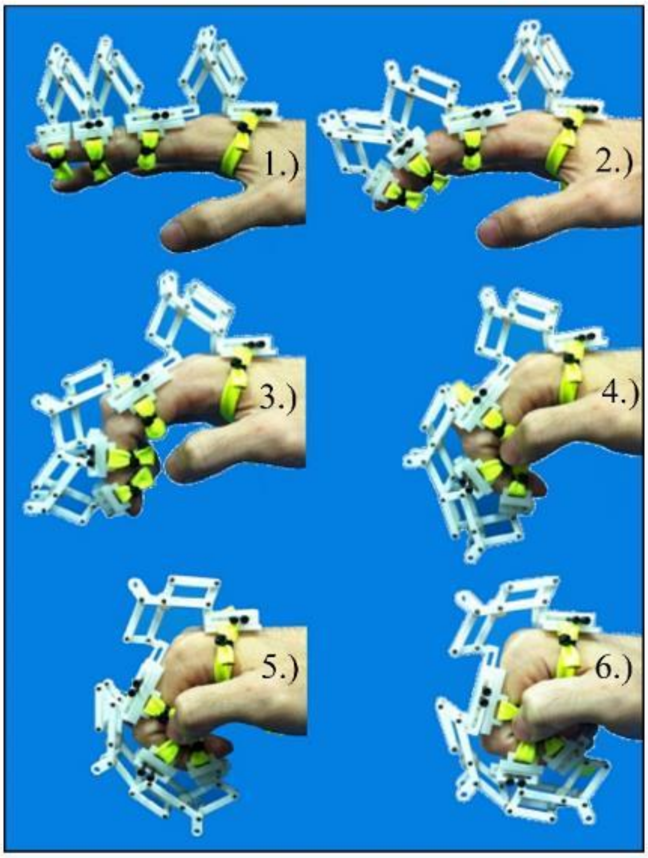


Figure 3.9 Sequence of movement of the prototype corresponding to the finger motion.

3.2 Driving System Design

The finger exoskeleton has 3 active joint mechanisms driven by 3 driving modules. Each one is designed for a bidirectional independent control. Cable transmission is selected for driving system because of its backdrivability and smoothness, which increases comfort of use. The actuation forces will be transmitted from driving module through close-loop Bowden cable system to the joint capstan at the interconnection of the six-bar parallelogram as illustrated in Figure 3.10.

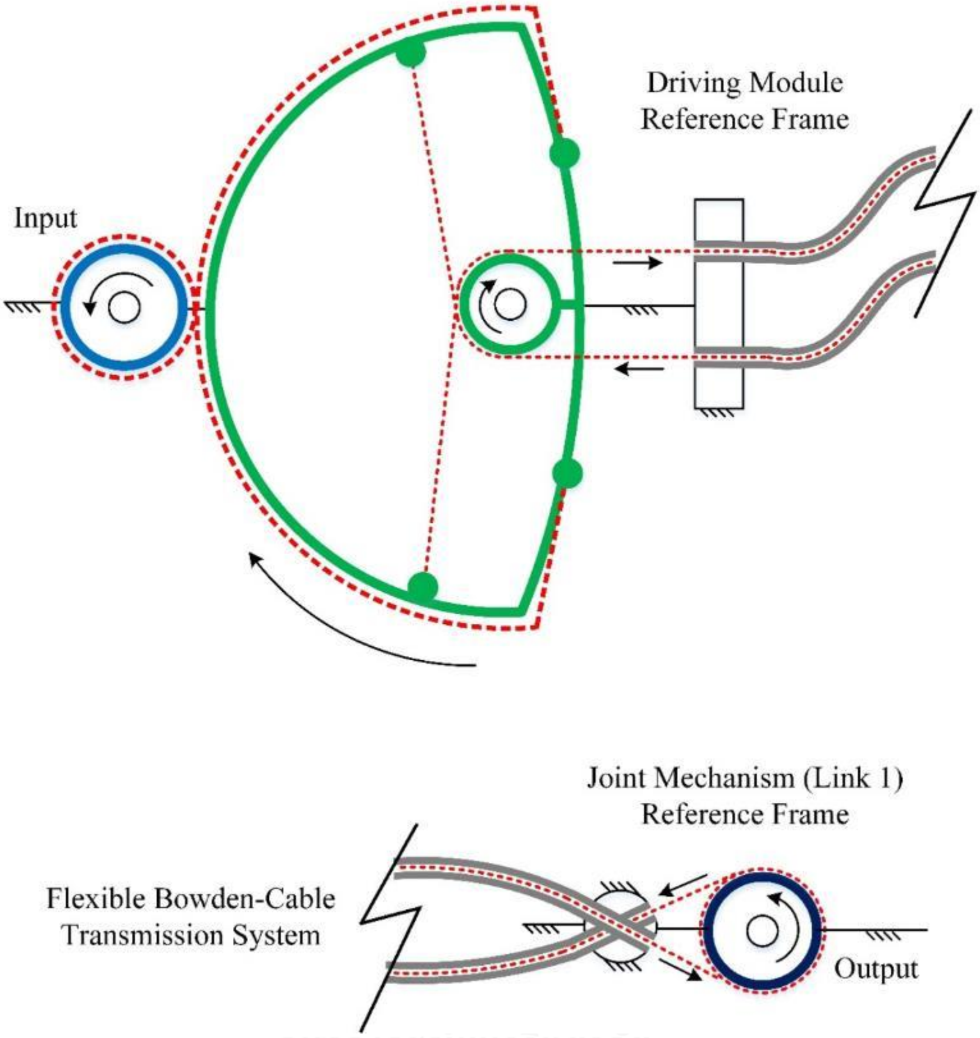


Figure 3.10 A schematic diagram of one driving module connected to one joint mechanism by close-loop Bowden cable system.

Bowden cable is a transmission system that has a cable moving inside a flexible hose. The ends of the hoses are fixed to different reference frames, which allow tension transmission through the inner cable between the reference frames. Since the transmission system is flexible, an actuation module and a device can be mounted separately. The aim of use is to reduce burden from actuation modules on a hand.

The driving module is carefully designed as a reduction system, an actuator mounting system and a cable routing system. We implement 5:1 reduction ratio to increase motor torque by using an arc plate with common capstan-cable drive. For transmission to a joint mechanism, the Bowden hose is fixed to the reference where the inner cable is routed around a capstan of the arc plate to the preload screws.

Maxon flat EC motors with encoders (APPENDIX B) are selected to produce sufficient torque, which is designed from about one fourth of maximum joint torque of healthy people [31, 51, 52]. The 30W motors are used to drive a PIP joint and a

DIP joint at 0.33 Nm of maximum continuous torque (included transmission), and the 50W motor is for an MCP1 joint at 0.45 Nm of maximum continuous torque (included transmission). Copley Accelus servo-amplifiers (APPENDIX B) are selected to drive motors individually with current control mode. Meanwell switching power supply (48V 5.2A) connected to the Schaffner line filter (APPENDIX B) are used as the power source of the system (APPENDIX B). Figure 3.11 shows the mechatronics diagram of the overall system.

The system is controlled by a desktop PC through Sensoray PCI card Model626 (APPENDIX B) connected with the servo-amplifiers. Control mode and important parameters are set up on CME2, and programming is developed on Simulink. PID controller is implemented to achieve simple position control for each joint. As a result, the finger exoskeleton will be controlled in joint space from predefined paths. Figure 3.12 shows flowchart of the designed control step. The position profile (time series) will be first generated from specified via points and time intervals. Then, the main loop program will deliver the desired trajectory by a control loop at 1 ms.

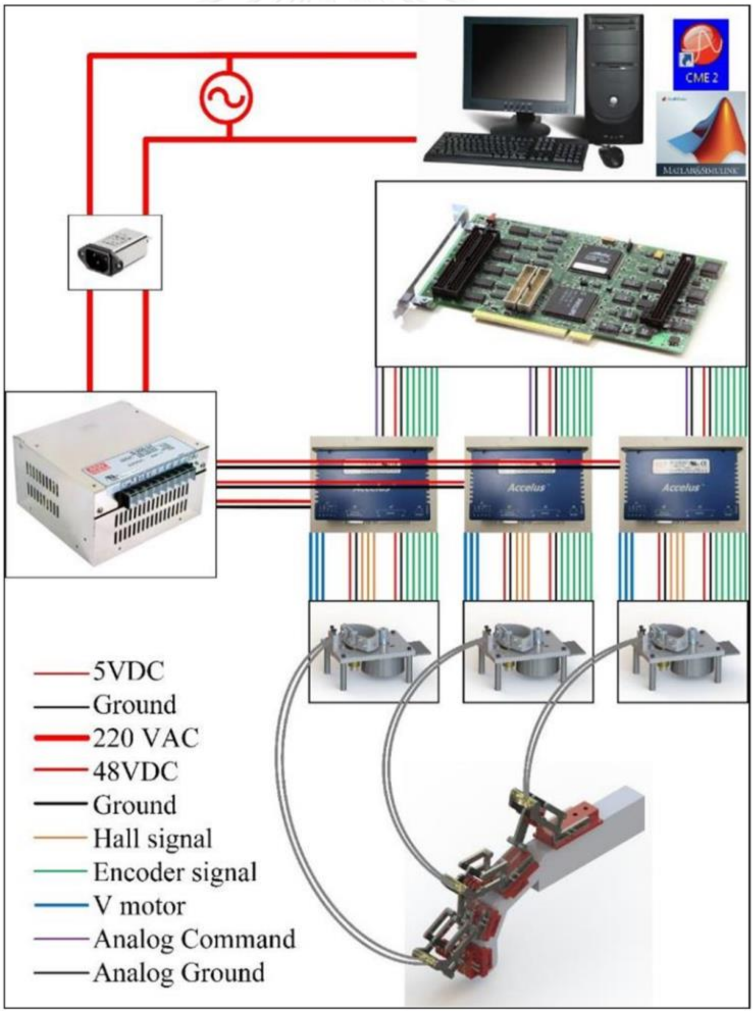


Figure 3.11 A mechatronics diagram of the finger exoskeleton system.

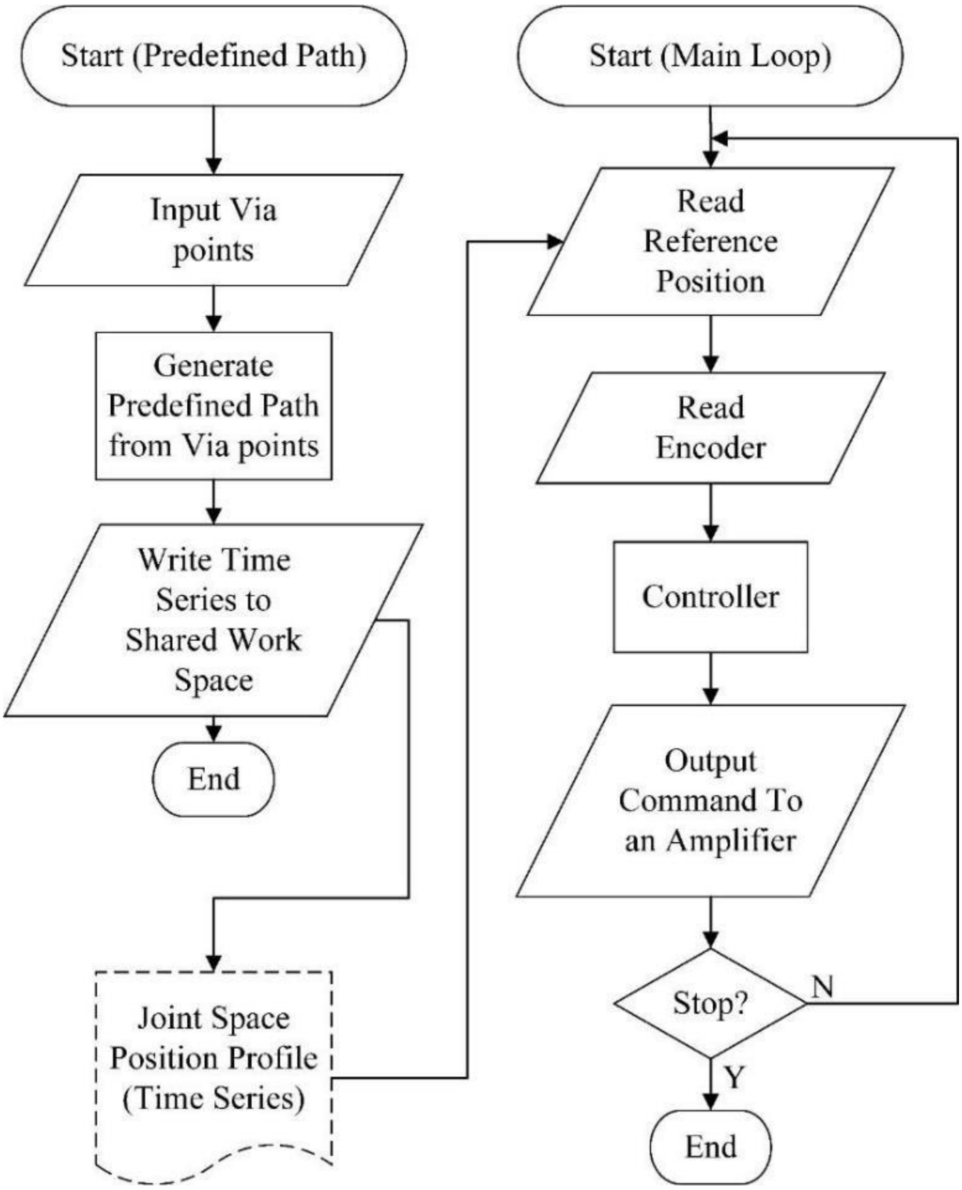


Figure 3.12 Programming flowchart of the position profile generation (left) and the control loop (right).

3.3 System Construction

The design realization is explained in the next 2 sections, i.e. mechanical system assembly and electronic system assembly.

3.3.1 Mechanical System Assembly

The finger exoskeleton design is in Figure 3.13. The components consist of 3 parts: 2D fabricated parts (APPENDIX A), 3D fabricated parts (APPENDIX A) and parts that are available on the market (APPENDIX B).

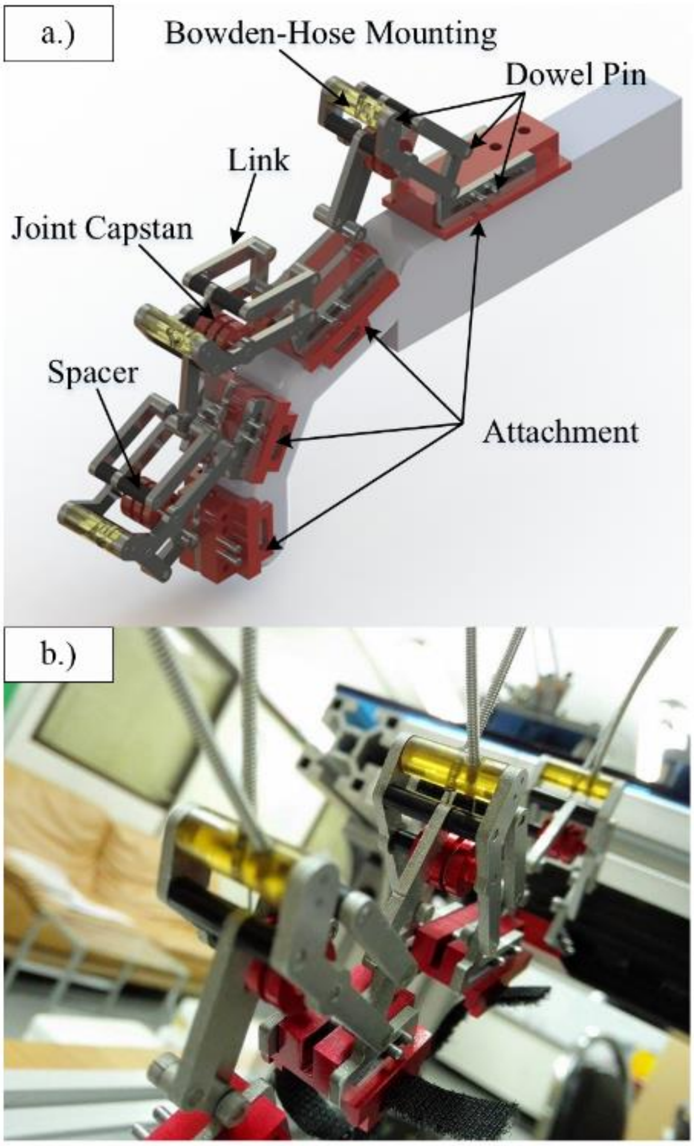


Figure 3.13 3D CAD model of a finger exoskeleton with sliding six-bar joint mechanisms (a.) and the realized prototype (b.).

Illustrated in Figure 3.13, Links are fabricated by wire-cut EDM from A5083. Attachment and Joint Capstan are fabricated from A6010-red anodized. Bowden-Hose Mounting is fabricated by ULTEM1000. Spacers and dowel pins are purchased from the available suppliers.

The joint mechanism is assembled by tolerance fitting in order to minimize space for fasteners. Revolute joints are constructed by stainless dowel pins and precise holes on aluminum plates. Prismatic joints are constructed by aluminum plate and precise slots in 3D parts.

The driving module design is in Figure 3.14. There are 3 driving modules to drive 3DoFs finger exoskeleton. For each, the components consist 2 parts: 3D fabricated parts (APPENDIX A) and parts that are available on the market (APPENDIX B). Flat EC motor (APPENDIX B) is mounted below the base.

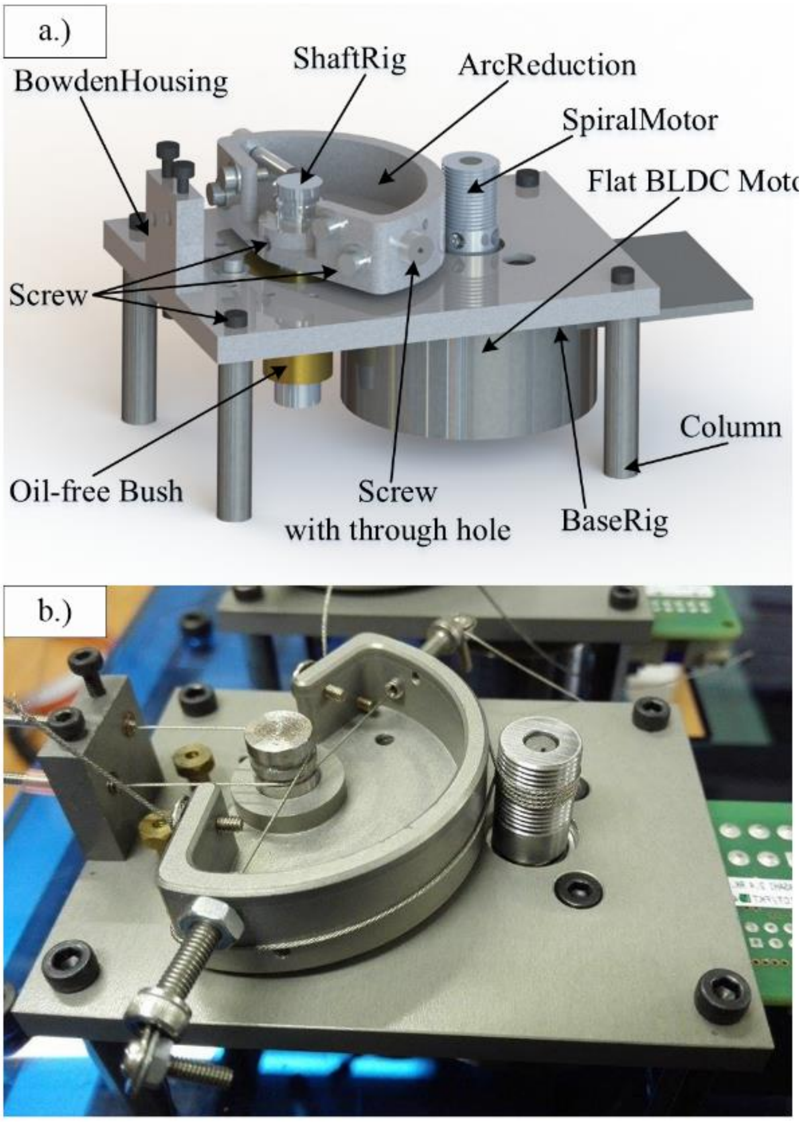


Figure 3.14 3D CAD model of one Driving Module without cable routing (a.) and the realized prototype (b.).

Illustrated in Figure 3.14, Base, Bowden-Hose Housing and Reduction Arc are fabricated from A6010-clear anodized. Shaft Capstan and Spiral Capstan are fabricated by steel. Oil-free bush, screws with through hole, columns and common screws are purchased from the available suppliers.

The finger exoskeleton and the driving modules are mounted on the experimental rig which is constructed by aluminum profiles and 2D acrylic plates (Figure 3.15). Driving effort from motors is transmitted through Bowden cable system to each joint mechanism.

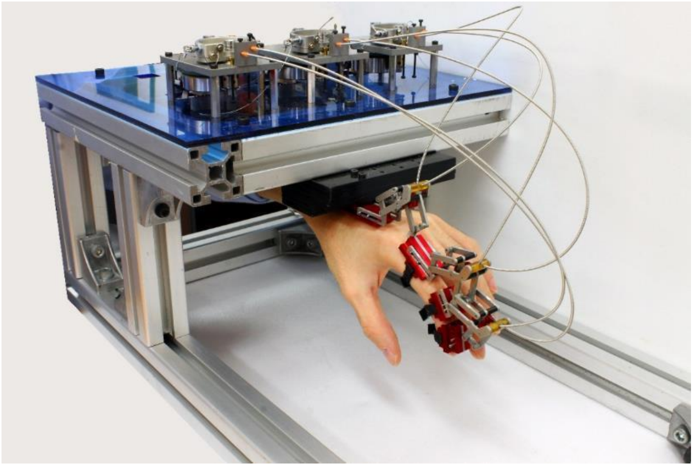


Figure 3.15 The experimental rig.

3.3.2 Electronic System Assembly

All electronic devices, except the desktop PC with the Sensoray card, are mounted in a multipurpose box. Connectors, an LED display, an AC plug, an enable switch, and other switches are on the interface panel as shown in Figure 3.16. The desktop PC and control box are connected with a 50p ribbon cable.

The finger exoskeleton system is designed and realized in this chapter. The prototype is able to move subject's fingers with sufficient forces along the predefined path. However, the evaluation is essential in development process. The next chapter provides evaluation details of the system on important aspects.

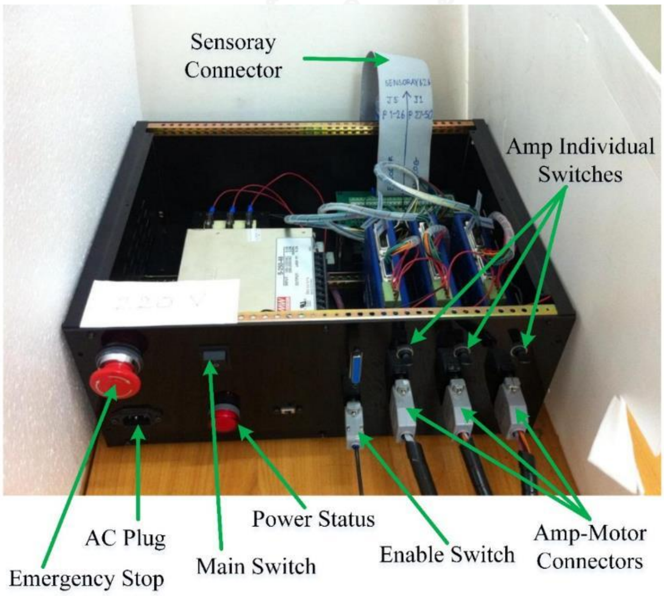


Figure 3.16 The control box with an interface panel.

CHAPTER 4

EVALUATION

Chapter 2 explains finger biomechanics and the problems in finger exoskeleton design which leads to the appropriate design requirements. Chapter 3 provides detail in design methodology and system construction. This chapter will provide evaluations of the prototype (Figure 3.15) on 3 aspects, i.e., the simulation with a real anatomical joint, evaluation based on design requirements, and subjective tests.

4.1 The Simulation with a Real Anatomical Joint

Only some of researchers design the devices to fully fit an anatomical joint motion. However, none of them provides any verification. We adopt the more accurate motion model of a human PIP in order to proof full accommodation of all configurations to guarantee safe motion. Based on the idea that a real finger joint is not perfect revolute as explained in chapter 2, the designed mechanism will be simulated with the more realistic joint trajectory. The movement of a PIP joint from [6] is adopted as a case study. The joint excursion is simply illustrated in Figure 4.1. As a result, the mechanism can accommodate a finger joint at every configuration. The simulation with an anatomical joint shows that the mechanism does not impede the natural joint motion. Although, the design, in theory, suffers from degeneracy of the mechanism form, which may cause unreachable configuration. In reality, compliance of the soft tissue allows extra DoFs, as a result of which the mechanism is able to adjust itself to the corresponding configuration, and works properly.

4.2 Evaluation Based on Design Requirements

At each joint mechanism, the prismatic connections are actually functioning during joint motion as illustrated in Figure 4.2. It suggests that the mechanism is adjusting itself to a proper configuration that does not interfere with the finger. Moreover, translational forces are supposed to be very small since the mechanism moves freely in axial direction of phalanges.

The mechanism of the finger exoskeleton itself can move in full range of motion as well as the plastic prototype (Figure 3.9). However, after set up driving modules and Bowden cable transmission with expected ROM of $[0^{o}\text{-}100^{o}, 0^{o}\text{-}100^{o}, 0^{o}\text{-}100^{o}]$ for $[\mathrm{MCP1,PIP,DIP}]$, the device cannot achieve full range of motion due to design mistake of mechanical hard limits and loss of motion of Bowden cable transmission. The ROM of the joint mechanisms is estimated to be $[22^{\circ}-80^{\circ}, 4^{\circ}-64^{\circ}, 7^{\circ}-69^{\circ}]$ (illustrated in Figure 4.3.) while the ROM angles at the actuation module is $[0^{\circ}-91.13^{\circ}, 0^{\circ}-91.39^{\circ}, 7^{\circ}-91.26^{\circ}]$ calculated from encoders at the motors. The lost motion inside the Bowden hoses makes the available range of motion of each joint mechanism reduced approximately by 30°. In this case, the loss of motion is caused mainly by clearance between the cable and the hose resulting in significant backlash. Also, bending in cable system affects the output displacement. These effects are explained in Sava-Cable datasheet [53] for cable control design. The author has attached the document in APPENDIX C as an example.

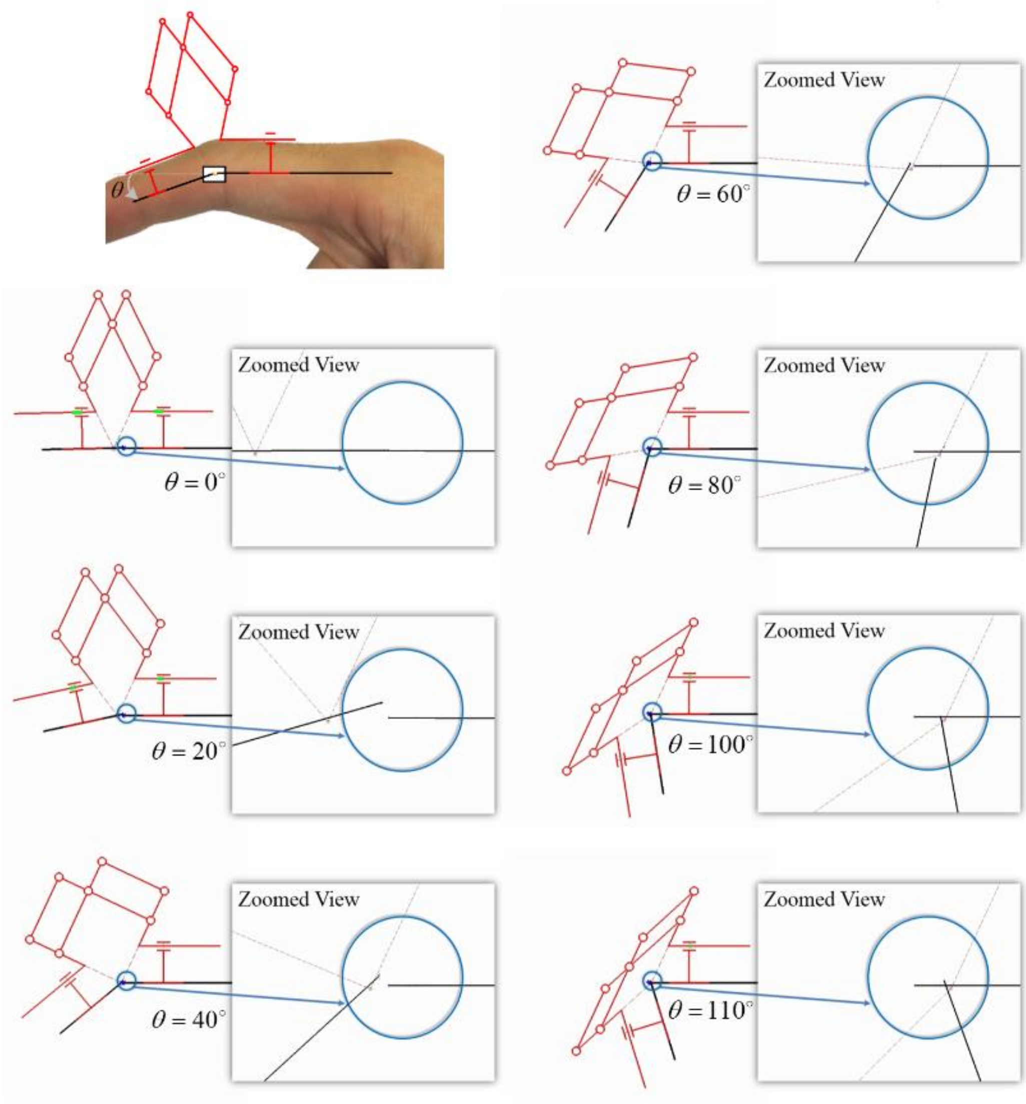


Figure 4.1 The simulation with a realistic model of a PIP joint trajectory.

The prototype finger can accommodate every phalanx length because it is designed as a planar open-loop mechanism at each joint. Figure 4.4 shows that the prototype can be set up with an index finger, a middle finger, a ring finger and a little one of the same user. This illustration also suggests that the prototype can operate with different dimension of user's fingers without interference.

The device can achieve independent joint control. Actuation forces from the motors from the driving modules pass through Bowden cable systems to drive the finger joint one by one. However, the Bowden cable transmission has loss of motion, as a result of which precise position control cannot be achieved.

Backdrivability is tested with a healthy index finger. All three motors are turned off, and the finger tries to move the system. As a result, an MCP1 joint and a PIP joint are able to overcome stiffness of the system and drive the motors. A DIP joint cannot move the motor because it has lower effort compared with others. Also, more bending of Bowden hose yields more friction inside.

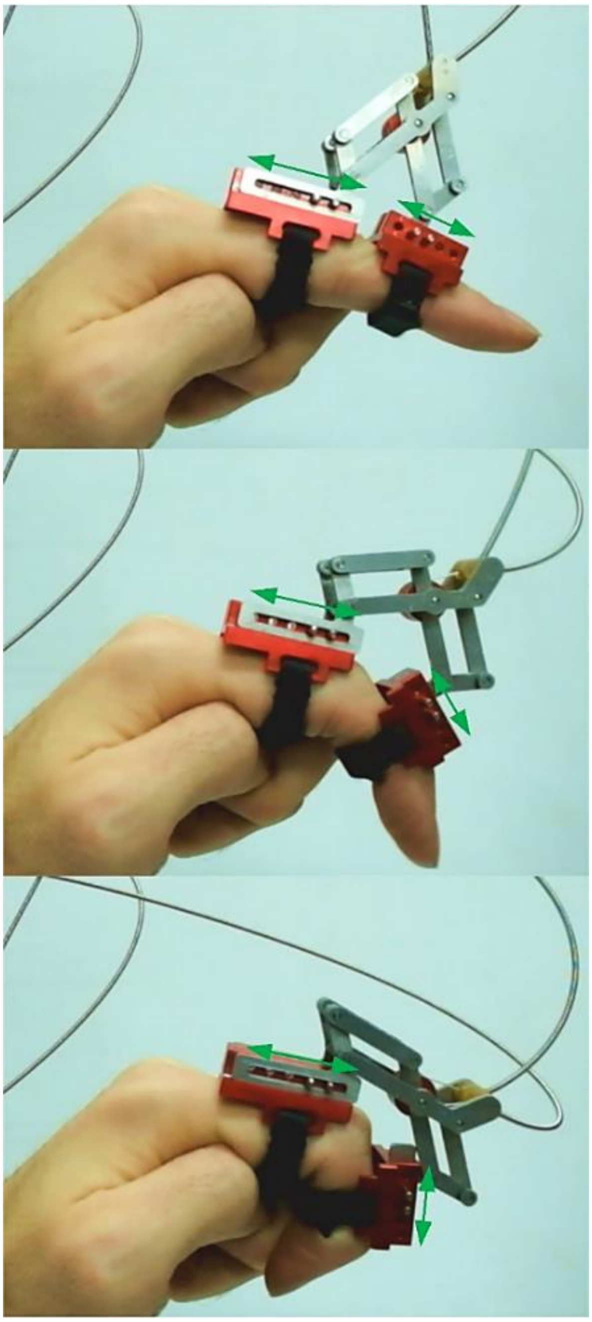


Figure 4.2 The mechanism self-adjusts to the finger configuration by sliding along the guided ways.

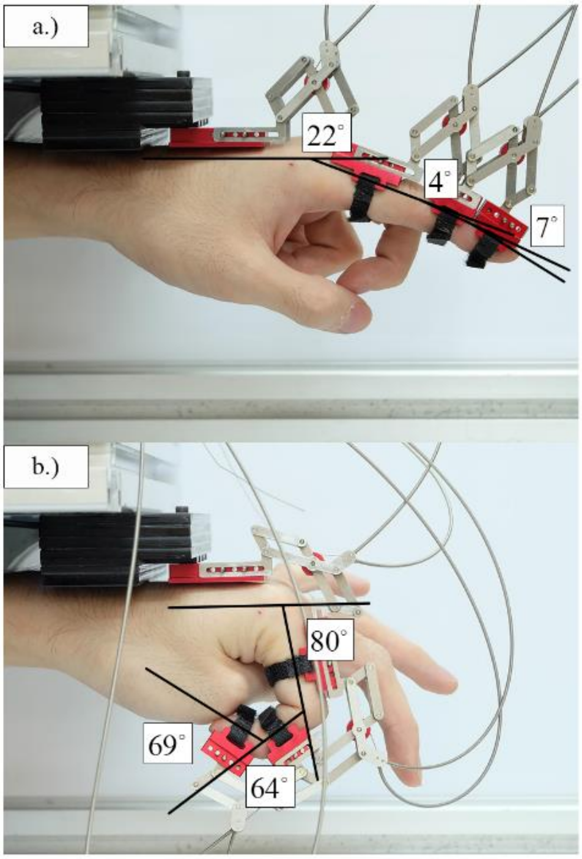


Figure 4.3 The maximum ROM of the mechanism at the fully extended configuration (a.) and fully flexed configuration (b.).

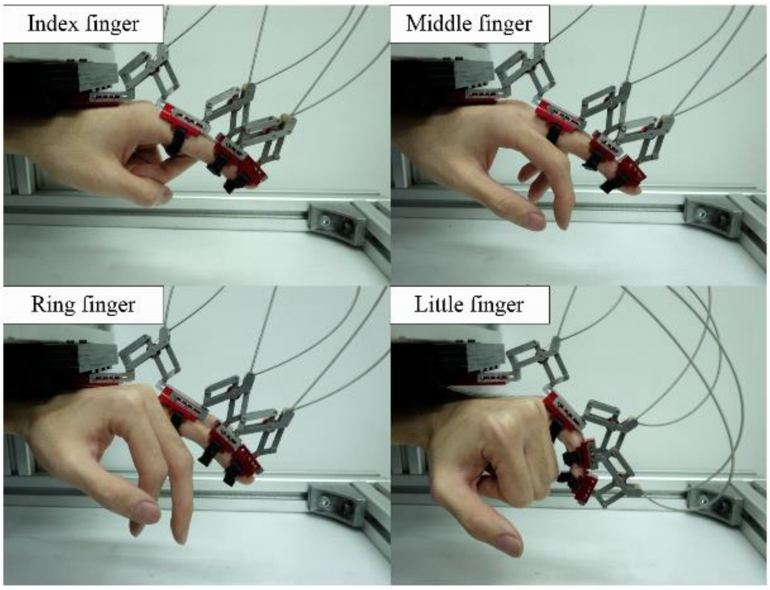


Figure 4.4 The prototype can adapt to all fingers of the same user except a thumb which has different biomechanical structure.

4.3 Subjective Tests

The subjective test is conducted to evaluate users' feeling about the operating prototype, and also evaluate the workable prototype. The experiment is set up for a passive range of motion mode. The exoskeleton will move a finger of a subject under the predefined path. The evaluation takes into accounts, the aspect of appearance, comfort and safety.

4.3.1 Test Protocol

Fourteen healthy persons are selected in this experiment. The subjects are first explained about how the device works and asked to give feedback from their feeling. The exercise is set up to move $[\mathrm{MCP1,PIP,DIP}]$ of an index finger from $[30^\circ, 10^\circ, 10^\circ]$ to $[70^\circ, 50^\circ, 50^\circ]$ back and forth by sine wave signal at 0.25 Hz. Figure 4.5 shows the experimental setup. After exercise, the subject will be asked to do questionnaire. The score for each question will be either "positive", "neutral" or "negative". Also, "comment" space is provided for additional feedback for every question.

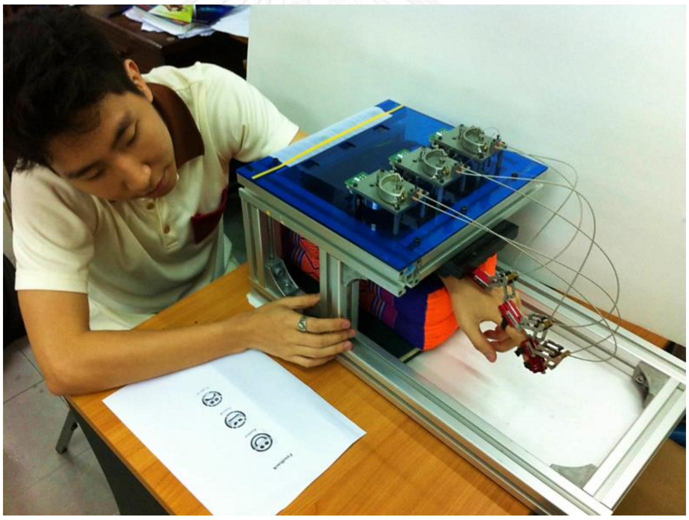


Figure 4.5 Experimental setup for the subjective test.

4.3.2 Test Result

The subjective test result is illustrated in Figure 4.6. 14 subjects were asked by 7 questions shown in the figure. Most of the answers are positive or neutral. Only some persons feel uncomfortable with the device.

Apart from the test result, some users have left useful comments. About one third of them suggest that the test rig is too big, which obstructs vision to their fingers. They prefer to have a clear view of an exercise which would make them feel more secured. Also, one third of users have negative feeling with metallic attaching elements with Velcro strap. About one fourth of subjects feels too tight at the distal phalanges and feels unnatural when the device performs maximum ROM.

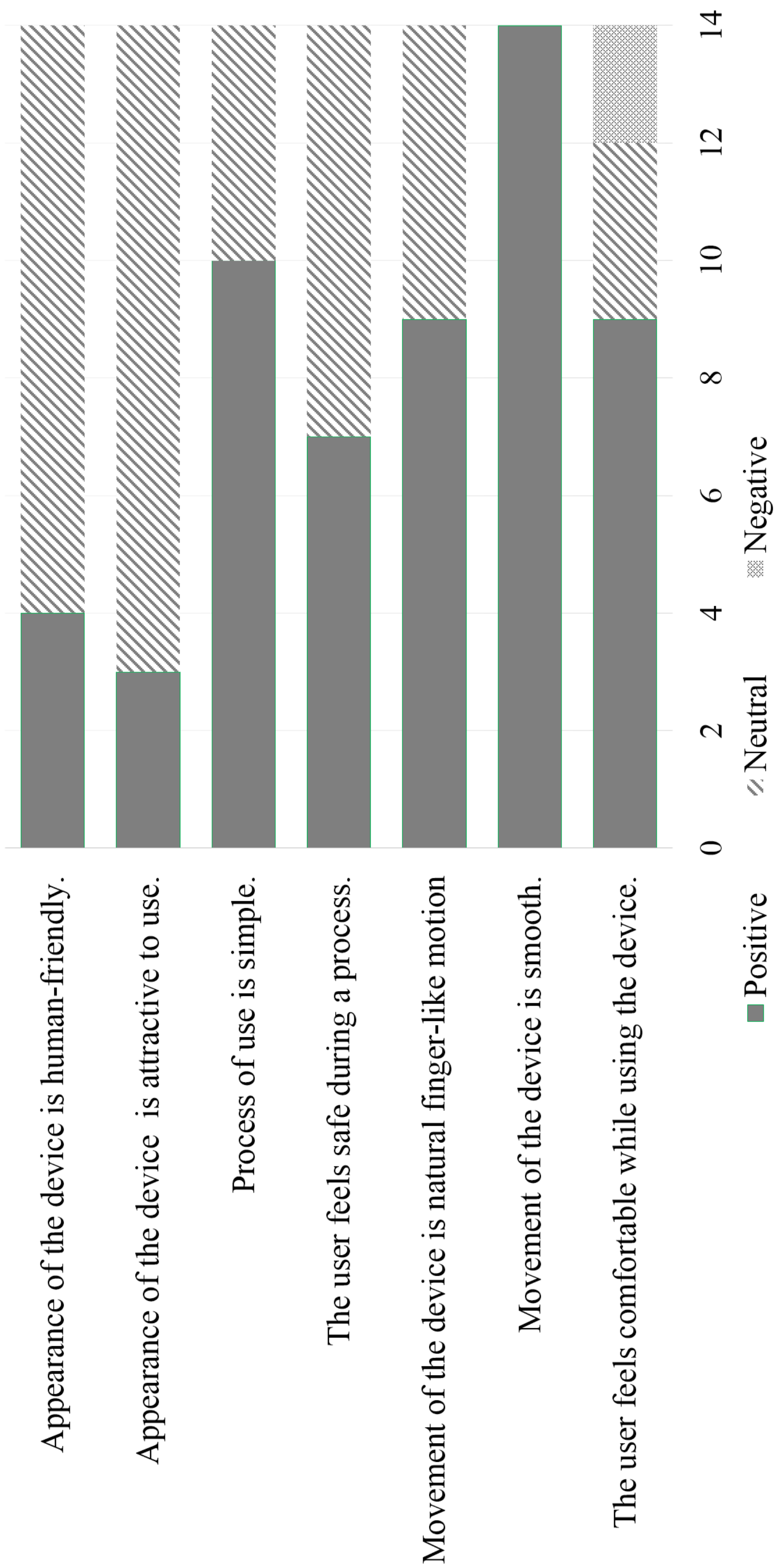


Figure 4.6 Users’ feedback of ROM exercise by the finger exoskeleton.

CHAPTER 5
DISCUSSION AND CONCLUSION

This research is conducted to develop a robotic finger exoskeleton under rehabilitation purpose. All of knowledge the author has acquired are summarized concisely in this book. In Chapter 2, the essential knowledge, fundamental design problems and other related works are gathered and synthesized. Continually, Chapter 3 is led by design synthesis from the most primitive conception towards the design solution. Also, system construction is elaborately explained in this chapter. Chapter 4 provides the basic evaluation of this works in a systematic way.

Reviewing fundamental knowledge, there are desirable qualities that finger exoskeleton should have, i.e. lightness, no interference, no translational force, high backdrivability, high adaptability, covering full ROM. The project is led by joint mechanism design by 2 fundamental concepts, i.e. eliminating interference by designing open-chained mechanism and reducing translational forces by prismatic joints on phalanges. The six-bar parallelogram is finally adopted to reduce sliding displacement. The result finger exoskeleton consists of 3 sliding six-bar joint mechanisms and 1 passive revolute joint for 4 anatomical joints, i.e. an MCP1 joint, a PIP joint, a DIP joint and an MCP2 joint. The SSJM exploits the function of an RCM mechanism incorporating with prismatic connections to generate a corresponding motion with a human finger. The exoskeleton system is driven by 3 motors. Each joint is individually actuated by one motor. Actuation forces from the motors pass through Bowden cable transmission to a finger, which allows human limbs to be free from weight of actuation system. Close-loop cable is adopted to achieve bidirectional control for each joint mechanism. Figure 5.1 shows the result finger exoskeleton. 3 evaluations are conducted to verify functionality of the prototype. Simulation with the realistic human joint model verifies feasibility of kinematic design. Design requirement evaluation studies qualities of the prototype and also proves design concepts. The subjective test is conducted to evaluate users’ feeling and that the device is workable.

5.1 Discussion

Simulation with the more realistic model of an anatomical joint verifies that the designed mechanism can accommodate a finger joint at all configurations on a sagittal plane. However, the design might face 2 problems from degeneracy at a small flexion angle. First, the required sliding displacement will go large at a small angle if the mechanism operates with an anatomical joint which IRA changes along its ROM. Another problem is that at the exact angle of zero, the mechanism can theoretically slide out of collinear prismatic joints on the phalange. However, these 2 problems will never happen in reality because compliance of soft issue will always compensate small changes of IRA, and the exact angle of zero cannot be hold long enough for the mechanism to slide out.

The evaluation based on design requirements shows that the prototype can achieve most of the desired requirements. Self-adjusting sliders suggests that the mechanical system has no interference, and translational force is small. Friction in sliders in the axial direction of phalanges always exists. As a result, this design does not completely eliminate translational forces on phalanges. Nevertheless, small translational forces are acceptable because biomechanics of a real finger also has this force due to a behavior of underactuated tendons in vivo. The mechanism itself is verified to have full ROM by the plastic prototype. However, with Bowden cable transmission and a driving module, the overall system cannot realize full ROM. The main cause is loss of motion in Bowden hose. The inner diameter of a hose and the outer diameter of a cable are not fully fitted, which results in loss of motion between the driving modules and the finger exoskeleton. The loss of motion behavior results in compliance-like property. It is worth to mention that proper design can reduce the effect of motion loss in this type of transmission system. The prototype also has high adaptability as testing with the other four digits and still being functional. Although, the current prototype is not designed to be adaptable in width dimension, it works well in wide range of people. The individual joint control requirement is achieved but position control is not accurate because of compliance-like property of the transmission system. Nevertheless, the problem turns into the advantage of the system in aspect of safety where a user’s finger could always have small backdrivability. The backdriving effort may not reach upstream actuators, but will be absorbed by the compliant transmission. Precise position control is absolutely possible just by embed a direct angle sensor at a joint mechanism, e.g., a potentiometer, etc. Backdrivability of the system is possible but not reaching the satisfying level. Friction in the system and inertia of motors and linkages affects this quality. Pre-tensioning for a close-loop cable also causes more friction in the transmission system. Improving backdrivability is also absolutely possible by redesigning the system with the proper components to lessen friction, e.g., linear sliders, bushes, etc. Moreover, reducing inertia of the system would have significant improvement of this property, for examples, reselecting material or motors, and also redesigning the reduction systems.

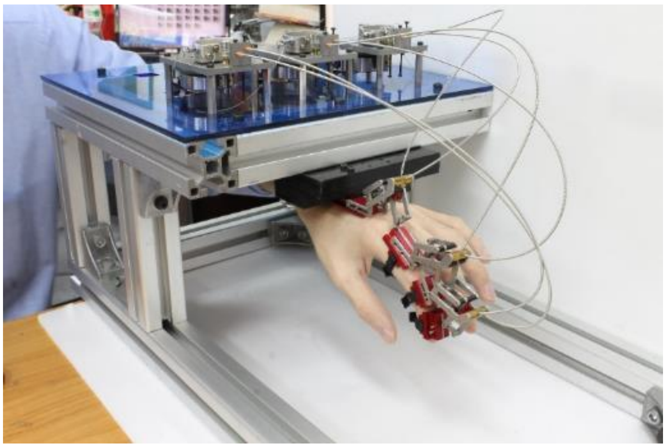


Figure 5.1 The finger exoskeleton system. Please note that electronic box and desktop PC are not shown in this picture.

Subjective test evaluates users' feeling about the device and to show that the device is workable. The device is able to moves subject's fingers along the predefined paths. The motion generated by the prototype is quite natural and not impeding. Most of subjects feel positive with the prototype as shown in Chapter 4. More than half of them say training is comfortable, movement is natural, device is smooth and the process is simple. There are some people that feel tight and unnatural at a distal phalanx when a large flexion angle is performed. It is possible that the flexion ratio of a PIP joint and a DIP joint is not proper for the persons because ROM of two joints are different.

5.2 Conclusion

In accordance with the 3 objectives, this research is conducted in order to design and construct a finger exoskeleton system, and also to make a basic rehabilitation mode. As accomplishing the research goals, a novel mechanism for a finger exoskeleton is designed and successfully tested with a real human finger in both passive mode (with actuation) and active mode. The finger exoskeleton system is realized, where the system consists of finger exoskeleton mechanism, driving modules, a control box, a desktop PC and programming. The system is capable of independent joint control, but position control is not accurate. The result device is able to perform passive ROM training which can move a finger along any predefined paths in a workspace. The training is successfully tested with 14 healthy subjects.

5.3 Future Work

In this research, the finger CPM device has been developed and tested. The result prototype is proven safe and functional. The next suggested milestone is to apply the device to the real rehabilitation process, some further improvement is required. First and foremost, imprecise joint position control must be fixed by integrating a position sensor directly to a finger joint. The maximum ROM of the device must be larger by redesigning proper driving modules. The working process of the device must be carefully design. Also, understandable user interface for a therapist is critically important for the sakes of both safety and usability.

Besides the objective of ROM rehabilitation, this finger exoskeleton also contributes to hand exoskeleton design. By this architecture, the designed exoskeleton would be able do fine manipulation. The future cooperating thumb exoskeleton and good control strategy would make the application not limited only to ROM exercise.

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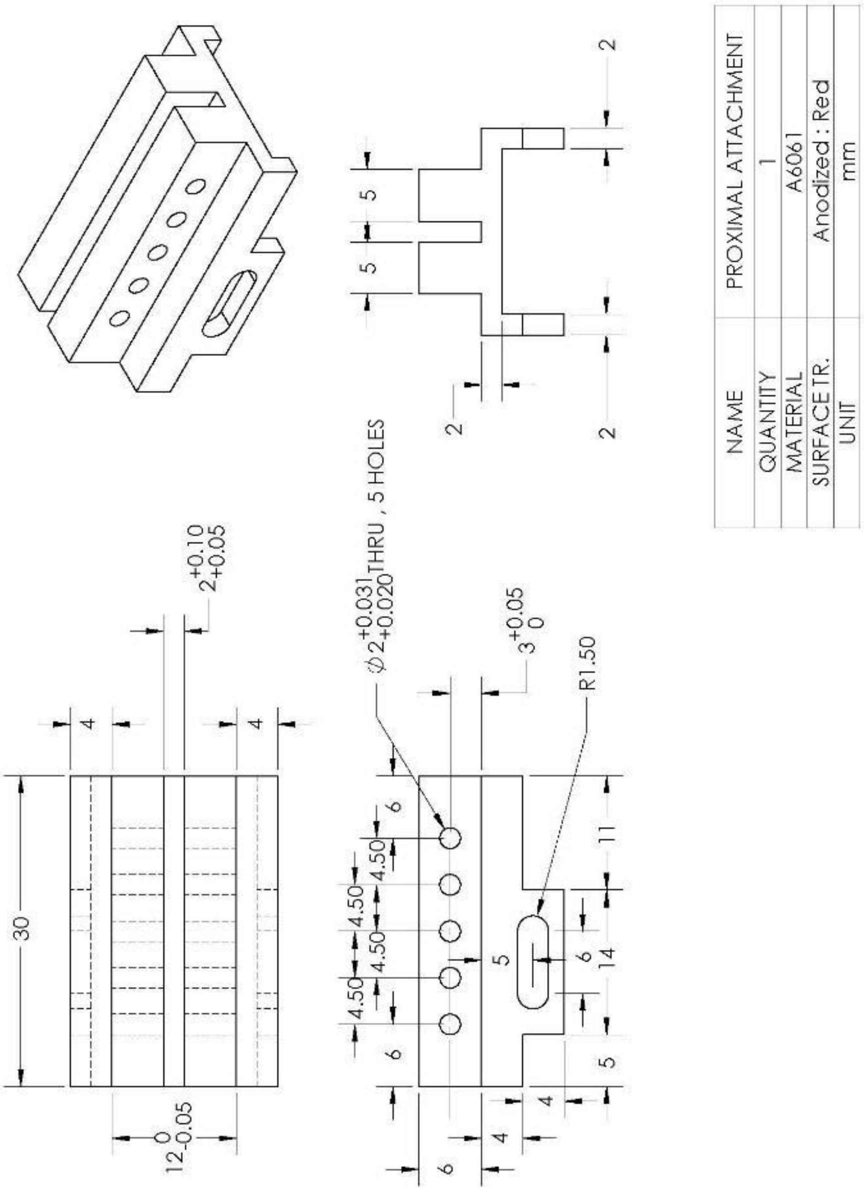
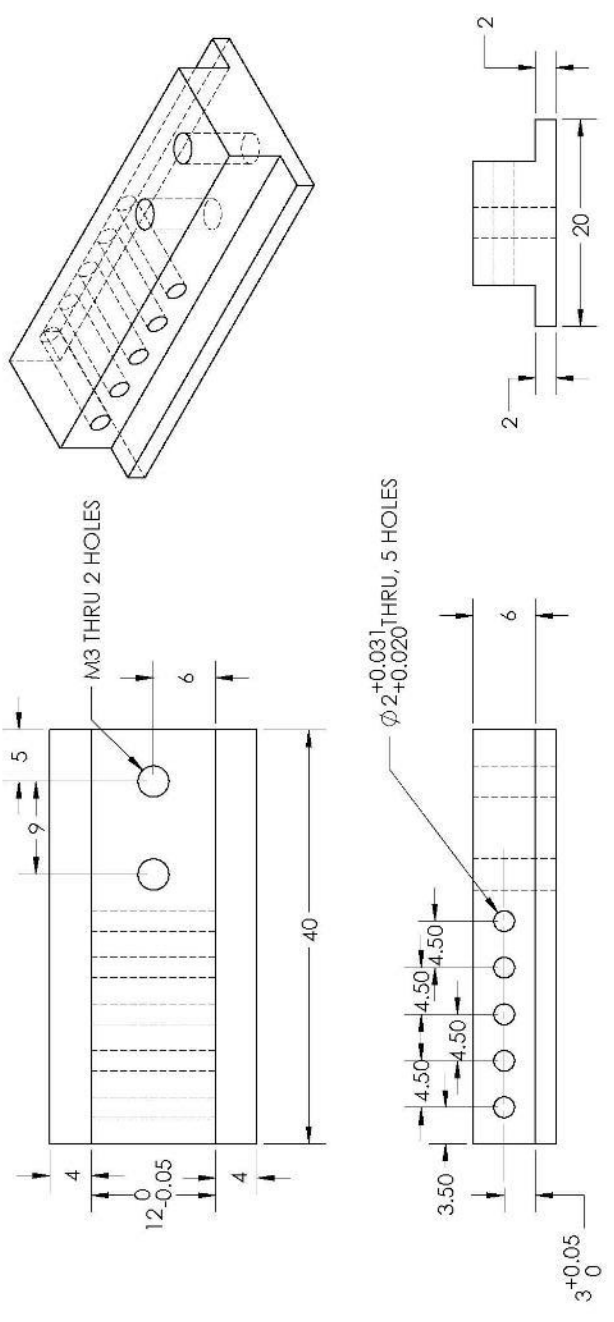
[57] *http://www.copleycontrols.com/*.

[58] *http://www.sensoray.com/*.

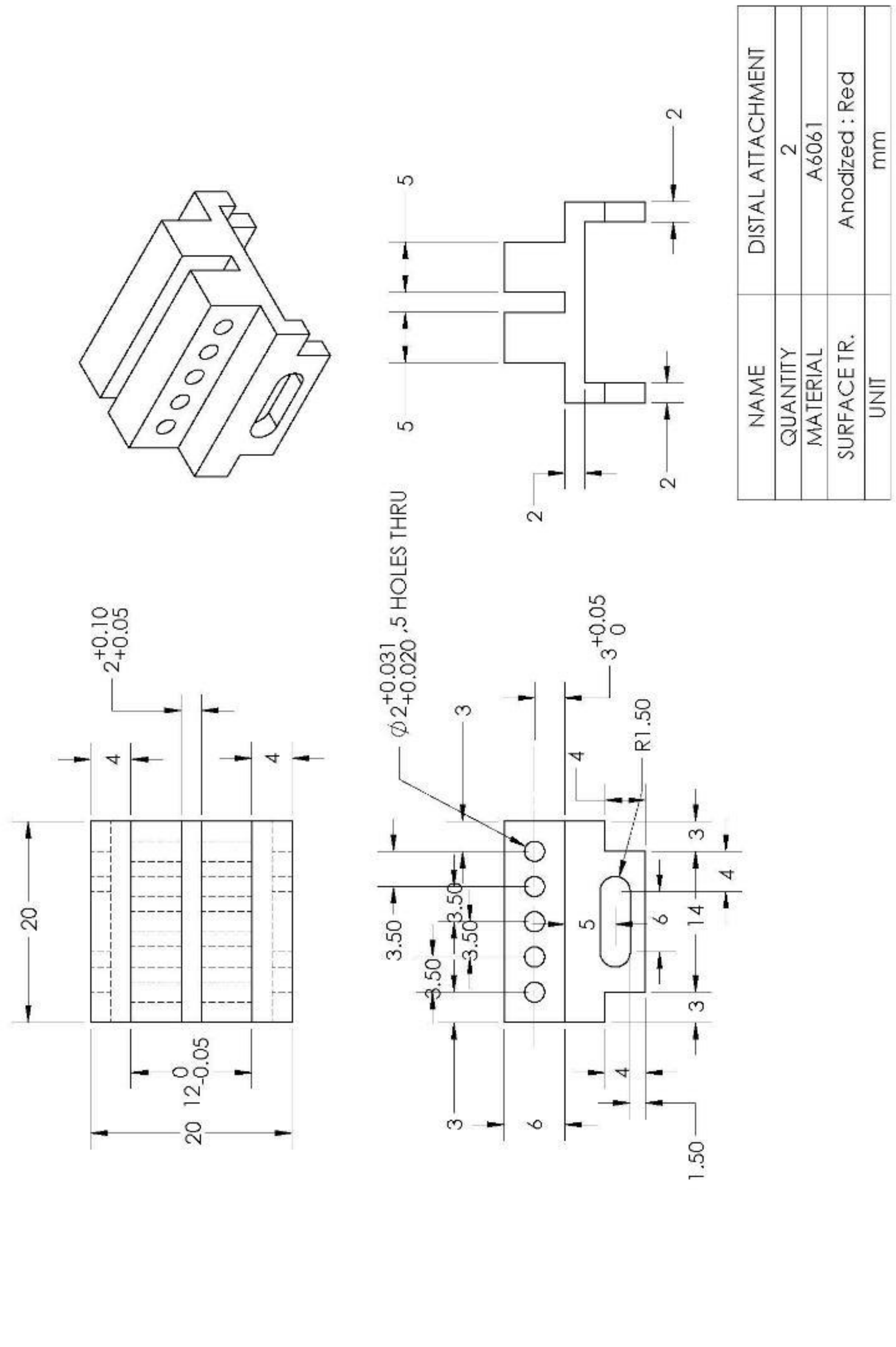
APPENDICES

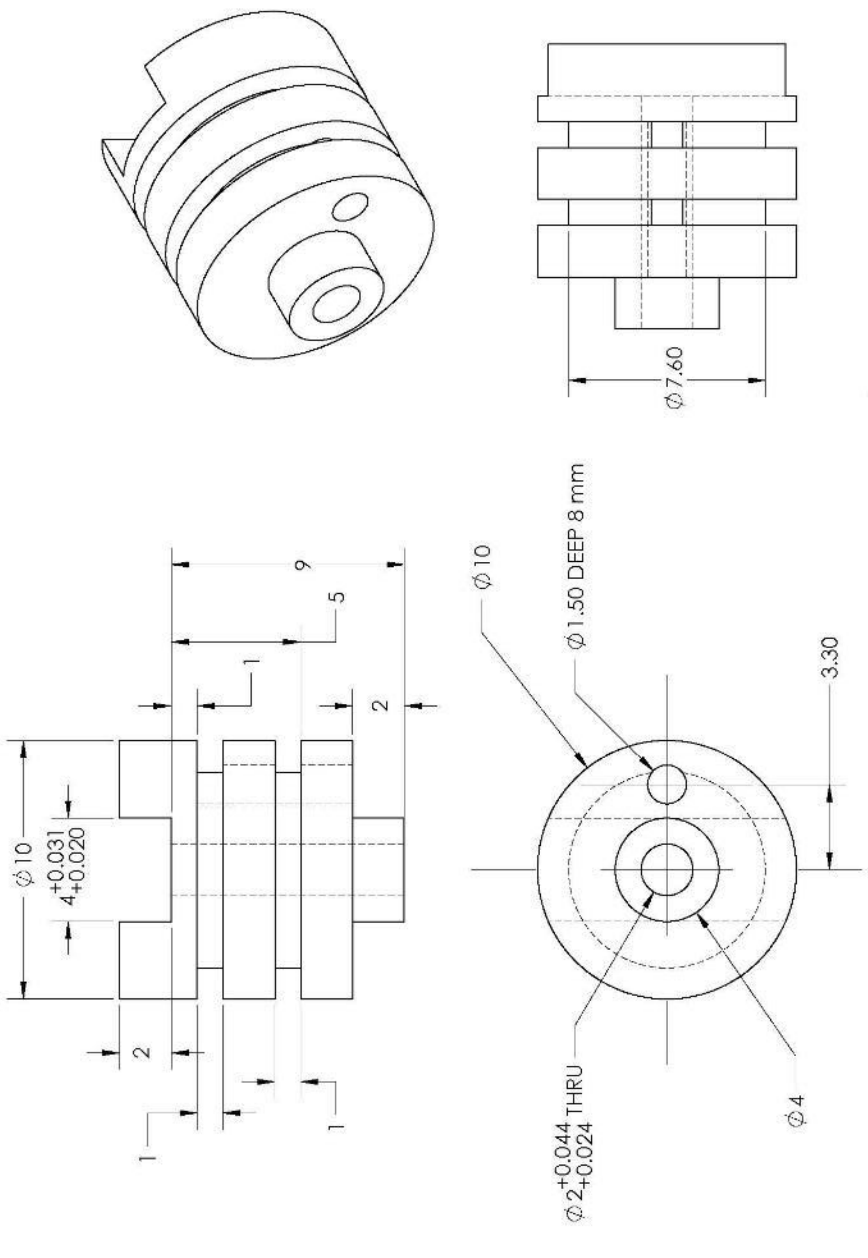
APPENDIX A
FABRICATED PARTS


NAME
PROXIMAL ATTACHMENT
QUANTITY
1
MATERIAL
A6061
SURFACE TR.
Anodized : Red
UNIT
mm
30
$12^{0}_{-0.05}$
$2^{+0.10}_{+0.05}$
$\phi 2^{+0.031}_{+0.020}$ THRU , 5 HOLES
$3^{+0.05}_{0}$
R1.50
4.50
14
11

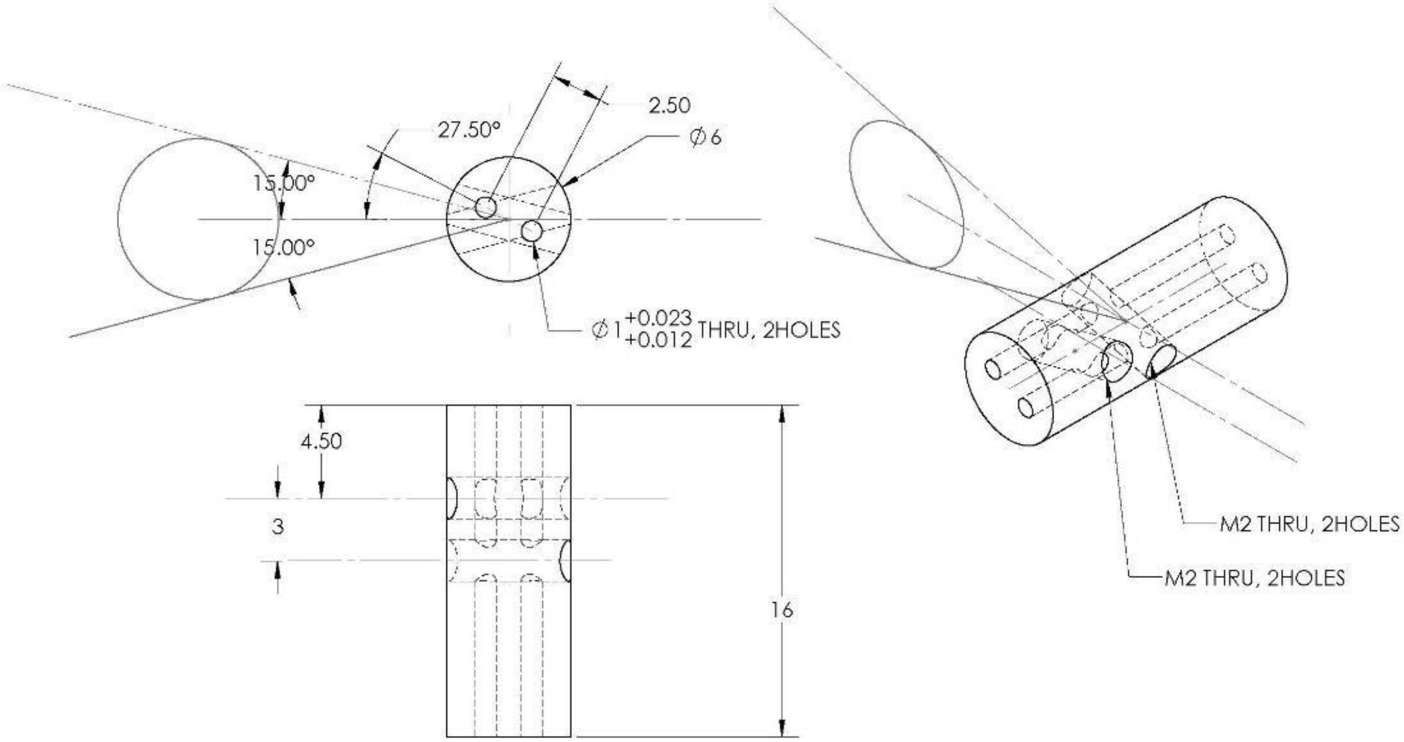


NAME	METACAPAL ATTACHMENT
QUANTITY	1
MATERIAL	A6061
SURFACE TR.	Anodized : Red
UNIT	mm


NAME
DISTAL ATTACHMENT
QUANTITY
2
MATERIAL
A6061
SURFACE TR.
Anodized : Red
UNIT
mm
Ø2+0.031 +0.020 ,5 HOLES THRU
R1.50

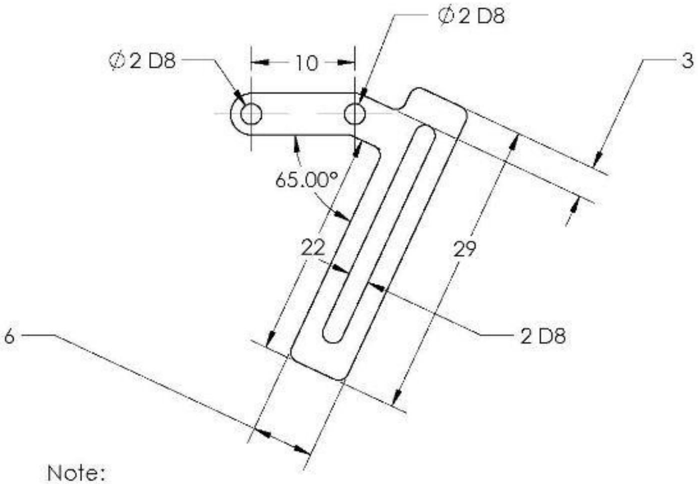


NAME	JOINT CAPSTAN
QUANTITY	3
MATERIAL	A6061
SURFACE TR.	Anodized : Red
UNIT	mm



NOTE:
DRILL 1mm THROUGH HOLES BEFORE THREADING

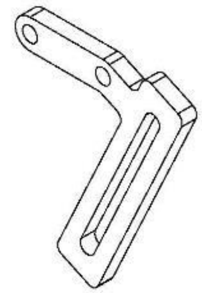
NAME	BOWDEN-HOSE MOUNTING
QUANTITY	3
MATERIAL	ULTEM1000
SURFACE TR	Anadized: Red
UNIT	mm



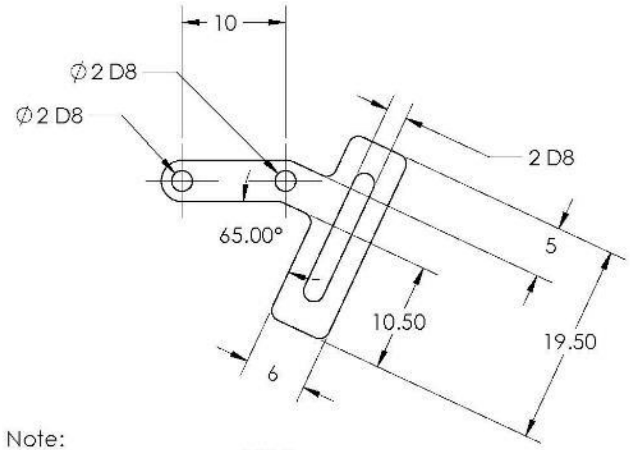
Note:

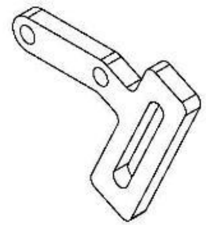
H7 is Hole Tolerance $^{+0.010}_{+0.000}$ (Interference Fit with m6 shaft)

D8 is Hole Tolerance $^{+0.034}_{+0.020}$ (Clearance Fit with m6 shaft)



NAME	PLINK.2
QUANTITY	4
MATERIAL	A5083 2 mm
UNIT	mm



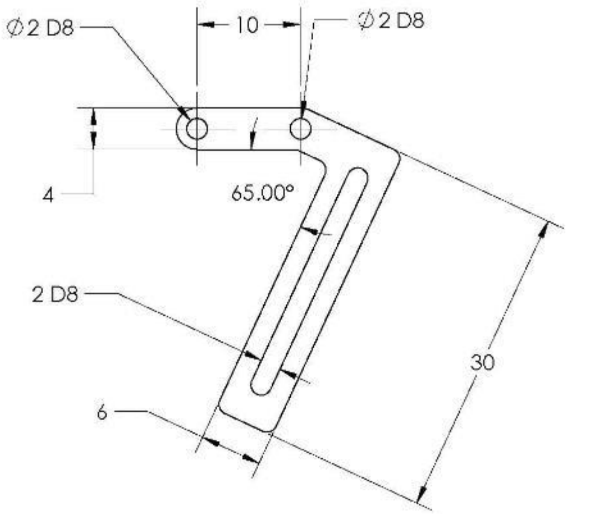


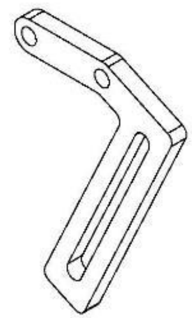
Note:

H7 is Hole Tolerance $^{+0.010}_{+0.000}$ (Interference Fit with m6 shaft)

D8 is Hole Tolerance $^{+0.034}_{+0.020}$ (Clearance Fit with m6 shaft)

NAME	PLINK.1
QUANTITY	10
MATERIAL	A5083 2 mm
UNIT	mm



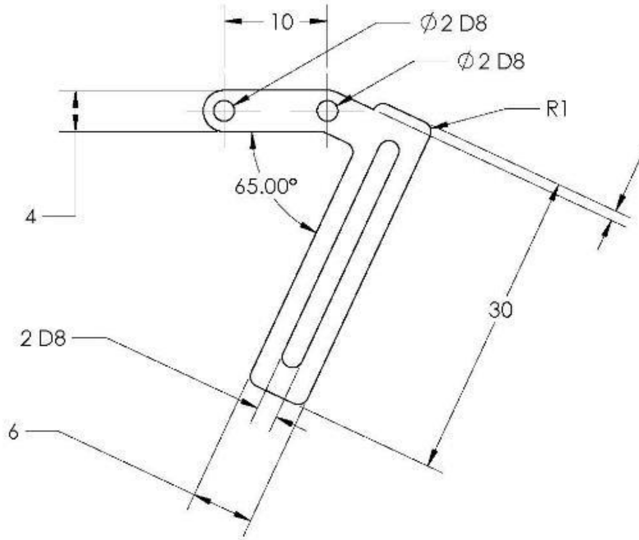


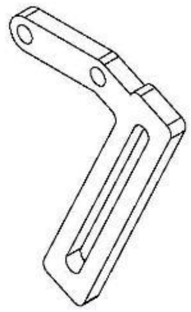
Note:

H7 is Hole Tolerance $^{+0.010}_{+0.000}$ (Interference Fit with m6 shaft)

D8 is Hole Tolerance $^{+0.034}_{+0.020}$ (Clearance Fit with m6 shaft)

NAME	MLINK.2
QUANTITY	4
MATERIAL	A5083 2 mm
UNIT	mm



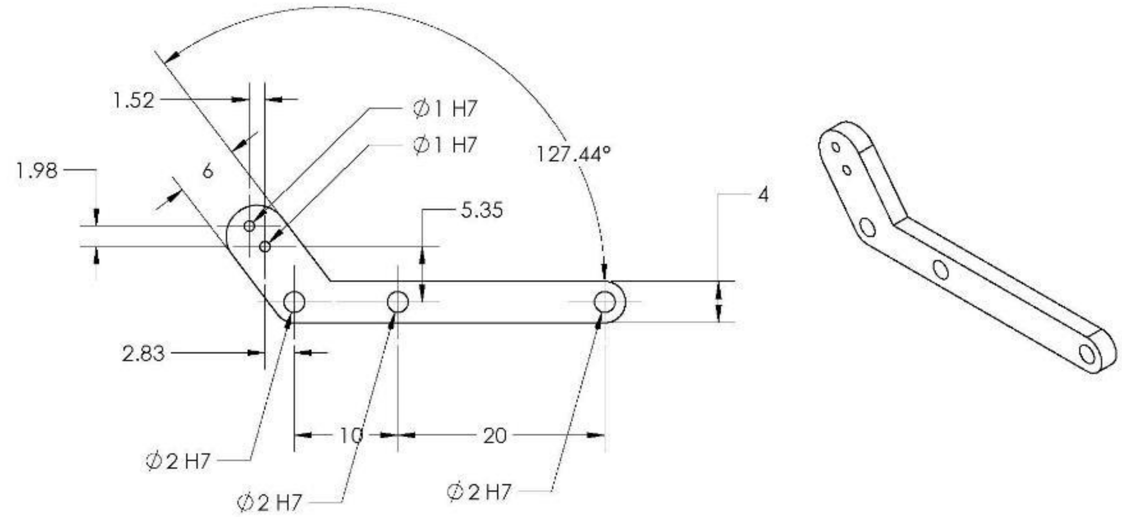


Note:

H7 is Hole Tolerance $^{+0.010}_{+0.000}$ (Interference Fit with m6 shaft)

D8 is Hole Tolerance $^{+0.034}_{+0.020}$ (Clearance Fit with m6 shaft)

NAME	MLINK.1
QUANTITY	3
MATERIAL	A5083 2 mm
UNIT	mm

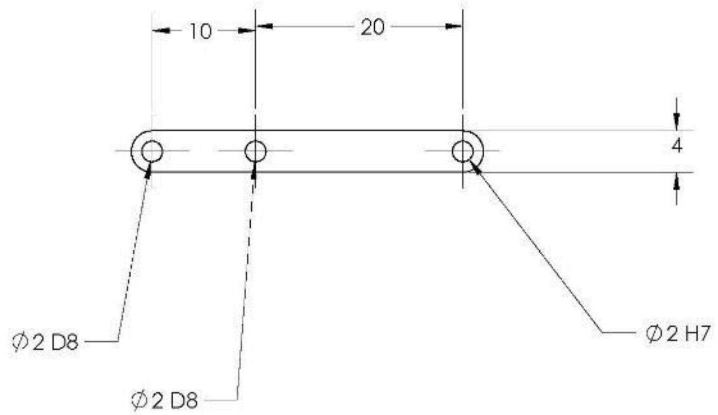


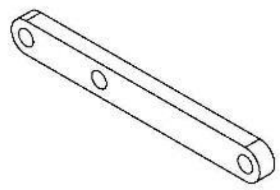
Note:

H7 is Hole Tolerance $^{+0.010}_{+0.000}$ (Interference Fit with m6 shaft)

D8 is Hole Tolerance $^{+0.034}_{+0.020}$ (Clearance Fit with m6 shaft)

NAME	LINK1.2
QUANTITY	12
MATERIAL	A5083 2 mm
UNIT	mm



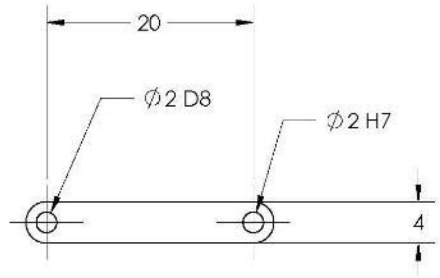


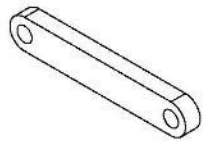
Note:

H7 is Hole Tolerance $^{+0.010}_{+0.000}$ (Interference Fit with m6 shaft)

D8 is Hole Tolerance $^{+0.034}_{+0.020}$ (Clearance Fit with m6 shaft)

NAME	LINK1.1
QUANTITY	6
MATERIAL	A5083 2 mm
UNIT	mm



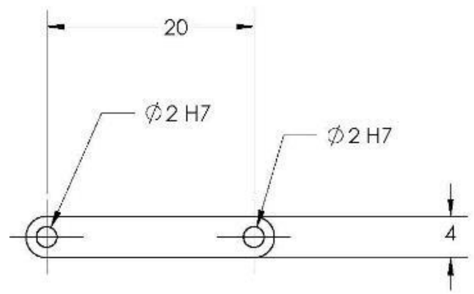


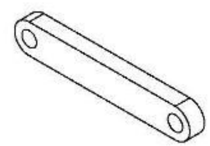
Note:

H7 is Hole Tolerance $^{+0.010}_{+0.000}$ (Interference Fit with m6 shaft)

D8 is Hole Tolerance $^{+0.034}_{+0.020}$ (Clearance Fit with m6 shaft)

NAME	LINK2.2
QUANTITY	6
MATERIAL	A5083 2 mm
UNIT	mm



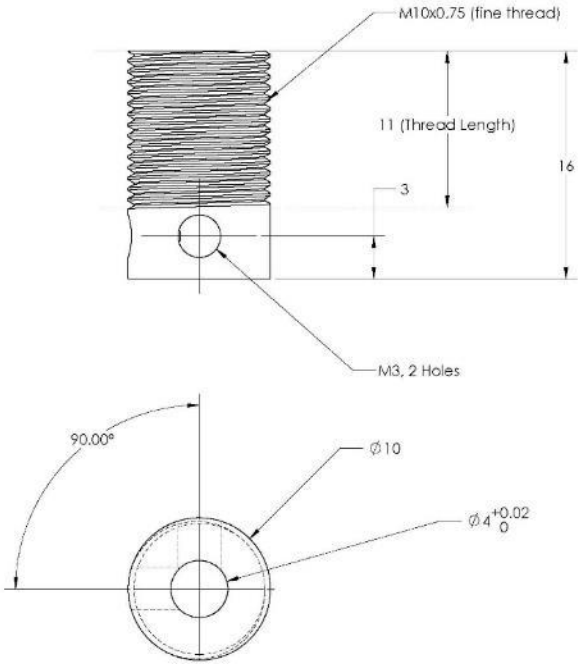


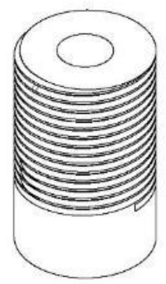
Note:

H7 is Hole Tolerance $^{+0.010}_{+0.000}$ (Interference Fit with m6 shaft)

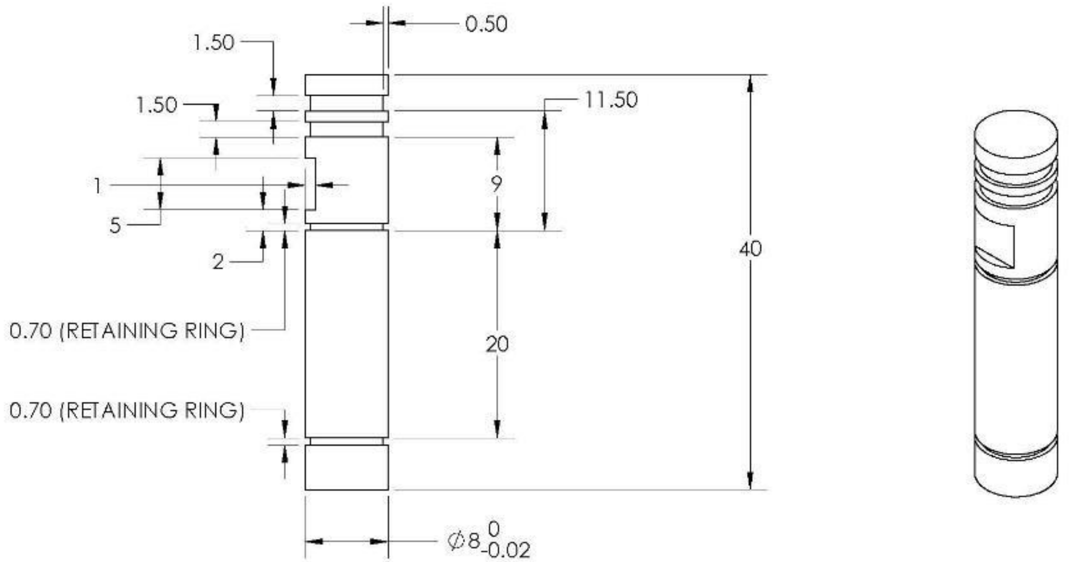
D8 is Hole Tolerance $^{+0.034}_{+0.020}$ (Clearance Fit with m6 shaft)

NAME	LINK2.1
QUANTITY	12
MATERIAL	A5083 2 mm
UNIT	mm





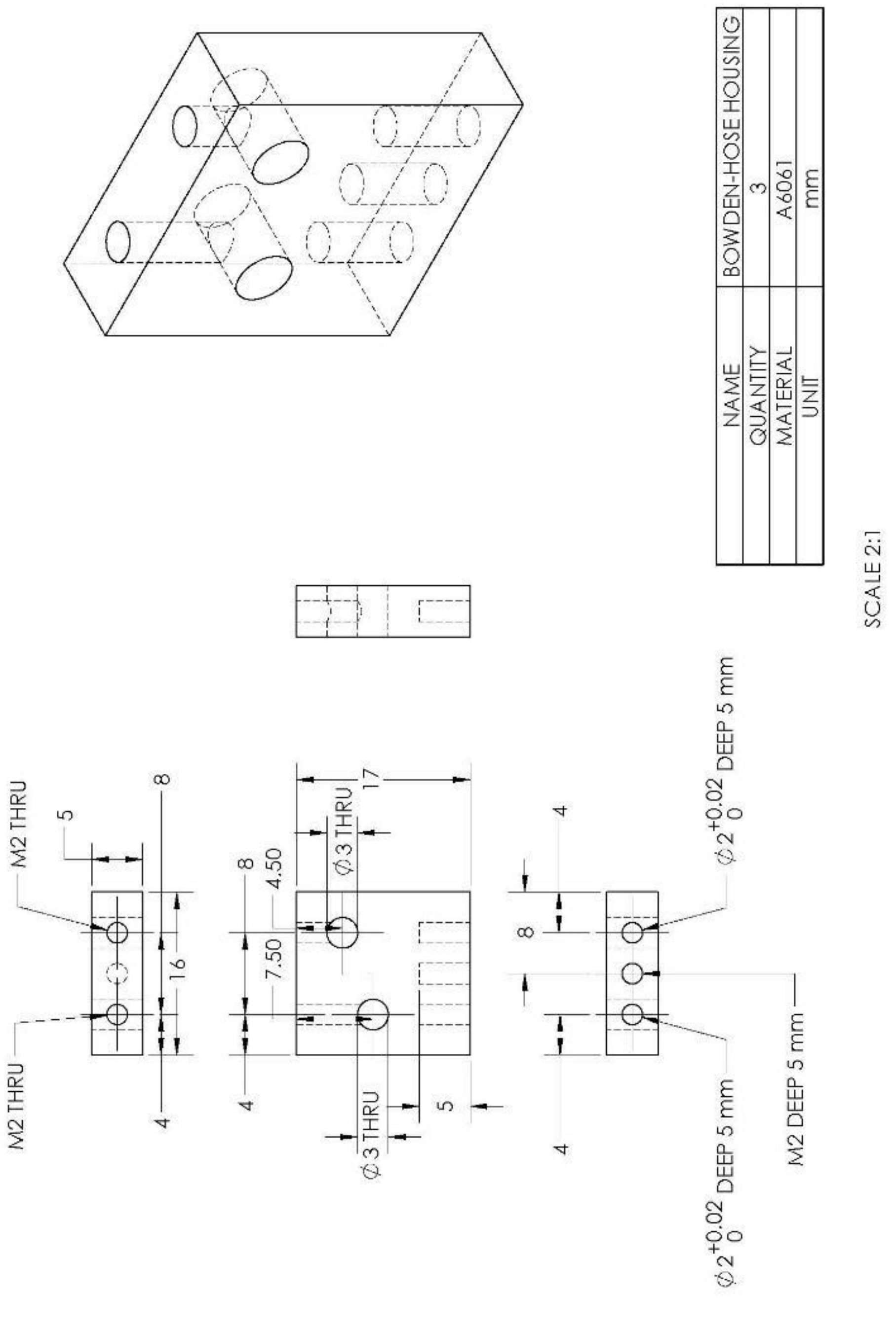
NAME	SPIRAL SCAPSTAN
MATERIAL	SCM 400
QTY	3

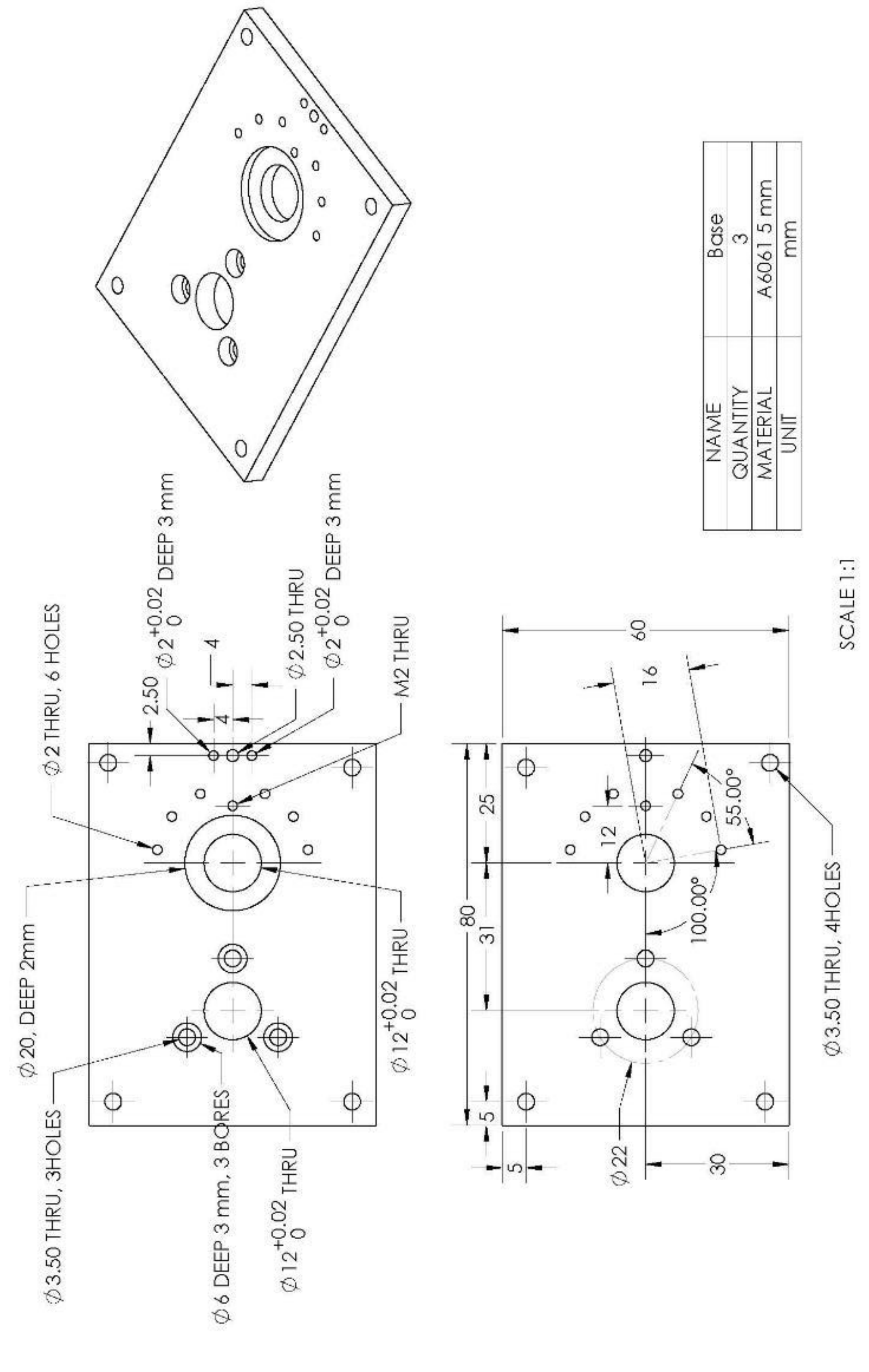


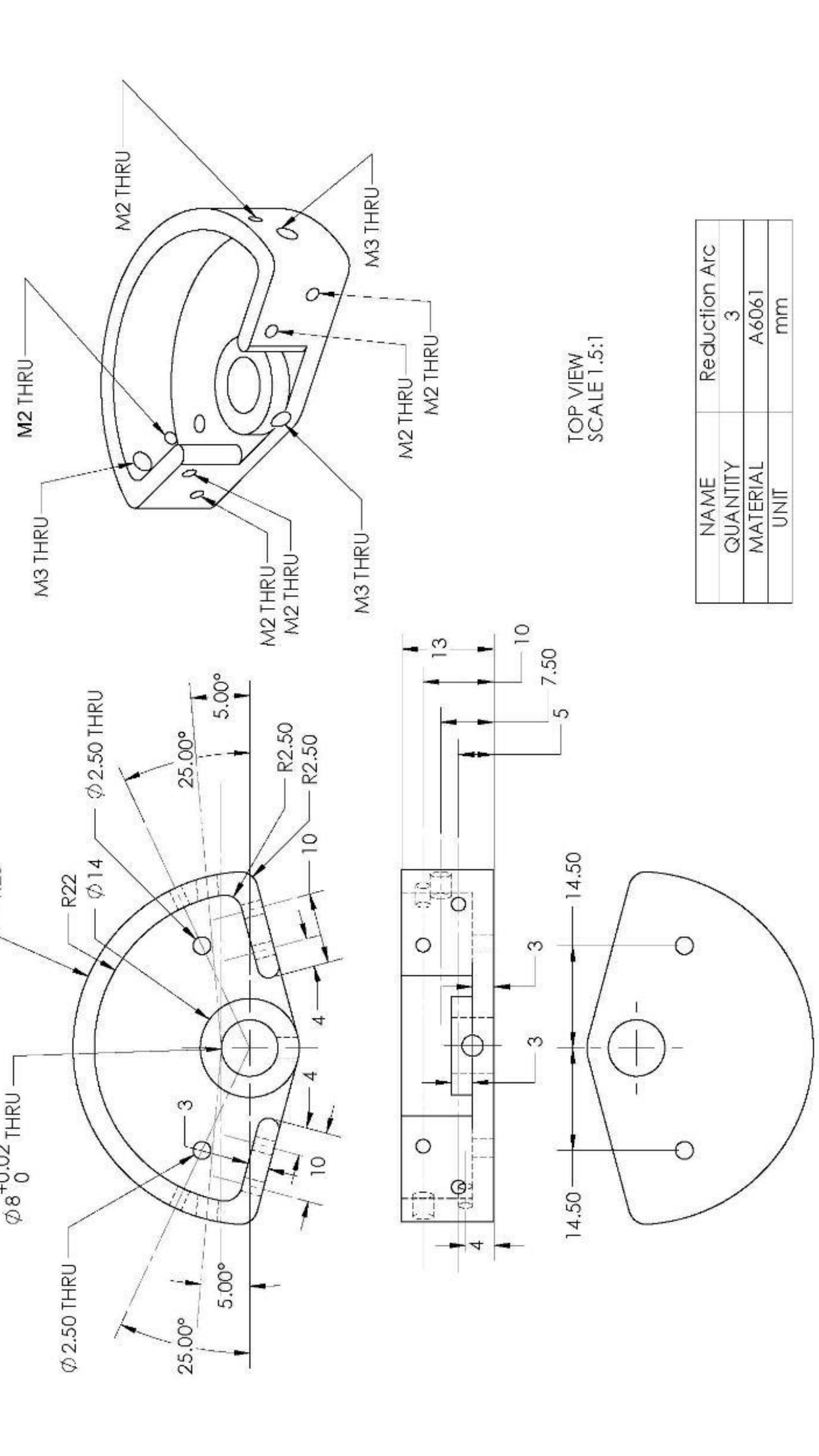
SCALE 2:1

NOTE :
ALL GROOVES ARE 0.5 mm DEEP
WRENCH FLAT IS 1 mm DEEP

NAME	SHAFT CAPSTAN
QUANTITY	3
MATERIAL	SCM400
UNIT	mm


M2 THRU
5
8
16
4
M2 THRU
4.50
7.50
ϕ3 THRU
17
5
ϕ3 THRU
4
8
4
ϕ2 +0.02 0 DEEP 5 mm
M2 DEEP 5 mm
ϕ2 +0.02 0 DEEP 5 mm
NAME BOWDEN-HOSE HOUSING
QUANTITY 3
MATERIAL A6061
UNIT mm
SCALE 2:1

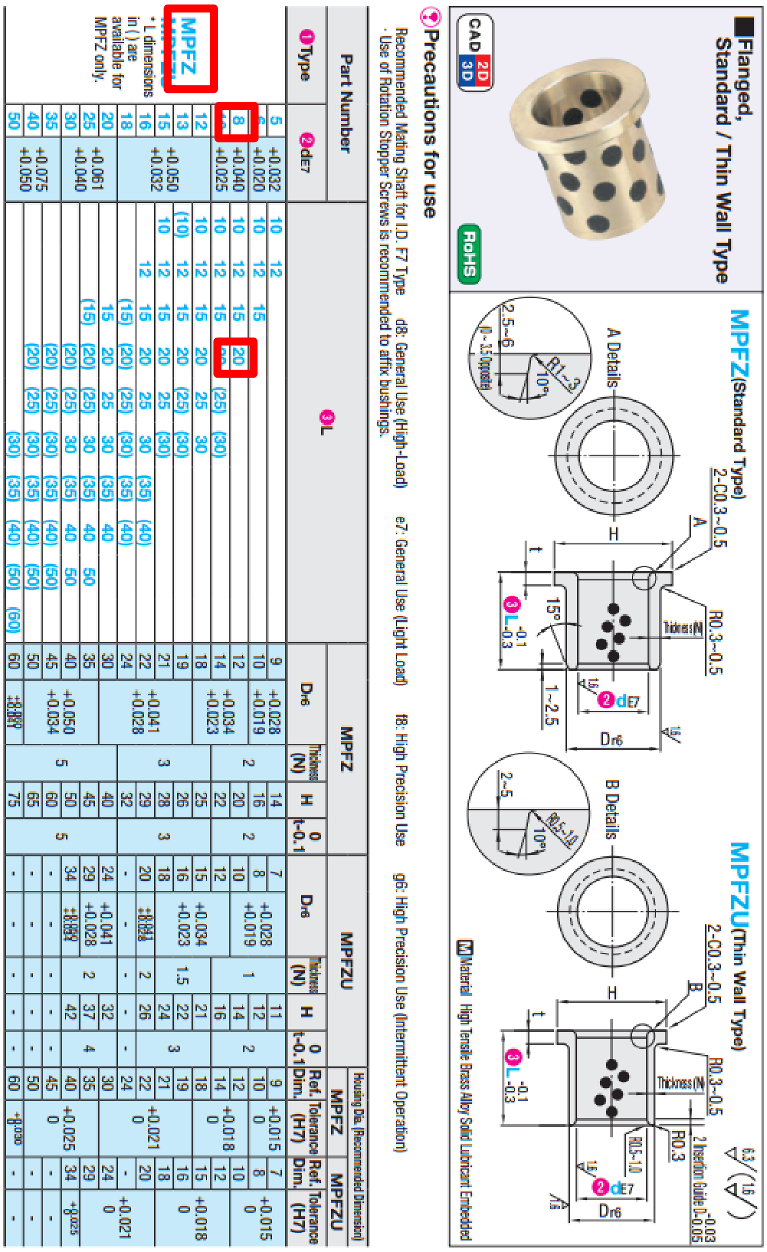

Ø2 THRU, 6 HOLES
2.50
Ø2 +0.02 0 DEEP 3 mm
4
4
Ø2.50 THRU
Ø2 +0.02 0 DEEP 3 mm
M2 THRU
Ø20, DEEP 2mm
Ø12 +0.02 0 THRU
Ø3.50 THRU, 3HOLES
Ø6 DEEP 3 mm, 3 BORES
Ø12 +0.02 0 THRU
80
25
31
5
5
12
16
60
55.00°
100.00°
Ø22
30
Ø3.50 THRU, 4HOLES
SCALE 1:1
NAME Base
QUANTITY 3
MATERIAL A6061 5 mm
UNIT mm



NAME	Reduction Arc
QUANTITY	3
MATERIAL	A6061
UNIT	mm

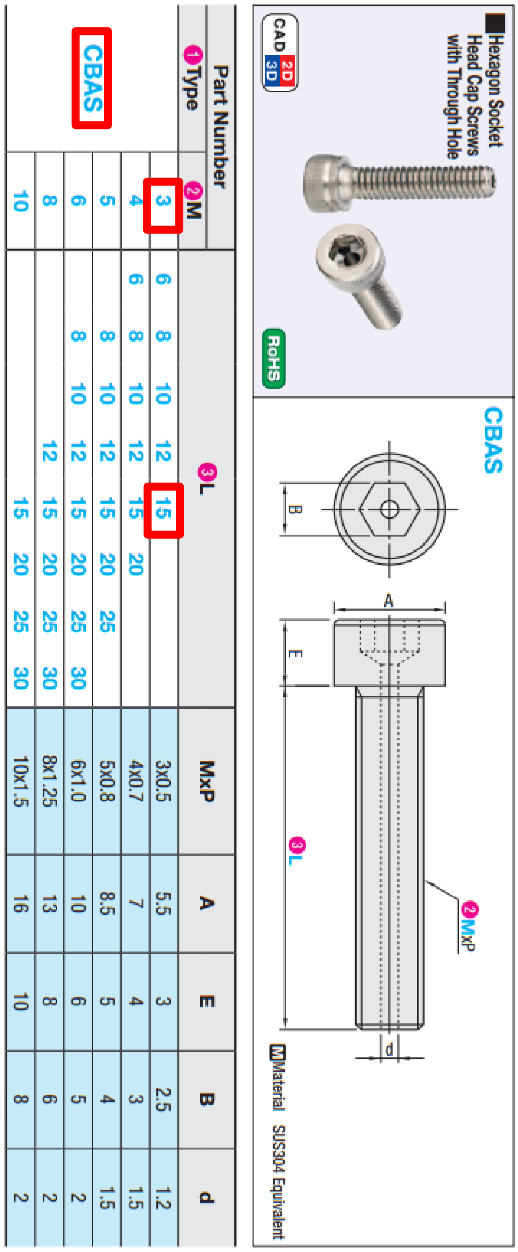
APPENDIX B

PARTS FROM SUPPLIERS



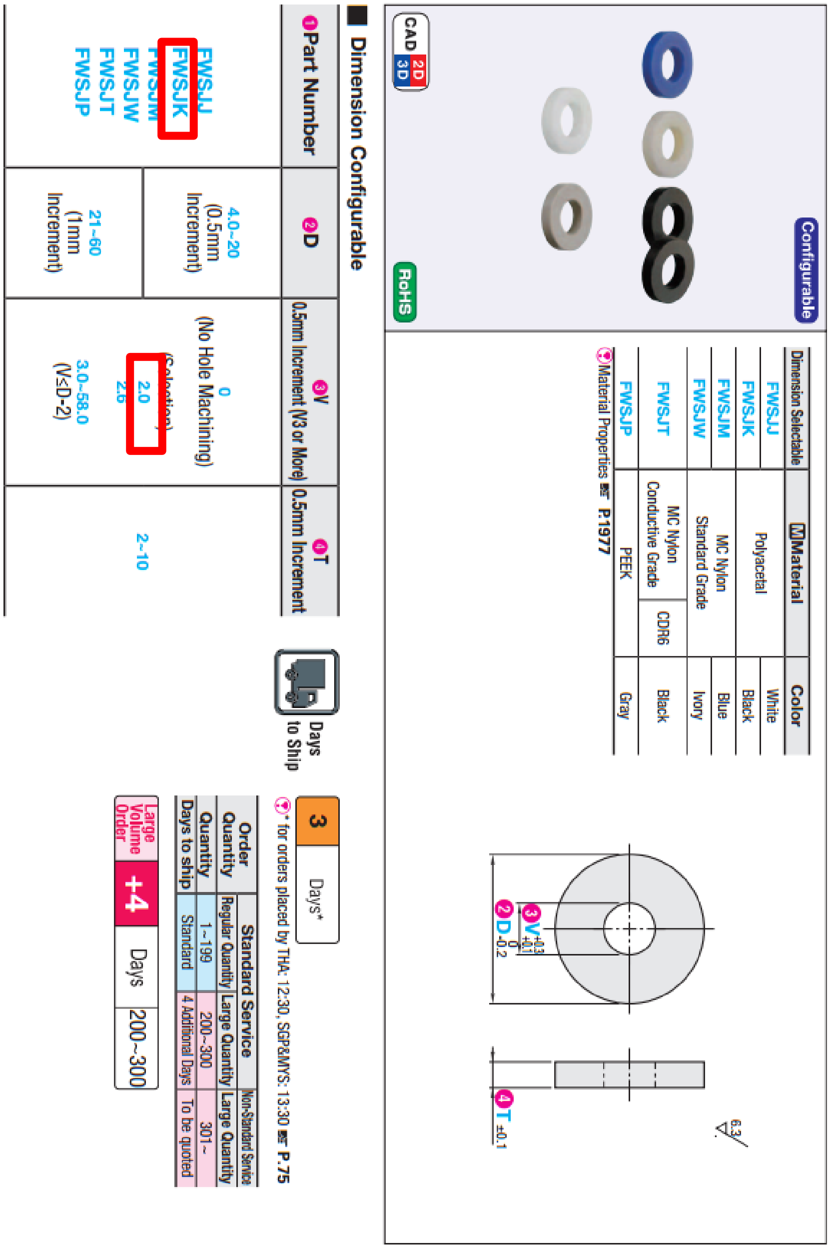
Type	dE7		L	MPFZ Dr6		MPFZ Thickness (N)	MPFZ H	MPFZ t (0/-0.1)	MPFZU Dr6		MPFZU Thickness (N)	MPFZU H	MPFZU t (0/-0.1)	Housing MPFZ Ref. Dim.	Tolerance (H7)	Housing MPFZU Ref. Dim.	Tolerance (H7)
MPFZ	5	+0.032 +0.020	10 12	9	+0.028 +0.019	2	14	2	7	+0.028 +0.019	1	11	2	9	+0.015 0	7	+0.015 0
	6		10 12 15	10			16		8			12		10		8	
	8	+0.040 +0.025	10 12 15 20	12	+0.034 +0.023		20		10			14		12	+0.018 0	10	
	10		10 12 15 20 (25) (30)	14			22		12			16		14		12	
	12	+0.050 +0.032	10 12 15 20 25 30	18		3	25	3	15	+0.034 +0.023	1.5	21	3	18		15	+0.018 0
	13		(10) 12 15 20 (25) (30)	19	+0.041 +0.028		26		16			22		19	+0.021 0	16	
	15		10 12 15 20 25 (30)	21			28		18			24		21		18	
	16		12 15 20 25 30 (35) (40)	22			29		20	+0.041 +0.028	2	26		22		20	
	18		(15) (20) (25) (30) (35) (40)	24			32		-	-	-	-	-	24		-	+0.021 0
	20	+0.061 +0.040	15 20 25 30 (35) 40	30		5	40	5	24	+0.041 +0.028	2	32	4	30		24	
	25		(15) (20) (25) 30 (35) 40 50	35	+0.050 +0.034		45		29			37		35	+0.025 0	29	
	30		(20) (25) 30 (35) 40 50	40			50		34	+0.050 +0.034		42		40		34	+0.025 0
	35	+0.075 +0.050	(20) (25) (30) (35) (40) (50)	45			60		-	-	-	-	-	45		-	-
	40		(20) (25) (30) (35) (40) (50)	50			65		-	-	-	-	-	50		-	-
	50		(30) (35) (40) (50) (60)	60	+0.060 +0.041		75		-	-	-	-	-	60	+0.030 0	-	-

Oil Free Bush (picture from MISUMI (THAILAND) CO., LTD [54])



Part Number: Type	M	L								MxP	A	E	B	d
CBAS	3	6	8	10	12	15				3x0.5	5.5	3	2.5	1.2
	4	6	8	10	12	15	20			4x0.7	7	4	3	1.5
	5		8	10	12	15	20	25		5x0.8	8.5	5	4	1.5
	6		8	10	12	15	20	25	30	6x1.0	10	6	5	2
	8				12	15	20	25	30	8x1.25	13	8	6	2
	10					15	20	25	30	10x1.5	16	10	8	2

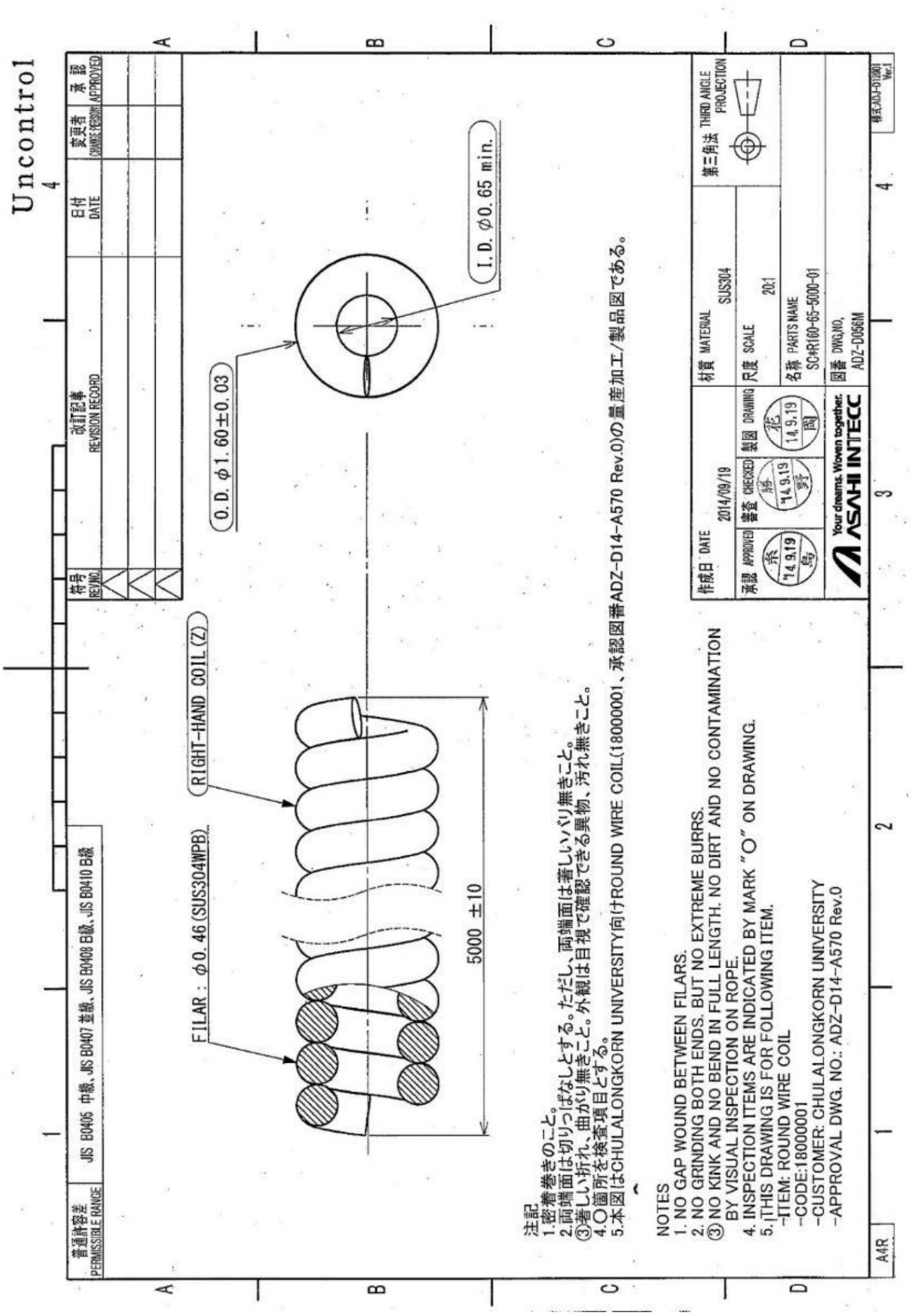
Screw with through hole (picture from MISUMI (THAILAND) CO., LTD [54])



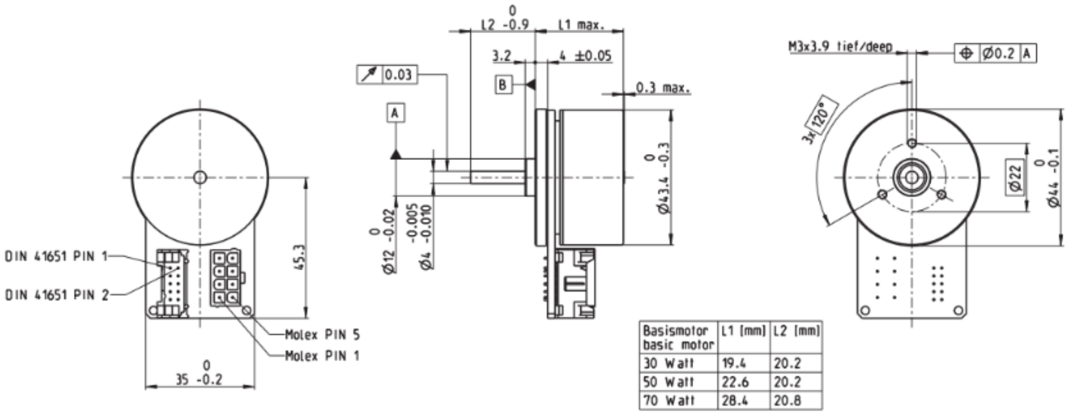
Spacer (picture from MISUMI (THAILAND) CO., LTD [54])

Note: Used as Spacer FWSJK D4 V2 T5

FWSJK D4 V2 T9



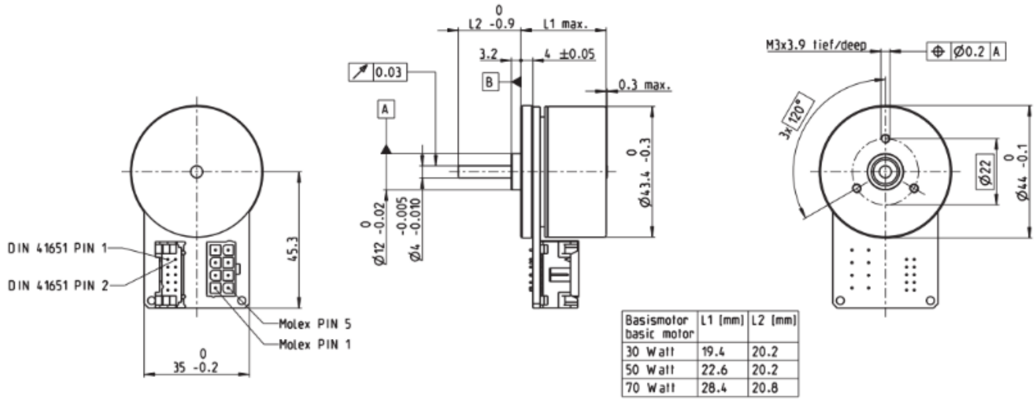
Bowden Cable Hose (supported by ASAHI INTECC THAILAND CO.,LTD. [55])



Values at nominal voltage

	Nominal voltage	36 V
	No load speed	4750 rpm
	No load current	61.6 mA
	Nominal speed	3290 rpm
	Nominal torque (max. continuous torque)	66 mNm
	Nominal current (max. continuous current)	0.847 A
	Stall torque	380 mNm
	Stall current	5.38 A
	Max. efficiency	80 %

30 W Flat EC motor (picture from Maxon Motor [56])



Values at nominal voltage

Nominal voltage	36 V
No load speed	3360 rpm
No load current	42.3 mA
Nominal speed	2360 rpm
Nominal torque (max. continuous torque)	90.5 mNm
Nominal current (max. continuous current)	0.828 A
Stall torque	484 mNm
Stall current	4.81 A
Max. efficiency	82 %

50 W Flat EC motor (picture from Maxon Motor [56])

Control Modes
- Gearing, Position, Velocity, Torque

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

Communications
- RS232

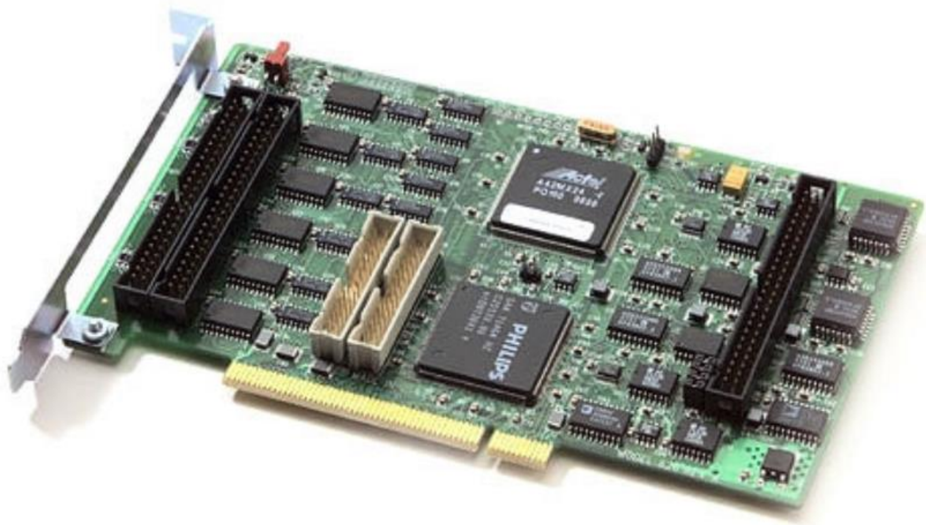
Feedback
- Digital Quad A/B encoder
- Digital Halls

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 Accelus Servo Amplifier (picture from Copley Controls Corporation [57])



Features

- Six versatile 24-bit counters support incremental encoders
- 48 bi-directional digital I/O -- 40 with edge detection
- Four 14-bit analog outputs, 20 KHz update rate
- Sixteen 16-bit differential analog inputs, 15 KHz rate
- Watchdog timer with mechanical relay output
- Battery backup of counters

Sensoray PCI card Model 626 (picture from SENSORAY [58])

APPENDIX C
AN EXAMPLE OF CABLE CONTROL ASSEMBLIES

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PUSH-PULL CONTROL ASSEMBLIES

Push-pull and pull-pull cable controls offer a reliable method of transmitting motion between two fixed points or between points which are changing their relative position. Because of flexibility, they can be routed up, down, over obstacles and around corners without intermediate links or pulleys. Fewer working parts increase operational dependability of cable controls. They are virtually maintenance free as no periodic adjustments are necessary due to wear and tear of worn connections. Cable controls do not transmit noise and vibration.

SAVA is flexible enough to handle small as well as large volume orders for cable controls. A wide variety of end fittings are available to the designer for use with the casings and core cables.

CONSTRUCTION

The basic component of a push-pull control consists of a solid wire with a casing of plastic tube or spirally wrapped wire. See Figure 1. Substituting a flexible cable for the solid wire allows the control system to be bent to facilitate routing.

Different fittings as shown in the following text can be attached to the ends of the casing and cable for ease of operation.

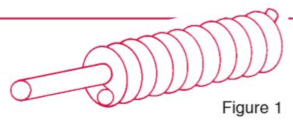


Figure 1

LOSS OF MOTION

The principal elements of lost motion in a control system are backlash and deflection. See Figure 2. Backlash is caused by the core member moving inside the casing with the change in direction of motion. It is a function of the clearance between the core and casing and total number of degrees of bend in the cable. This can be reduced by careful design. The other cause of loss of motion is deflection of the core wire under compressive load. Elastic strain in the core member due to compressive or tensile force also contributes to the loss of motion. The casing must be anchored securely to keep it from responding to the compression or tension modes of input loading.

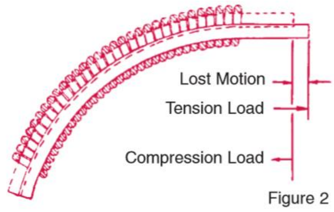


Figure 2

TRAVEL

Travel of the core inside the casing should be kept to a minimum since longer travel increases friction and decreases output. In the push-pull type of application, the chance of buckling of the core becomes greater. The travel should be limited to less than 5˝ if possible. The linear speed of operation should be relatively low.

BEND RADII AND LIFE

Cable bend radii should always be as generous as possible for maximum cable life and efficiency. Smaller bends cause reduced service life because of added friction. Depending on the size of the casing and the construction of the moving core member, the minimum recommended radius can vary from 2 to 8 inches.

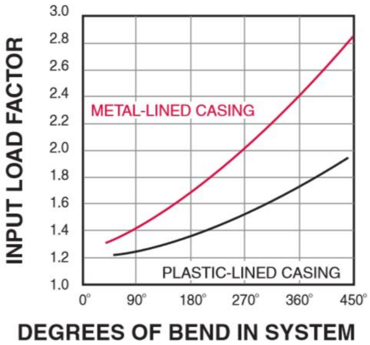
INPUT LOAD FACTOR

Friction between the core and the casing causes a loss in output force for a certain amount of input force. Friction is a function of the degrees of bend in the system. The ratio of the input force to the output force is called the Input Load Factor. The Input Load Factor has been plotted against the degrees of bend in the system and is shown in the accompanying graph. For selecting the right control system, the input load has to be determined by multiplying the output load with the Input Load Factor obtained from the graph using the following formula:

I = Input Load
P = Output Load
F = Input Load Factor (from graph)
I = P x F

Example: Consider a push-pull assembly with metal-lined casing requiring an output load of 6 lbs. Total degrees of bend in the system–270°. Input Load Factor from chart–2.05.

Input Load = 6 x 2.05 = 12.30 lbs.



Push-Pull Control Assemblies (picture from SAVACABLE [53])

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PUSH-PULL CASING AND CORES

For light load applications casing made from nylon can be used. For heavier loads casing made from a round or half round wire tightly wound to resemble a closed spring is good for most applications. This type of casing is flexible, resists kinking and can be clamped or terminated without distortion of the wall. The casing can be ordered with a plastic coating. Casing with a plastic liner offers reduced friction and less start-up inertia.

Casings available from stock are shown in the chart at right. For other types of casing such as **stainless steel** consult factory.

PART NO.	CASING O.D. REF.	CASING I.D. REF.	STANDARD CASING MATERIAL	SOLID CORE WIRE SIZE	1x7, 1x19 7x7 CORE CABLE RANGE
C090N	.090	.040	Nylon	.020 S.S.	.015 - .027
C130N	.130	.060	Nylon	.032 S.S.	.024 - .040
C070 C070VC	.070 .090 Black PVC	.035	Galv. Steel	.020 S.S.	.018 - .027
C096	.096	.050	Galv. Steel	.032 S.S.	.027 - .037
C132 C132VC	132 .170 Black PVC	.060	Galv. Steel	.036 S.S.	.036 - .050
C187 C187PC	.187 .225 Black HDPE	.080	Galv. Steel	.054 S.S.	.045 - .063
C187PL C187 PLPC	.187 .225 Black HDPE	.080	Galv. Steel with HDPE Lining	.054 S.S.	.045 - .063
C277PL C277PLPC	.277 .305 Black HDPE	.140	Galv. Steel with HDPE Lining	N/A	3/32

NOTES: Nylon casing is molybdenum disulfide impregnated for friction reduction.
C277 casing may be provided with HDPE lining, based on availability.

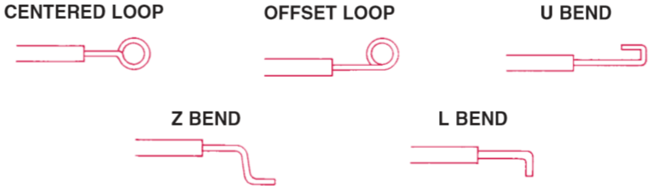
LUBRICATION

Generally, lubrication is not advised in the casing. Lubricant tends to collect dirt, which impedes the movement of the core inside the casing. The core cable can perform efficiently with little or no lubrication. If lubricant is desired for a particular application, it must be specified by the customer which lubricant to be applied to the core cable prior to the assembly.

END TERMINALS FOR CORE WIRES

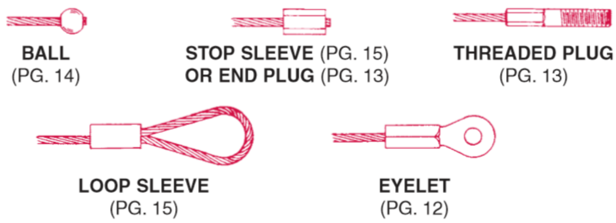
The simplest core is a solid wire which is adequate for low input loads and minimum bends. If the force is only in the pull direction, a stranded cable can be used with much tighter bends.

Simple terminations can be provided on a solid core wire by forming the high tensile steel wire in the typical shapes shown below. Some catalog fittings, such as eyes, end plugs, etc. can be used on solid wire. Please consult factory.



END TERMINALS FOR CORE CABLES

At right are shown typical cable fittings used as push-pull cable core terminals. The dimensions for these should be taken from our catalog using the proper cable core size. Special terminals can also be manufactured.



Push-Pull Control Assemblies (picture from SAVACABLE [53])

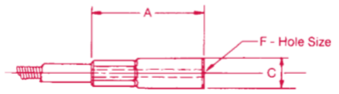
END TERMINALS FOR CORE CASING

For many applications simply clamping the casing close to the end of the control is acceptable. However, casing fittings can be applied directly to the ends. Special fittings developed for this purpose are shown below.

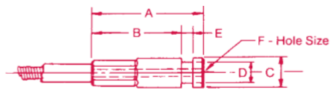
CAP AND GROOVE TERMINALS

PART NO.[1] GROOVED TERMINAL	PART NO.[1] CAP TERMINAL	AVAILABLE WITH CASING NO.	A REF.	B REF.	C REF.	D REF.	E[2] REF.	F REF.
6005	6105	C070,C070VC,C096	.98	.74	.19	.125	.090	.047
6006	6106	C132, C132VC	.98	.74	.25	.180	.090	.063
6008	6108	C187, C187PC C187PLPC C187PL	1.00	.76	.25	.180	.090	.080
6013	6113		1.25	.87	.38	.250	.130	.125
6014	6114	C277, C277PC	1.50	1.12	.44	.344	.130	.125

NOTES: [1]State material required by suffix - B (Brass) - S (S.S.) - P (Plated Steel).
[2]This dimension can be modified for special snap rings.



SHOWN AFTER CRIMPING
CAP TERMINAL

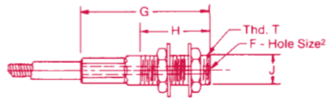


SHOWN AFTER CRIMPING
GROOVE TERMINAL

BULKHEAD TERMINALS

PART NO.	AVAILABLE WITH CASING NO.	G REF.	H REF.	J REF.	T REF.
6465	C070, C070VC	1.62	1.00	.19	#10-24
6475	C070, C070VC, C096	2.06	1.25	.25	1/4-20
6477	C096, C132, C132VC	1.94	1.00	.31	5/16-18
6480	C132, C132VC, C187, C187PC, C187PL, C187PLPC	2.25	1.25	.38	3/8-16
6482	C187, C187PC, C187PL, C187PLPC	2.81	1.50	.50	1/2-13
6485	C277, C277PC	3.38	1.75	.63	5/8-11

NOTES: Part no. 6465 is available in brass and stainless steel; the rest of the terminals are available in plated or stainless steel. State material required by suffix B (Brass), S (S.S.), O (Plated Steel). Other thread lengths and specials are available; see page 13. Jam nuts and washers furnished unless otherwise specified.
To complete part no., add... casing no. desired. (such as 6475S096)
Hole size will match inside diameter of casing.



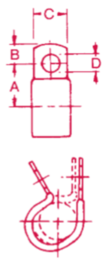
SHOWN AFTER CRIMPING
BULKHEAD TERMINAL

CLAMP TERMINALS FOR CASING

PART NO.	MATERIAL	USED FOR CASING	A REF.	B REF.	C REF.	D REF.
951N	Nylon	C130N	5/16	13/64	1/2	3/16
952N	Nylon	C070	9/32	5/32	3/8	1/8
953P	Plated Steel	C132 C132VC	11/32	3/16	3/8	11/64
954P	Plated Steel	C187, C187PLPC C187PL, C187PC	13/32	7/32	1/2	13/64
955P	Plated Steel	C277	7/16	7/32	1/2	13/64
956P	Plated Steel	C277PC	5/8	3/8	5/8	11/32

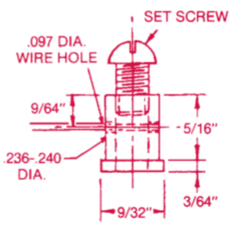
NOTE: The steel clamps are vinyl lined.

CLAMP TERMINAL



WIRE CLAMP

PART NO. WC-1
MATERIAL: PLATED STEEL



Push-Pull Control Assemblies (picture from SAVACABLE [53])

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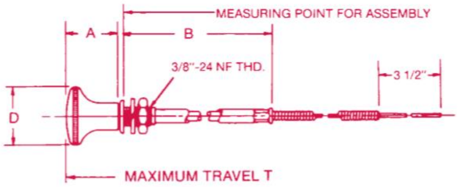
OTHER TYPES OF CONTROLS AVAILABLE

PUSH-PULL CONTROL

This type of push-pull assembly is ideal for choke or damper control.

Fits wire size .054″ or cable diameter .045-.063 with C187 series casing (see pg. 24).

PART NO. PPC1 AND PPC11



ITEM	A REF.	B REF.	D REF.	T REF.
PPC1	31/32	3-9/16	1-1/16	2-1/4
PPC11	3/4	3-1/8	7/8	1-1/2

LOCKING PUSH-PULL CONTROL

This control provides infinite adjustment for its entire travel. The operator can position the control where desired and then lock it in place by turning it clockwise.

Specially suited for applications where spring tension or vibration causes ordinary controls to creep.

Fits wire size .054″ or cable diameter .045-.063 with C187 series casing (see pg. 24).

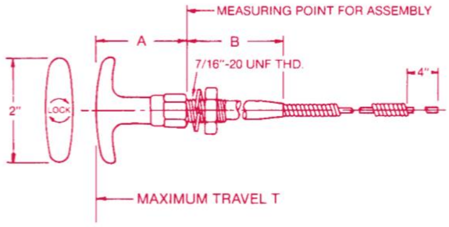
All PPC part numbers will consist of the following:

1 knob with plunger	1 lock washer
1 sleeve with face plate	1 jam nut

For assembly order please specify length of casing and wire.

Part numbers PPC11 and PPC22 are less expensive, have shorter travel, and are intended for lighter duty applications.

PART NO. PPC2 AND PPC22



ITEM	A REF.	B REF.	T REF.
PPC2	1-3/4	4-1/8	3
PPC22	1-5/8	2-15/16	2

NOTE: PPC2 may not be available in small quantity. Consult factory.

DESIGN PROCEDURE

1. Select a cable suitable to withstand the load. Keep in mind, the more number of wires in a cable the more flexible the cable will be. For push-pull types of application the solid core wire will be most suitable. Next to that a 1x7 or 1x19 construction cable may be used where the movement is small and the casing is adequately constrained.

   Select a casing and make a scale layout drawing. Try to keep the number of bends to a minimum and the radii of bends to a maximum. The radius should not be less than 100 times the core diameter. Remember, the lighter casing with a light load will be more flexible.

2. Build a prototype of the design in its final configuration. Apply loads to determine performance characteristics.

3. Determine exact dimensions of the assembly from the prototype. Check tolerances on all components to keep the length at a minimum so extra bends are not necessary. Indicate the movement of the core inside the casing.

4. Prepare a drawing and indicate the distance moved by the core inside the casing. Include lengths, tolerances, end fittings, casing, core, quantities, and send to SAVA with a request for quote.

TYPICAL APPLICATIONS INCLUDE

Dampers • Releases • Valves • Vents • Doors • Connectors • Linkages • Shutoffs • Reset Devices

Push-Pull Control Assemblies (picture from SAVACABLE [53])

APPENDIX D
PUBLISHED WORKS

Title Design of a Simple Underactuated Mechanical Gripper

Authors Mahasak Surakijboworn and Wittaya Wannasuphoprasit

Abstract The objective of this paper is to design and develop a simple geometry of an underactuated mechanical gripper which can provide most common hand grasps, fingertip grasp and enveloping grasp. The gripper consists of 2 2-DOF fingers underactuated by a pulley-tendon system, and a movable pulley for underactuation between fingers. Each finger has 2 links and 2 pulleys. A parallel linkage is used to translate distal phalanx toward an object such that fingertip grasp is improved. This work implements stability and force isotropy criteria to optimize the design. The prototype has 0.43 of pulley-radius ratio and 1.72 of link-length ratio. From primitive-shape grasping test, the gripper is able to achieve the stable configuration.

Reference M. Surakijboworn and W. Wannasuphoprasit, "Design of a Simple Underactuated Mechanical Gripper," in *Applied Mechanics and Materials*, 2014, pp. 44-48.

Title Design of a Novel Finger Exoskeleton with a Sliding Six-Bar Joint Mechanism

Authors Mahasak Surakijboworn and Witaya Wannasuphoprasit

Abstract The objective of the paper is to propose a novel design of a finger exoskeleton. The merit of the work is that the proposed mechanism is expected to eliminate interference and translational force on a finger. The design consists of 3 identical joint mechanisms which, for each, adopts a six-bar RCM as an equivalent revolute joint incorporating with 2 prismatic joints to form a close-chain structure with a finger joint. Cable and hose transmission is designed to reduce burden from prospective driving modules. As a result, the prototype coherently follows finger movement throughout full range of motion for every size of fingers. This prototype is a part of the research that will be used in hand rehabilitation.

Reference M. Surakijboworn and W. Wannasuphoprasit, "Design of a novel finger exoskeleton with a sliding six-bar joint mechanism," in *Proceedings of the 6th Augmented Human International Conference*, 2015, pp. 77-80.

VITA

Mahasak Surakijbowom was born on 13th December 1991, the eldest child of Jomsak Surakijbowom and Ruenkaew Surakijbowom. He graduated from Chulalongkorn University Demonstration School. He received a bachelor's degree in mechanical engineering from Chulalongkorn University in 2014. With academic motivation, he pursues a master's degree in mechanical engineering at Chulalongkorn University majoring control and robotics.