HAND EXOSKELETON FOR ASSISTIVE FUNCTION

A Final Year Project Report

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In Partial Fulfillment

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Bachelors of Mechanical Engineering

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ABSTRACT

Hand exoskeletons offer a promising avenue for assisting individuals with hand impairments and enhancing rehabilitation outcomes. However, current designs often confront challenges related to vibrations and backlash, hindering user comfort and control. This research delves into the development of a novel three-spring hand exoskeleton specifically designed to address these issues while simultaneously providing personalized assistive force based on user-specific needs.

The proposed design incorporates a three-layered sliding spring mechanism that closely mimics human finger biomechanics, ensuring natural and safe hand movements. This system leverages a slider spring mechanism to effectively mitigate excessive bending in the force-bearing spring, thereby reducing vibrations and backlash. Furthermore, the exoskeleton employs EMG-based actuation, harnessing electromyography (EMG) signals to personalize force delivery by individual muscle activation patterns. The integration of EMG sensors enables real-time control without the need for bulky controls, significantly enhancing user experience and promoting independence. This approach not only promotes intuitive control but also contributes to an improved user experience. The Bowden cable transmission system, with its inherent flexibility and compactness, facilitates integration into various hand functionalities, further enhancing the design's potential.

To establish a strong foundation for the proposed design, the thesis undertakes a comprehensive literature review. This review dives into the realms of finger biomechanics, pneumatic and hydraulic actuation methods, and remote actuation approaches, ensuring a well-informed and theoretically sound design basis.

The report also discusses future advancements in EMG-based control systems, highlighting their potential to further enhance the functionality and usability of assistive hand exoskeletons. Recommendations include continued research in EMG-based control systems, exploration of innovative manufacturing techniques, and collaboration with healthcare professionals to ensure the exoskeleton meets the diverse needs of users.

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We extend our appreciation to the National University of Sciences & Technology for providing the necessary resources, facilities, and funding that enabled us to conduct this research effectively. Their support has been crucial in the successful completion of this project.

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Sarah Naeem & Zinia Nadeem Bhutta

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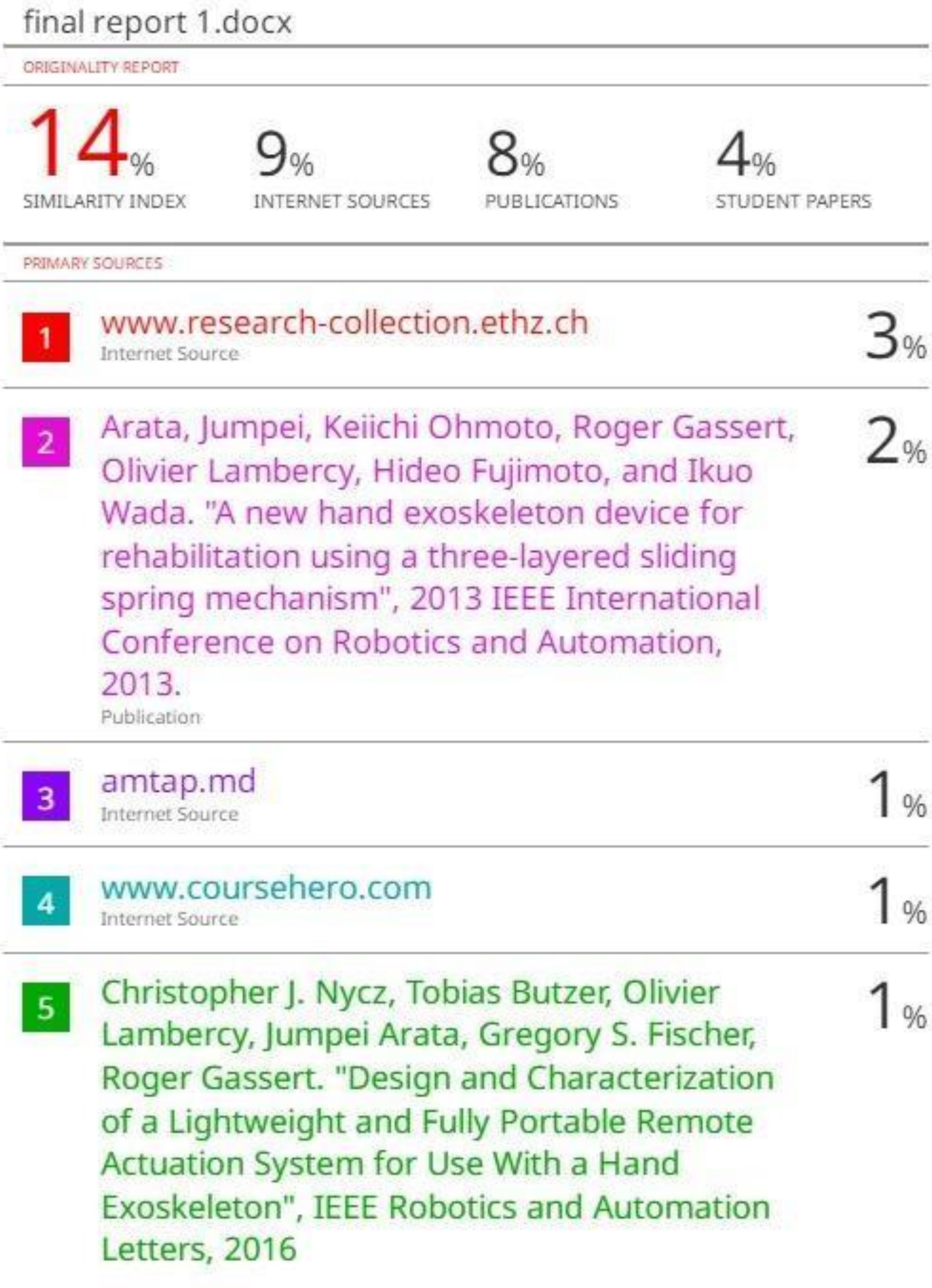

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ABBREVIATIONS

ADL	Activities of Daily Life
CIMT	Constraint-Induced Movement Therapy
BIM	Bimanual Intensive Therapy
DOF	Degree Of Freedom
RAS	Remote Actuation System
EMG	Electromyography
BLE	Bluetooth Low Energy
ROM	Range Of Motion
MCP	Metacarpophalangeal
PIP	Proximal Interphalangeal
DIP	Distal Interphalangeal
CMC	Carpometacarpal
EEG	Electroencephalogram
ECG	Electrocardiogram
MVC	Maximum Voluntary Contraction
BCI	Brain-Computer Interface

NOMENCLATURE

F	Fingertip Force
m	Mass of hand
g	Gravitational Acceleration
μ	Coefficient of Friction of Bowden Cable
S_i	Inner Spring
S_c	Center Spring
S_o	Outer Spring
R_t	Rigid body Tip
R_i	Rigid body Inner
R_o	Rigid body Outer
S_{i1}	Inner Spring on Joint 1
S_{i2}	Inner Spring on Joint 2
S_{i3}	Inner Spring on Joint 3
S_{c1}	Center Spring on Joint 1
S_{c2}	Center Spring on Joint 2
S_{c3}	Center Spring on Joint 3
R_{o1}	Rigid Body Length 1
R_{o2}	Rigid Body Length 2
R_{o3}	Rigid Body Length 3
LSi1	Length of Inner Spring Blade 1

LSi2	Length of Inner Spring Blade 2
LSi3	Length of Inner Spring Blade 3
LSc1	Length of Center Spring Blade 1
LSc2	Length of Center Spring Blade 2
LSc3	Length of Center Spring Blade 3
LSo1	Length of Outer Spring Blade 1
LSo2	Length of Outer Spring Blade 2
LSo3	Length of Outer Spring Blade 3
HDIP	Length of DIP Joint
θDIP	Maximum angle of DIP joint
HPIP	Length of PIP Joint
θPIP	Maximum angle of PIP joint
HMCP	Length of MCP Joint
θMCP	Maximum angle of MCP joint
Hi	Length of Inner Body
Ho	Length of Outer Body
D(DIP-PIP)	Distance between DIP and PIP Joints
D(PIP-MCP)	Distance between PIP and MCP Joints
T(DIP)	Thickness of Finger at DIP Joint
T(PIP)	Thickness of Finger at PIP Joint
T(MCP)	Thickness of Finger at MCP Joint
w_o	Output winch radius

R_p	Pinion Radius
S	Security Factor
F_{out}	Required Output Force
$F_{r, max}$	Maximum Rope Tension
r_{in}	Torque at the Input Wench
$ŋ_t$	Efficiency of Transmission System
$ŋ_{rp}$	Efficiency of rack and pinion
σ	Bending angle for Bowden Cable
r_{wi}	Pitch radius input wench
Ŋ	Efficiency of rack and pinion mechanism
N	Number of periods in moving average
Di	Demand in period i
MA_n	Smoothed bio-signal

CHAPTER 1: INTRODUCTION

Hands are an essential part of our daily lives, playing a crucial role in performing a wide range of tasks and activities. From simple actions like grasping objects to complex movements requiring precision and dexterity, our hands enable us to interact with the world around us in meaningful ways. The ability to effectively use them is crucial to our independence and overall well-being. Beyond their physical purpose, hands serve as a means of communication, expression, and creativity. Our hands are also instrumental in our professional lives, enabling us to carry out tasks that require fine motor skills and meticulous attention to detail, such as surgery, engineering, and craftsmanship.

The intricate structure of the hand, with its complex network of muscles, tendons, and nerves, highlights the remarkable design of the human body and the importance of preserving its functionality.

Upper limb hand impairments are some of the most common impairments a person can experience. The World Health Organization has estimated that over 310 million people live with hand disabilities that greatly affect their daily life activities and their dependency on other people. In the United States alone, over 30% of the adult population reports hand pain and impairments. [1– 2]

1.1. Background

Exoskeletons are a major development in wearable technology, presenting a viable solution to improve human function, mobility, and rehabilitation in multiple aspects. These wearable devices were first created for military and commercial use to increase physical strength and endurance. Since then, they have developed into adaptable tools with vast applications.

These medical devices have proved to be essential for mobility aid and rehabilitation in the medical industry. Powered lower limb exoskeletons have enabled individuals with lower limb limitations or spinal cord injuries to stand, walk, and regain mobility. These gadgets enable gait training and rehabilitation exercises by supporting and assisting with movement using sophisticated actuators, sensors, and control systems.

Upper limb exoskeletons have gained a separate fanbase in the healthcare industry, with a pointed focus on stroke rehabilitation and assistive technologies for patients. These exoskeletons aid in arm function restoration, repetitive movement therapy, and advocating neuroplasticity for enhanced motor function.

With applications beyond the medical field, exoskeletons are also found in the industrial and military domains where they supplement human capacities for jobs demanding power, stamina, and accuracy. Industrial exoskeletons increase workplace safety and productivity by lowering the risk of musculoskeletal injuries among employees performing heavy lifting or repetitive jobs. Military exoskeletons improve a soldier's ability to move, be agile, and carry more weight, which improves their operational efficacy and lessens fatigue on extended operations.

Even with the advances in exoskeleton technology, there are still several obstacles to overcome, especially in the creation of helpful hand exoskeletons. Although hands are essential for completing fine motor skills and interacting with the environment, there aren't many user-friendly options available for hand augmentation and rehabilitation as of now. Currently, available hand exoskeletons frequently lack the intuitive control, flexibility, and dexterity needed for complicated hand movements and precision grasping. [3]

1.2. Motivation

There is an ever-growing need to address the challenges faced by individuals with hand impairments and disabilities. Despite the advancements in exoskeleton technology, there is still a visible gap in hand rehabilitation. An assistive device that is unable to meet these basic needs loses its purpose.

This project aims to close this gap and provide individuals with the ability to restore control and functionality by creating an assistive hand exoskeleton that conforms to the needs of end-users. We aim to improve the standard of living for people suffering from hand impairments by empowering them to carry out necessary tasks with comfort and assurance, enhancing assistive technology, and increasing equality and inclusivity in society via innovation and hard work is the goal.

1.3. Problem Statement

This paper aims to create a hand exoskeleton design that can perform the basic hand motions while weighing as little as possible to allow donning for longer intervals for assistance in activities of daily life (ADLs). These types of exoskeletons have more value within the market for individuals with partial mobility and post-stroke circumstances as they provide actual use to the individual by helping in carrying out ADLs and improving the quality of life of individuals.

1.4. Objectives

- The aim is to develop an Assistive Hand Exoskeleton that allows 1 DOF movement of the fingers.
- Designing and finalizing the CAD model to achieve the end product.
- Use of EMG sensor to determine the expected motion of the hand, this will include the filtering and amplification of the signal obtained.
- Determining the appropriate material for the printing of all the parts.
- Prototype and manufacturing of the final part after testing and material selection.

CHAPTER 2: LITERATURE REVIEW

2.1. Anatomy, Physiology, and Biomechanics of a Human Hand

Anatomy encompasses the internal and external structures of the body while physiology refers to the functioning of these parts. Physiology refers to the scientific study, the physics and chemistry behind the structures, and the interactions between these structures of the body that enable the body to conduct tasks. It is essential to understand the anatomy and physiology of the human hand to design a functioning and useful assistive device. We must first understand the workings of a healthy hand to equip ourselves with the concepts required to design a functioning exoskeleton for a human hand.

The human hand is a marvel of biomechanics that allows us to grasp, manipulate, and interact with objects and the environment. The bones, joints, ligaments, muscles, and tendons of a hand work collectively to achieve the wide range of functions carried out by our hands.

It is essential to understand the general anatomy associated with the human body, common terminologies, and the detailed anatomy and physiology of the human hand. The concepts discussed in these sections will be referenced throughout this report.

2.1.1. Standard Anatomical Position

The standard anatomical position of a human body is the specific body orientation used to describe an individual’s anatomy and physiology. This position is described as a body fulfilling the following constraints:

- Standing upright, facing forward.
- Legs parallel to one another.
- Upper limbs or arms straight downwards, hanging by the hips with palms open and facing forward.
- Feet placed parallel with toes facing forward.

For a body lying flat with the same limb positions instead of being upright, the position is then referred to as the supine position instead of the anatomical position. [4]

Additional anatomical terms are then used about the standard anatomical position. These terms are generally used to provide a clearer image and detail on a person’s anatomy when describing the relative position of various appendages. We briefly describe relevant terminology used across the span of this project:

- **Posterior or dorsal:** the back of the body
- **Anterior:** the front of the body
- **Proximal:** refers to how close something is. Generally used as ‘proximal end’ refers to the side or part of a limb or a body part that is closer to the body center. For example, in the hand, the wrist is the proximal end.
- **Distal:** refers to how far away something is. Generally used as ‘distal end’ refers to the part or side furthest from the body center for a given limb or body part. E.g. the fingertips are the distal end of the hand. [5, 6]

Given an individual, positioned according to the standard anatomical orientation, we describe three general reference planes. The same planes are then used as reference planes for the description of each body part.

- **The sagittal plane** passes vertically through the middle of the human. This plane divides the body into the left and right sides.
- **The coronal plane** runs vertically through the body dividing it into the anterior (front of the body) and posterior (back of the body) sides.
- **The transverse (or axial) plane** passes horizontally through the body dividing it into the top half and bottom half of the body. [4]

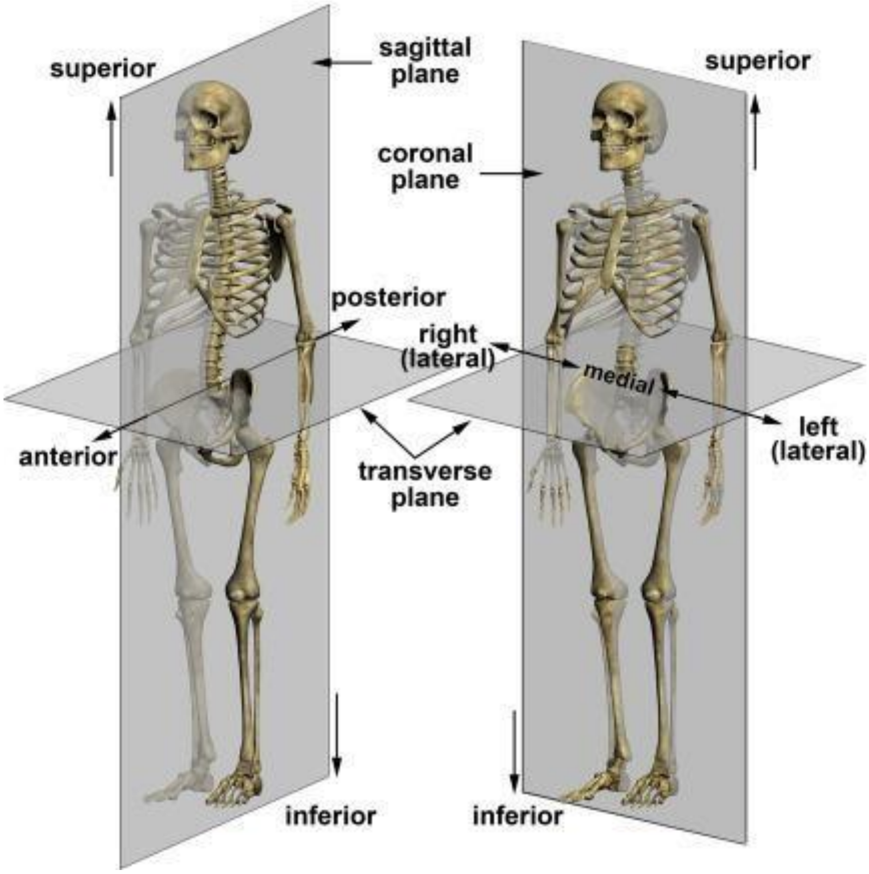


Figure 1. Standard Anatomical Planes [14]

2.1.2. Bones, Ligaments & Joints of a Human Hand

The hand is a highly complex entity, and its osseous anatomy plays an integral role in its impressive functionality. The hand serves as the primal connection between a body and its surroundings. While it is composed of an intricate system of muscles, ligaments, and joints, we can present the structure of a human hand in a relatively simplified form for easier understanding.

The human hand is composed of 27 bones, 24 muscles, numerous ligaments, tendons, blood vessels, and nerves. These bones are categorized into three segments: the **carpals**, the **metacarpals**, and the **phalangeal** bones.

Starting at the wrist, which contains two rows of four bones, collectively referred to as the eight carpal bones. The irregularly shaped carpal bones act as a bridge between the hand and the forearm. The proximal row of carpals is further connected to the five metacarpal bones. The proximal row also houses no tendon insertions. Actuation is in turn carried out by the mechanical forces of the surrounding joints. The distal row of carpal bones is connected to the ulna and radius.

The human hand is composed of 5 digits: 4 fingers and thumb. Each finger is characterized by four phalanges (bones) and three articulations (joints). The thumb includes three phalanges and three articulations. Five long metacarpal bones connect the carpal bones to the proximal phalanges. The metacarpal heads then articulate with the proximal phalanges. The phalanges are divided into proximal, middle, and distal phalanges as per their orientation and placement. The thumb only contains two phalanges: the proximal and distal phalanges.

The hand contains six joints, connecting this bone allowing various movements:

- Interphalangeal **(IP)** joints that enable the flexion and extension of their targeted regions. These are further divided into:
    - **distal interphalangeal** (DIP) which connects the distal phalange (tip of bone) to the middle phalange of each finger, which allows for the flexion and extension of the fingertips.
    - The **proximal interphalangeal** (PIP) connecting the middle phalange to the proximal phalange (first bone)
    - The **interphalangeal** (IP) which connects the thumb's distal phalange and the proximal phalange, allows the flexion and extension of the thumb.
- The **metacarpophalangeal** (MCP) connects the proximal phalanges to the metacarpals. These allow flexion, extension, adduction, abduction, and some circumduction.

- The **carpometacarpal** (CMC) is the joint between the thumb proximal phalange and the metacarpal. The thumb's wide range of motion is credited to the fact that the CMC has a wider range of motion when compared to the MCP joints.
- The **radiocarpal** (RC) joint which controls wrist flexion, extension, adduction, and abduction.

The CMC at the base of the thumb is a saddle joint allowing greater ROM to the thumb. Each digit has almost the same anatomical design except for the thumb.

Ligaments are strong, fibrous tissues connecting bones and provide stability to joints. These help avoid excessive movement and joint dislocation. [9]

For the sake of simplicity, we assume the phalanges as rigid links and the articulations as frictionless joints.

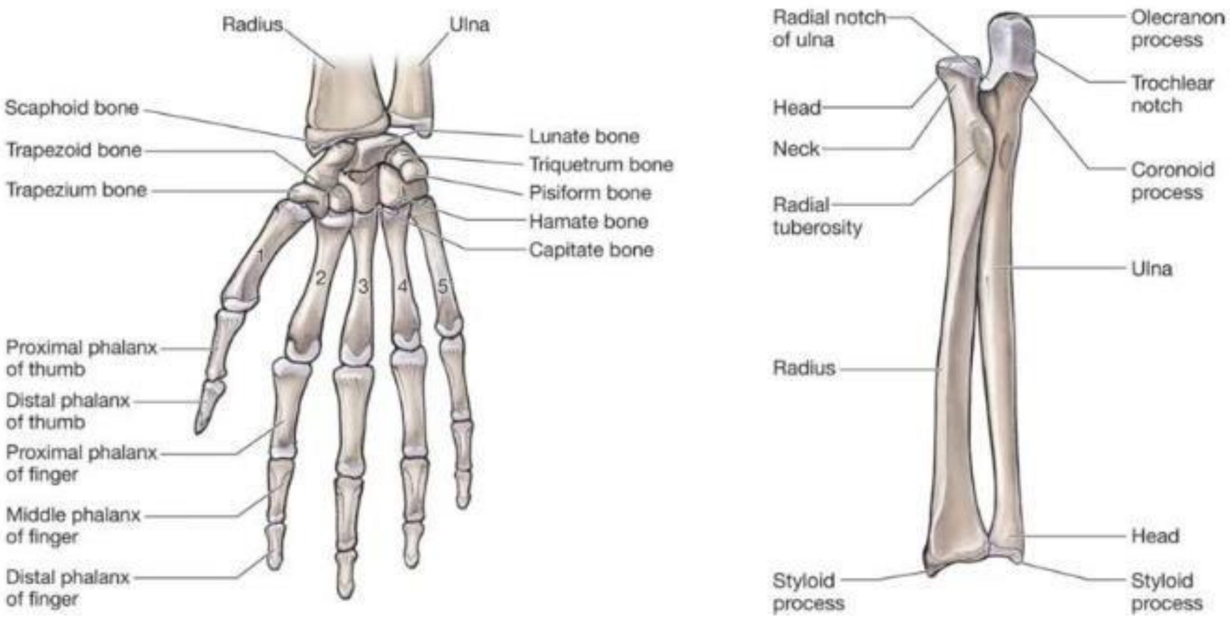


Figure 2: Bones, joints, and Ligaments of Hand and Forearm [6]

2.1.3. Muscle Movement and Biomechanics Postulates

Biomechanics is the study of analyzing the human body structures, their functions, and their reactions to external forces as they create movement. A strong understanding of biomechanics helps professionals in sports, physical therapy, and human and physical performance, or in our case in designing effective exoskeletons and assistive devices. In biomechanics, we discuss the motion, forces, levers, momentum, and balance at play that when acting together allow complex outputs. Our main movements as described in anatomical terms are:

- **Flexion:** a bending motion that decreases the angle (e.g. closing of hand) between the bones of the hand and those in the forearm, i.e. bringing the pal of the hand closer to the anterior surface of the forearm.
- **Extension**: a straightening of the fingers or hand that increases the angle (e.g. opening of palm). This is the opposite of flexion and is characterized by straightening or opening of the hand.
- **Abduction:** the movement that brings the hand away from the midline of the body. The same is true for fingers (a movement about the middle finger that brings the fingers away from the middle finger). E.g. splaying fingers apart.
- **Adduction:** characterized by movement towards the midline of the body. In anatomical position, adduction brings the fingers close together.

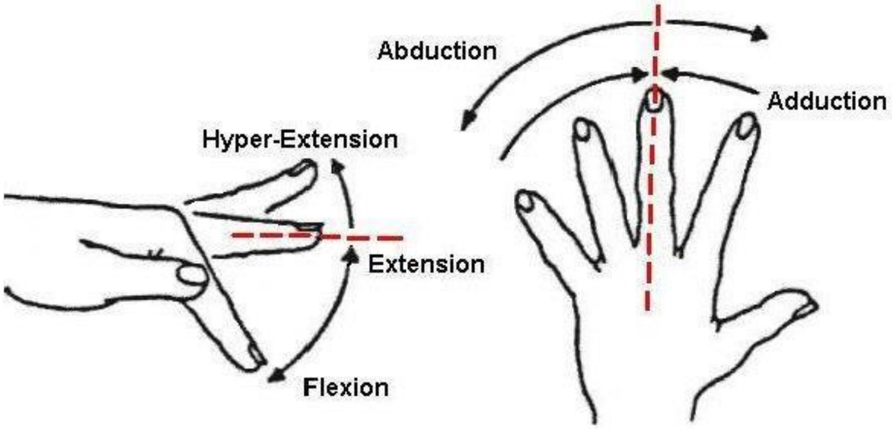


Figure 3. Abduction/adduction, flexion/extension for one finger. [15]

In biomechanics, **motion** refers to any process or body movement that causes a change in position in space. These may be linear, rotary, or general. **Forces** are the efforts realized by a person or object that cause a change in its direction. **Levers** are formed by muscles in the human body which in turn allow for bodily movement. The muscles act as levers, where the bones make up the **fulcrums**. The force exerted by muscles, the point of attachment (which defines the moment arm), and the weight of the object being moved define the moment, power, and range of a limb. In biomechanics, **momentum**, like the general notion is a dynamic concept. It is a measure of the mass of a body and its speed when the object moves. And lastly, we talk about **balance**. Balance is achieved at a bodily position that ensures stability while preventing failure. The hand must always maintain a balance between stability and mobility and a well-designed exoskeleton will always conform to this balance while assisting with everyday tasks.

Additionally, **synergy** is another important concept seen in the working of our bodies. Understanding how muscles work in collaborative groups is essential to replicating natural hand movements.

The muscles of the human hand are broadly classified into two types: the extrinsic and the intrinsic muscles.

- The **extrinsic muscles:** these muscles originate in the forearm and are attached to the bones via tendons and drive high-strength wrist and finger movements. These muscles originate in the radius-ulna, passing over the carpal bones and connecting to the metacarpals via tendons.
- The **intrinsic muscles** are located within the hand itself, originating from the carpal bones, and are responsible for controlling the finer motor movement of the fingers.

Tendons are responsible for connecting bones to muscles, acting as cables that transmit the force generated by muscles to the bones for movement.

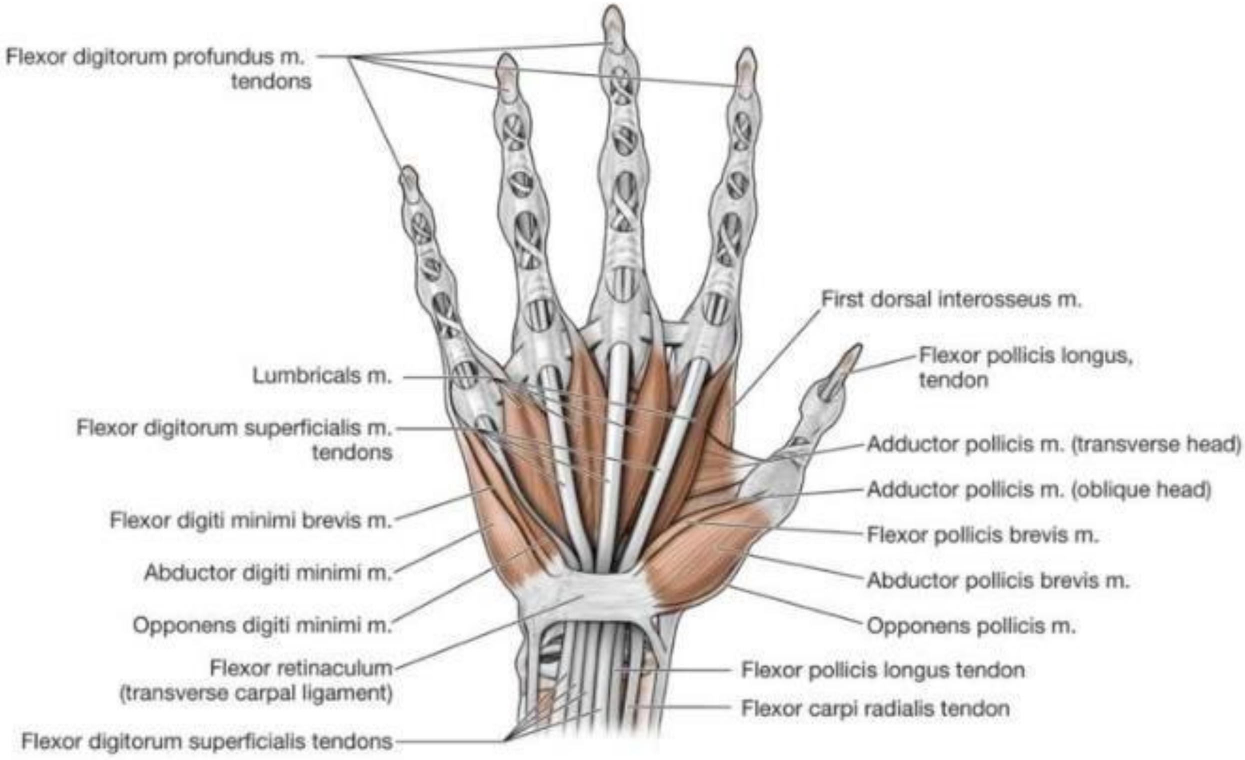


Figure 4: Tendons and Ligaments [6]

Before proceeding forward, we discuss some basic biomechanical principles relevant to this project.

1. **Principle of force:** simply put, forces cause movements. An undesirable movement reflects bad force.
2. **The principle of linked segments**: this postulate presents the simplest model of a body. The body and any part of the body can be assumed as a series of linked rigid sticks (individual segments) connected at frictionless hinges (joints). On one hand, the muscle forces can be determined by the speed and force production at the distal end or vice versa.
3. **The principle of impulse-causing momentum:** Understanding how impulse or an external force affects a body’s momentum, the resulting movement, and how it leads

to the slowing and speeding up of a body can help design an exoskeleton that provides the desired fingertip movements.

4. **The principle of summing joint forces:** Force application at a distal end is governed and defined by multiple joints. It is important to ensure all relevant joints are engaged and each joint maximizes forces to enhance overall force application for the desired movement.
5. **The principle of continuity of joint forces:** understanding how force application involves multiple joints and contributors can help ensure the exoskeleton engages all relevant joints, maximizing for each segment or smooth motion.
6. **The principle of impulse direction:** this postulate ensures that the applied forces from the exoskeleton are directed such that the desired movement is achieved. This direction is governed by the impulse required for proper motion.

These postulates and concepts are important for designing an effective exoskeleton that reflects and mimics the natural hand and finger movements.

2.2. Hand Movements and Grasp Types

We’ve discussed in detail the working behind the hands. This intricate structure is in turn capable of a wide range of movements that are crucial for interacting with the world around us. For the sake of simplicity, we broadly classify hand movements into two categories.

2.2.1. Gross Motor Skills

These involve larger movements of the entire hand, wrist, and arm. Examples include reaching, grasping, pushing, pulling, and manipulating objects of various sizes and weights.

2.2.2. Fine Motor Skills

Fine motor skills are defined as the precise movements of the fingers, thumb, and wrist. These movements focus on precision instead of power. Examples include picking up small objects, tying shoelaces, writing, using tools, and manipulating buttons.

2.2.3. Grasp patterns

Grasp patterns refer to the specific configurations a hand forms to hold or manipulate objects. These patterns utilize the hand's muscles, tendons, and skeletal structure to achieve a secure and functional grip. A clear understanding of grasp patterns is essential when dealing with upper limb impairments, rehabilitation, and assistive devices.

Grasp Types

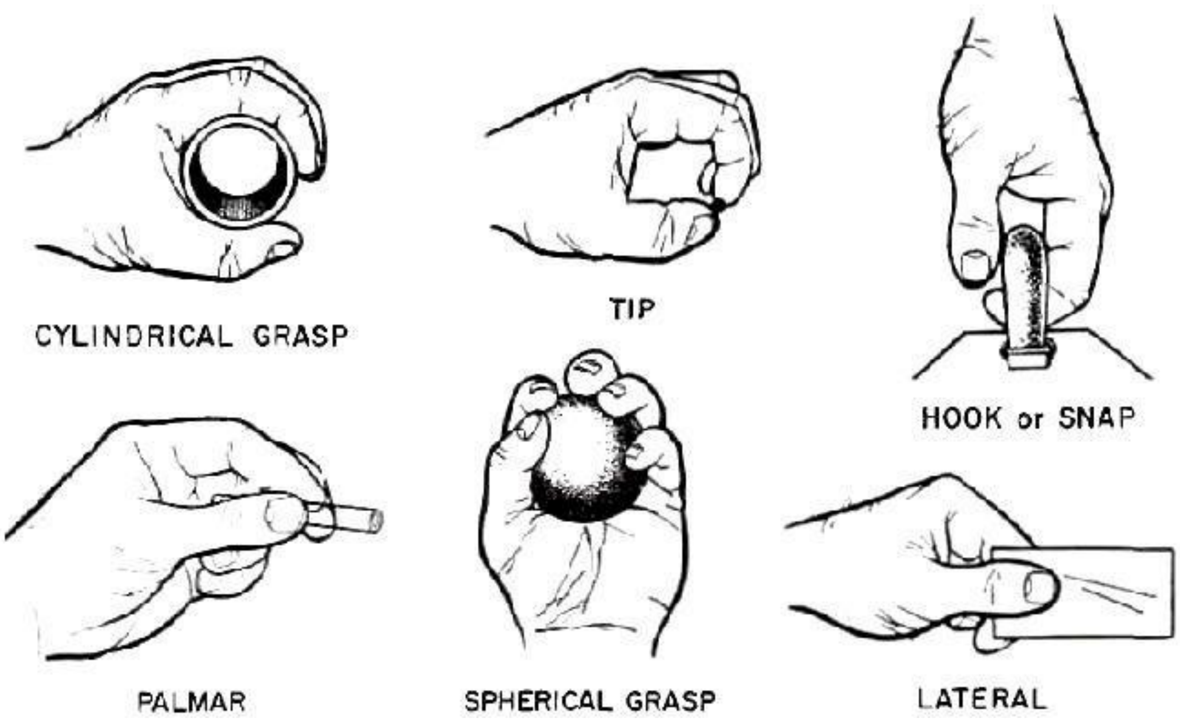


Figure 5. Major Grasp Types [10]

These patterns, achieved through coordinated movement of fingers, thumb, and wrist, enable us to interact with objects of varying shapes, sizes, and textures. For the design of an assistive hand exoskeleton, focusing on a subset of fundamental grasp types is crucial to maximize functionality and user benefit. Here, we explore the four major grasp types that collectively encompass a significant portion of daily activities:

- **Palmar Pinch**

This grasp pattern involves the opposition of the thumb with the fingertips of the index finger, middle finger, or both. The palmar surface of the fingertips contacts the object, creating a precise and controlled hold. This grasp is ideal for manipulating small, flat objects such as coins, credit cards, or buttons. The action requires flexion at the metacarpophalangeal (MCP) and distal interphalangeal (DIP) joints of the involved fingers, along with thumb abduction and opposition.

- **Lateral Pinch**

This grasp pattern utilizes the thumb positioned against the lateral side of the index finger to grip an object between them. The lateral surfaces of the thumb and index finger make contact with the object, providing a stable hold for tasks like writing with a pen or pencil. This grasp requires flexion at the MCP joint of the thumb and index finger, along with thumb abduction.

- **Parallel Extension**

This grasp pattern involves all fingers extending straight and parallel to each other, with the palmar surface of the fingertips contacting the object. This grasp is well-suited for grasping large, cylindrical objects or applying pressure over a broad area. It necessitates full finger extension at the MCP, PIP, and DIP joints, along with minimal wrist flexion or extension depending on the object's size and orientation.

- **The Median Wrap Grasp**

This grasp involves wrapping multiple fingers (typically the index, middle, and ring fingers) around the object, with the thumb positioned on the opposite side for stabilization and additional securing force. The median wrap grasp is particularly useful for grasping objects with irregular shapes or those requiring a secure hold for lifting or manipulation. It necessitates flexion at the MCP and PIP joints of the involved fingers, along with thumb abduction and opposition.

These four major grasp types represent a significant portion of daily hand activities. By focusing on enabling these grasp patterns within the design of an assistive hand exoskeleton, the device can significantly improve the functional independence of individuals with hand impairments.

2.3. Hand Pathologies Leading to Limited Mobility

Upper limb hand impairments are some of the most common impairments a person can experience. The World Health Organization has estimated that over 310 million people live with hand disabilities that greatly affect their daily life activities and their dependency on other people. In the United States alone, over 20% of the youth report hand pain and impairments. [2]

Upper limb hand impairments are caused by certain diseases that attack the hands and arms of an individual. These include:

- Arthritis: Particularly severe cases of rheumatoid arthritis or osteoarthritis in the hands can cause significant stiffness, pain, and weakness, limiting movement and grip strength.
- Tenosynovitis: Chronic tenosynovitis, especially in the thumb (de Quervain's tenosynovitis) or fingers, can restrict movement and make daily tasks like grasping objects difficult.
- Complex regional pain syndrome (CRPS): A chronic pain condition that can cause stiffness, swelling, and weakness in the hand, making even simple movements problematic.

Upper limb hand impairments can also be caused by various conditions including:

- **Neurological Disorders**

  Approximately 10 million people survive a stroke each year and 45 to 70% of these people suffer from hand impairments that tend to persist afterward (Dijkerman et al., 1996; Lawrence et al., 2001; Jørgensen et al., 1999). Spinal Cord Injury is also a major factor that leads to hand impairments, each year about 250,000 to 500,000 people suffer from spinal cord injuries globally of which 50% experience tetraplegia that leads to loss of motor function (Beekhuizen, 2005; SPS, 2018). Multiple Sclerosis is experienced by 2.9 million people globally and of those 80% have to deal with hand tremors and diminished motor skills. Every 1 in 100,000 people experience spinal muscular atrophy of which over 90% experience hand impairments.

- **Traumas**
  Injuries to the hand caused by burns, fractures, amputations, etc., are estimated to cause 5.9 million hand injuries globally each year.
- **Musculoskeletal Disorders**
  Diseases such as osteoarthritis and rheumatoid arthritis can lead to significant hand impairments. Globally, over 300 million people are affected by osteoarthritis which commonly impacts the hand function. Tendonitis can also cause hand impairments.
- **Congenital Conditions**
  It is estimated that 6% of babies worldwide are born with congenital disorders that lead to the deterioration of motor functions over time. [17]

Furthermore, age-related hand disabilities are also experienced as the population ages.

Hand impairments can have profound effects on individuals, impacting both their physical abilities and emotional well-being. The consequences of these impairments can be far-reaching, affecting various aspects of daily life and overall quality of life.

- **Physical Consequences**
  - Reduced Motor Function: Individuals may experience difficulty in grasping objects, manipulating tools, or performing fine motor tasks. Simple activities like buttoning a shirt or holding a utensil become challenging.
  - Pain and Discomfort: Constant pain and discomfort can limit movement and disrupt sleep, leading to fatigue and decreased overall well-being.

  - Limited Mobility: Hand impairments can restrict mobility, making it challenging to perform basic tasks like reaching for objects or using public transportation.
- **Emotional Consequences**
  - Psychological Distress: Frustration, isolation, and depression are common among individuals with hand impairments. The loss of independence and the need for assistance in daily activities can lead to feelings of helplessness and low self-esteem.
  - Social Impact: Hand impairments can impact social participation, as individuals may avoid social gatherings or activities due to difficulties in interacting with others or fear of being judged.
- **Impact on Daily Life**
  - Challenges in Activities of Daily Living (ADLs): Simple tasks like dressing, eating, and writing become challenging, requiring assistance from others or the use of adaptive devices.
  - Work Limitations: Individuals may face challenges in the workplace, affecting their ability to perform certain tasks and potentially leading to job loss or reduced work hours.
- **Financial Burden**
  - Cost of Treatment: The cost of medical treatment, therapy, and assistive devices can place a financial burden on individuals and their families.
  - Loss of Income: Work limitations due to hand impairments can lead to a loss of income, further exacerbating financial difficulties.

2.3.1. Treatment and Recovery

Rehabilitative interventions for individuals with neuromotor impairments, which may be partially curable, encompass a range of treatments including antispastic medication, orthopedic surgery, and occupational and physical therapy (Kleim & Jones, 2008). Among these, occupational and physical therapy play a pivotal role, with both intensity and dosage being critical factors for optimizing outcomes (Kleim & Jones, 2008). Therapeutic strategies often emphasize the promotion of affected hand usage through targeted training of functional abilities within intensive, activity-based, goal-oriented interventions such as constraint-induced movement therapy (CIMT) and bimanual intensive therapy (BIM) (Reid et al., 2015). Physical and occupational therapy interventions commonly result in improvements in both motor and sensory functions of the affected hand (Ottenbacher & Jannell, 1993). In recent years, robot-assisted therapy has gained popularity due to its ability to deliver high doses of therapy and has demonstrated positive effects on upper limb rehabilitation outcomes (Kwakkel et al., 2008). Additionally, robot-assisted rehabilitation offers advantages such as assisting as needed and enhancing patient motivation through interactive features like video games and performance feedback (Lambercy et al., 2018).

2.4. Wearable Robotics

Historically, two primary approaches have been prevalent in designing robotic devices for hand rehabilitation: end-effector-based and exoskeleton devices.

2.4.1. End-Effector-based

End-effector-based devices are mechanically grounded and thus less restricted in size and weight compared to exoskeleton devices that offer general assistance for grasping and manipulation tasks. However, they have limitations in controlling each finger joint involved in the motion. This lack of granularity restricted their effectiveness in addressing specific aspects of hand impairment, hindering targeted rehabilitation efforts.

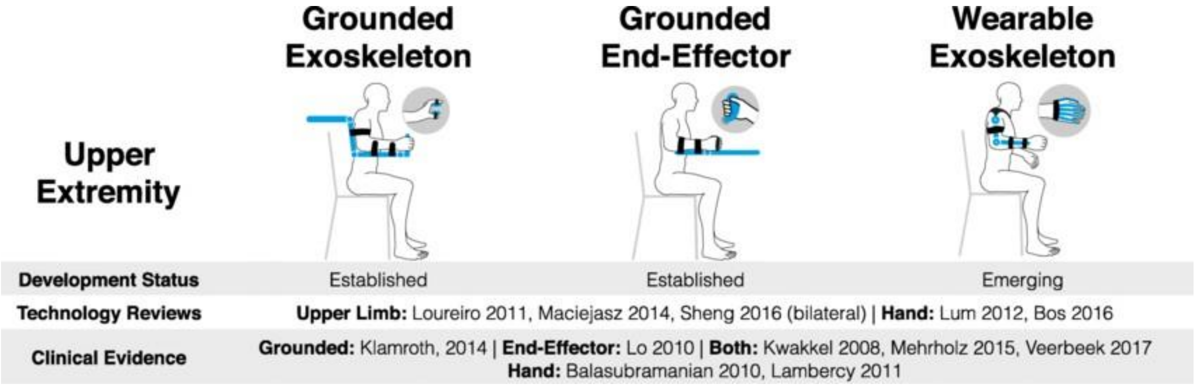
Conversely, exoskeleton devices, designed to conform to the hand's complex structure can be placed around the hand to guide or actuate its movement without impeding natural joint motion. Exoskeletons like HandCARE and Amadeo offer the advantage of controlling individual finger movements and have been favored for hand rehabilitation due to their ability to accommodate the small and complex structures of the hand. This allows for targeted therapy addressing specific deficits, paving the way for more personalized rehabilitation approaches. While early exoskeleton designs faced challenges in terms of bulkiness and potential restriction of natural movement, advancements in miniaturization and actuation technologies have led to the development of lighter, more dynamic devices.

2.4.2. Robotic devices

Robotic rehabilitation devices can generally be categorized into three main types based on the stage of rehabilitation they target.

- Early-stage rehabilitation devices, designed for individuals with severe hand impairments, often utilize end-effector mechanisms to mobilize the hand and train range of motion or specific movements (Van Hedel et al., 2011).
- In contrast, late-stage rehabilitation devices, intended for individuals with mild impairments, focus on functional tasks in virtual reality scenarios and are typically passive (Keller et al., 2013).
- Recently, powered robotic hand exoskeletons have become commercially available, offering intermediate solutions that actively support users in functional tasks (e.g., Gloreha and Hand of Hope) (Rehab-Robotics Ltd., Hong Kong).

Despite advancements in rehabilitation therapy and the availability of robotic devices, many individuals with persistent hand impairments experience limited residual hand function, hindering their ability to engage in activities of daily living (ADL). Continued rehabilitation efforts often focus on relearning daily tasks and compensatory strategies to maximize independence (Beekhuizen, 2005). Assistive equipment, such as eating utensils and writing devices, is commonly used to improve ADL independence and reinforce the use of the affected hand, thereby mitigating learned non-use (Rosenbaum, 2003; Krigger, 2006).



Development Status	Established	Established	Emerging
Technology Reviews	**Upper Limb:** Loureiro 2011, Maciejasz 2014, Sheng 2016 (bilateral) | **Hand:** Lum 2012, Bos 2016		
Clinical Evidence	**Grounded:** Klamroth, 2014 | **End-Effector:** Lo 2010 | **Both:** Kwakkel 2008, Mehrholz 2015, Veerbeek 2017 **Hand:** Balasubramanian 2010, Lambercy 2011		

Figure 6. Types of Assistive Devices for Upper Extremities. [16]

2.4.3. Developments in Wearable Robotics

In the pursuit of enhancing residual hand function and preventing learned non-use, wearable robotics have emerged as promising tools for both rehabilitation therapy and assistance in daily life (Taub & Berman, 1968). Recent developments have seen a surge in the development of hand exoskeletons aimed at providing portable platforms for home-based rehabilitation or serving as wearable devices for daily living activities (Bos et al., 2016). These devices often utilize rigid link structures to exert forces normal to the phalanges, aiming to produce natural grasp patterns and facilitate adaptation to objects (Troncossi et al., 2016).

However, a key challenge lies in achieving effective decoding of user intention based on physiological signals to optimize therapy outcomes (Dietz et al., 2011). Many hand exoskeletons incorporate systems for detecting user intent, hypothesized to stimulate neuroplasticity and aid in rehabilitation (Troncossi et al., 2016). For assistance in daily living, hand exoskeletons must strike a delicate balance between wearable design and mechanical complexity, often employing tendon-based mechanisms to mimic physiological tendons while ensuring lightweight and lean solutions (Nycz et al., 2015; Xiloyannis et al., 2016).

Despite substantial progress in the field of wearable hand exoskeletons for rehabilitation and assistance, there remains a gap in developing devices that effectively combine these two concepts to provide comprehensive support for individuals with hand impairments in both therapy and daily life.

2.4.4. Exoskeleton devices

2.4.4.1. Based on Actuation Mechanisms

The actuation system is responsible for the initiation, control, and halting of the exoskeleton. The system generally includes a power source, sensors, and control electronics that include the microcontroller and the related circuitry to run the motor.

2.4.4.1.1. Pneumatic Actuation

The pneumatic system works on the concept of movement generation using compressed air. The system uses compressors, valves, and actuators to control the flow of compressors and convert it to useful mechanical motion. This type of actuation is seen in many recent robots and exoskeletons due to the high power-to-weight ratio, which leads to relatively high speed and force for the component, and the precise movement control that aids in dynamic motion control. Pneumatic actuation is also a complex system that can be susceptible to leaks and pressure fluctuations. Furthermore, they are less energy efficient and are rather noisy during functioning.

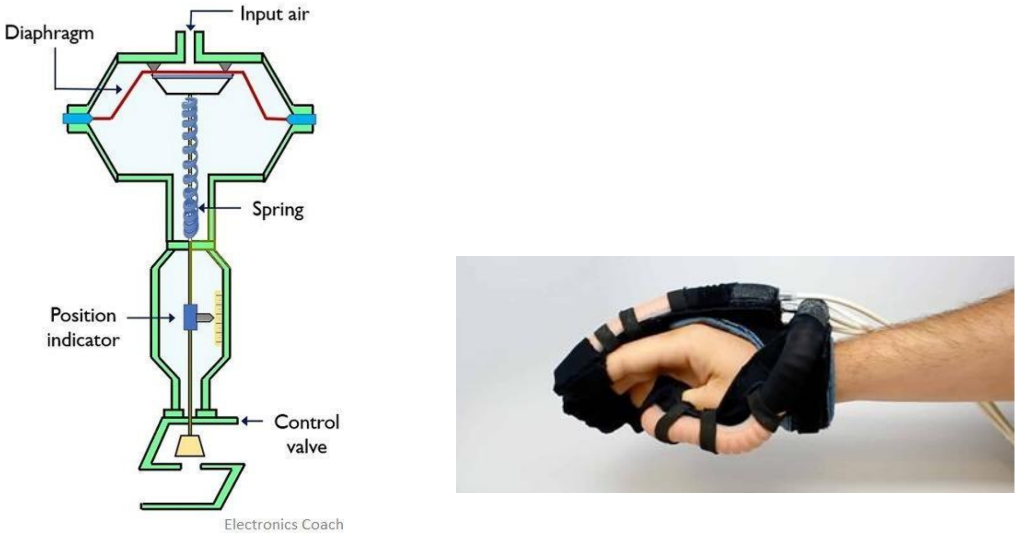


Figure 7. ***(Right to left) Working of Pneumatic Actuation,*** **Pneumatic Actuation Exoskeleton [18]**

2.4.4.1.2. Hydraulic Actuation

Hydraulic actuation makes use of pressurized fluids, usually oil, to generate movement in the mechanical system. A typical hydraulic system consists of hydraulic pumps, valves, actuators, and fluid reservoirs that work in combination to control the flow of pressurized fluid and convert it into mechanical motion. Hydraulic actuation results in a high-power output, they are robust and cause durability that can withstand high loads. These systems are complex and require careful installation and maintenance. These systems are also more expensive and require regular inspection.

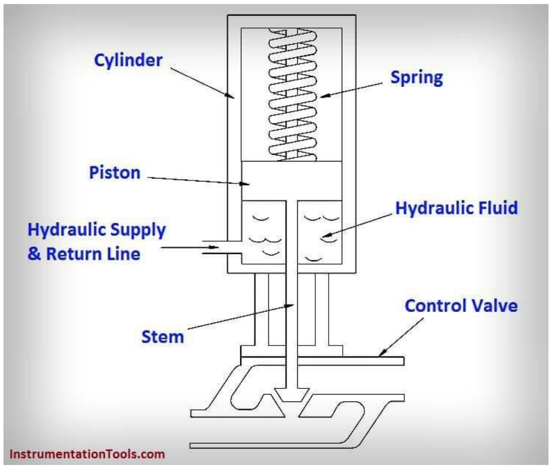


Figure 8. Working of Hydraulic Actuator. [19]

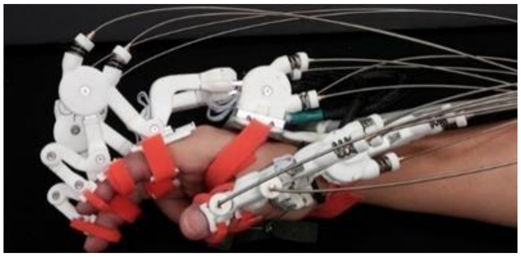


Figure 9. Hydraulic Actuation Exoskeleton [19]

2.4.4.1.3. Motor Actuation

This type of actuation requires electric motors to be used as the power source that generates movement. The motor converts electrical energy into mechanical energy by use of magnetic fields, which results in rotational motion. This type of motion results in precise control over speed, torque, and position. Motors are compact, lightweight, and relatively simpler to integrate within the system. However, motors have a limited power output, so they deliver relatively lower torques and forces. They also require a continuous electrical supply that limits the output of the motor as well.

2.4.4.1.4. Hybrid Actuation

In this system, multiple actuation principles are combined to achieve enhanced performance and versatility in mechanical systems. These models improve the strengths of different actuation systems resulting in improved performance, efficiency, adaptability, and robustness. One example of a hybrid actuation model is the three-layered finger mechanism, which combines passive springs with motor-driven actuation in hand exoskeletons for rehabilitation and assistive technology. This hybrid approach allows for improved efficiency and adaptability compared to single-actuation systems, as the passive springs provide compliance and assist in closing the hand, while the motor-driven actuation allows for precise control and adjustment of finger movements. This type of actuation is more complex and requires careful design and control. These models can be more expensive.

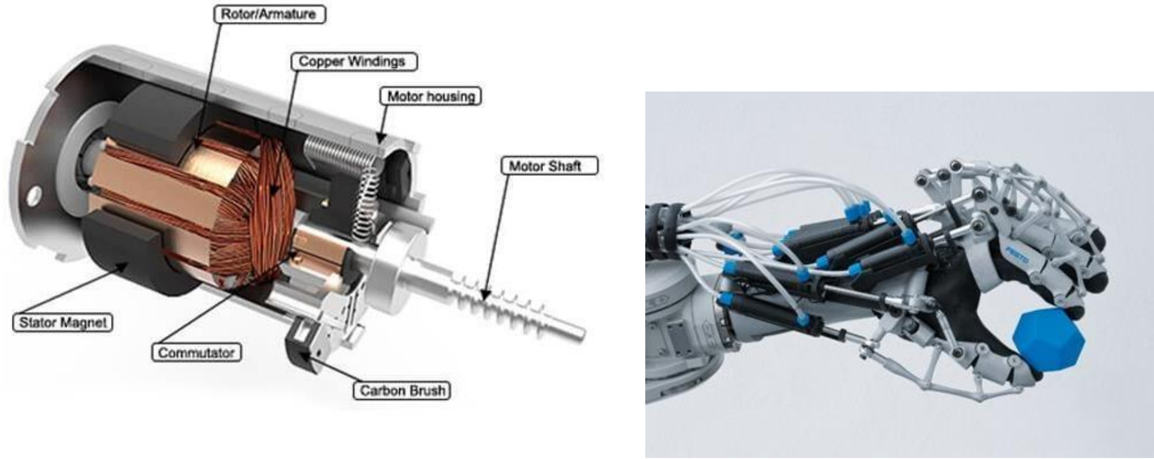


Figure 9. Working of a linear actuator *(Left)*, A mechanically actuated exoskeleton *(Right)*. [20]

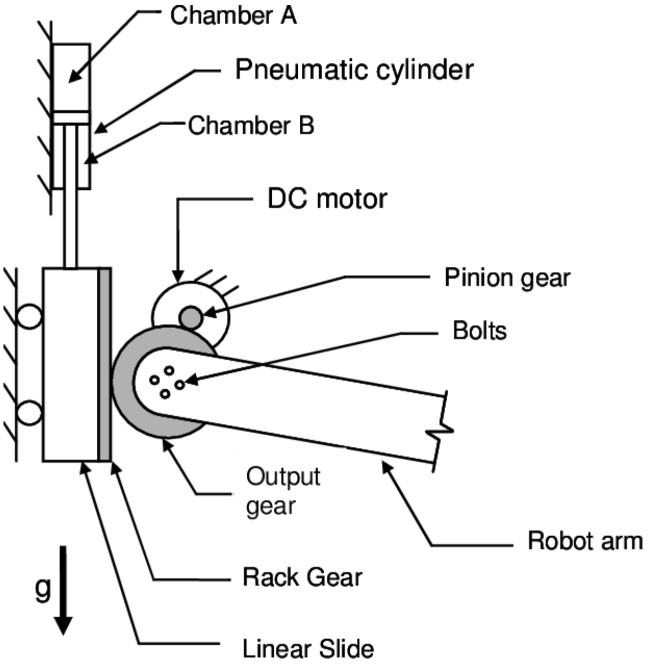


Figure 10: Hybrid Actuation System. [21]

2.4.4.2. Remote Actuation Models

Remote actuation models in exoskeleton technology enable users to control the movement of the exoskeleton from a distance using various input devices or interfaces by separating the power source and actuators from the user's limb. These models offer several advantages, including increased safety for users working in hazardous environments, improved accessibility for individuals with mobility impairments, and enhanced flexibility in operation. The Remote Actuation system includes:

- Input Devices: Allows for remote input commands and control signals to be sent to the Exoskeleton. These devices translate the user’s commands into signals that can be interpreted by the exoskeleton.
- Wireless Communication: Remote Actuation systems rely on wireless communication protocols to transmit control signals from the input devices to the exoskeleton's control

system. These technologies enable seamless and real-time communication between the user and the exoskeleton over short distances.

- Control Systems: the exoskeletons receive control signals from input devices and process them to initiate and regulate the movement of the exoskeleton's joints and limbs.
- Feedback Mechanisms: remote actuation incorporates feedback mechanisms to provide users with information about the performance of the exoskeletons. They enhance user awareness and control over the exoskeleton's operation, improving overall usability and safety.

Remote Actuation places the actuators away from the body, which reduces the overall weight on the critical areas. This leads to a more comfortable and long-term wearable design.

The Remote Actuation System methods that make it possible to carry out safe and efficient actuation include:

Bowden Cables: These are flexible cables that transmit force over long distances with minimal energy loss. They are a popular choice for remote actuation due to their simplicity, low weight, and ease of routing.

Hydraulic Lines: It is like traditional hydraulic systems, but with smaller and lighter tubing to connect remote actuators. This method offers high force transmission efficiency but can be more complex and require careful leak prevention.

Wireless Power Transmission: Emerging technologies allow for transmitting power wirelessly to implanted or wearable actuators within the exoskeleton. This eliminates the need for physical tethers but is still under development in terms of efficiency and power output.

2.4.4.3. Control Mechanisms

Control mechanisms are components that govern how the exoskeleton moves and interacts with the user as well as the environment. They are categorized as mentioned below:

1. Active Models:

   These involve continuous joint torque adjustment based on the sensory feedback and the user’s input. These models actively regulate the interaction between the exoskeleton and the user by dynamically adjusting control parameters in response to changing conditions. Active control mechanisms are typically implemented using sophisticated control algorithms and sensor feedback systems to monitor user intent, environmental conditions, and biomechanical factors. These tasks are done with sensors that obtain information about the user’s state and environment and the processors that analyze the data. These typically include force sensors, position sensors, and electromyography sensors.

   Active models provide dynamic adjustment based on real-time sensory feedback and user input. This dynamic adaptation allows for precise control over movement and responsiveness to changes in the user's motion or external forces. This model therefore provides adaptive assistance tailored to the user's needs and preferences. The control system continuously adapts control parameters to optimize assistance levels, minimize user effort, and maximize task performance.

2. Passive Models:

   These rely on mechanical or compliance-based designs to assist or augment human movement without active control. These models operate based on the mechanical properties of the exoskeleton, such as springs, dampers, and compliant materials, to provide passive assistance or resistance to movement. Passive control models are simpler and more mechanically robust than active models, making them well-suited for applications where simplicity, reliability, and energy efficiency are critical. These models are more energy-efficient, as they rely on mechanical energy storage and release mechanisms rather than active power sources.

2.4.4.4. Commercially Available Devices

With time and technological advancement, there has been an increase in hand exoskeletons within the market. These include:

- Hand of Hope by Motorika [22]
- MyoPro by Myoma [23]
- Carbonhand by Bioservo Technologies [24]
- Smart Glove by Neofect [25]

Figure 11. ***(Top, from left to right)*** **Hand of Hope by Motorika [22], MyoPro by myomo [23], Carbonhand by Bioservo [24],** ***(Bottom)*** **Smart Glove by Neofect [25]**

2.4.4.5. Motors and Actuators

Motors and the actual actuation play a very critical role in the functionality as well as the performance of the assistive hand exoskeleton. They generate the forces and movements that are required for proper actuation of the hand mechanism to carry out the necessary tasks.

- Linear Actuators: they convert rotary motion to linear motion and are used regarding straight-line motion. The stator houses the electromagnet in a particular arrangement. The mover has a conductive plate or additional magnets that interact with the magnetic field created in the stator due to the electronically controlled current. The interaction of the magnetic fields creates a force that propels the mover in a straight line. The actuator consists of a lead screw that drives the motor and a belt that moves the load along a linear path.

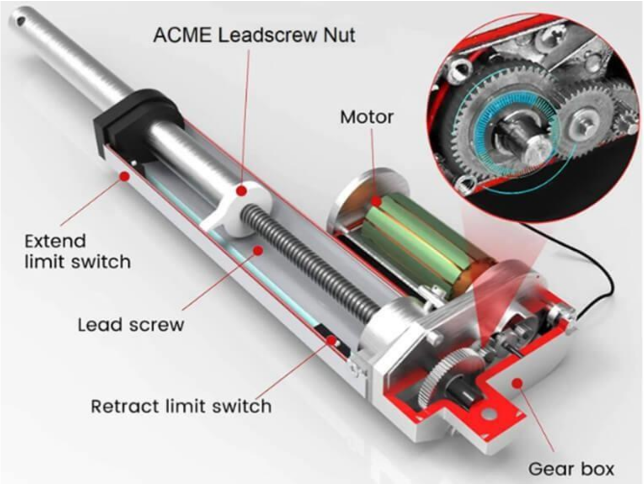


Figure 12: Linear Actuator Components [26]

- Stepper Motors: they are electromechanical devices that convert digital input signals into precise and incremental shaft rotations. Specific stator coils are energized in a particular sequence to generate magnetic fields that attract the rotor teeth. The energized coil sequence determines the direction of rotation, and each pulse energizes a different coil combination that causes the rotor to rotate to a specific step angle. With a precise pulse control system, a controlled, step-by-step rotation of the motor shaft is achieved.

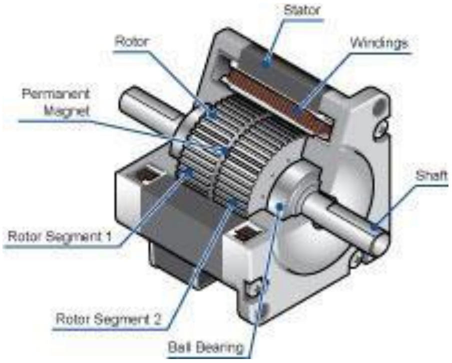


Figure 13: Stepper Motor Components [27]

- DC Motors: they convert electrical energy into mechanical energy. When DC flows through the armature coils, a magnetic field is generated around them. The field interacts with the permanent magnetic field of the stator which creates an opposing force on the armature coil and rotor in a particular direction. This causes the motor to work and provides the required rotary motion.

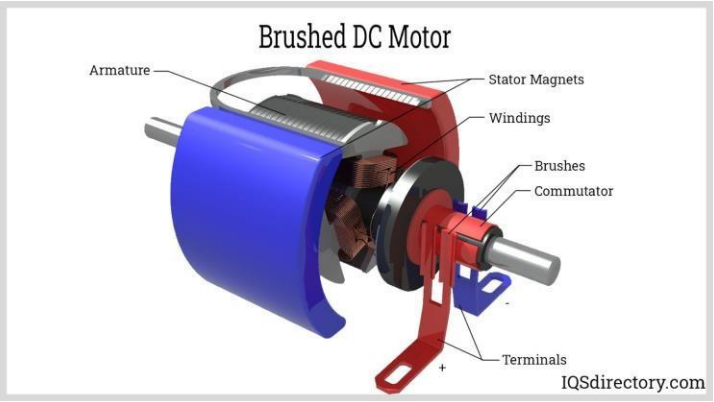


Figure 14: DC Motor Components [28]

- Servo Motor: a control signal specifies the desired servo shaft angle, and this angle is continuously monitored by an angle sensor. The control circuit compares the desired and actual angles and in case of a difference the circuit sends power to the motor to reduce this difference. The motor continues until the actual shaft angle is the same as the desired angle where the motor stops.

Figure 15. Servo Motor [29]

Table 1. Comparison of different Actuation Types

Characteristic	**DC Motor**	**Linear Actuator**	**Stepper Motor**	**Servo Motor**
Motion Type	Rotary	Linear	Rotary	Rotary
Torque Output	High	High	Medium to High	High
Speed	High (variable)	High	Lower (variable)	Moderate (variable)
Position Control	Precise (proportional to current	Less precise (dependent on encoder accuracy)	Very precise (step-based)	precise (feedback-based)
Efficiency	Moderate	Moderate to High	Moderate	High
Cost	Moderate	High	Moderate	High
Complexity	Moderate	High	Moderate	High

Size	Compact	Moderate	Compact	Compact
Applications	Joints, Fingers	Linear Motion	Precise Position	Angular Position

CHAPTER 3: METHODOLOGY

3.1. Design Requirements

3.1.1. Functionality of the Product

Functionality refers to the ability of the exoskeleton to achieve its intended purpose and the effect of the device. This includes the ROM and the grip strength.

Activities of daily living (ADLs) encompass a diverse range of actions, typically categorized into four primary grasp types, which collectively constitute over 70% of all grasping motions. These grasp types include palmar pinch, medium wrap, parallel extension, and lateral pinch. Additionally, approximately 13% of grasping activities involve utilizing a flat hand without directly grasping the object. Consequently, these four fundamental grasp types enable the effective performance of over 80% of all grasping activities.

Individuals facing hand impairments commonly require assistance with essential tasks such as eating, writing, and drinking from bottles.

For the proposed design we will deal with the requirements of the four mentioned grasps in section 2.2.3.

3.1.1.1. Range of Motion

The range of motion (ROM) of the hand comprises the following movements:

- Finger flexion/extension and abduction/adduction.
- Thumb flexion/extension and abduction/adduction.
- radial/ulnar deviation of the wrist.

With varying tasks, the functional range of motion (ROM) exhibited by the distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MCP) finger joints typically falls within the range of 19 to 87 degrees.

Table 2: Functional ROM for different Joints

Functional ROM (°)					
MCP		PIP		DIP	
min	max	min	max	min	max
19	71	23	87	10	64

The range of motion (ROM) for adduction/abduction of the metacarpophalangeal (MCP) joints of the thumb spans from -6 to 21 degrees, while the ROM for adduction/abduction of the carpometacarpal (CMC) joint ranges from -8 to 16 degrees. Additionally, it is imperative to account for the external rotation of the thumb concerning the neutral position lateral to the index finger, which measures 28 degrees. These parameters underscore the necessity of conducting a three-dimensional analysis when assessing the coordination of the three thumb joints during activities of daily living.

Moreover, it is essential to consider the position of the wrist; however, due to the intricacy of the design, the movement of the wrist and thumb is not factored into consideration.

3.1.1.2. Grip Strength

A hand can exert high forces, but most ADLs require low grip and pinch forces. Usually, these tasks require lifting of objects less than 1 kg, and therefore the fingertip force is set to 10 N. Most of the commonly occurring ADLs can be carried out within this 10 N fingertip strength. This force is calculated by the following equation (Polygerinos, P., Wang, Z., Galloway, K. C., Wood, R. J., and Walsh, C. J. (2015a). Soft robotic glove for combined assistance and at-home rehabilitation. Robotics and Autonomous Systems 73, 135–143):

the average coefficient of friction is assumed to be 0.25 which leads to a fingertip force of 10 N.

3.1.2. Usability

The usability of a device refers to the user's experience with the device. In this case, it means the efficiency and satisfaction of using the assistive hand exoskeleton.

3.1.2.1. Ergonomics and Weight

Hand exoskeletons are required to interact with users safely, particularly considering individuals with impaired hand function who may experience limitations in functional and passive range of motion (ROM) due to muscular stiffness or contracture. Thus, the target application necessitates the utilization of soft-compliant systems capable of accurately controlling output forces and force directions, while also mitigating undesirable interaction forces.

The hand exoskeleton should be lightweight—less than 200 g—and have an ergonomic, pleasant design. It should also measure less than 5 cm by 5 cm by 3 cm. To further attain high user acceptance, an attractive design—including appearance—and low noise emission are required. Exoskeletons weighing greater than 250 g are considered too heavy and uncomfortable for users.

3.1.2.2. Ease of Use

The most significant aspects of an exoskeleton that make it attractive are:

- Fast and independent donning and doffing, ideally within a few seconds.
- Continuous use for the whole day without the need for frequent donning and doffing, with a battery life of about 6 to 8 hours.
- Hand closing movement duration of 1 to 2 seconds.

- Unrestricted range of motion (ROM) of the arm.
- Impermeability, disinfection, and cleanability for safe use during daily activities.

3.1.2.3. Control of the device

An assistive hand exoskeleton system should be controlled intuitively and reliably with minimal effort. Reliability is crucial, as unreliable control has been a major factor leading to the abandonment of actuated assistive devices.

With more studies and tests, the use of control based on physiological signals like EMG, EEG, ECG, etc. has become more common.

Control based on push buttons, capacitive sensors, and voice control can also be used.

To optimize the trade-off between functionality and usability in daily life, our hand exoskeleton incorporates several key design decisions:

- **Dual Motor System:** Only two motors are used to generate high functionality, covering the four most commonly used grasp types, while maintaining a lightweight and sleek design.
- **Combined Actuation of Digits 2-5:** A single motor is used for flexion/extension and simultaneous ab/adduction of digits 2-5, based on the first principle component of postural synergies.
- **Compliant Finger Mechanism:** The compliant finger mechanism, which was adapted from Arata et al. (2013), resembles the kinematic chain when objects are touched, flexing the fingers from the proximal to the distal joints.
- **Soft Spring-like Finger Mechanism:** This mechanism reduces weight and complexity by ensuring safe operation without requiring position sensing of individual fingers or phalanges.
- **Remote Actuation:** By transferring weight from the hand to the trunk and lowering perceived weight overall, compliant transmission enables remote actuation.

- **Modular and Tailorable Design:** Various interfaces for fixation and control allow for maximal versatility, ensuring that a wide range of users can be optimally assisted by the hand exoskeleton.

3.3. Preliminary Design

3.3.1. Finger Mechanism

The mechanism is composed of rigid components identified as the tip, inner, and outside sections (referred to as R_t, R_i, and R_o respectively), in conjunction with three-layered sliding springs classified as inner, center, and outer (labeled as S_i, S_c, and S_o respectively). Positioned at the foundation of the mechanism, the inner spring is anchored to the rigid bodies R_t and R_o. As a result, the spring blades S_{i1}, S_{i2}, and S_{i3}, being affixed at both extremities to the stiff bodies, operate as flat springs.

Each proximal end of S_o incorporates a passive slider mechanism and a stopper, allowing for the adjustment of S_c's length during flexion. The terminations of these springs, S_i, S_c, and S_o, are fastened to the rigid tip body R_t. Additionally, rigid prismatic bodies R_{i1}, R_i2, and R_i3 are connected to the central spring (S_c), while hollow prismatic stiff bodies, denoted as R_{o1}, R_{o2}, and R_{o3}, function as the exterior bodies, facilitating the longitudinal sliding motion of the center spring and inner rigid bodies within the bodies.

This mechanism enables a bending motion reminiscent of that of a human finger by modifying the dimensions of the rigid bodies and the stiffness of the springs, with these factors playing a critical role in its operational efficacy. Factors such as finger dimensions, range of motion, and joint rigidity of the user must be taken into account. Essential parameters for evaluation on each finger include the distances between the distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints (referred to as DDIP−PIP) and between the PIP and metacarpophalangeal (MCP) joints (DPIP−MCP), as well as the thickness of the finger at the DIP joint (TDIP), PIP joint (TPIP), and MCP joint (TMCP).

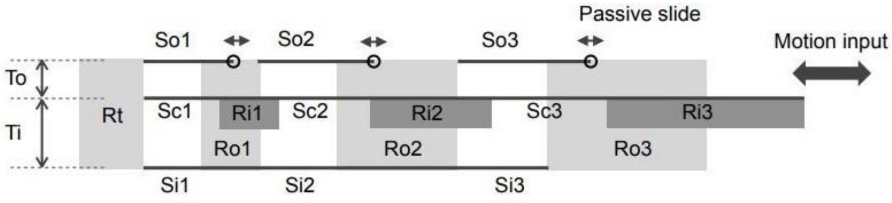


Figure 16: Lengths and Locations of the Parameters

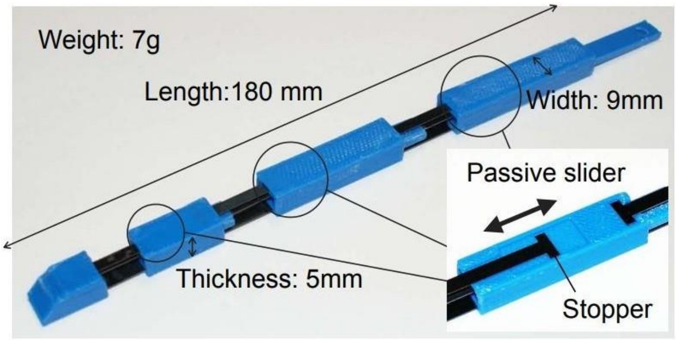


Figure 17: Overall Length of a Finger

Table 3: Distances between Loints, Joint Thicknesses

Parameter	Value
D(DIP-PIP)	23.0 mm
D(PIP-MCP)	44.0 mm
T(DIP)	11.3 mm
T(PIP)	16.4 mm
T(MCP)	26.5 mm

Table 4: Dimension taken for parts of the Hand Exoskeleton

Parameter/Part	Value	Parameter/Part	Value
T_o	1.7 mm	S_{o1}	L: 15.5, W: 3.0, T: 0.1
T_i	2.5 mm	S_{o2}	L: 21.7, W: 3.0, T: 0.1
S_{i1}	L: 8.9, W: 3.5, T: 0.1	S_{o3}	L: 22.9, W: 3.0, T: 0.1
S_{i2}	L: 14.3, W: 6.0, T: 0.1	R_{o1}	L: 17.2, W: 9.0
S_{i3}	L: 17.4, W: 7.5, T: 0.1	R_{o2}	L: 36.1, W: 9.0
S_{c1}	L: 12.8, W: 2.0, T: 0.2	R_{i1}	L: 17.2, W: 6.5
S_{c2}	L: 18.7, W: 3.0, T: 0.2	R_{i2}	L:36.1, W:6.5
S_{c3}	L: 20.6, W: 4.0, T: 0.2		

By using the arclength of the circular sector that contains the spring blade and the RCM, the lengths of the spring blades can be determined. These are defined by the following equations (Arata 2013 pg 4):

$$L_{Si1} = 2\pi \times \frac{H_{DIP}}{2} \times \frac{\theta_{DIP}}{360}$$

$$L_{Si2} = 2\pi \times \frac{H_{PIP}}{2} \times \frac{\theta_{PIP}}{360}$$

$$L_{Si3} = 2\pi \times \frac{H_{MCP}}{2} \times \frac{\theta_{MCP}}{360}$$

$$L_{Sc1} = 2\pi \times \frac{H_{DIP} + H_i}{2} \times \frac{\theta_{DIP}}{360}$$

$$L_{Sc2} = 2\pi \times \frac{H_{PIP} + H_i}{2} \times \frac{\theta_{PIP}}{360}$$

$$L_{Sc3} = 2\pi \times \frac{H_{MCP} + H_i}{2} \times \frac{\theta_{MCP}}{360}$$

$$L_{So1} = 2\pi \times \frac{H_{DIP} + H_i + H_o}{2} \times \frac{\theta_{DIP}}{360}$$

$$L_{So2} = 2\pi \times \frac{H_{PIP} + H_i + H_o}{2} \times \frac{\theta_{PIP}}{360}$$

$$L_{So3} = 2\pi \times \frac{H_{MCP} + H_i + H_o}{2} \times \frac{\theta_{MCP}}{360}$$

The stiffness of the spring is also a huge contributor to the proper functioning of the mechanism.

Material Selection:

- Spring Blades: Stainless steel trips, hardened, and cold rolled (JIS G3311, SK85M, 210 Gpa Young's modulus)
- Rigid Links: 3D printed links with an ABS filament.

3.2.1. Remote Actuation System

We looked into the usage of DC motors as actuators in a push-pull Bowden cable transmission system, which has benefits in terms of size, cost, controllability, and energy efficiency. Depending on the design of the exoskeleton, this arrangement can provide compressive and tensile pressures, allowing for finger flexion and extension. When utilized with a back-mounted device, the Bowden cable bend angle's operational range, as determined by a bending angle sensor, is 0 to 180 degrees, allowing for 90-degree bends at the elbow and shoulder. The anticipated operating range for the actuators was 10 to 40N. These factors were used to determine an efficiency range. It was anticipated that the efficiency would exceed 65% under all operational conditions, with most operations falling within the 70% to 80% efficiency range. This level of efficiency was considered acceptable, leading to the implementation of the Bowden cable design.

This system's main drawback is nonlinear friction, which can lead to control errors of up to 50% of the goal force and vary depending on the Bowden cables' overall bending angle.

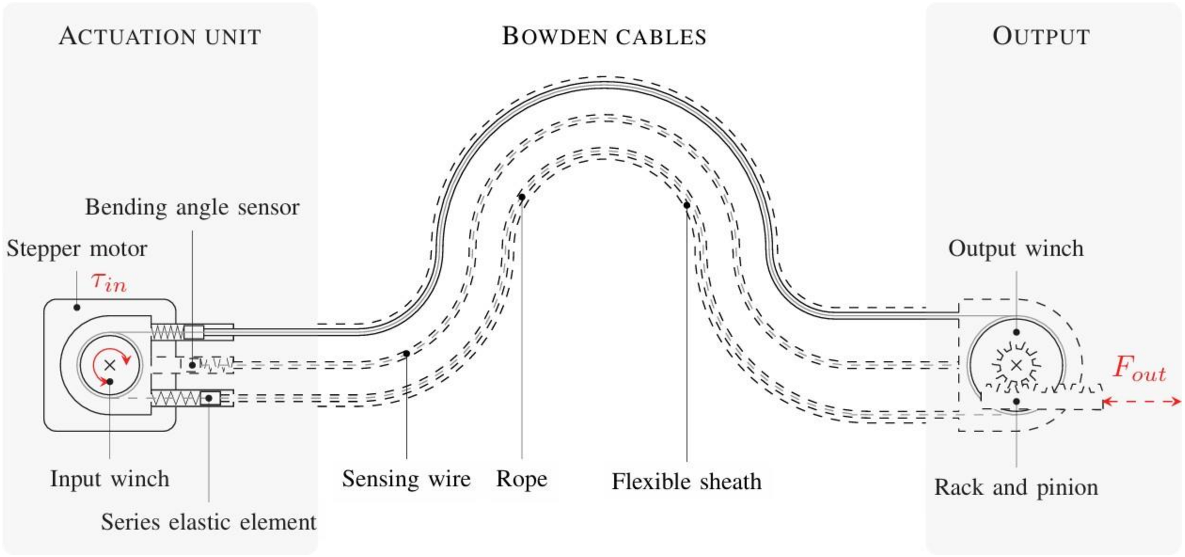


Figure 18: Bowden Cable Mechanism

The force transmitted to the springs via the Bowden cable is controlled using a rack and pinion system at the end of the cable. The diameter of the pinion and the length of the rack will determine how much force is transmitted to the finger. The diameter of the pinion is taken about the winch if the motor is used for the actuation. The torque calculated for run speed can be used to determine the force at the end of the cable, and the diameter is determined accordingly.

The radius of the output winch $r_{w,o}$ can be computed as a function of the needed output force Fout, taking into account a security factor S and the radius of the pinion up. This calculation is based on the maximum rope tension, the efficiency of the transmission system ηt, and the rack and pinion efficiency $\eta r\ p$:

$$rw, o \geq \frac{S \times F_{out} \times rp}{Fr, \max \square \times \eta t \times \eta rp}$$

where S is the security factor and rp is the radius of the pinion.

The rack is scaled proportionally in width and height to ensure sufficient output force Fout, and in length for the required stroke.

The output force Fout at the rack is related to the torque at the input winch τin according to:

$$F_{out} = \frac{\exp(-\mu \times \sigma) \times rw \times \eta}{rw, i \times rpi} \times r_{in}$$

Where,

μ= coefficient of friction;

σ=bending angle of the Bowden Cable;

rw,o= radius of the output winch;

rw,i= pitch radius of pinion;

η= efficiency of rack-and-pinion mechanism.

Transmission and Electronics

The exoskeleton is actuated by the use of 2 DC linear actuators along with four DC Linear actuators that will transmit force to the fingertips by use of the Bowden cables. The maximum transmission output force is between 25N-35N. The motors are light and compact which helps decrease the load on the back as well. The motors are held into place by the use of 3D-printed PLA plastic mountings with a cover. The actuation pack is 175x79x18 mm.

The electronics design comprises three main components: a main control board, a peripheral sensor board, and an interface device. The main control board utilizes a commercially available microcontroller board to manage wireless communication with the interface device and UART communication with the peripheral sensor board. It also controls motor operations through motor drivers. The control electronics and motors are powered by a 7.2 V, 1700 mAh Li-ion battery which, under heavy use, draws an average current of 500 mAh, providing a battery life of approximately 2.5 hours.

During testing, a PC is used to interface between the user and the device. Sensor data from the peripheral board, EMG inputs, and actuator positions are sent to the computer for storage or viewing. The PC can also issue motion commands directly to the device, which was the control method used for all testing. Communication between the PC and the main board is facilitated by a wireless radio transmitter. The electronics pack attached to the actuator pack to the back is 83 x 114 x 46.

3.2.2. Electromyographic Control

To mitigate the risk of learned non-use among individuals with neuromotor hand impairments, it is imperative to sustain rehabilitative efforts and promote ongoing utilization of the affected hands following discharge from clinical care. Within this context, the integration of robotic hand exoskeletons designed for daily living assistance holds considerable promise, not only for facilitating sustained hand usage but also for continuously perpetuating rehabilitation efforts. The incorporation of intuitive control mechanisms grounded in physiological signals represents a particularly auspicious avenue for enhancing the therapeutic efficacy of such interventions. Nevertheless, the implementation of such control systems often entails significant logistical challenges, including the need for extensive cabling, precise electrode placement, and the establishment of connections with external computing resources.

In our assistive hand exoskeleton, control commands governing the actuators stem from surface electromyography (EMG) signals. These signals are captured by surface electrodes strategically positioned on various muscles of the arm, hand, and shoulder, with their placement determined by the individual's residual motor function post-cervical cord injury. For instance, a C5 injury typically retains shoulder and elbow flexor innervation, while a C6 injury preserves wrist extensor function, and a C7 injury sustains elbow extensor function.

The EMG electrodes interface with a low-noise instrumentation amplifier (INA128, Texas Instruments Inc., Dallas, TX, USA), after which the EMG signals undergo bandpass filtering (10 to 500 Hz) and amplification (1000 times) via an operational amplifier (OPA188, Texas Instruments Inc., Dallas, TX, USA). Subsequently, a microcontroller (STM32F103, STMicroelectronics, Geneva, Switzerland) digitizes the signals to facilitate real-time biosignal processing aimed at identifying the most probable intended hand motion (see Figure).

Electromyography (EMG) serves as a method for recording and analyzing the electrical activity generated by muscles. In the context of assistive hand exoskeletons, EMG sensors are positioned on the skin's surface above the forearm muscles responsible for hand movement control. These sensors detect muscle contraction-induced electrical signals, which occur when the user intends to manipulate their hand or fingers.

The amplified and processed EMG signals yield valuable insights into the user's muscle activity. This processed data informs the control of the exoskeleton's actuators, which emulate natural hand movements. Typically implemented on a microcontroller, the control algorithm interprets the EMG signals to ascertain the user's intent, subsequently actuating the exoskeleton accordingly.

Microcontrollers, exemplified by the Arduino Mega2560 R3, are prevalent in assistive hand exoskeletons due to their real-time sensor data processing and actuator control capabilities. These microcontrollers receive processed EMG signals from the sensors, utilizing them to compute the desired exoskeleton movements. Consequently, the microcontroller dispatches control signals to the actuators, typically DC motors, to maneuver the exoskeleton's mechanical components and facilitate the user's hand movements.

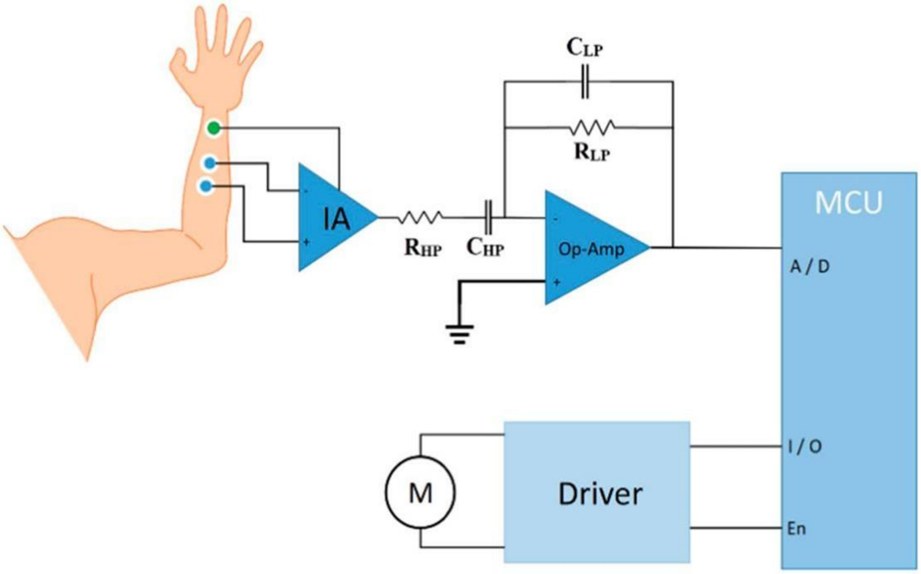


Figure 19: Schematics of the EMG control module.

The incorporation of EMG sensors and microcontrollers into assistive hand exoskeletons facilitates an intuitive and seamless interaction with the device, affording users a sense of naturalness and ease. This technological integration holds significant potential for enhancing the quality of life for individuals grappling with hand impairments, offering them increased autonomy and mobility.

In terms of bio-signal processing, a linear envelope detection approach is employed. Initially, the EMG signal undergoes rectification (|Xi|), followed by smoothing according to the equation:

$$\boldsymbol{MA_n = \sum_{i=1}^{n} \frac{1}{n} D_i}$$

where n is the number of periods in the moving average and Di is the demand in period i.

The control mechanism governing grasping relies on the maximum voluntary contraction (MVC) signals and is triggered by an adjustable threshold. Upon surpassing the predetermined MVC amplitude, a signal is dispatched to the driver circuit (DRV8833, Texas Instruments Inc., Dallas, TX, USA) to engage the motors, thereby initiating either a grasping or hand-opening action.

3.4. Final Design

3.4.1. Finger Mechanism / three-layered spring mechanism

The final design implemented for the finger mechanism follows the same as discussed in section 3.3.1. The three-layered spring mechanism as initially proposed by Arata et al. The finger guides were designed using the provided formulas for lengths and dimensions. The final dimensions were as per the 95th percentile male hand and were initially designed as individual parts in SolidWorks to be 3D printed in PLA. However, the individually printed parts drastically increased assembly complexities and decreased link strength. The links were then redesigned for simplicity.

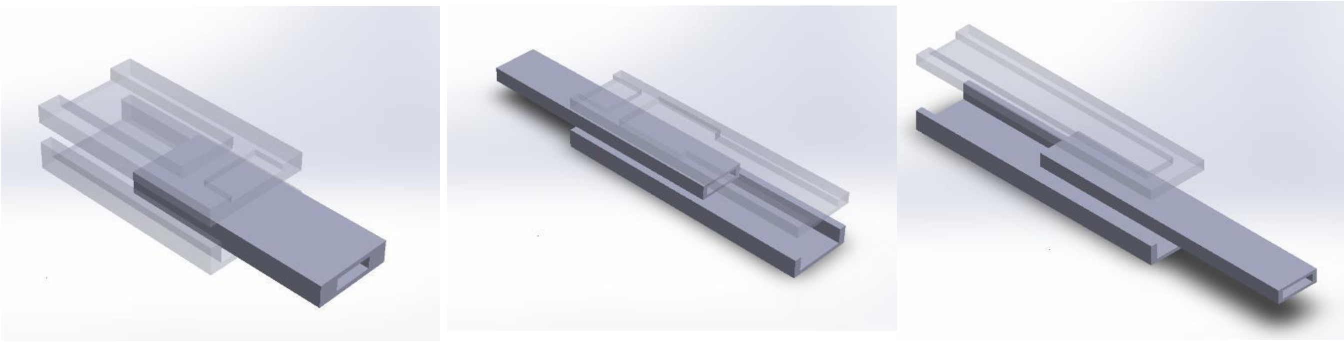


Figure 20. ***(Left to right) Exploded view of redesigned finger guides for middle phalanx, exploded view of redesigned finger guides for proximal phalanx, exploded view of redesigned finger guides for metacarpals.***

The new design included each guide as an assembly of three parts – the inner sleeve for the middle spring (actively sliding spring), the base housing the fixed spring, and the sleeve and the cover that houses the top spring (passively sliding spring). It is to be noted that the previous design was based on an assembly of 6 different parts. The new parts were reprinted in PLA.

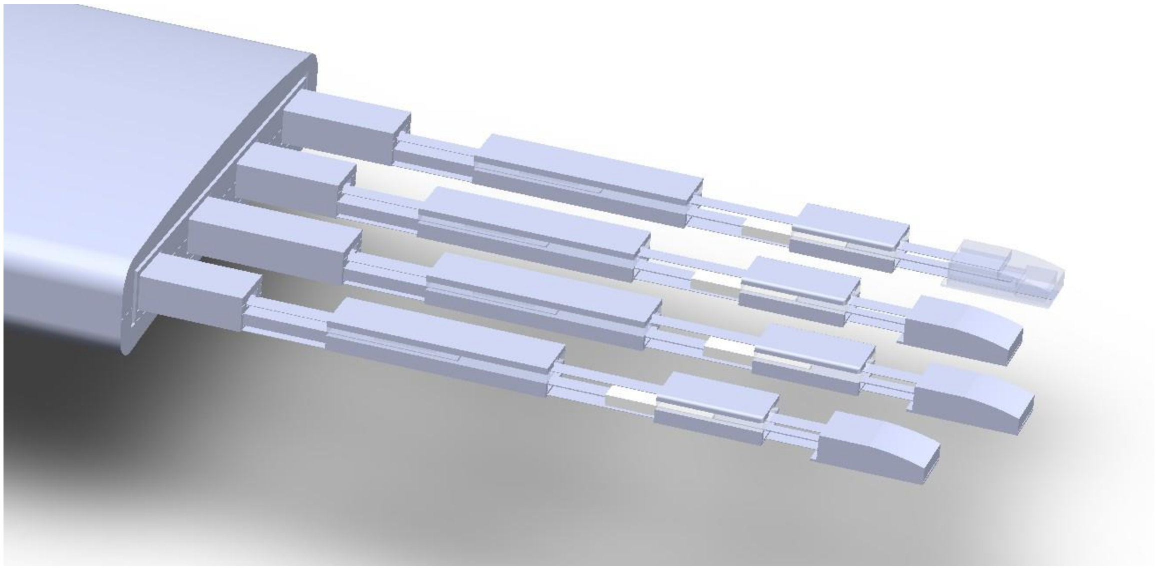


Figure 21. Final CAD model: Finger assembly.

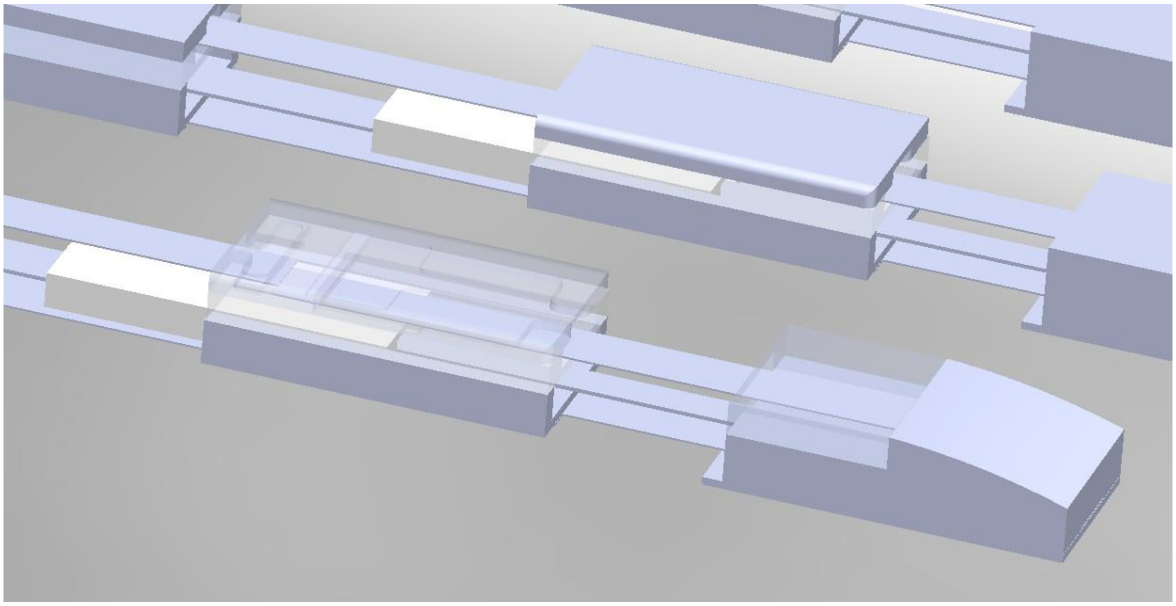


Figure 22. Final CAD Model: Close up of finger guides under partial transparency.

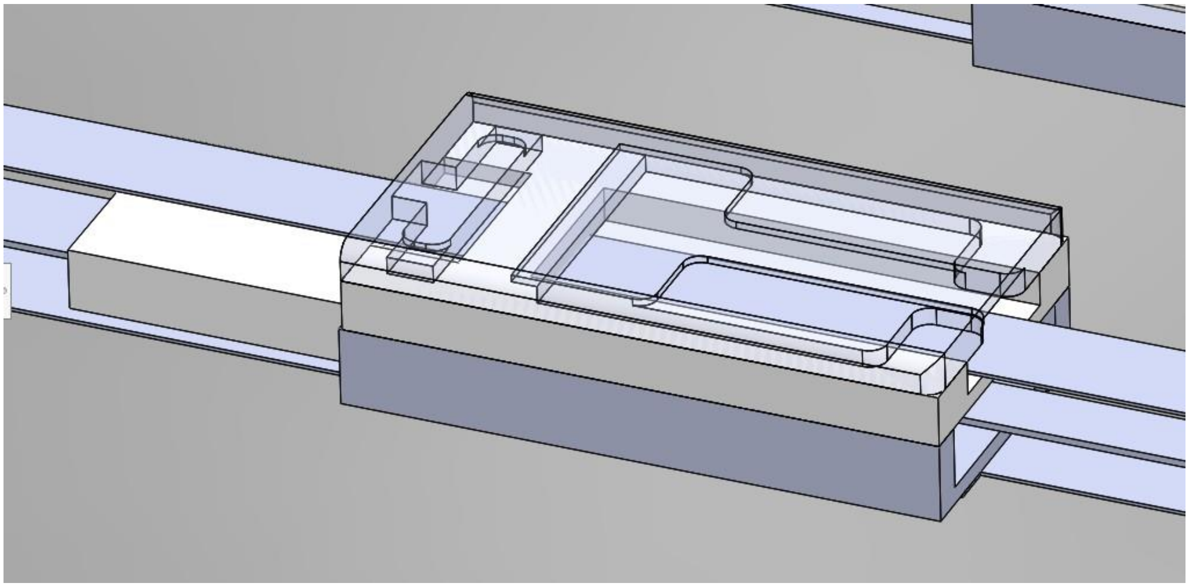


Figure 23. Final CAD Model: Assembly of middle finger guide and springs under partial transparency.

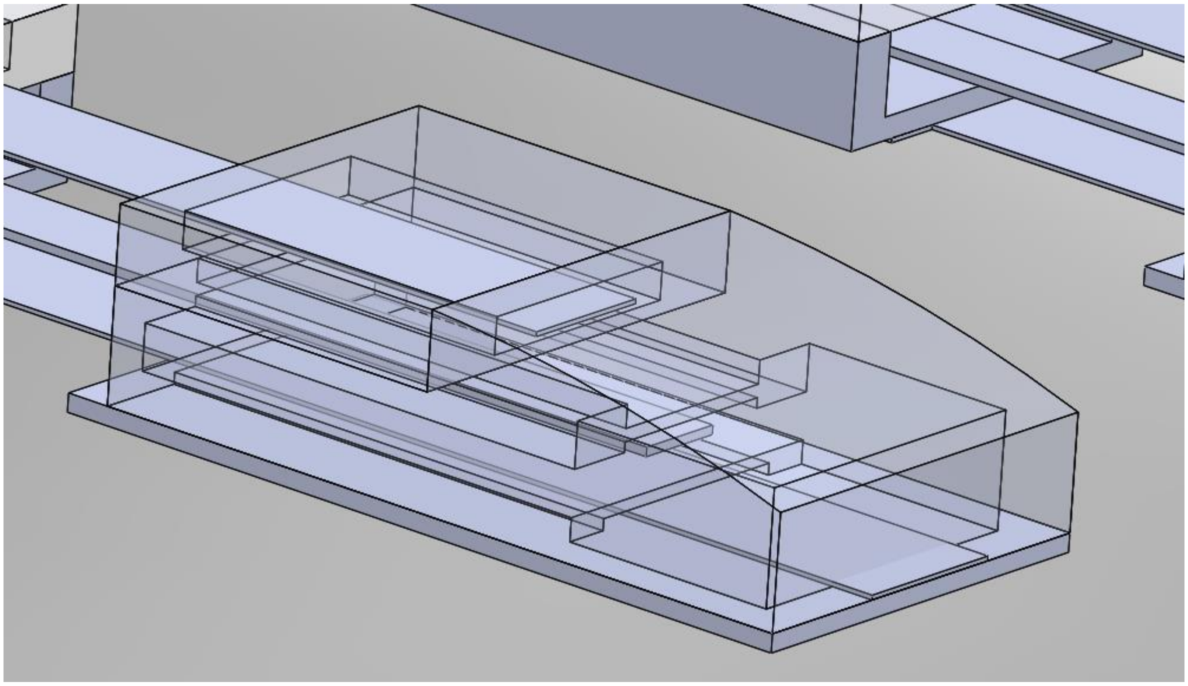


Figure 24. Final CAD Model: Assembly of distal phalanx/ finger guide under partial transparency.

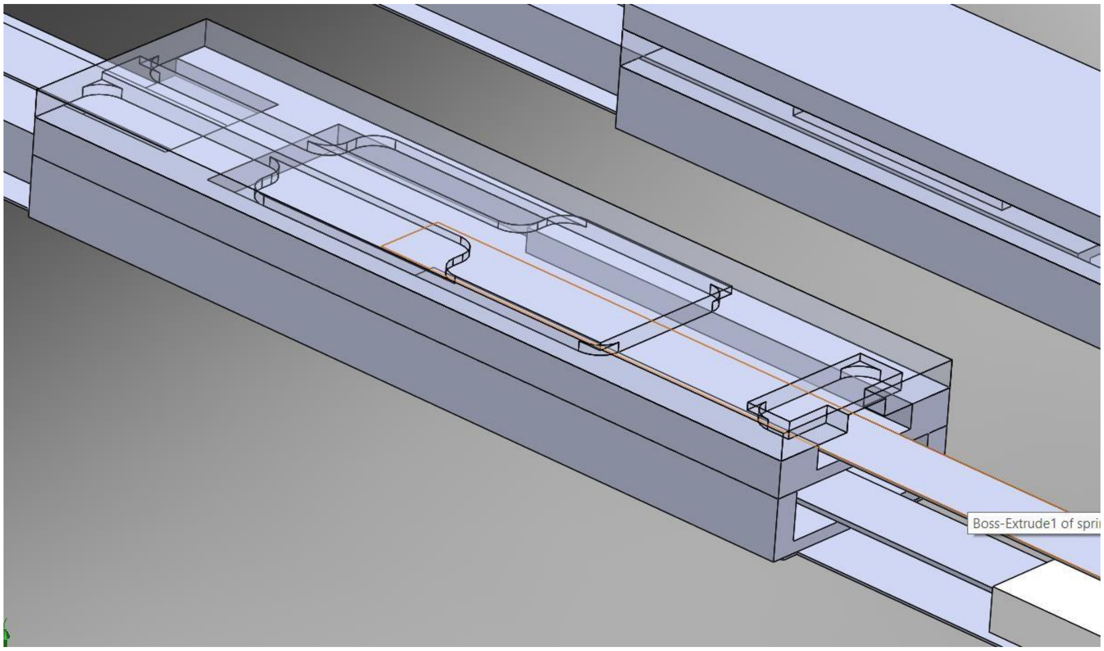


Figure 25. Final CAD Model: assembly of distal phalange/finger guide under partial transparency.

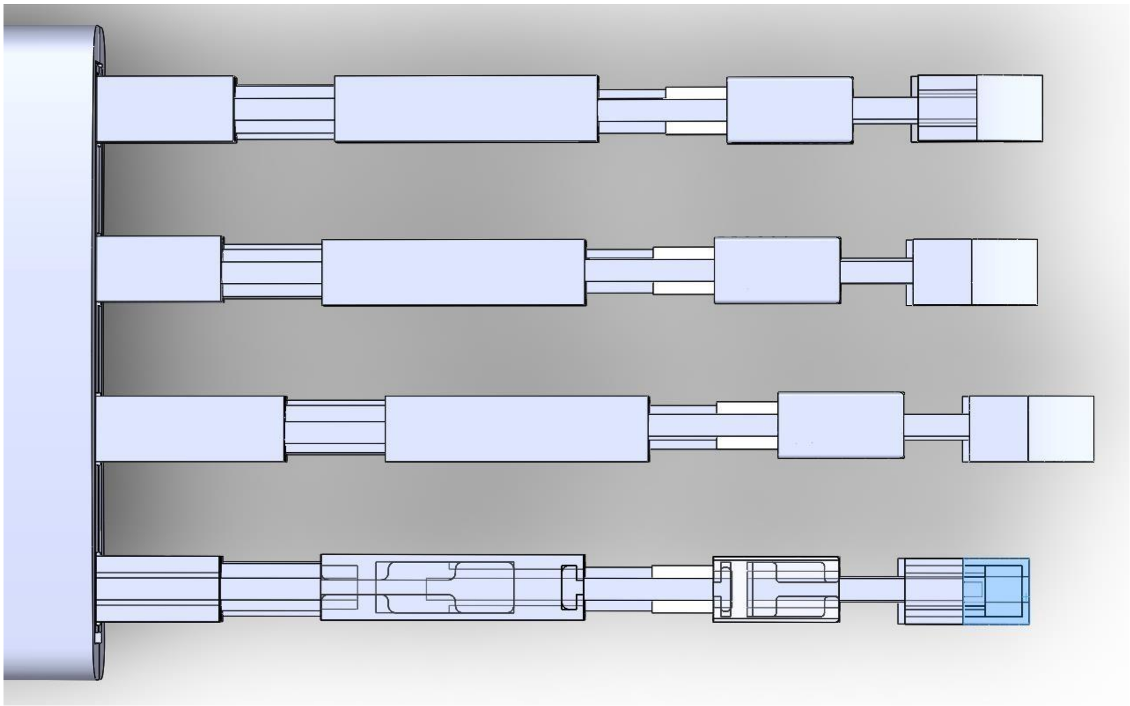


Figure 26. Final CAD Model: Assembly of all fingers connected to the hand module via the metacarpal links.

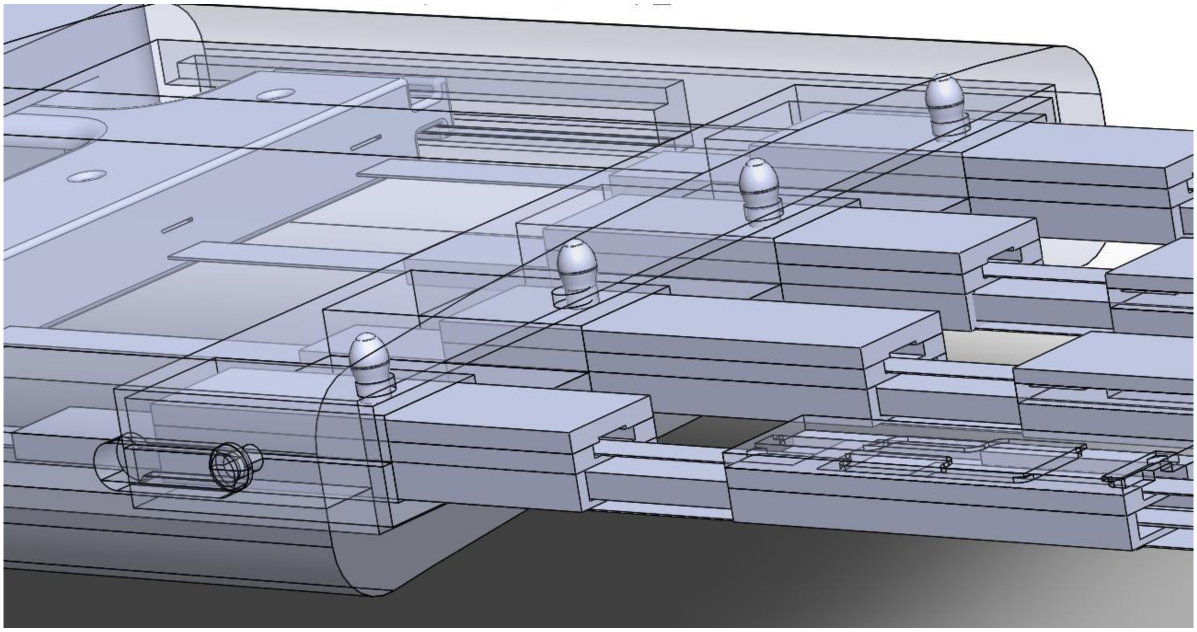


Figure 27. Final CAD Model: Detail of fingers connected to the T-bar shown under partial transparency.

3.4.2. Remote Actuation System

The remote actuation system saw major changes due to the lack of availability of resources and materials. After a thorough market analysis, preassembled motorbike brake cables and car clutch cable assemblies were used instead of high-test Bowden cables.

The Bowden cable assemblies were then connected to a set of customized winches. One is located in the actuation pack mounted onto the DC motor shaft and the other winch is attached to a pinion mated to a rack on the wrist module. The push-pull Bowden cables transmit the motor rotation from the actuation pack winch, through the cables to the hand winch which in turn drives the pinion.

The rack and pinion assembly located in the wrist module is connected to a slotted Tbar at the distal end of the rack. The bar is engaged with the middle layer of free-sliding springs of the finger mechanism. The proximal finger guide is then held constraint on the wrist module so when the entire system is actuated, rotational motion is converted to linear, and the linear motion, traveling through the rack is transmitted onto the three-layered sliding spring mechanisms which again convert one DOF linear mechanism into rotation motion over the DIP and PIP.

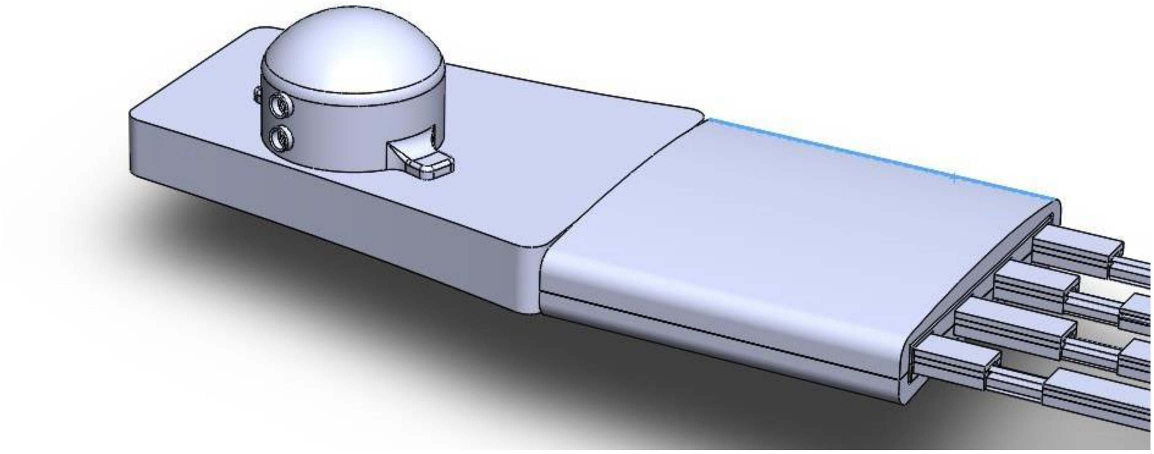


Figure 28. Final CAD Model: Hand module winch

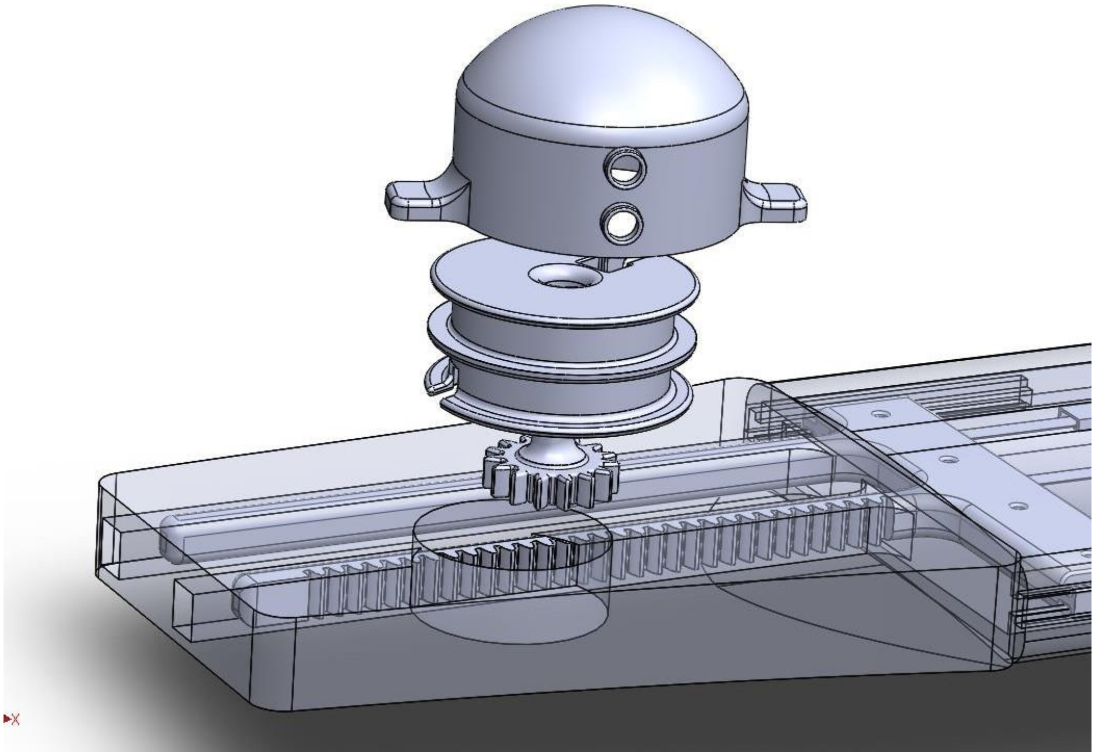


Figure 29. Final CAD Model: Hand module winch and transmission system exploded view. The pinion is mated to the sloted T-bar and is connected to the winch on the other end. The whole assembly is housed in the winch cover and hand module casing.

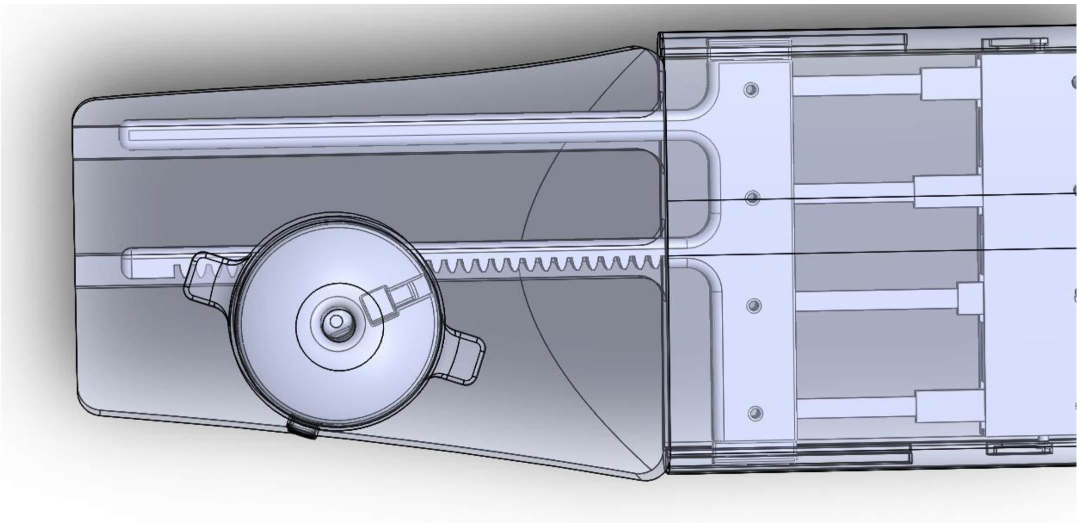


Figure 30. Final CAD Model: TOP VIEW of the transmission system under partial transparency.

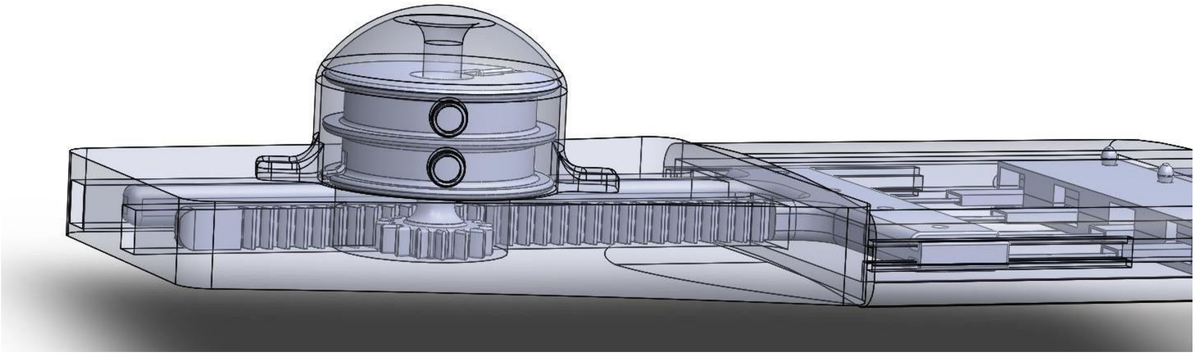


Figure 31. Final CAD Model: transmission system showing the mated rack and pinion system.

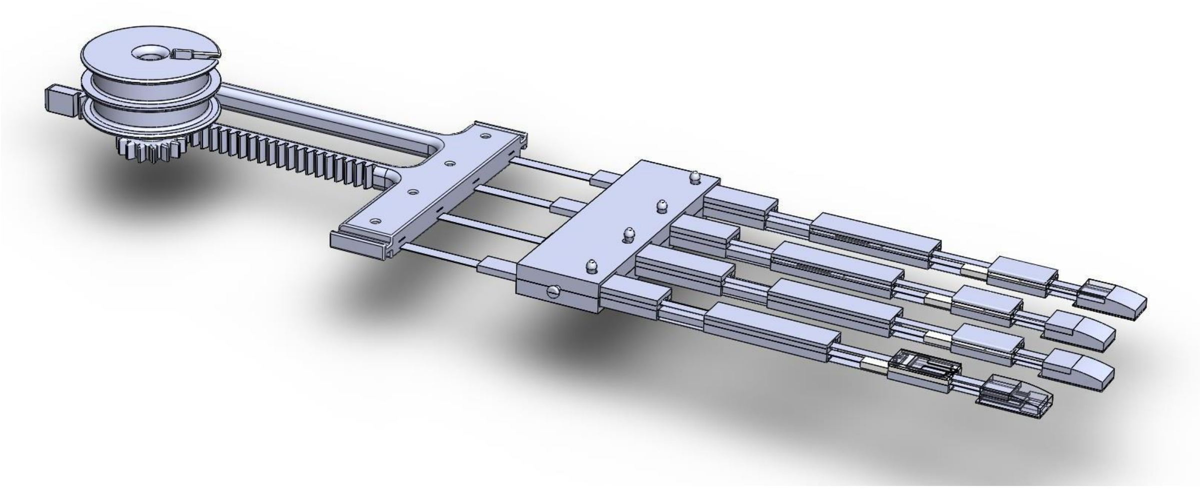


Figure 32. Final CAD Model: Inner mechanisms of hand module without housings and casings.

3.4.3. Motor Selection

A single-geared DC Motor is used to achieve the flexion and extension of the fingers to imitate the opening and closing of an actual hand. The motor provides high rpm that can be varied based on the task. The motor works accurately at a voltage rating of 12V. the Hennkwell is a 22mm diameter planetary gear brush motor that undergoes a smooth, quiet motion.

Specifications

- Operating Range: 6 to 24 V

- Dual Ball Bearings
- At 24Vdc: 142 RPM, no load. 113 RPM with load
- 6mm diameter ×14mm shaft with hole
- 2mm diameter shaft at the rear of the motor
- Overall length of motor and gearbox: 60mm
- Solder-lug terminals

Figure 33: Geared DC Motor

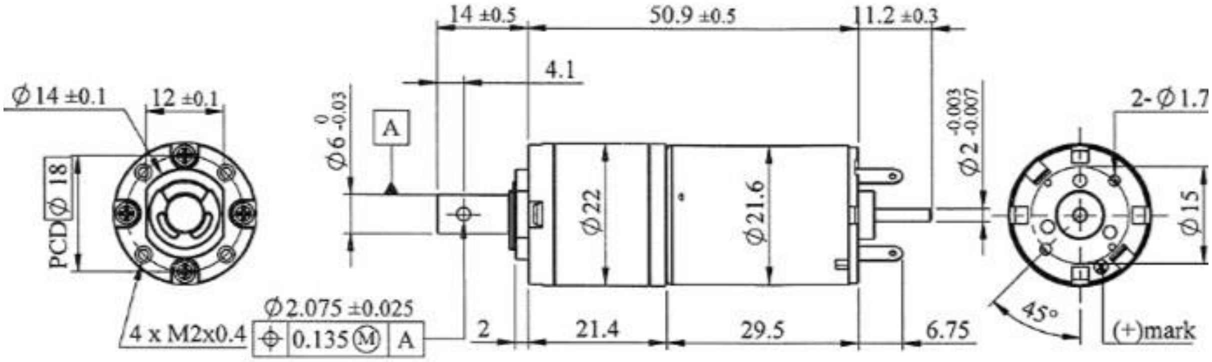


Figure 34: Motor Specifications

3.4.4. EMG Based Controls

After careful consideration surface EMG electrodes were chosen due to their noninvasiveness, ease of use, and compatibility with the design. The Advancer Technologies Muscle Sensor v3 was selected for its ease of integration and comparatively better signal-to-noise ratio. The sensor was tested to determine the reliability and understand the threshold that will have to be set to finalize the code.

Figure 35: EMG Sensor

Figure 36: Sensor Connections

The raw EMG signal obtained from the signal in real-time is filtered to reduce the noise and then the signal is amplified to attain more manageable readings. The processing algorithms were fine-tuned through repeated iterations and a feedback mechanism was incorporated to ensure real-time data reading and operation. The EMG control system underwent calibration to optimize the exoskeleton’s performance and accuracy for the individual users.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1. Finger Mechanism and testing

The finger mechanism was tested with an emphasis on assessing its performance in terms of multiple metrics, including opening and closing, finger position adjustment, and support for gripping activities involving a variety of items of varied sizes and shapes. The study employed quantitative measurements to evaluate factors like force exertion, speed of operation, and range of motion, and qualitative assessments to get insights into usability and user experience.

Test results showed that the three-layered spring system successfully provided controlled and smooth finger movements, enabling accurate object manipulation and grabbing. The mechanism exhibited sufficient force output to grip objects with different weights, and the elastomeric layers' elasticity allowed for adjustment to the shapes and curves of the objects.

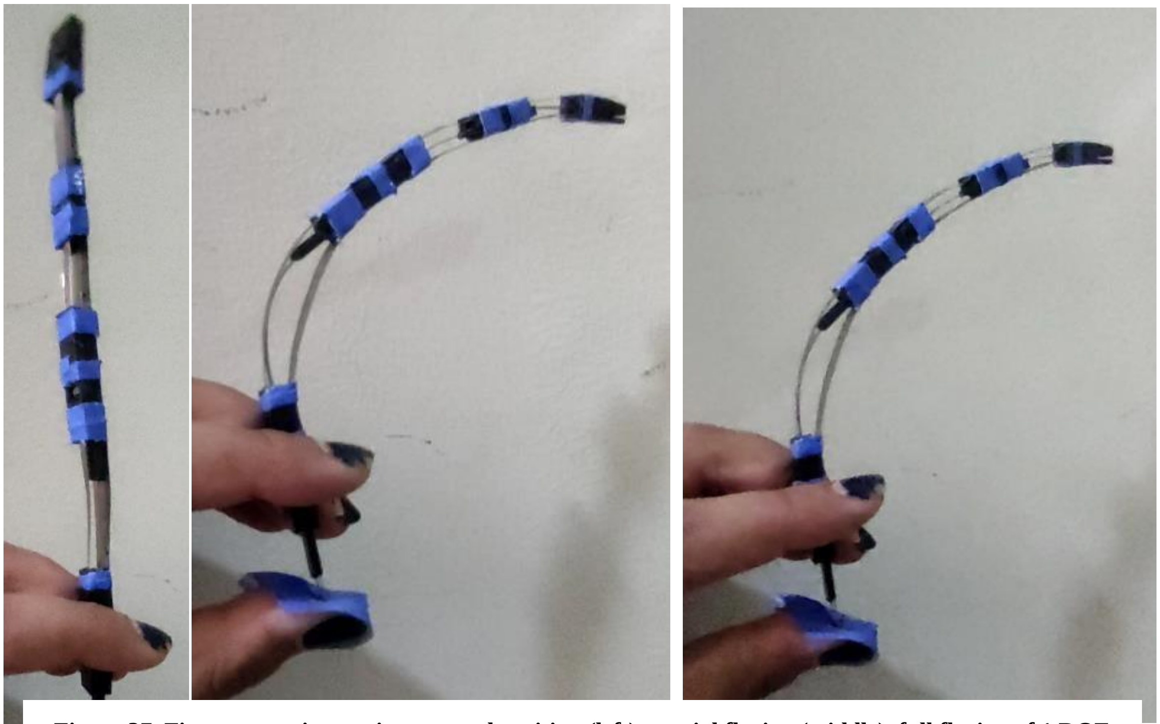


Figure 37. Finger actuation testing. neutral position (left), partial flexion (middle), full flexion of 1 DOF transformed over 3 joints via linear springs(right)

4.2. EMG Controls with Arduino UNO

The Hand Exoskeleton is controlled using the Arduino UNO which enables us to find the range of motion attainable and the motor rotation required for acceptable motion. The muscle sensor has 3 electrodes (Red, Green, and Yellow) that attain signals from the muscles in the forearm. The red and green electrodes are placed on the muscle whose signals we want to attain and the yellow electrode is placed on the bony part of the forearm i.e. just below the elbow. The sensor is connected to the Arduino Uno by connecting the SIG pin on the sensor to pin A0 on the Arduino as well as connecting the grounds. Signals are sent to the Arduino Uno then processes the signal, filters it, and compares the signal obtained from the threshold. The motor driver is connected to the Arduino such that the Arduino pins 7, 8, and 9 are connected to the IN1, IN2, and ENA pins on the driver. The driver is then connected to the motor by the OUT1 and OUT2 pins to the motor terminals. Once all these connections are made, a common ground is established.

When the EMG Sensor receives a signal from the hand, it sends it to the Arduino, the Arduino compares the received signal with the threshold signal. Upon comparison, it determines the direction of motion of the motor if the motor needs to be turned on. The respective signal is sent to the motor driver who will start the motor in the required direction

***Circuit Diagrams*:**

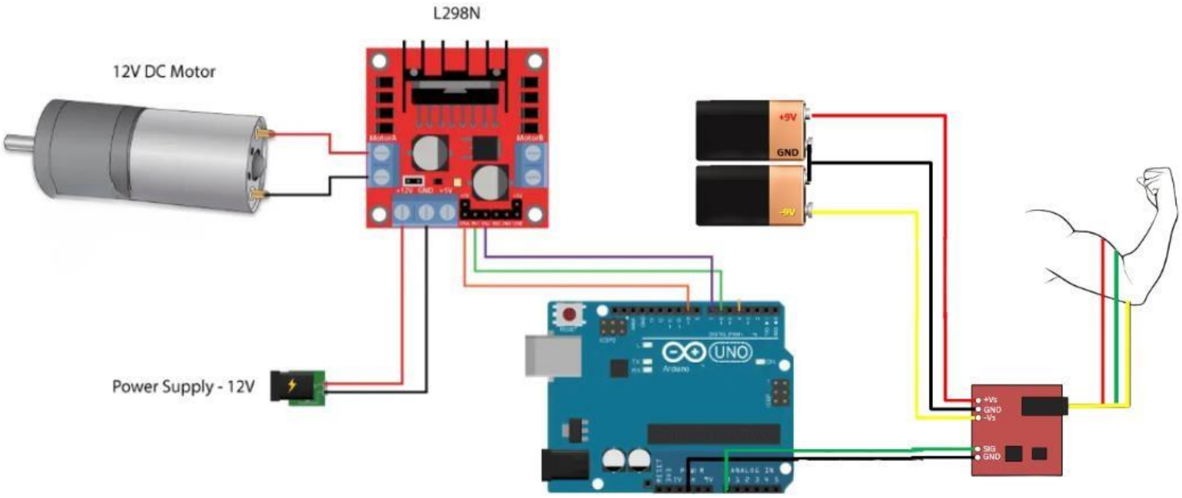


Figure 38. Circuit Diagram for control system.

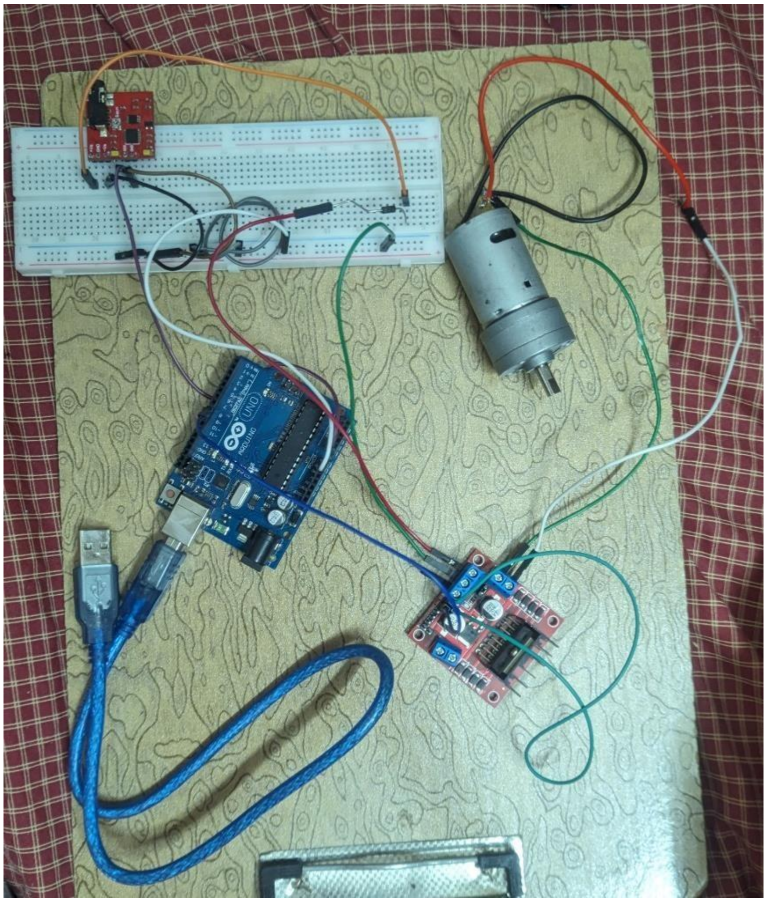


Figure 39: Working Circuit

The readings from the EMG Sensors were obtained in Excel as follows:

Table 5: Emg Sensor Readings

Reading	Reading	Reading	Reading
1023 (sensor not connected)	202 (fist closed)	22 (fist open)	21 (fist open)
1023 (sensor not connected)	224 (fist closed)	24 (fist open)	25 (fist open)
1023 (sensor not connected)	265 (fist closed)	25 (fist open)	203 (fist closed)
1023 (sensor not connected)	198 (fist closed)	30 (fist open)	256 (fist closed)
1023 (sensor not connected)	190 (fist closed)	34 (fist open)	30 (fist open)
1023 (sensor not connected)	90 (fist closed)	31 (fist open)	36 (fist open)
174	83	26 (fist open)	

Final Prototype Testing

After testing the Hand Exoskeleton without the sensor attached, the working of the mechanism was confirmed. Similarly, the sensor was tested without the hand to determine that both the components were in working condition because of assembly. Upon assembly, the hand was tested to determine the accuracy of the sensor and the movement of the fingers. It was determined that the mechanism contains a 1-second delay in the function.

The Bowden cable assembly works effectively and accurately when the motor begins and the losses, though present are already catered for in the calculations therefore, the final output is as expected.

Application Scenarios

The hand exoskeleton designed has promised to carry out assistive tasks that enhance an individual’s mobility, quality of life, and thereby independence. The exoskeleton can assist in basic household tasks that require grasping and movement. Furthermore, the exoskeleton can be used in rehabilitation therapy for patients with hand weaknesses after a stroke. The prototype can provide a range of motion that can aid individuals in regaining finger dexterity and improving grasping ability. This can be achieved through a range of ADLs, rehabilitation exercises, and occupational tasks.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1. Key Contributions and Strengths

The three-spring system introduces an innovative approach to vibration and backlash reduction, potentially enhancing user experience and safety.

Integration of EMG signals for actuation personalizes force delivery and promotes intuitive control, aligning with the growing trend of user-centric rehabilitation technologies.

The Bowden cable transmission system offers advantages in terms of flexibility and compactness, facilitating potential integration into various hand functionalities.

The integration of electromyography (EMG) sensors in assistive hand exoskeletons represents a significant advancement, enabling real-time control without the need for bulky controls or buttons. This intuitive and natural control can be further personalized through machine learning algorithms, adapting to individual muscle activation patterns and preferences. By analyzing EMG signals, these exoskeletons can minimize fatigue and optimize performance, enhancing the user experience and promoting independence.

The three-layered sliding spring mechanism used in the design adds a crucial element of functionality and safety. This mechanism, comprising inner, center, and outer springs, mimics the kinematic chain of human fingers, ensuring a natural bending motion. The use of cheap and readily available materials, such as hardened, cold-rolled stainless steel for the springs and 3D-printed ABS filament for the rigid links, makes the exoskeleton affordable and accessible.

5.2. Way Forward

As we look ahead, there are several avenues for further enhancing the capabilities and applicability of the developed hand exoskeleton. The following sections outline potential directions for future research and development:

In summary, the future development of the hand exoskeleton involves expanding its capabilities through thumb and wrist actuation, improving control accuracy with advanced EMG algorithms, and validating its effectiveness through rigorous clinical trials. These endeavors aim to create a more versatile, intuitive, and clinically validated assistive device that enhances the mobility, independence, and quality of life of individuals with hand impairments.

5.2.1. Thumb Actuation

While the current design focuses primarily on the fingers, integrating thumb actuation into the exoskeleton presents an exciting opportunity to expand its functionality. The thumb plays a crucial role in hand dexterity and grip strength, enabling tasks such as precision grasping and tool manipulation. By incorporating mechanisms for thumb movement and control, we can create a more comprehensive assistive device that better mimics the natural hand's capabilities. This addition would involve designing a thumb mechanism compatible with the existing finger mechanism and implementing intuitive control strategies to synchronize thumb and finger movements effectively.

5.2.2. Wrist Actuation

Incorporating wrist actuation into the exoskeleton can further enhance its versatility and utility across a wider range of activities. Wrist movements are essential for tasks such as orientation adjustment, object manipulation, and tool usage. By enabling controlled wrist articulation, users can perform more intricate movements with greater precision and efficiency. This addition would require developing a mechanism to support wrist flexion, extension, abduction, and adduction while maintaining ergonomic comfort and natural movement patterns. Integrating wrist actuation will broaden the exoskeleton's application domain, making it suitable for a diverse range of tasks and environments.

5.2.3. Expanding on Intuitive Control with Higher Accuracy EMG controls

The integration of electromyography (EMG) signals for intuitive control represents a significant advancement in assistive technology. However, there is room for improvement in terms of control accuracy and responsiveness. Future efforts should focus on refining the EMG control algorithms to achieve higher accuracy and reliability in translating user intent into precise hand movements. This may involve incorporating machine learning techniques to adaptively learn and adapt to individual user patterns and preferences. By enhancing the accuracy of EMG-based control, we can provide users with a more intuitive and seamless interaction experience, ultimately improving their overall satisfaction and usability of the exoskeleton.

Future advancements in EMG-based control systems hold great promise and improve reliability, accuracy, and usability. However, in case of corruption of signal, the user may end up practicing the wrong activation pattern. The aim is to achieve greater accuracy and precision in user muscle signals to hand movements. By carrying out advanced signal processing techniques, real-time pattern recognition and muscle activity classification is achieved for finer hand movement control. The use of better, more accurate EMG sensors with advanced sensor arrays and electrode designs offers an improved signal-to-noise ratio, spatial resolution, and enhanced sensitivity and responsiveness. Incorporating closed-loop feedback systems such as visual or haptic feedback provides users with real-time information on muscle activation for further refined control strategies and precise manipulation of tasks.

5.2.4. Clinical Trials

To evaluate the efficacy and safety of the created hand exoskeleton, clinical trials with people who have hand impairments are required. Clinical trials will give important information on the device's performance in real-world scenarios, its impact on user functionality and quality of life, and any potential hazards or limitations.

We reached out to the National Institute of Rehabilitation and Medicine, a workshop on prosthetics and orthotics for healthcare provider insight and user requirements. The clinical trials are to be carried out at the same institutions and are one of the upcoming milestones moving forward.

We can build thorough clinical study protocols with healthcare professionals and rehabilitation institutions to examine the exoskeleton's therapeutic advantages and refine its design and functioning depending on user feedback and clinical outcomes. Successful clinical trials will eventually lead to regulatory approval and widespread use of the exoskeleton as standard rehabilitation and assistive equipment for people with hand disabilities.

REFERENCES

[1] Bodin J., Nambiema A., Evanoff B. (2021). Proportion and Number of Upper-Extremity Musculoskeletal Disorders Attributable to the Combined Effect of Biomechanical and Psychosocial Risk Factors in a Working Population. *National Library of Medicine.*

[2] Almomani F., Alghwiri A., Alghadir A., Almomani., Iqbal A. (2019). Prevalence of upper limb pain and disability and its correlates with demographic and personal factors. *Journal of Pain Research 2019:12 2691–2700*

[3] Shahid T., Gouwanda D., Nurzaman S G., Gopalai A A. (2018). Moving toward Soft Robotics: A Decade Review of the Design of Hand Exoskeletons. *School of Engineering, Monash University Malaysia.*

[4] O. Jones, "Anatomical Planes," 2018. [Online]. Available: https://teachmeanatomy.info/the-basics/anatomical-terminology/planes/.

[5] M. Patel and M. Varacallo, Anatomy, Shoulder and Upper Limb, Forearm Bones. 2020.

[6] D. Morton and K. Albertine, Gross Anatomy- The Big Picture. 2011.

[7] S. Standring, Gray's Anatomy E-Book: The Anatomical Basis of Clinical Practice. 2016

[8] Bailey R. (2019). Anatomical Directional Terms and Body Planes. *ThoughtCo.*

[9] McGraw S. (2014). Biomechanics for Dummies. *John Wiley & Sons. Vol 1.* https://www.thoughtco.com/anatomical-directional-terms-and-body-planes-373204

[10] Image from (2019). Grasp -General Responsibility Assignment Software Patterns Explained. https://www.kamilgrzybek.com/blog/posts/grasp-explained

[11] Starr, M. (2014). *Harvard wants everyone to build soft robots.* CNET. https://www.cnet.com/science/harvards-soft-robotics-toolkit-robots-for-everyone/

[12] Image from *Maestro Hand Exoskeleton.* RenoRobotics Lab. https://reneu.robotics.utexas.edu/maestro-hand-exoskeleton-0

[13] Image Taken from Langnau, L. (2012). *3D Printing technology helps build service robot exoskeletons*. Make Parts Fast. https://www.makepartsfast.com/3d-printing-technology-helps-build-service-robot-exoskeleton/

[14] Image taken from Selinger A. (2007). *Standard Anatomical Position.*The Human Bone Manual, 2005. ScienceDirect. https://www.sciencedirect.com/topics/medicine-and-dentistry/standard-anatomical-position

[15] Image taken from Pena-Pitarch E. (2010). *Virtual Human Hand: Grasping Strategy and Simulation.* Academic Dissertion for the Degree of PhD. https://www.researchgate.net/publication/279493096_Virtual_Human_Hand_Grasping_Strategy_and_Simulation/figures?lo=1

[16] Image taken from Gassert R., Dietz V. (2018). *Rehabilitation robots for the treatment of sensorimotor deficits: a neurophysiological perspective.* Journal of NeuroEngineering and Rehabilitation. https://jneuroengrehab.biomedcentral.com/articles/10.1186/s12984-018-0383-x

[17] World Health Organization. *Congenital disorders.* https://www.who.int/health-topics/congenital-anomalies#tab=tab_1

[18] Image taken from *Pneumatic Actuator.* Electronics Coach. https://electronicscoach.com/pneumatic-actuator.html

[19] Image taken from *What is a Hydraulic Actuator?* Inst Tools. https://instrumentationtools.com/what-is-a-hydraulic-actuator/

[20] Image taken from (2021). *Part 2:Components of an Electric Linear Actuator.* TiMOTION. https://www.timotion.com/en/news-and-articles/part-2-components-of-an-electric-linear-actuator

[21] Image taken from Bone G M., Chen X. (2012). *Position control of hybrid pneumatic-electric actuators.* American Control Conference (ACC), 2012. https://www.researchgate.net/figure/Design-of-the-hybrid-actuator_fig1_261158493

[22] *Hand of Hope.* Exoskeleton Report. https://exoskeletonreport.com/product/hand-of-hope/

[23] *What is MyoPro Orthosis?* Myomo. https://myomo.com/what-is-a-myopro-orthosis/

[24] *Carbonhand.* Bioservo. https://www.bioservo.com/products/carbonhand

[25] *Smart Glove – Rebuilding Your Life With Your Hands.* Neofectt. https://www.neofect.com/us/smart-glove

[26] Image taken from FUYU Advantages. https://www.fuyumotion.com/news/what-are-can-stack-linear-actuators/

[27] Image taken from https://www.orientalmotor.com/images/stepper-motors/5-phase-stepper-motor-cross-section.jpg

[28] Image taken from *Leading DC Motor Manufacturers.* AutomationDirect. https://www.electric-motors.net/dc-motors/

[29] Image taken from *Servo Motor Fundamentals.* Islproducts. https://islproducts.com/design-note/servo-motor-fundamentals/

Abbasi, B., Noohi, E., Parastegari, S., and Žefran, M. (2016). Grasp taxonomy based on force distribution. 2016 25th IEEE International Symposium on Robot and Human Interactive Communication(RO-MAN),1098–1103

Andrianesis, K., & Tzes, A. (2008). Advancements in Heat-Driven Shape Memory Alloys for Remote Actuation. Journal of Intelligent Material Systems and Structures, 19(12), 1457-1472.

Andrianesis, K. and Tzes, A. (2008). Design of an anthropomorphic prosthetic hand driven by shape memory alloy actuators. In IEEE/RAS-EMBS Int. Conf. on Biomedical Robotics and Biomechatronics (Scottsdale, AZ, USA), vol. 2, 517–522

Arata, J., Ohmoto, K., Gassert, R., Lambercy, O., Fujimoto, H., and Wada, I. (2013). A new hand exoskeleton device for rehabilitation using a three-layered sliding spring mechanism. In IEEE Int. Conf. on Robotics and Automation (Karlsruhe, Germany), 3902–3907

Asbeck, A. T., De Rossi, S. M., Holt, K. G., and Walsh, C. J. (2015). A biologically inspired soft exosuit for walking assistance. Int. J. Rob. Res. 34, 744–762

Ates, S., Mora-Moreno, I., Wessels, M., and Stienen, A. H. (2015). Combined active wrist and hand orthosis for home use: Lessons learned. In 2015 IEEE International Conference on Rehabilitation Robotics (ICORR) (IEEE), 398–403

Atzori, M., Muller, H., and Baechler, M. (2013). Recognition of hand movements in a trans-radial amputated subject by sEMG. IEEE International Conference on Rehabilitation Robotics

Bae, J.-h. and Moon, I. (2012). Design and control of an exoskeleton device for active wrist rehabilitation. In Int. Conf. on Control, Automation, and Systems. 12, 1577–1580

Balasubramanian, S., Wei, H. R., Perez, M., Shepard, B., Koeneman, E., Koeneman, J., et al. (2008). Rupert: An exoskeleton robot for assisting rehabilitation of arm functions. In Virtual Rehabilitation (Vancouver, Canada), 163–167

Bangor, A., Kortum, P., and Miller, J. (2009). Determining what individual sus scores mean: Adding an adjective rating scale. Journal of Usability Studies 4, 114–123

Bechet, T., & Ohnishi, K. (2014). Application of Hydraulic Power Transmission Systems in Wearable Robotics. International Journal of Advanced Robotic Systems, 11(5), 79-91.

Benatti, S., Casamassima, F., Milosevic, B., Farella, E., Schönle, P., Fateh, S., et al. (2015). A Versatile Embedded Platform for EMG Acquisition and Gesture Recognition. IEEE Transactions on Biomedical Circuits and Systems 9, 620–630

Bhakta, B. B. (2000). Management of spasticity in stroke. British medical bulletin 56, 476–485

Bhardwaj, P., Nayak, S. S., Kiswar, A. M., and Sabapathy, S. R. (2011). Effect of static wrist position on grip strength. Indian Journal of Plastic Surgery: official publication of the Association of Plastic Surgeons of India 44, 55

Biddiss, E., Beaton, D., and Chau, T. (2007). Consumer design priorities for upper limb prosthetics. Disabil. Rehabil. Assist. Technol. 2, 346–357

Boser, Q. A., Dawson, M. R., Schofield, J. S., Dziwenko, G., and Hebert, J. S. (2018). Defining the design requirements for an assistive powered hand exoskeleton. bioRxiv

Bos, R. A., Haarman, C. J. W., Stortelder, T., Nizamis, K., Herder, J. L., Stienen, A. H. A., et al. (2016). A structured overview of trends and technologies used in dynamic hand orthoses. Journal of Neuro Engineering and Rehabilitation 13

Braido, P. and Zhang, X. (2004). Quantitative analysis of finger motion coordination in hand manipulative and gestic acts. Human movement science 22, 661–678

Bullock, I. M., Zheng, J. Z., Rosa, S. D. L., Guertler, C., and Dollar, A. M. (2013). Grasp frequency and usage in daily household and machine shop tasks. IEEE Transactions on Haptics 6, 296–308

Bundhoo, V., Haslam, E., Birch, B., and Park, E. J. (2009). A shape memory alloy-based tendon-driven actuation system for biomimetic artificial fingers, part i: design and evaluation. Robotica 27, 131–146

Burssens, A., Schelpe, N., Vanhaecke, J., Dezillie, M., and Stockmans, F. (2017). Influence of wrist position on maximum grip force in a post-operative orthosis. Prosthetics and Orthotics International 41, 78–84

Bützer, T. (2019). Fully Wearable Actuated Hand Exoskeleton for Assistance in Daily Life and Therapy (Diss. ETH No. 26010) [Doctoral dissertation, ETH Zurich].

Bützer, T., Lambercy, O., Arata, J., & Gassert, R. (2020). Fully Wearable Actuated Soft Exoskeleton for Grasping Assistance in Everyday Activities. Soft Robotics, 00(00). https://doi.org/10.1089/soro.2019.0135

Chen, L., Wang, X., and Xu, W. L. (2014). Inverse transmission model and compensation control of a single-tendon-sheath actuator. IEEE Trans. Ind. Electron. 61, 1424–1433

Chiri, A., Vitiello, N., Giovacchini, F., Roccella, S., Vecchi, F., and Carrozza, M. C. (2012). Mechatronic design and characterization of the index finger module of a hand exoskeleton for post-stroke rehabilitation. IEEE/ASME Trans. Mechatron. 17, 884–894

Choi, C. and Kim, J. (2007). A real-time EMG-based assistive computer interface for the upper limb disabled. In 2007 IEEE 10th International Conference on Rehabilitation Robotics, ICORR’07. 459–462

Cruz, E., Waldinger, H., and Kamper, D. (2005). Kinetic and kinematic workspaces of the index finger following stroke. Brain 128, 1112–1121

Cutkosky, M. R. et al. (1989). On grasp choice, grasp models, and the design of hands for manufacturing tasks. IEEE Transactions on robotics and automation 5, 269–279

Dinh, B. K., Cappello, L., Xiloyannis, M., and Masia, L. (2016). Position control using adaptive backlash compensation for Bowden cable transmission in the soft wearable exoskeleton. In IEEE/

Edwards, S. J., Buckland, D. J., and McCoy-Powlen, J. D. (2002). Developmental and functional hand grasps (Slack)

Festo(2012). Festo ExoHand,Festo. [Online]https://www.youtube.com/watch?v=EcTL7Hig8h4,

Fischer, H., Stubblefield, K., Kline, T., Luo, X., Kenyon, R., and Kamper, D. (2007). Hand Rehabilitation Following Stroke: A Pilot Study of Assisted Finger Extension Training in a Virtual Environment. Topics in Stroke Rehabilitation 14, 1–12

Gopura, R. and Kiguchi, K. (2008). A human forearm and wrist motion assist exoskeleton robot with EMG-based fuzzy-neuro control. Proceedings of the 2nd Biennial IEEE/RAS EMBSInternational Conference on Biomedical Robotics and Biomechatronics, BioRob 2008, 550–555

Gordon, K. E., Sawicki, G. S., and Ferris, D. P. (2006). Mechanical performance of artificial pneumatic muscles to power ankle–foot orthosis. J. Biomech. 39, 1832–1841

Guo, Z., Pan, Y., Wee, L. B., and Yu, H. (2015). Design and control of a novel compliant differential shape memory alloy actuator. Sens. Actuators, A 225, 71–80

Hadi, A., Alipour, K., Kazeminasab, S., Amerinatanzi, A., and Elahinia, M. (2016). Design and prototyping of a wearable assistive tool for hand rehabilitation using shape memory alloys. In Proc. of the ASME 2016 Conf. on Smart Materials, Adaptive Structures and Intelligent Systems (Stowe, USA), 1–7

Hazelton, F. T., Smidt, G. L., Flatt, A. E., and Stephens, R. I. (1975). The influence of wrist position on the force produced by the finger flexors. Journal of Biomechanics 8, 301–306

Hofmann, U. A., Bützer, T., Lambercy, O., and Gassert, R. (2018). Design and evaluation of a Bowden-cable-based remote actuation system for wearable robotics. IEEE Robotics and Automation Letters 3, 2101–2108

In, H., Kang, B. B., Sin, M., and Cho, K.-J. (2015). Exo-glove- a wearable robot for the hand with a soft tendon routing system. IEEE Robot. Automat. Mag. 22, 97–105

Jeong, U. and Cho, K.-J. (2016). A novel low-cost, large curvature bend sensor based on a Bowden cable. Sensors 16, 1–20

Jeong, U. and Cho, K.-J. (2017). A feasibility study on tension control of Bowden-cable based on a dual-wire scheme. In IEEE Int. Conf. on Robotics and Automation (Singapore: IEEE), 3690–3695

Jones, A., & Wang, B. (2019). Wire-Driven Soft Exoskeleton for Hand Rehabilitation. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2784-2789.

Kang, B. B., Choi, H., Lee, H., and Cho, K.-J. (2018). Exo-glove poly ii: A polymer-based soft wearable robot for the hand with a tendon-driven actuation system. Soft robotics

Kargov, A., Werner, T., Pylatiuk, C., and Schulz, S. (2008). Development of a miniaturized hydraulic actuation system for artificial hands. Sens. Actuators, A 141, 548–557

Khokhar, Z. O., Xiao, Z. G., Menon, C., and Others (2010). Surface EMG pattern recognition for real-time control of a wrist exoskeleton. Biomedical Engineering Online 9, 41

Kim, B., In, H., Lee, D.-Y., and Cho, K.-J. (2017). Development and assessment of a hand assist device: Gripit. Journal of Neuroengineering and Rehabilitation 14, 15

Kim, C., et al. (2020). Development of Pneumatically Actuated Soft Exoskeleton for Hand Rehabilitation. IEEE International Conference on Robotics and Automation (ICRA), 6185-6190.

Kwakkel, G. (2006). Rehabilitation Strategies for Stroke Patients. Neurorehabilitation and Neural Repair, 20(1), 167-171.

Lai, Y. J., Yeh, L. J., and Chiu, M. C. (2012). An experimental investigation on shape memory alloy dynamic splint for a finger joint application. Sens. Act

Lange, G., Lachmann, A., Rahim, A. H. A., Ismail, M. H., and Low, C. Y. (2015). Shape memory alloys as linear drives in robot hand actuation. Procedia Comput. Sci. 76, 168–173

Laurentis, K. J. D. and Mavroidis, C. (2002). Mechanical design of a shape memory alloy actuated prosthetic hand. Technol. Health Care 10, 91–106

Lawrence, E. S., Coshall, C., Dundas, R., Stewart, J., Rudd, A. G., Howard, R., et al. (2001). Estimates of the prevalence of acute stroke impairments and disability in a multiethnic population. Stroke 32, 1279–1284

Lucas, L., DiCicco, M., and Matsuoka, Y. (2004). An EMG-controlled hand exoskeleton for natural pinching. Journal of Robotics and Mechatronics 16, 482–488

Lund, A. M.(2001). Measuring usability with the use of a questionnaire12. Usability interface 8, 3–6

Masson, S., Fortuna, F. S., Moura, F. S., and Soriano, D. C. (2016). Integrating Myo Armband for the Control of Myoelectric Upper Limb Prosthesis. In XXV Congresso Brasileiro de Engenharia Biomédica- CBEB2016. 1–4

Martinez, A., et al. (2008). Pneumatic Power Transmission Systems for Wearable Robotics. Proceedings of the IEEE International Conference on Robotics and Automation.

McKenna, C., Peii, C., and Barrett, A. (2017). Stroke: Impact on Life and Daily Function. In: Chiaravalloti N., Goverover Y. (eds) Changes in the Brain (Springer, New York, NY)

Nazari, V., Pouladian, M., Zheng, Y.-P., & Alam, M. (2021). A Compact and Lightweight Rehabilitative Exoskeleton to Restore Grasping Functions for People with Hand Paralysis. Sensors, 21(6900). Retrieved from https://doi.org/10.3390/s21206900

Nishad, S. S., Saxena, A., and Dutta, A. (2015). Design and control of a three-finger hand exoskeleton for translation and rotation of a slender object. In ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (American Society of Mechanical Engineers), V05AT08A041–V05AT08A041

Noda, T., Teramae, T., Ugurlu, B., and Morimoto, J. (2014). Development of an upper limb exoskeleton powered via pneumatic electric hybrid actuators with Bowden cable. In IEEE Int. Conf. on Intelligent Robots and Systems. 3573–3578

Nycz, C. J., Bützer, T., Lambercy, O., Arata, J., Fischer, G. S., and Gassert, R. (2016). Design and characterization of a lightweight and fully portable remote actuation system for use with a hand exoskeleton. IEEE Robotics And Automation Letters 1, 976–983

Nycz, C. J., Delph, M. A., and Fischer, G. S. (2015). Modeling and design of a tendon-actuated soft robotic exoskeleton for hemiparetic upper limb rehabilitation. In Conf. Proc. IEEE Eng. Med. Biol. Soc. (Milan, Italy), vol. 37, 3889–3892

O’Driscoll, S. W., Horii, E., Ness, R., Cahalan, T. D., Richards, R. R., and An, K.-N. (1992). The relationship between wrist position, grasp size, and grip strength. The Journal of Hand Surgery 17, 169–177

Ottenbacher, K. and Jannell, S. (1993). The results of clinical trials in stroke rehabilitation research. Archives of Neurology 50, 37–44

Ouyang, X., Ding, S., Fan, B., Li, P. Y., and Yang, H. (2016). Development of a novel compact hydraulic power unit for the exoskeleton robot. Mechatronics 38, 68–75

Polygerinos, P., Wang, Z., Galloway, K. C., Wood, R. J., and Walsh, C. J. (2015b). Soft robotic glove for combined assistance and at-home rehabilitation.

Rob. Auton. Syst. 73, 135–143 Pryce, J. C. (1980). The wrist position between neutral and ulnar deviation facilitates the maximum power grip strength. Journal of Biomechanics 13, 505–511

Pylatiuk, C., Kargov, A., Schulz, S., and Döderlein, L. (2006). Distribution of grip force in three different functional prehension patterns. Journal of medical engineering & technology 30, 176–182

Roland, V. (2017). Arduino library and firmware for HM-11. https://github.com/vroland/MyoBridge, [Online]

Schweighofer, N., Choi, Y., Winstein, C., and Gordon, J. (2012). Task-oriented rehabilitation robotics. American Journal of Physical Medicine & rehabilitation 91, 270–279

Scheme, E., & Englehart, K. (2011). Myoelectric Intention Detection for Improved Control of Robotic Exoskeletons. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 19(6), 649-657.

Smith, J., et al. (2018). Design and Evaluation of a Soft Robotic Hand Exoskeleton for Assisting Activities of Daily Living. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 26(7), 1425-1433.

ThalmicLabs (2017a). Myo Gesture Control Armband | Wearable Technology by Thalmic Labs, Canada. [Online] https://www.myo.com/

ThalmicLabs (2017b). Thalmic Labs Bluetooth protocol for Myo armband. Thalmic Labs, Canada. [Online]https://github.com/thalmiclabs/myo-bluetooth

Troncossi, M., Mozaffari-Foumashi, M., and Parenti-Castelli, V. (2016). An original classification of rehabilitation hand exoskeletons.

Veale, A. J. and Xie, S. Q. (2016). Towards compliant and wearable robotic orthoses: A review of current and emerging actuator technologies. Medical Engineering and Physics 38, 317–325

Vergara, M., Sancho-Bru, J., Gracia-Ibáñez, V., and Pérez-González, A. (2014). An introductory study of common grasps used by adults during the performance of activities of daily living. Journal of Hand Therapy 27, 225–234

Villoslada, A., Flores, A., Copaci, D., Blanco, D., and Moreno, L. (2015). High-displacement flexible shape memory alloy actuator for soft wearable robots. Rob. Auton. Syst. 73, 91–101

Wang, S., Li, J., Zhang, Y., and Wang, J. (2009). Active and passive control of an exoskeleton with cable transmission for hand rehabilitation. In Int Conf. on Biomedical Engineering and Informatics. vol. 2

Williams, N. (2013). DASH. Occupational Medicine 64, 67–68 Wormstetter, K. (2018). Feasibility of applying a commercial surface EMG armband early after stroke. Master Thesis

Xiloyannis, M., Cappello, L., Khanh, D. B., Yen, S. C., and Masia, L. (2016). Modeling and design of a synergy-based actuator for a tendon-driven soft robotic glove. In Proc. of the IEEE RAS and EMBS Int Conf. on Biomedical Robotics and Biomechatronics. vol. 2016-July, 1213–1219

Yap, H. K., Lim, J. H., Nasrallah, F., Goh, J. C. H., and Yeow, R. C. H. (2015). A soft exoskeleton for hand assistive and rehabilitation applications using pneumatic actuators with variable stiffness. In IEEE Int. Conf. on Robotics and Automation (Seattle, Washington: IEEE), 4967 4972

APPENDIX A: DESIGN CONCEPT

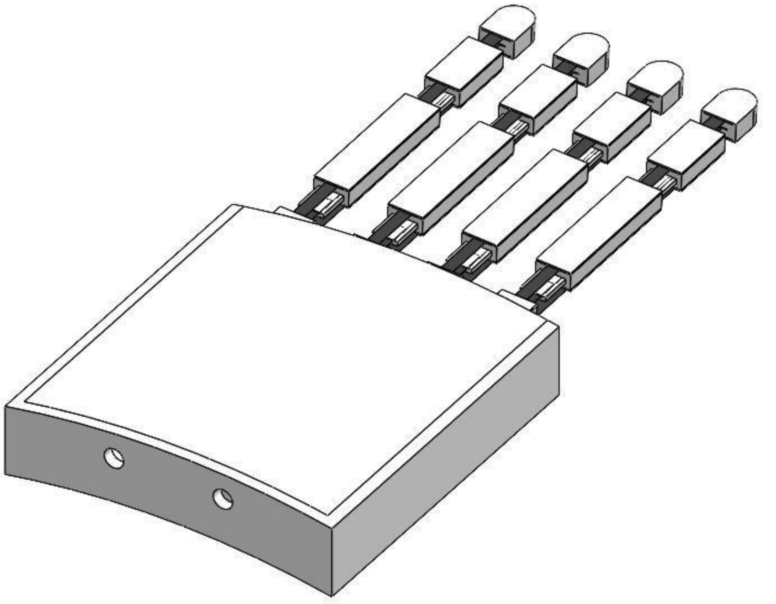


Figure 40. CAD Model of Hand Module (Isometric View)

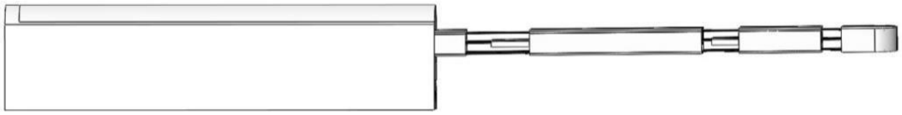


Figure 41: CAD Model of Hand Module (Right View)

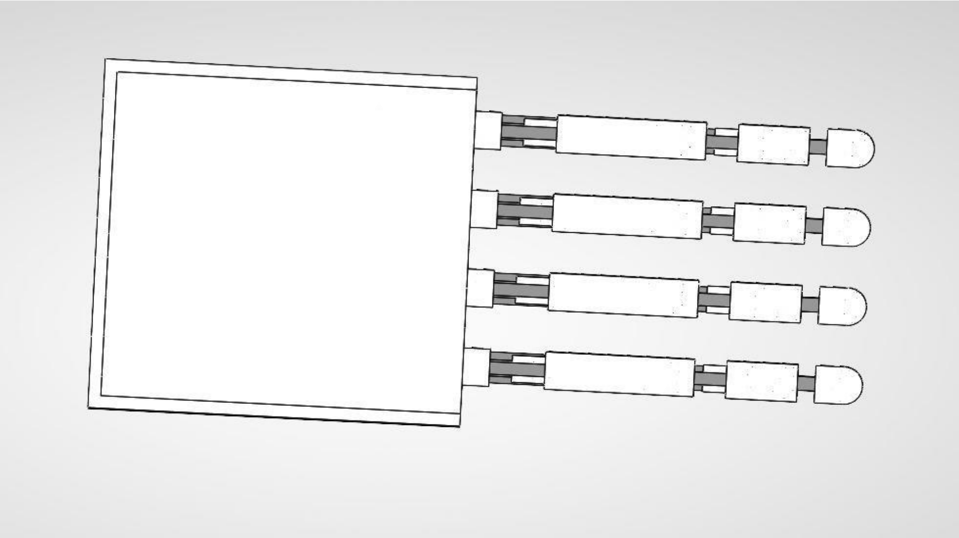


Figure 42: CAD Model of Hand Module (Top View)

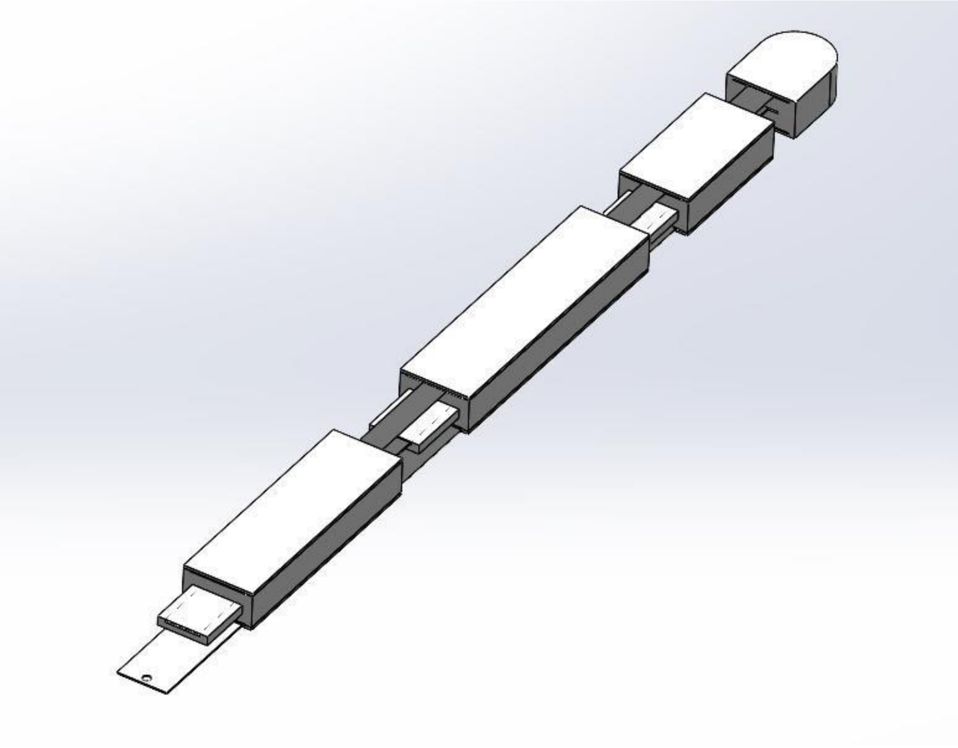


Figure 43: CAD Model of Independent Finger Mechanism (Isometric View)

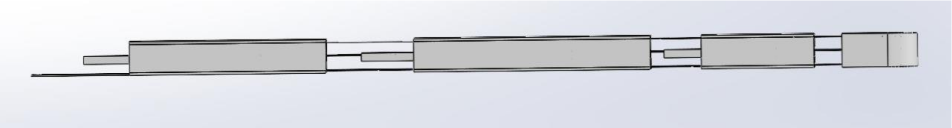


Figure 44: CAD Model of Independent Finger Mechanism (Right View)

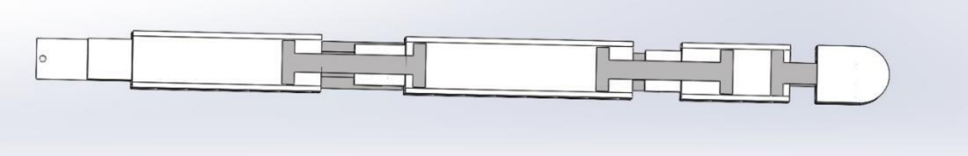


Figure 45: CAD Model of Independent Finger Mechanism (Top View)

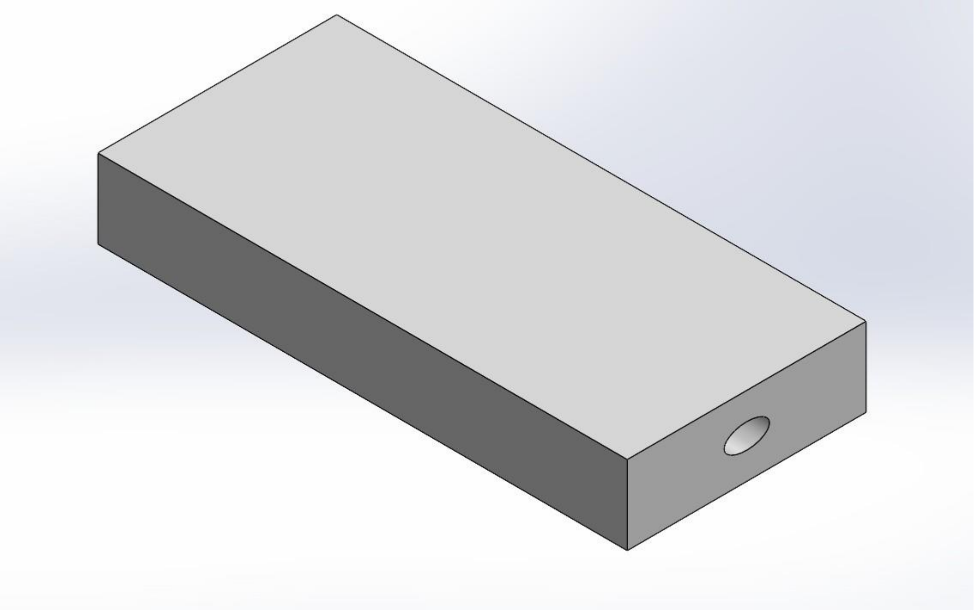


Figure 46: CAD Model of Actuator Pack (Isometric View)

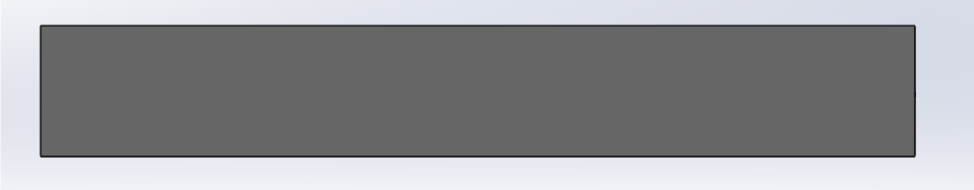


Figure 47: CAD Model of Actuator Pack (Right View)

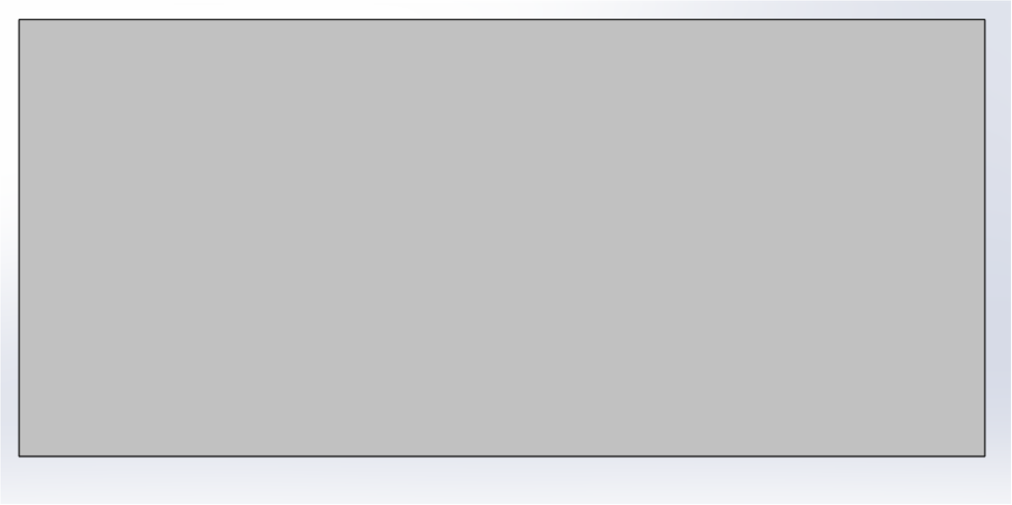


Figure 48: CAD Model of Actuator Pack (Top View)

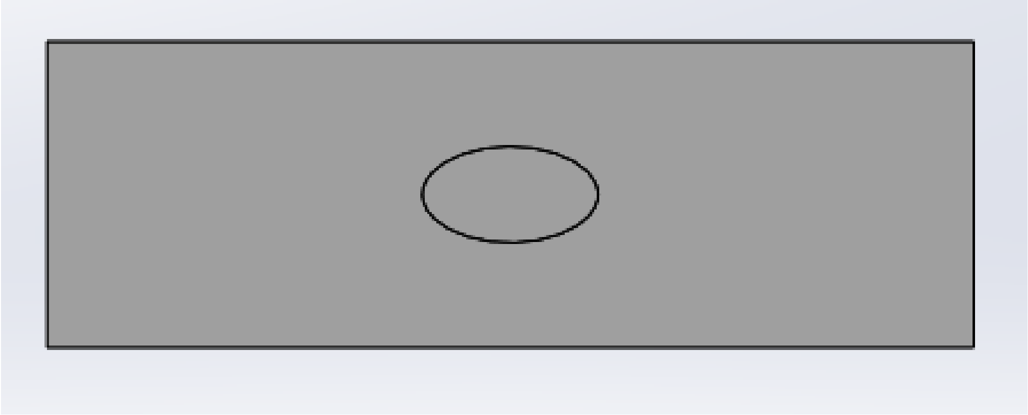


Figure 49: CAD Model of Actuator Pack (Front View)

APPENDIX B: FINAL CAD MODELS FOR HAND MODULE

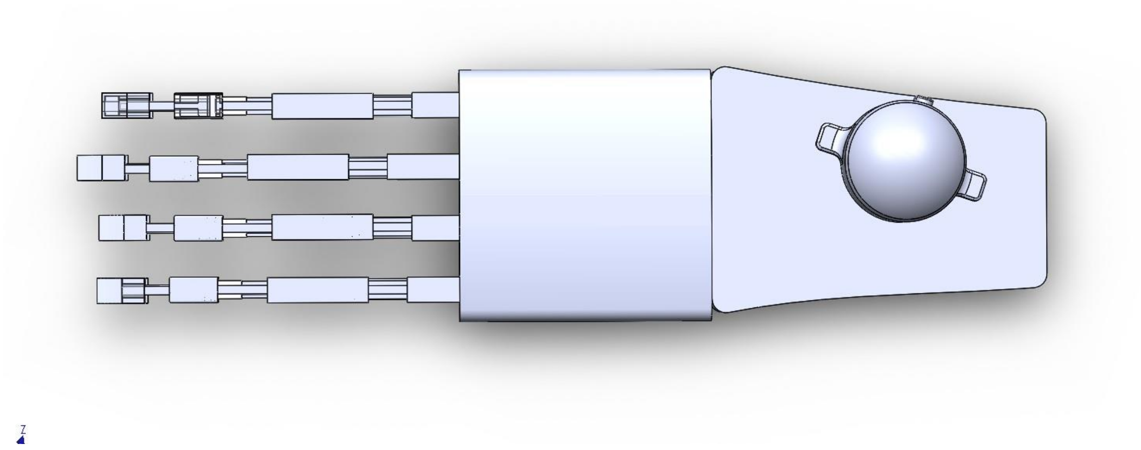


Figure 50. Final CAD Model: Top View (Hand Module)

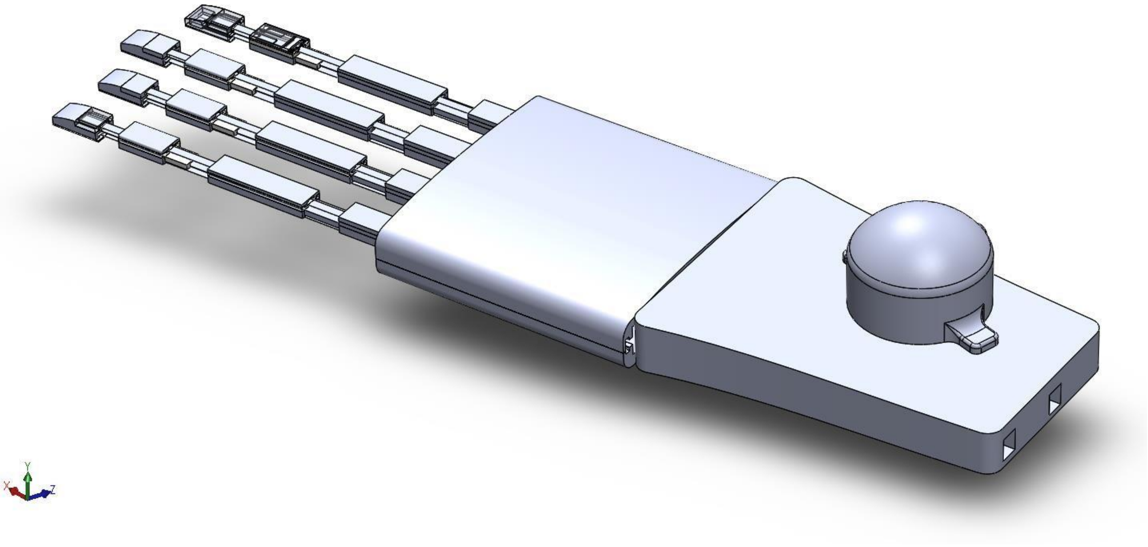


Figure 51. Final CAD Module: Isometric View (Hand Module)

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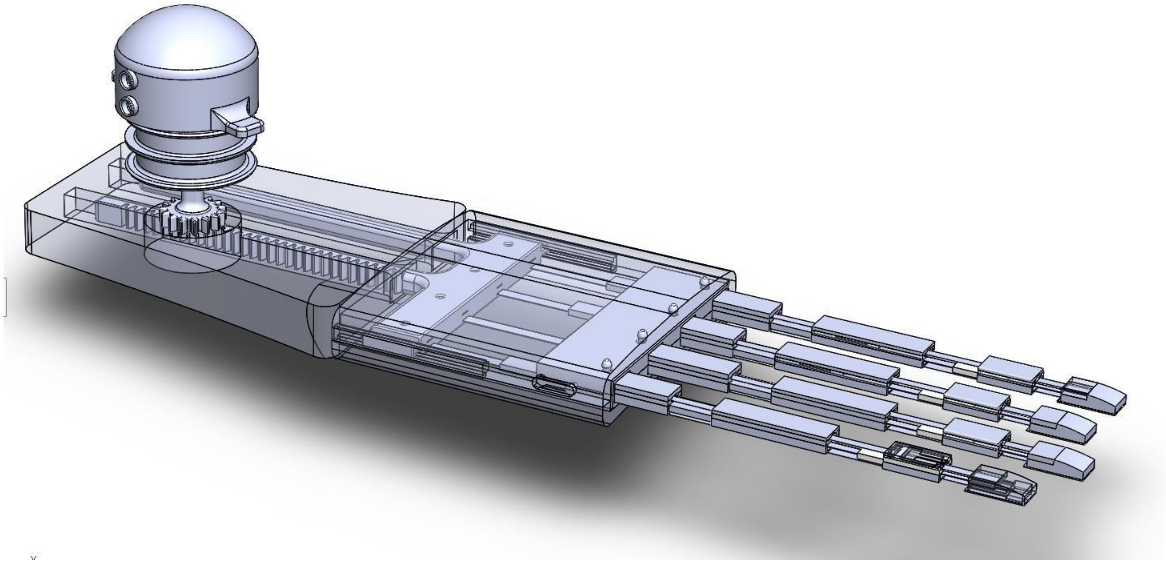


Figure 52. Final CAD Model: Hand Module, exploded and partial transparency

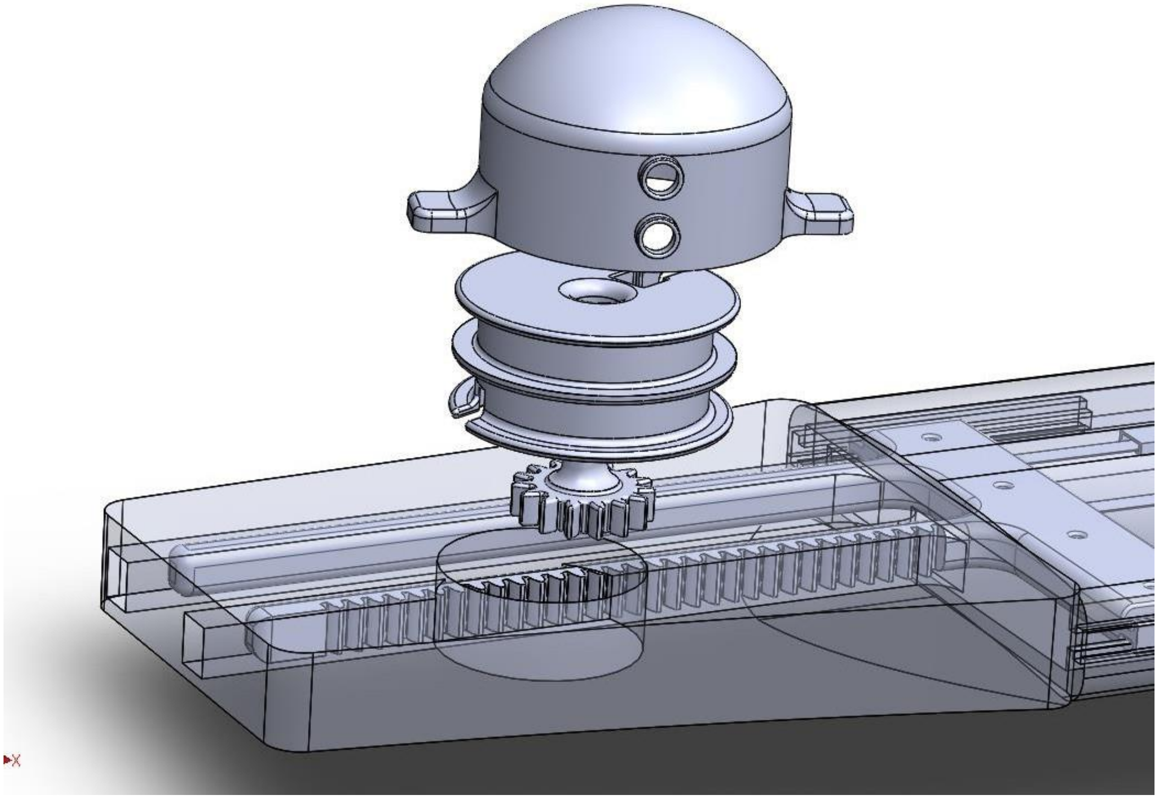


Figure 53. Final CAD Model: Exploded view of actuation system on Hand module.

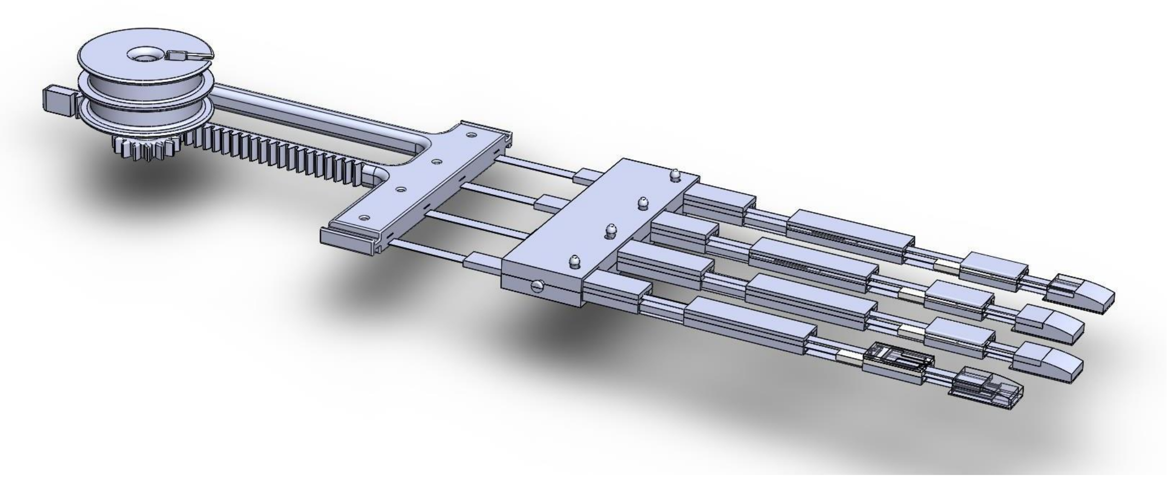


Figure 54. Final CAD Model: mechanisms without housing and casings (Isometric View)

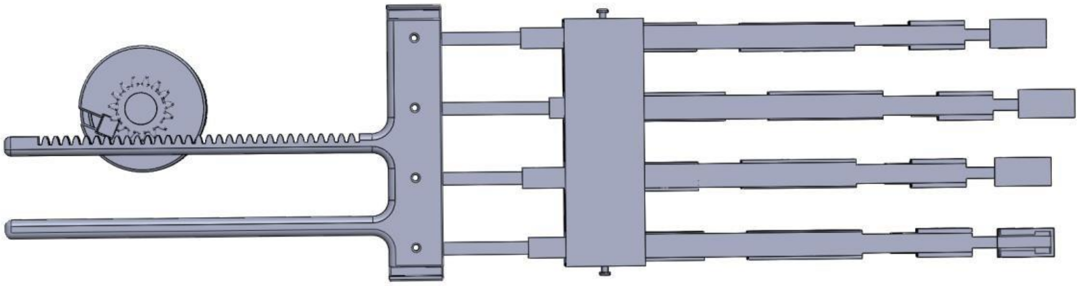


Figure 55. Final CAD Model: Bottowm view of mechanism

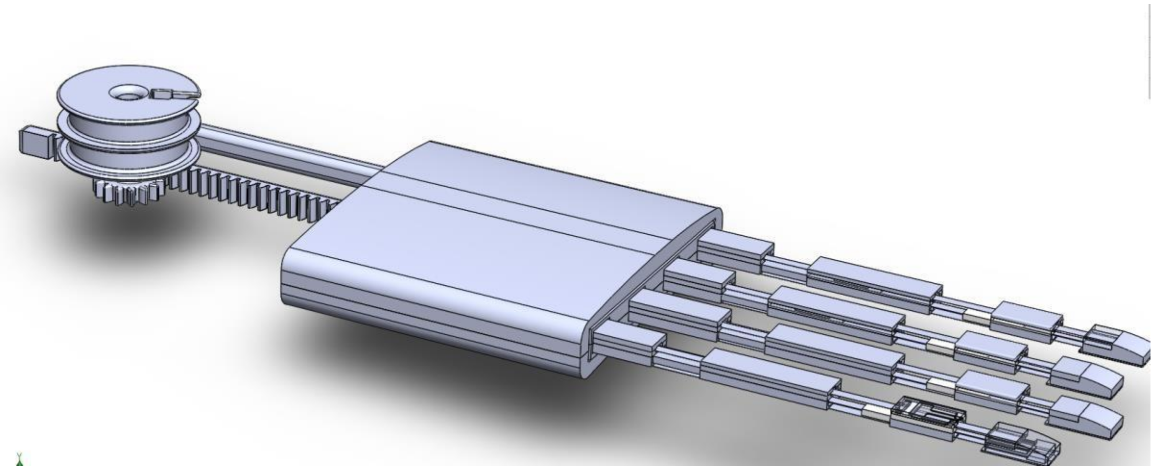


Figure 56. Final CAD Model: Mechanism with hand casing. (The finger casing slides into it).

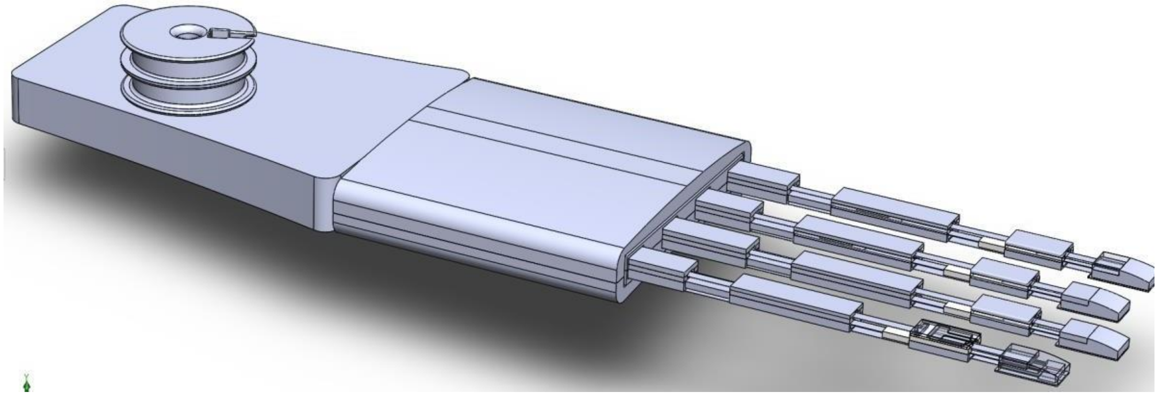
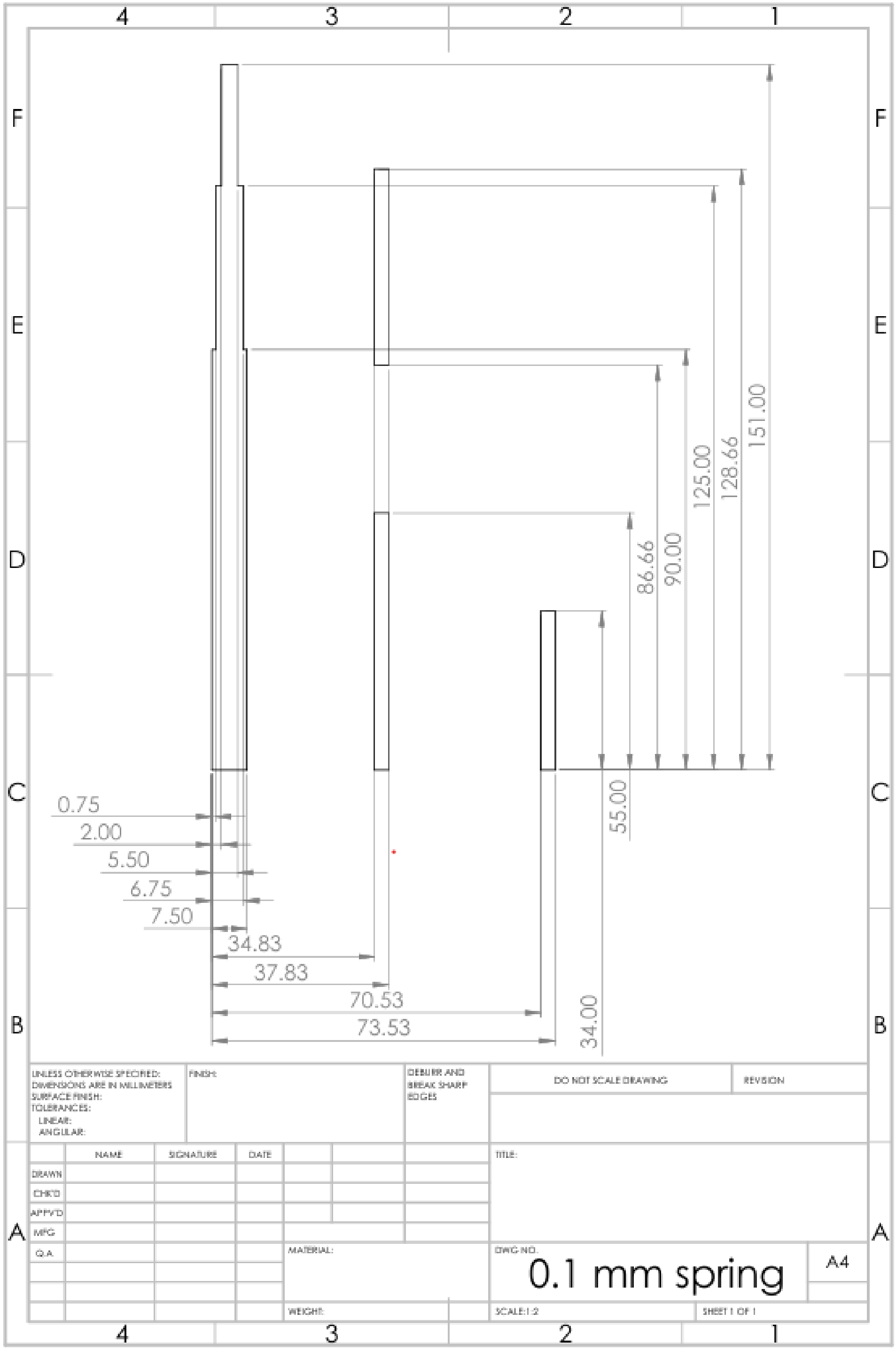
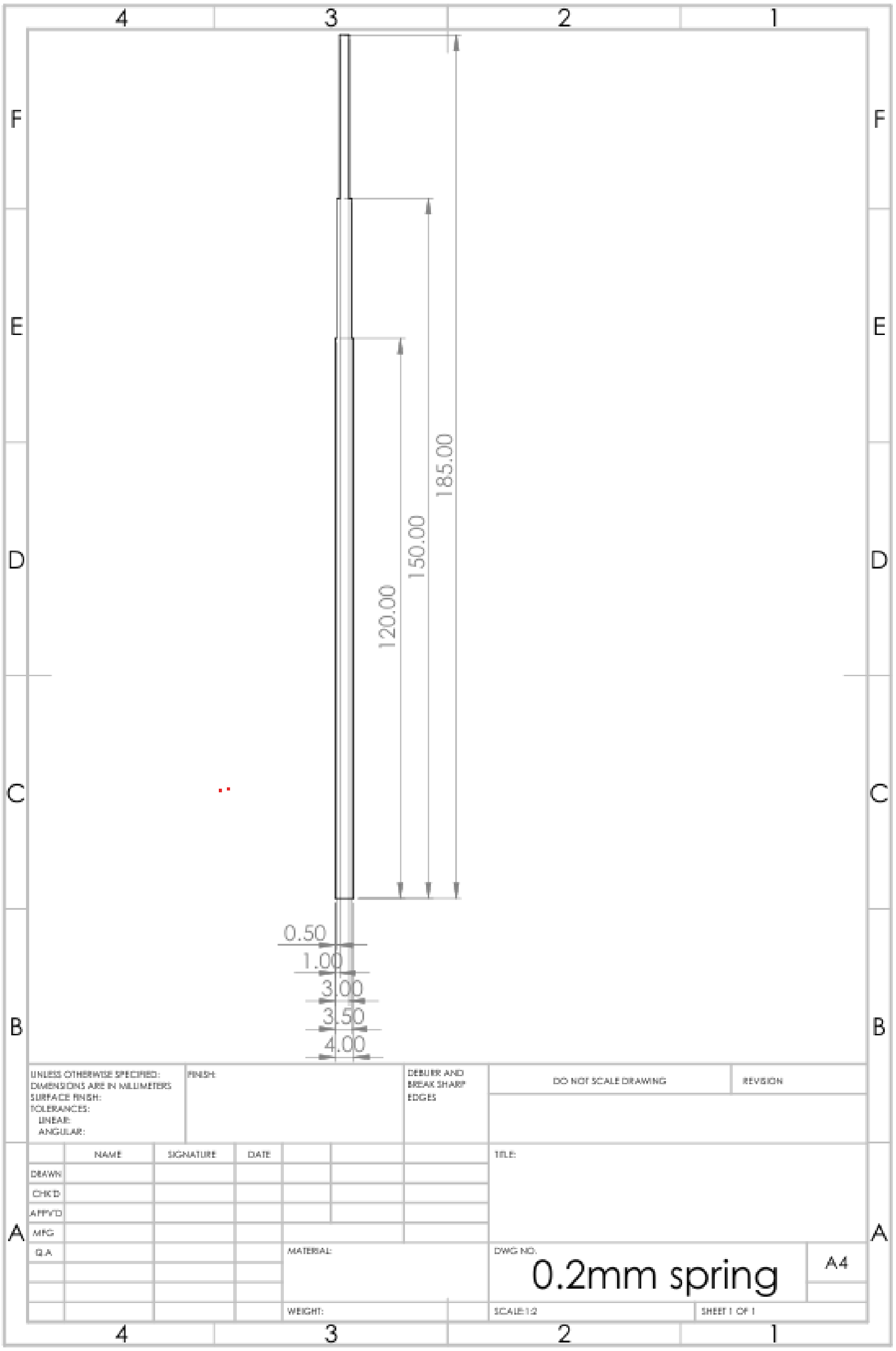


Figure 57. Final CAD Model: Hand module without winch cover.

APPENDIX C: SPRING BLADE DRAWINGS

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SHEET 1 OF 1