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Abstract

Injury to the upper part of the spinal cord or to the brain results usually in upper limb weakness and reduction in hand dexterity. Wearable robots, such as hand exoskeletons, have been introduced for assisting patients in accomplishing activities of daily living or for rehabilitation purposes. Different mechanisms and methods have been developed to reduce the size and weight of the exoskeletons, while providing the hand with sufficient grasp force and dexterity to accomplish the required daily tasks. The overall objective of this Ph.D. was to develop comprehensive support for human hand movements, including finger extension and flexion, using a soft exoskeleton glove. Three different studies have been conducted to investigate tendon-based methods to actuate a hand exoskeleton for supporting hand opening and closing.

The first study aimed at designing, implementing, and testing a bio-inspired tendon-based mechanism to provide the fingers with natural flexion and extension motions. The mechanism mimics the tendon structure of the extrinsic muscle-tendon units in the human hand including the flexors and extensors. The design has been implemented on a fabric glove to be tested on healthy subjects. The middle finger flexion and extension trajectories have been collected and compared with voluntary flexion and extension motions. The results showed that the proposed designs are promising solutions to actuate a soft hand exoskeleton for rehabilitation and assistive purposes.

The second study presents an under-actuated system used to drive the thumb, index, and middle fingers using an actuation module based on a single motor and a mechanism of pulleys. The differential design of the mechanism allowed the fingers and the thumb to adapt and grasp irregularly shaped objects. The kinetics of the fingers when grasping these objects was evaluated experimentally. The results showed that the mechanism provided a stable and natural grasp for irregularly shaped objects, meanwhile, it provided proper distribution of contact forces across the fingers and the thumb.

In the third study, an upgraded version of the under-actuated system, presented in study 2, and a human/machine interface based on electromyography signals were integrated to develop a soft hand exoskeleton. The under-actuated system was implemented with differential gear sets instead of pulleys. The differential mechanism allowed the exoskeleton to perform different hand gestures including extension, power grasp, tripod grasp, lateral pinch, and index pointing. The soft hand exoskeleton was controlled intuitively using electromyography data from the extrinsic hand muscles of the user. The functionality of the exoskeleton and the controller were tested by holding and manipulating versatile objects using different grasps/postures. The results proved the ability of the device to accomplish selected daily life activities and its potential to assist patients suffering from hand weakness.

Resume

Skade på den øverste del af rygmarven eller hjernen resulterer normalt i svækkelse af de øvre lemmer og reduceret håndfærdighed. Bærbare robotter, såsom håndeksoeskeler, er blevet introduceret til at hjælpe patienter med at udføre daglige aktiviteter eller til rehabiliteringsformål. Forskellige mekanismer og metoder er blevet udviklet til at reducere størrelsen og vægten af exoskeletterne, samtidig med at de giver hånden tilstrækkelig grebskraft og færdighed til at udføre de nødvendige daglige opgaver. Det overordnede mål med denne ph.d.-afhandling var at udvikle omfattende støtte til menneskelige håndbevægelser, herunder fingerudstrækning og -bøjning, ved hjælp af en blød exoskelet-handske. Der er blevet gennemført tre forskellige undersøgelser for at undersøge senebaserede metoder til at aktuere en håndeksoeskelet til understøttelse af håndåbning og -lukning.

Den første undersøgelse havde til formål at designe, implementere og teste en bioinspireret senebaseret mekanisme til at give fingrene naturlige bøjnings- og strækningsbevægelser. Mekanismen efterligner sene strukturen i de ekstrinsiske muskel-sene-enheder i den menneskelige hånd, herunder fleksorer og ekstensorer. Designet er blevet implementeret på en stofhandske for at blive testet på raske forsøgspersoner. Bøjnings- og strækningsbevægelserne for langefingeren er blevet indsamlet og sammenlignet med frivillige bøjnings- og strækningsbevægelser. Resultaterne viste, at de foreslåede design er lovende løsninger til at aktuere et blødt håndeksoeskelet til rehabilitering og hjælpemiddelformål.

Den anden undersøgelse præsenterer et underaktueret system, der bruges til at drive tommelfingeren, pegefingeren og langefingeren ved hjælp af en aktuator baseret på en enkelt motor og en mekanisme af skiver. Den differentielle udformning af mekanismen gjorde det muligt for fingrene og tommelfingeren at tilpasse sig og gribe uregelmæssigt formede objekter. Kinematikken for fingrene, når de greb disse objekter, blev evalueret eksperimentelt. Resultaterne viste, at mekanismen gav et stabilt og naturligt greb om uregelmæssigt formede objekter og samtidig sikrede en passende fordeling af kontaktkræfter på tværs af fingrene og tommelfingeren.

I den tredje undersøgelse blev en opgraderet version af det underaktuerede system, præsenteret i studie 2, og en menneske/maskine-interface baseret på elektromyografi-signaler integreret for at udvikle et blødt håndeksoeskelet. Det underaktuerede system blev implementeret med differentielle gear i stedet for skiver. Den differentielle mekanisme gjorde det muligt for exoskelettet at udføre forskellige håndbevægelser, herunder udstrækning, kraftgreb, tripod-greb, lateral klemning og pegefingerpegen. Det bløde håndeksoeskel blev intuitivt styret ved hjælp af elektromyografidata fra brugerens ekstrinsiske håndmuskler. Funktionaliteten af exoskelettet og styreenheden blev testet ved at holde og manipulere alsidige objekter ved hjælp af forskellige greb/positioner. Resultaterne beviste enhedens evne til at udføre udvalgte daglige aktiviteter og dens potentiale for at hjælpe patienter med håndsvaghed.

Contents

List of Figures

Chapter 1

Introduction

Neurological disorders encompass a broad range of conditions that affect the nervous system, including motor skills. The transmission of the motor control signal, responsible for voluntary limb movement, occurs from the primary motor cortex in the brain, through the corticospinal tract in the spinal cord, and via the peripheral nerve that exits the spinal cord from the anterior horn, ultimately reaching the target skeletal muscle [1]. Any trauma or lesion that disrupts this neural pathway can result in a neurological disorder. The specific symptoms of the disorder depend on the location of the trauma or lesion. The segment extending from the brain to the spinal cord is referred to as the upper motor neuron, while the neurons spanning from the gray matter of the spinal cords anterior horn to the skeletal muscle are known as the lower motor neuron. Consequently, damage to the brain, such as a stroke, or injury to the white matter of the spinal cord at any level is classified as an upper motor neuron lesion. Lesions falling into this category typically exhibit similar symptoms, which may include limb weakness or complete paralysis, minimal or no muscle atrophy, and increased muscle tone (hypertonia). Conversely, lower motor neuron lesions manifest symptoms such as limb weakness or paralysis, reduced muscle tone (hypotonia), or muscle atrophy [2]. Overall, these symptoms significantly impact a patient's ability to carry out activities of daily living (ADL), prompting the development of rehabilitation methods and assistive devices aimed at mitigating these symptoms and enhancing the patients' quality of life.

Upper motor lesions caused by cervical SCI or stroke are typically followed by deficits in the function of the upper limbs and hands. Most of the basic tasks and ADLs depend on the hands for accomplishment; therefore, the therapists focus on training the hands during the rehabilitation period to regain their function. This aligns with the desires of SCI patients [3], [4], and stroke survivors [5] who suffer from upper limb impairment, as reported in the literature. In the rehabilitation sessions, the occupational therapist tends to focus on training the patients to perform life skills through task-specific trainings (i.e., ADL trainings) [6].The training program is usually individualized and dependent on the injury level, clinical presentation, and the health condition of the patient before the injury. The rehabilitation process takes a long time, and it is better to be supervised by a therapist to optimize the outcome [7]. However, due to the individualized training program and limited resources, supervised therapy is often not available on a regular basis for enough time. Advanced rehabilitation technology and assistive devices have been introduced to improve hand function and assist the patients in performing ADLs at home without supervision [8]. The goal of this Ph.D. study is to design and develop a wearable and portable hand exoskeleton with an intuitive controller for assisting patients in performing a variety of grasps and hand gestures. The exoskeleton is particularly suitable for training and assisting purposes.

1.1. State-of-the-art wearable hand exoskeletons

Over the past decade, numerous active hand exoskeletons have been developed for grasping assistance and rehabilitation applications. These technologies are valuable in supporting ADLs and interventions conducted by occupational or physical therapists [9]. Some of these exoskeletons are still in the research prototype phase, while others are already commercially available for patients. This section provides an overview of the state-of-the-art hand exoskeletons, with a focus on the three main components that comprise the device for restoring or supporting the flexion and/or extension of the fingers: 1) the glove, 2) the actuation method, and 3) the user interface. The different types of gloves, actuation methods, and control approaches are presented, along with their performance assessment and potential strengths and weaknesses.

1.1.1. The Glove

The design requirements of the hand exoskeleton depend on the purpose of the device, whether it targets assistance or rehabilitation applications. These two groups of exoskeletons have different requirements [10]. The requirements for an assistive device are primarily low weight and high mobility. Therefore, it is preferable for the device to be light and portable. Additionally, it should be comfortable for the user by conforming to average hand dimensions, easy to put on and take off, and allow a considerable range of movement for the fingers without restricting motion. For a rehabilitation device, the main requirement is precise control of finger motion, necessitating mechanical robustness. Safety is a common requirement for both types of devices. Due to these different functional requirements, devices are often proposed for a single application. However, there are devices in the literature that are proposed for both applications [11], [12], [13].

To fulfil these requirements different types of gloves are conventionally designed for the hand exoskeletons and they are divided into three different categories based on how they transfer power from the exoskeleton (i.e. actuators) to the hand digits (i.e. thumb and fingers); 1) Rigid Linkage gloves, 2) Pneumatic/Hydraulic gloves, and 3) Tendon-based gloves. Exoskeletons based on these types of gloves typically reside at the extremes of the rigid-soft spectrum, Figure 1. According to the

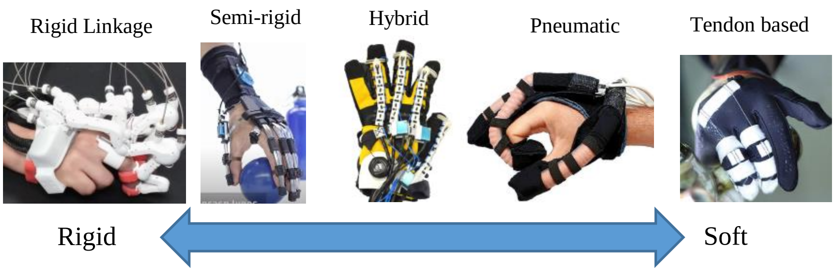


Figure 1. The rigid-soft spectrum with the devices fall along it including rigid linkage device, semi-rigid, hybrid, pneumatic based and tendon based devices.

exoskeletons presented in Table 1, Gloves with rigid Linkage that reside at the rigid end of the spectrum are in many cases limited to the rehabilitation applications as they provide limited functionality in terms of range of motion [11]. They also show significant size and weight, which limit the wearability of the device [14]. While, Gloves with either pneumatic/hydraulic or tendon-based transmission mechanisms that reside at the soft end of the spectrum are used as assistive devices [15]. They provide flexible, small and light active gloves with remote actuation systems. Even though, some soft gloves are proposed to be used as assistive and rehabilitation devices, but in other cases they are limited to the assistance applications [16], due to the low degree of freedom of the mechanisms and the inability to control them precisely. In addition to the three conventional categories of the hand exoskeleton, there are two new categories proposed in the literature that reside in the middle of the rigid-soft spectrum; 1) Flexible Linkage mechanisms 2) Hybrid mechanisms [11]. These devices are developed in an attempt to be used for both applications by reducing the limitations in the devices at the extremes of the spectrum.

The rigid linkage mechanisms are mainly made of metallic or 3D-printed rigid links connected together. The most intuitive method to connect the links is to be in series to form consecutive joints where each joint coincide with the anatomical joints of the user [17]. The joints axes, for both the finger and the exoskeleton, have to be aligned, otherwise the device may collide with the user finger

Table 1. Example of soft hand exoskeletons in the literature categorized according to their glove types.

Glove type (Transmission method)	Exoskeleton (Name, Ref.) (Year, Ref.)	Purpose	Material (Glove/ Transmission)	ROM ° (MCP/PIP/DIP)	Weight (glove only)/ volume
Rigid linkage gloves	HANDEXOS, [17]	Rehab	Neoprene/ Metal	29/67/26	- / M
	Maestro, [14]	Rehab	Velcro/ 3D print	69/91/56	205g / L
	2015, [18]	Rehab	-/ Metal	-/ - /-	950g / L
Semi-rigid	Gloreha, [19]	Rehab	Fiber/ Flexible beam	-/ - /-	- / S
	2021, [20]	Assist	-/ Flat spring	-/ - /-	33g / S
Hybrid	SPAR, [11]	Assist / Rehab	Fabric/ tendons, 3D print	72/ 66/ -	220g / S
Pneumatic gloves	2015, [12]	Assist / Rehab	Fiber/ Silicon	-/ -/ -	285g / M
	2018, [21]	Assist	Fiber/ Fabric	-/ -/ -	79 g / M
Tendon-based gloves	BiomHED [22]	Assist / Rehab	Fiber/ Steel	32/50/24	- / S
	Exo-Glove [23]	Assist / Rehab	Fiber/ -	46/46/8	194g / S
	Graspy Glove [24]	Assist	Fiber/ Dyneema	44/70/48	250g / M
	2016, [25]	Assist	Fiber/ Steel	80/ - / -	205g / S
	2019, [26]	Assist	Fiber/ -	-/ - / -	55g / S
	2019, [27]	Rehab	Fiber/ Nylon	-/ - / -	258g / S

and be harmful [28]. This method requires significant space at the finger side to locate the mechanism which makes it difficult to implement a multi-fingered device using the same method. On the other side, links can be connected together to form 4-bar/redundant mechanism [14]. This mechanism does not need space between the fingers as the linkage is implemented on the dorsal side of the finger. Moreover, the structure transmits the movement of the actuator directly to the spatial motion of the joints, which makes the control of exoskeleton precise and straightforward. Despite all these advantages, the exoskeletons based on rigid links are relatively heavy and large due to the adjustment done to avoid the joints misalignment. In average, the weight of the component that is wearable on the hand is approximately (577 g), Table 1.

The pneumatic glove mainly consists of an inflatable chamber at the dorsal side of the finger that flexes/extends the finger by inflating/deflating the chamber. The pneumatic based solutions are divided into two main categories according to the inflatable chamber used by the device; 1) Soft Elastomer Actuator (SEA), 2) fabric-based actuator [15]. The Latest SEA version is the soft Fabric Reinforced bending actuator (FBRA) [12]. It is mainly made from hyper-elastic silicon and reinforced by thin fabric thread to limit the radial expansion and predefine the shape of the actuator when it is inflated. FBRA provides active motion in the flexion direction only. The second category of pneumatic mechanisms is the fabric-based actuator, which can provide active motion in both directions. An example this is the fabric-based actuator developed by Conor J. Walsh [21], which consists of three layers of fabric. These layers create two fabric pockets, each containing two air bladders. The actuator flexes when the bladder in the upper pocket inflates and returns to its original shape when the lower bladder inflates. The pneumatic mechanisms reduce the glove's weight and provide a shape-adaptive feature.

Over the past two decades, there has been significant progress in the development of hand exoskeletons based on tendons, with several prototypes being developed and some even commercially released. The routing configuration of the tendons used by these exoskeletons can be either bio-inspired or engineered. Bio-inspired designs aim to replicate the efficient tendon routing patterns found in human fingers, as seen in the Exo-glove [23] and Graspy glove [24] where the Flexor Digitorum Profundus (FDP) tendon route has been replicated to mimic its function. Other bio-inspired designs include the BiomHED glove [22], which replicates the FDP, Extensor Digitorum Communis (EDC), radial and ulnar interosseous tendons routes of the natural finger. On the other hand, the engineered designs are typically based on mathematical models and analysis, without any inspiration from natural fingers, as seen in the FLEXotendon glove [29] and the routing configuration proposed by Jianyu Yang et al. [30]. Fabric gloves were usually used as a base for the tendon-based soft exoskeleton, with the exo-tendon routing components attached directly to the fabric to transmit the tension force to the fingers for flexion or extension [31]. Recently, polymer materials have also been introduced as the base for these exoskeletons [32]. The light weight of the materials used in implementing the glove in these systems, either with fabric or polymer bases, improves its wearability and portability features compared to the other types of exoskeletons. However, reproducing normal finger motion trajectory using exo-tendons is challenging due to the underactuated mechanism per finger, limited space and options around the finger, and the use of flexible materials for implementation [30]. The exo-tendon routed on the glove can be easily displaced, altering the pre-planned finger motion trajectory unless the routing path is designed carefully to minimize displacement. However, it is challenging to accurately mimic the complex motion of the natural finger using tendon-based designs due to depending on an under-actuated mechanism per finger, as it is preferable in such devices to reduce the number of actuators and make the design more practical.

1.1.2. The Actuation method

The actuation mechanisms for the soft hand exoskeletons are designed to increase the device portability by reducing the number of actuators. However, this should not compromise the hand dexterity which is necessary to grasp objects of various sizes and irregular shapes used in daily life activities. The dexterity comes from the independency of the hand digits (i.e. Thumb and the fingers). The more independency given to the digits, especially the thumb and index finger, the more activities the hand could engage [33]. The actuation methods presented in the literature usually fall in one of four categories; Actuator for Multiple Exo-tendons (AME), Actuator for Each Exo-tendon (AEE), Synergy-based methods, Adaptive-based methods, Table *2*.

Actuator for Multiple Exo-tendons AME method is considered the basic conventional method used to design the under-actuated mechanism of the hand exoskeleton where one actuator is used to actuate multiple exo-tendons to flex different fingers. HERO glove [34] depends on one linear motor to flex the thumb, index and middle fingers. This design provides a light device, around 280 g, however it degrades the independency of the digits and may reduce the grasping ability to the objects with high irregular dimensions. To increase the hand dexterity, SEM glove [35] actuates the thumb, middle and ring fingers while the index finger is left free allowing the finger to be independent as it depends on its passive movement and force to grasp the objects.

Table 2. Example of soft hand exoskeletons in the literature categorized according to their actuation methods.

Actuation Method	Year	Ref.	Actuated Digits*	Independency**					No. of Actuators used for flexion
				Thumb	Index	Middle	Ring	Pinky	
Actuator for Multiple Exo-tendons (AME)	2020	[34]	T, I, M	×	×	×	---	---	1
	2012	[35]	T, M, R	×	---	×	×	---	1
	2022	[36]	I, M	---	×	×	---	---	1
Actuator for Each Exo-tendon (AEE)	2018	[37]	T, I, M, R, L	✓	✓	✓	✓	✓	10
	2022	[29]	T, I, M	✓	✓	✓	---	---	5
	2016	[24]	T, I, M, R	✓	✓	✓	✓	---	4
Synergy-based	2017	[25]	T, I, M	×	×	×	---	---	1
	2019	[27]	T, I, M, R, L	✓	✓	✓	✓	✓	10
Adaptive-based	2018	[26]	T, I, M	✓	×	×	---	---	1
	2019	[32]	I, M	---	✓	✓	---	---	1
	2015	[38]	T, I, M	✓	✓	✓	---	---	2

* T: Thumb, I: Index finger, M: Middle finger, R: Ring finger, L: Little finger.
** The independent digit is the exo-skeleton's digit that could stay extended while the other digits are flexed using the actuation mechanism.

Actuator for Each Exo-tendon (AEE) method provides the highest degree of independency for the actuated digits between the different types of actuation methods. Each exo-teondon is actuated by a separate actuator to flex a digit or a phalanx. Graspy glove [24] depends on 4 actuators to flex the thumb, index, middle and ring fingers. The actuators were placed on the dorsal side of the hand, which limits the number of actuators, due to the limited space available on the hand and consequently limits the hand's degree of freedom. Unlike the FLEXotendon glove [29] where the actuators are located away from the hand and Bowden cables are used to transmit the power to the fingers. Five linear motors used to flex the Thumb, index and middle fingers. This allow the designers to increase the degree of freedom of the digits (i.e. dexterity of the hand) by controlling the Metacrpophalangeal (MCP) joint of the index finger and the Carpometacarpal joint of the thumb independently.

Synergy-based methods are used to increase hand dexterity while keeping the number of actuators limited. These methods use principle component analysis (PCA) to extract kinematic synergies that summarize the coordination patterns of joints involved in primary hand movements. One example of this is the glove designed by Michele Xiloyannis et al. [25], which uses the first hand synergy to explain approximately 60% of daily living activities. The glove relies on a single actuator that drives an array of spools dimensioned according to that synergy. Another example is the work of Ramana Vinjamuri et al. [27], who used three manually defined synergies to perform different grasps and postures by combining the three synergies with different levels. This required five actuators for flexion. The three synergies corresponded to the thumb, index, and the other three fingers in the flexion direction, respectively.

The adaptive concept reduces the number of actuators needed. It allows the actuated digits to adapt to the dimensions of the grasped objects, resulting in a better grasp. The Exo-glove Poly II [32], as an example, actuates the index and middle fingers using an under-actuated mechanism that consists of one exo-tendon routed around the two fingers and pulled using a single actuator to create a differential mechanism. This allows either finger to flex even if the other is blocked by the environment. However, in this design, the thumb is flexed by a separate actuator. The exoskeletons developed by Minas Liarokapis et al. [26] also use the adaptive method to actuate the thumb and two fingers using only one actuator and a differential mechanism comprises of a differential gear that divide the actuator torque between the thumb on one side and the index & middle fingers on the other side. Although this differential mechanism drives the thumb and the two fingers in an adaptive manner, the index finger loses its independency and becomes independent on the middle finger, which may make it difficult to perform different types of grasps/postures such as index pointing. In general, these adaptive actuation systems allows the exoskeleton to adopt with the irregular shapes in the environment with limited numbers of actuators, however the designs presents in the literature may exclude essential DoFs required for performing different grasps/postures.

In conclusion, previous designs of under-actuated mechanisms require more than one actuator to independently flex the thumb, index, and middle fingers. Relying on a single actuator usually limits the independence of at least one of these three digits.

1.1.3. The User Interface

Determining human's intention to operate the hand exoskeleton is considered a challenging issue for human-machine studies in general. For hand assistive devices, the human intention is necessary for the user to select the desired hand motion between the different motions that has pre-programmed trajectory in the system [27], [39], [29]. For the rehabilitation devices, the intention detection is necessary to maximize the outcome from it therapeutic intervention and to operate the different rehabilitation modes such as Passive-assisted, active-assisted, active unassisted, active-resisted and bimanual-assisted [9]. Therefore, either assistive or rehabilitation devices they need a user interface that works as a communication module between the user and the device to accommodate the user's need and estimate the human intention correctly. The most common interfaces used in the literature are graphical user interface, embedded sensors, voice, vision and surface electromyography (sEMG) [9].

Graphical user interface GUI is a direct method for interfacing. In this type of interface the user sends the intention directly to the device [40]. Graphical user interface are more reliable than any other method, however it requires the unaffected hand to move and interact with the interface. Furthermore, the GUI method is not a practical solution for tetraplegia patients.

For embedded sensors method, the exoskeletons rely, in most cases, on flex/bend or pressure/force sensors to determine human intention. Flex/bend sensors are typically placed on joints that can be voluntarily moved by the user, such as the wrist in the Exo-Glove system [38], to control the motion of the device. They can also be fixed on fingers to detect intention in patients with hemiparesis as proposed by M. Ciocarlie [41]. Pressure/force sensors are used in simple threshold controlling systems like the SEM glove to trigger grasping motion. In some cases, Inertial measurement units (IMUs) are used, such as in the HERO glove [31], to detect vibration and trigger finger flexion.

Recently, voice and vision based interfaces have been proposed. The Voice based interface, proposed in FLEXotendon glove-III [29], collects the user's voice continuously to extract pre-saved keywords that trigger the actuation system of the glove to perform a pre-programed motion. Almost the same algorithm is followed by the vision based interface where the wearable camera collects the video continuously for a machine learning model to actuate the glove autonomously.

The most used method between the known user interfaces is the sEMG [9]. This method of interfacing identifies the user's intention, indirectly, by classifying the neuromuscular signals, extracted from the muscles dedicated for the grasping movements, using machine learning algorithms [39]. In most cases, it is used to distinguish between hand opening and closing activities. The neuromuscular data could also be used either as a trigger in a threshold algorithm [26] or as an input for a proportional controller. The drawback of this method could be concluded mainly in high ability to cross-talk between the adjacent muscles and in its high sensitivity to various sources of external noises [42]. Several efforts have been done to address these issues such as using advanced techniques to filter the noises and the involuntary signal from the recorded sEMG signal. Recently, High density sEMG is introduced to collect more data to improve the classification accuracy in addition to using deep learning algorithms.

1.2. Objective and research questions

Given the challenges associated with the development of hand exoskeletons and their interface with humans, *the objective of this thesis is to propose and implement a method based on exo-tendons to provide natural hand motion for supporting activities of daily living.*

Designing a tendon routing configuration to perform natural finger extension/flexion trajectory, and an under-actuation system to provide a natural, adaptive & stable grasp to any irregular shape object in the environment, controlled intuitively to perform different gestures, remain major concerns for the research community. Therefore, this Ph.D. work investigates the tendon routing configurations around the fingers and the actuation methods that could be used to mimic the human musculoskeletal system and provide natural grasps and movements for hand physical assistance and rehabilitation. The work analyzes the impact of these solutions driven by human/machine interface on the functionality of the hand in activities of daily living. It is hypothesized that:

1- *"Mimicking the functions of the extrinsic hand muscles on the finger by following their natural tendons routing configuration using exo-tendons provides normal finger flexion/extension movements"*,
2- *"Coupling the thumb, index and middle fingers by a differential mechanism based on pulleys, provides a natural and adaptive hand grasps for objects with various dimensions"* and
3- *"A soft hand exoskeleton, based on tendons and under-actuated by a differential mechanism, can be designed and optimized for functional performance in assisting users with impaired hand function to accomplish activities of daily living. By integrating weak forearm muscle activity as a control mechanism, the exoskeleton can enable users to perform a range of hand gestures and postures required in daily life, such as grasping and manipulating objects of various sizes and shapes."*

To fulfil the objective and bridge the research gap, the following research questions were addressed in this study.

Q1. How can the exo-tendons be routed to mimic the natural tendons of the extrinsic hand muscles?

Q2. How does the Bio-inspired tendon routing configuration inspired by the extrinsic tendons affect the finger flexion/extension movements compared to the conventional methods?

Q3. How can the differential mechanism based on pulleys be designed to actuate the thumb, index and middle fingers for adaptive and natural grasps?

Q4. How can a soft hand exoskeleton based on differential actuation module be optimized to maximize the functional performance in assisting users with impaired hand function to accomplish activities of daily living.

1.3. Scope of work

In response to the research questions, the following research tasks were performed during this thesis work.

- Design and development of an active soft glove made from fabric and actuated by the proposed tendon routing configuration around the glove finger for both flexion and extension motions (Q1).
- Run experiments on healthy subjects to test the ability of the proposed flexion and extension tendon routing configuratins to move the fingers naturally (Q2).
- Design and development of an under-actuated mechanism, using a group of pulleys, to flex the thumb, index and middle fingers for adaptive and natural grasps (Q3).
- Conduct experiments on healthy subjects' hands to assess the ability of the proposed under-actuated mechanism to provide an adaptive grasp for irregular shape objects and perform different hand gestures (Q3).
- Design and development of a full tendon-based exoskeleton that actuates the hand in both flexion and extension directions and interfaced with the user, intuitively using electromyography (EMG) signals and machine learning algorithms (Q4).
- Evaluate the functionality of the developed tendon-based exoskeleton, to accomplish basic daily activities (Q4).

1.4. Outline of thesis

The thesis consists of five chapters and is based on the following papers:

1- Study I: Biomimetic Tendon-Based Mechanism for Finger Flexion and Extension in a Soft Hand Exoskeleton: Design and Experimental Assessment. Abdelhafiz MH, Andreasen Struijk LN, Dosen S, Spaich EG. Sensors. 2023 Feb 17;23(4):2272.

2- Study II: Self-adaptive Under Actuated Mechanism for a Biomimetic Soft Robotic Hand Exoskeleton to Improve Dexterity and Grasping Capabilities. Abdelhafiz MH, Spaich EG, Dosen S, Andreasen Struijk LN. In preparation.

3- Study III: Adaptive, Multi-Gesture, Soft Hand Exoskeleton with Tendon-Driven Structure to Assist with Activities of Daily living. Abdelhafiz MH, Andreasen Struijk LN, Dosen S, Awad MI, Spaich EG. In preparation.

Chapter 1 introduces the hand exoskeletons by presenting the recent technologies in this field regarding the methods used to actuate the device, the mechanical designs and the human/machine interface methods, in addition to highlighting the issues with the different methods and designs. Furthermore, the objective and the research questions of the Ph.D. study is highlighted at the end of the chapter.

Chapter 2 is based on the first paper and describes the proposed tendon routing configuration for finger flexion and extension applied by soft hand exoskeleton. The method of routing the exo-tendons around the glove finger and the analogy between the routing method and the musculoskeletal structure of the human hand is presented. The proposed mechanisms is tested and the results are evaluated kinematically.

Chapter 3 is based on the second paper and proposes a new design for a differential mechanism used to flex the thumb, index and middle fingers in the soft hand exoskeleton for grasping objects. The concept of the design is presented and the method of implementation, using pulleys, is described. Finally, the design is tested and evaluated kinetically.

Chapter 4 is based on the third paper and presents the integrated soft hand exoskeleton and the method of interfacing it with the user. The functionality of the device to accomplish basic daily tasks is evaluated, in addition to evaluating the device characteristics.

Chapter 5 presents the contribution of this thesis work to the state-of-the-art, in addition to the suggestions for the future work.

Chapter 2

Study I

The conventional tendon-based mechanism for the soft hand exoskeletons, according to the literature, consists of one exo-tendon on each side of the finger (i.e. the flexion and extension sides) [43]. The exo-tendon spans the MCP, Proximal interphalangeal (PIP) and Distal interphalangeal (DIP) joints and inserts at the distal phalanx. Jiashun Shi et. al. [30], tested this tendon routing configuration on an artificial finger. In these tests the passive joints stiffness were neglected. The conventional routing configuration produced an incorrect bending sequence where the distal phalanx bent first until it reached its limit, followed by the middle then the proximal phalanx. The first section in this chapter describes the extension /flexion trajectories of the finger actuated by the conventional tendon routing in more details.

The musculoskeletal system of the human finger consists of a group of small bones (i.e. distal, middle, proximal phalanges and metacarpal bone), ligaments connect these bones together and a system of muscle tendon units attached to the phalanges at different points to move the finger. Some of these muscles originate at the forearm. They are called extrinsic muscles like Flexor digitorum profundus (FDP) flexor digitorum superficialis (FDS) muscles that contribute to the finger flexion and extensor digitorum communis EDC muscle that contributes to the finger extension [44]. On the other hand, the intrinsic muscles that originate at the hand itself are responsible for the precise movements of the finger to increase the dexterity and help to stabilize during delicate tasks [45].

Experiments and simulations have shown that extrinsic muscles are primarily responsible for flexing and extending fingers. Studies by Sung jae kim et. al. [46] on cadaver fingers found that extrinsic tendons had a greater effect than intrinsic tendons on extending the PIP joint, especially when the MCP joint was flexed. Derek G. Kamper et. al. [47] simulated finger flexion and found that extrinsic muscles could flex all three finger joints simultaneously, even with the presence of passive joint stiffness. According to these conclusions, the first study in this Ph.D. targets the following:

- Develop a new tendon-based mechanism for finger flexion and extension that mimics the routing configuration of the extrinsic muscle-tendon units (MTUs).
- Investigate the ability of the proposed tendon routing configuration which is inspired by the routing of the extrinsic MTUs, to achieve normal finger flexion/extension motion.
- If necessary, compensate for the absence of intrinsic muscles and restore their essential functions to perform normal finger motion by modifying the design of the tendon-based mechanism.

2.1. The characteristics of normal finger motion

In the musculoskeletal structure of the human hand, the contraction of the extrinsic extensor, EDC muscle tendon unit, forces the MCP, PIP and DIP joints to extend, simultaneously. The EDC muscle-tendon unit originates from the forearm and runs along the hand and finger's dorsal side, dividing into three slips at the proximal phalanx: a central slip and two lateral slips (as shown in Figure 2). The central slip attaches to the proximal side of the middle phalanx, while the lateral slips run along the PIP joint's ulnar and radial sides before reuniting on the middle phalanx's dorsal side and inserting into the distal phalanx (Figure 2). When the PIP joint extends, the lateral slip of EDC tightens, pulling the distal phalanx and extending the DIP joint [48]. This structure couples the interphalangeal joints (IP), meaning the DIP joint's extension is highly reliant on the PIP joint's extension, as proven by mathematical modeling conducted by Spoor et al. [48]. The EDC tendon's attachment to the distal and proximal phalanges generates torque, which is transmitted through the kinetic chain of the finger until it reaches the MCP joint, leading to its extension [49].

For flexion, both FDP and FDS tendons contribute to the motion. In a study by Ashish D. Nimbarte et al. [51], each tendon was separately pulled to examine their individual contributions to flexion in cadaveric hands. Results showed that the FDP tendon flexed the MCP, PIP, and DIP joints by 19.7°, 41.8°, and 29.4°, respectively, while the FDS tendon flexed the MCP and PIP joints by 24.8° and 47.9°, respectively. The two tendons co-activate the finger simultaneously. However, the dominance of the FDS can lead to the inactivation of the IP coupling mechanism, between the DIP and PIP joints Figure 3(a). Conversely, the dominance of the FDP flexes the DIP joint until it reaches its limit and activates the IP coupling to be strained [52], Figure 3(b). Increasing dominance of the FDP tendon leads to increased strain on the IP coupling.

The conventional tendon-based mechanism, with its single tendon that spans the MCP, PIP and DIP joints and inserts at the distal phalanx, mimics the FDP tendon function alone without the FDS tendon. Therefore, the IP coupling of the finger is always activated when the conventional tendon mechanism is applied to the finger during flexion, as the case presented in Figure 3(b). The DIP joint angle always exceeds its maximum permissible angle that is limited by the IP coupling. Therefore, flexing the finger using the conventional mechanism actives the IP coupling and strains it, throughout the flexion motion.

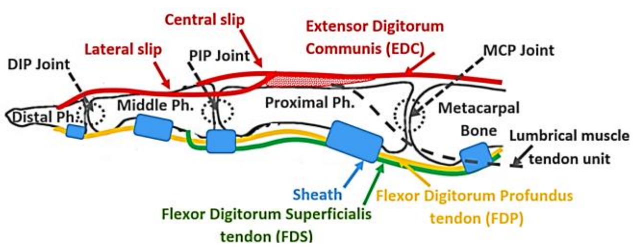


Figure 2. The anatomical structure of a finger, highlighting the Flexor Digitorum Profundus (FDP) and Flexor Digitorum Superficialis (FDS) tendons with yellow and green lines respectively, and the extensor tendon with a red line. The tendons are enclosed within blue sheets [50].

(a) (b)

Figure 3. (a) The effect of the FDS tendon dominance during flexion where the IP coupling is inactivated and the Lateral slip is lose. (b) The effect of the FDP tendon dominance during flexion where the IP coupling is activated and the Lateral slip is strained.

2.2. Conventional tendon-based mechanism.

The conventional flexion and extension mechanisms, as found in the literature [23], [31], insert the exo-tendons at the distal part of the distal phalanx. For flexion, the tendon spans the MCP, PIP and DIP joints from the palmar side of the finger to be fixed on the distal phalanx. While for extension, the tendon passes from the dorsal side of the finger. This study estimated the finger trajectories during both flexion and extension motions using the conventional tendon routing method. To estimate the trajectories, two artificial fingers were used, one was used to simulate the finger during flexion and the other during extension. This differentiation was made due to the difference in the passive joint stiffness between the flexion and extension directions. Both artificial fingers consisted of three links and a base connected to create the three joints of the finger. Torsional springs were fixed at the joints to simulate the passive joint stiffness. The reference profiles for the passive joint stiffness were taken from Kamper et. al. [47] and linearized by the least square method between 0° and 90°. The kinematics of the artificial finger during flexion and extension was captured using Qualisys motion capture system and five spherical reflective markers at a sampling rate of 100 Hz. The reflective markers were fixed directly over the artificial finger joints at the fingertip, the DIP, PIP and MCP joints, and at the base representing the Carpometacarpal joint.

The expected trajectory to have a normal finger flexion/extension motion is described as following:

1- During flexion, the DIP joint angle can either lay in the range [65%, 75%] of the PIP joint angle or less (i.e. grey region in Figure 4(a)) [53]. In the specified range, the IP coupling is loose, especially during flexion. (i.e. it is the region of a normal finger flexion)
2- During flexion, the PIP joint angle is preferred to lay in the range [80%, 200%] of the MCP joint angle (i.e. grey region in Figure 4(b)) [53]. The finger is preferred to be in between this range, which is the typical range of relations between the MCP and PIP joint angles during grasping for healthy subjects [53].
3- During extension, the DIP and PIP joints are coupled. The DIP joint angle is almost between the range [65%, 75%] of the PIP joint angle (i.e. grey region in Figure 4(c)) [53].

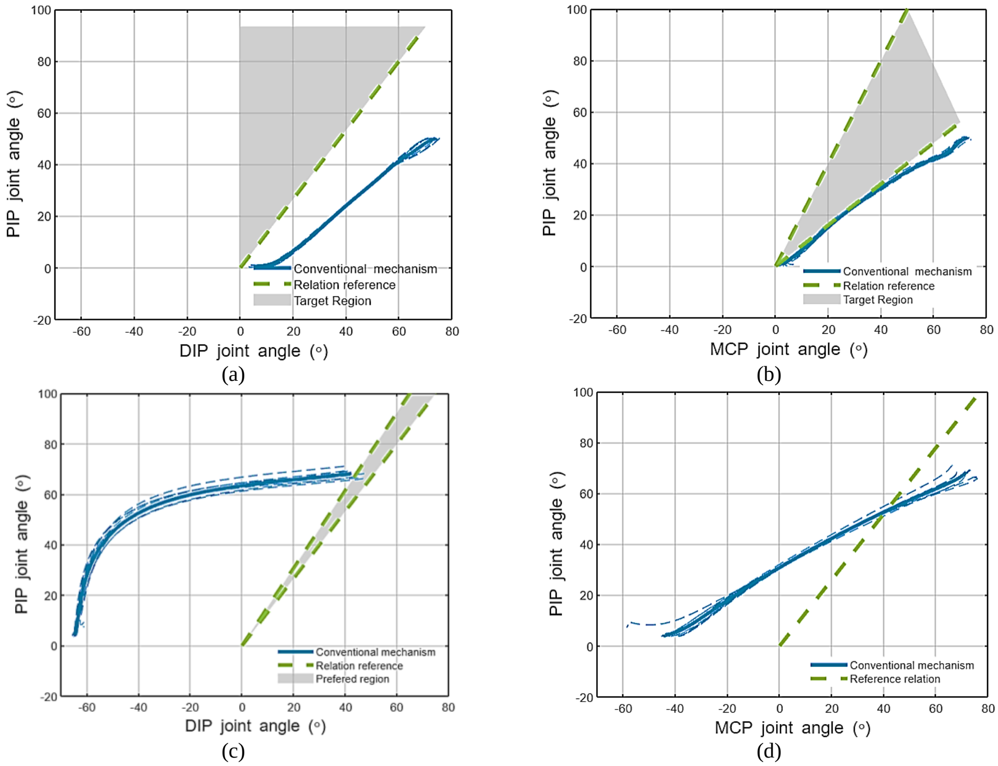


Figure 4. The phase plots for the finger joint angles during flexion and extension of the artificial finger using the conventional tendon routing configuration: (a) PIP-DIP joint angle relation during flexion. (b) PIP-MCP joint angle relation during flexion. (c) PIP-DIP joint angle relation during extension. (d) PIP-MCP joint angle relation during extension. Stippled lines are individual trials, and thick lines are the averages for the conventional mechanism (blue). The dashed green lines are the reference inter-joint relations taken from the literature [51], [53]. The grey regions are the preferred regions to perform a normal finger flexion. (The figure is modified from [50])

4- During extension, the PIP joint angle is around 130% of the MCP joint angle (i.e. $\angle MCP = 0.77 * \angle PIP$) [51].

The conventional mechanisms for both flexion and extension were used to actuate the artificial finger. The trajectories of the fingers are shown in Figure 4. From the trajectories of the artificial fingers, obtained using the conventional tendon routing methods, the following conclusions can be drawn:

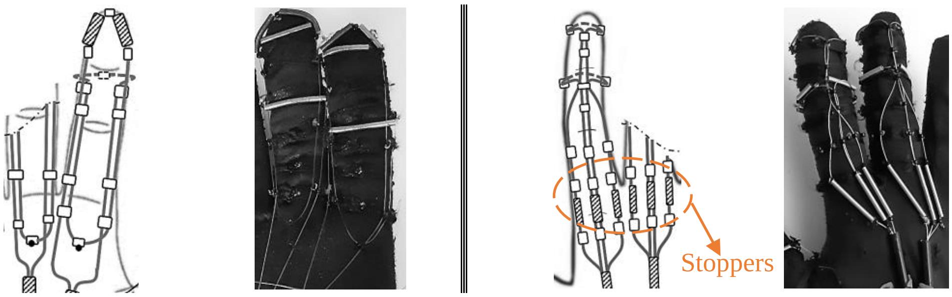
1- During flexion, the DIP joint flexes more than expected with respect to the PIP joint (i.e. finger is at region 3 in Figure 4(a)). This will force the natural PIP-DIP coupling of the finger to be always tensed as described in the previous section.
2- During flexion, the PIP joint does not flex with the same pace of the MCP joint, tending the MCP joint to flex more than the PIP joint, Figure 4(b).
3- During extension, the conventional mechanism over-extends the DIP joint and bend the finger to create a PIP-DIP joints posture away from the normal region postures (i.e. finger is at region 2 in Figure 4(c)).

4- During extension, the conventional mechanism over-extends the MCP joint and bend the finger to create a PIP-MCP joints posture away from the normal postures (i.e. finger is away from the PIP-MCP reference relation in Figure 4(d)).

2.3. Bio-inspired tendon-based mechanism

In this study a bio-inspired tendon based mechanism mimics only the extrinsic muscle tendon units is proposed and analyzed. For flexion, the proposed mechanism is inspired by the FDP and FDS tendons, while for extension, it is inspired by the EDC tendon.

On the flexion side of the mechanism, one exo-tendon is used to provide the functions of the FDP and FDS tendons by routing the exo-tendon twice around the finger. The exo-tendon route once around the distal phalanx to mimic the function of the FDP tendon, while the exo-tendon is routed again around the middle finger to mimic the function of the FDS tendon as shown in Figure 5(a), (b). For extension, two exo-tendons are used to mimic the EDC tendon. One exo-tendon span over the MCP joint to be attached to the middle phalanx, while the other exo-tendon spans from the sides of the MCP joint and PIP joints then spans over the DIP joint to be attached to the distal phalanx. The exo-tendons were passed through stoppers, which were short Bowden cable sheaths positioned on the dorsal side of the MCP joint (refer to Figure 5(c), (d)). These stoppers were installed to ensure that the guidance beads, located before and after the joint, did not move closer to each other than their length, thus preventing any further shortening. Consequently, the MCP joint was prevented from hyperextension by stopping its movement at a specific angle.



(a) (b) (c) (d)

Figure 5. (a) The proposed flexion tendon routing configuration. (b) The soft glove with the implemented flexion tendon configuration. (c) The proposed extension tendon routing configuration showing the placement of the stoppers for the MCP joints. (d) The soft glove with the implemented extension tendon configuration. (The figure is from [50])

The proposed flexion/extension tendon routing configurations are tested on the artificial finger, as described earlier, and on the middle finger of eight healthy subjects, using the implemented soft glove presented in Figure 5. The trajectory of the artificial fingers using the proposed flexion/extension mechanisms is presented in Figure 6:

1- During flexion, the DIP joint flexion does not exceed the permissible limits (i.e. finger is at the grey region in Figure 6(a)). This will keep the PIP-DIP coupling of the finger lose during flexion.
2- During flexion, the PIP joint angle lies in the range [80%, 200%] of the MCP joint angle (i.e. grey region in Figure 6(b)), where the PIP-MCP joints bending angles are suitable for most of daily life activities.
3- During extension, the proposed mechanism avoids the DIP from being overextended and bends the DIP-PIP joints of the finger closer to the normal finger flexion motion region compared to the conventional mechanisms (i.e. Figure 6(c)).
4- During extension, the proposed mechanism avoids the MCP from being overextended and bends the PIP_MCP joints of the finger closer to the normal finger flexion motion region compared to the conventional mechanisms (i.e. Figure 6(d)).

In the experiments conducted on eight healthy subjects (Study I) [50], the soft active glove with the implemented flexion/extension mechanism, as shown in Figure 5, was utilized to flex/extend the middle finger. The subjects wore the glove along with a costume motion measurement system placed on top of it. Throughout the trials, the hand had to remain relaxed (monitored with EMG) and

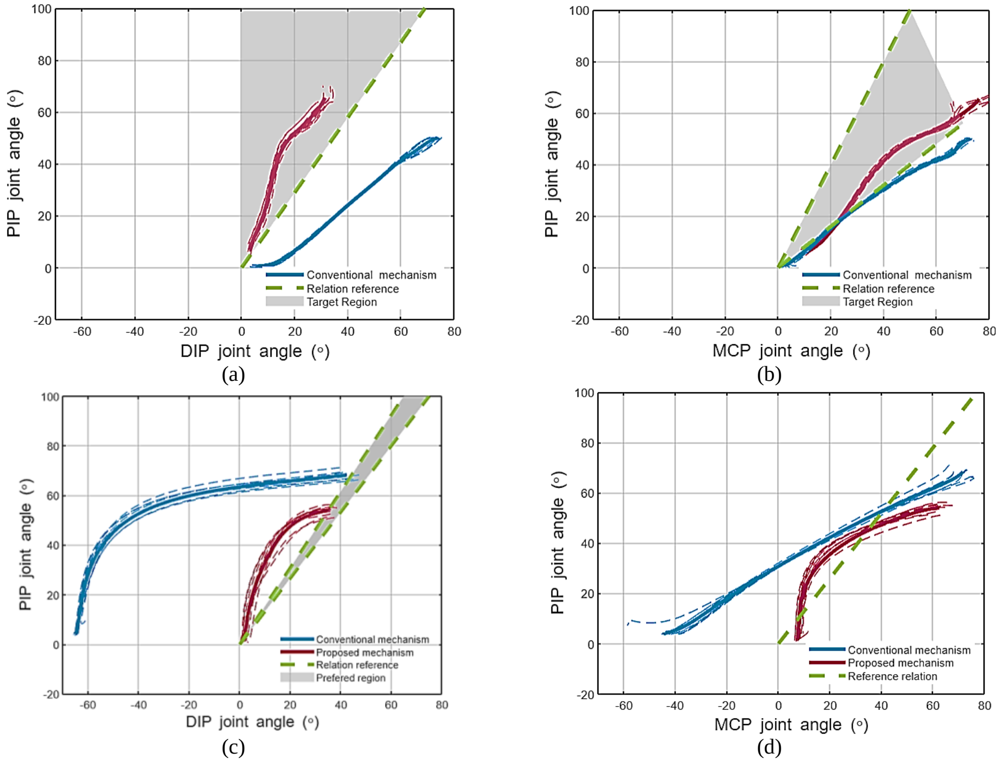
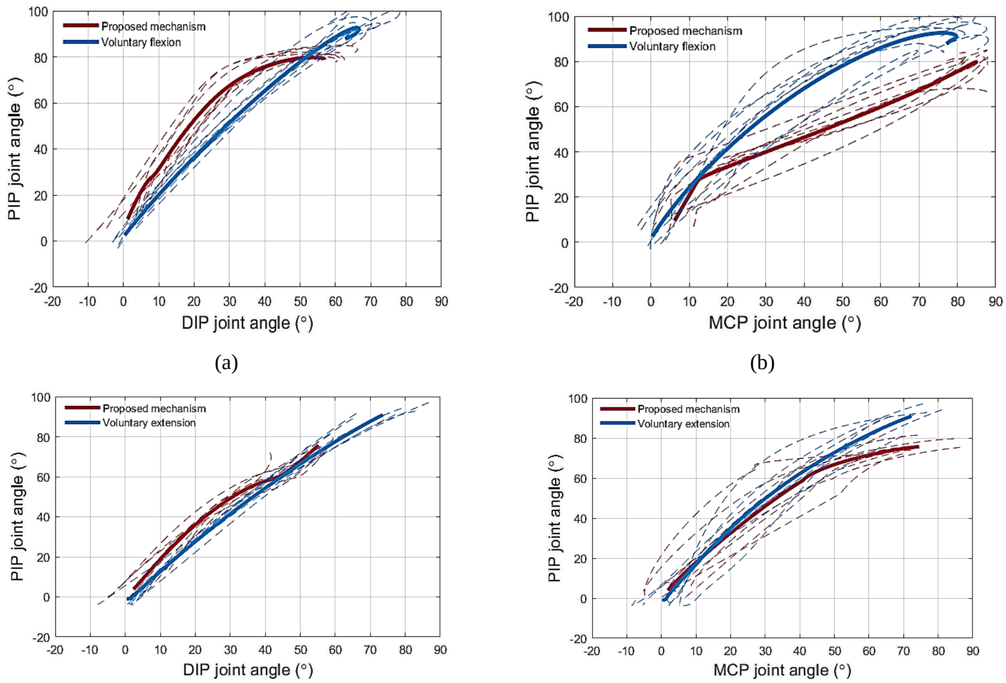


Figure 6. The phase plots for the finger joint angles during flexion and extension of the artificial finger using the proposed tendon routing configuration versus the conventional configuration: (a) PIP-DIP joint angle relation during flexion. (b) PIP-MCP joint angle relation during flexion. (c) PIP-DIP joint angle relation during extension. (d) PIP-MCP joint angle relation during extension. Stippled lines are individual trials, and thick lines are the averages for the proposed (red) and conventional mechanism (blue). The dashed green lines are the reference inter-joint relations taken from the literature [51], [53]. The grey regions are the preferred regions to perform a normal finger flexion. (Figure is modified from [50])

perpendicular to the surface of a table. The flexion motion began with the soft glove extending the middle finger from a fully flexed position. Subsequently, the soft glove flexed the finger from this extended position to full flexion. The same process was repeated for the extension motion. Simultaneously, the motion measurement system recorded the flexion and extension motions. The voluntary, unassisted movement of the middle finger was measured from a fully flexed position (hand in a fist) to a fully extended position, and vice versa for the extension motion.

The costume motion measurement system is a glove with bend sensors used to measure finger joint angles (MCP, PIP, and DIP). Three unidirectional flexible bend sensors (Spectra symbol Inc., 5.5 cm length) were attached to the glove directly over each joint. Angles were recorded at 50 Hz for analysis.

The experiments conducted on healthy subjects concluded that the mechanism on the flexion side provides a natural flexion the finger. At DIP joint, the proposed mechanism flexed the joint with an angle smaller than the maximum permissible flexion angle throughout the motion, Figure 7(a). This maximum limit represents the point at which the DIP joint cannot flex any further. The limitation is due to the coupling between the DIP and the PIP joints, which is created by the EDC tendon within the musculoskeletal structure. The PIP-MCP joints angle relation is within typical and natural range of relations grasping, Figure 7(b) [53].



(a) (b) (c) (d)

Figure 7. The phase plots for the finger joint angles during flexion and extension for the middle finger of healthy subjects using the novel mechanism: (a) PIP-DIP joint angle relation during flexion. (b) PIP-MCP joint angle relation during flexion. (c) PIP-DIP joint angle relation during extension. (d) PIP-MCP joint angle relation during extension. Thick lines are the averages for the proposed mechanism (red) and the voluntary motion (blue). (The figure is from [50])

For extension, the mechanism provided the finger a natural finger extension motion similar to the voluntary finger extension, Figure 7(c) and (d) [50]. However for stiff fingers (i.e. spastic fingers) this result might change. The tendon routing configuration, for extension, creates a strong coupling relation between the DIP and PIP joints, which does not depend on the joints stiffness, therefore the PIP-DIP joints angle relation is almost the same for stiff and non-stiff fingers. However, for the PIP-MCP joints angle relation, the coupling created by the exo-tendon across these two joints is not strong, it depends on the stiffness of the joints, therefore the relation changes for the stiff fingers. In all cases, the mechanism prevents the finger from being hyper-extended at the DIP joint, due to the PIP-DIP coupling, and at the MCP joint, due to the stoppers (i.e., Bowden cable) at the MCP joint that stops the joint from being extended any further after certain limit.

In conclusion, this study successfully introduces a novel tendon routing configuration for soft hand exoskeletons, aiming to mimic the functionality of the FDS and FDP muscles tendon unit on the flexion side of the finger, as well as the EDC muscle tendon unit on the extension side. The effectiveness of the proposed routing configuration was evaluated using artificial fingers and compared with conventional routing configurations. Additionally, the configuration was applied to healthy subjects to validate the results. The proposed mechanism enables the finger to exhibit more natural movements in both flexion and extension. On the flexion side, the proposed configuration allows for flexion angles suitable for various daily life activities. On the extension side, it effectively prevents hyper-extension of the finger at the DIP or MCP joints. These findings highlight the potential of the proposed tendon routing configuration in enhancing the functionality and natural movement of soft hand exoskeletons.

Chapter 3

Study II

Grasping and manipulating objects, using the hand, requires the movement and the coordination of several joints together. These joints provide multiple degrees of freedom (DoF) for the hand. The DoF are critical for the hand's dexterity in performing a vast array of grasping and motion tasks required for daily life [33], [55]. For the soft hand exoskeleton, it is not applicable to control all DoF of the hand individually. A conventional design of the under-actuated mechanism, used to drive a soft hand exoskeleton, involves using a small number of actuators to control a set of exo-tendons that are connected to multiple fingers. This allows multiple fingers to be flexed with a single actuation, rather than using a separate actuator for each finger [31]. This approach reduces the number of actuators required and makes the exoskeleton lighter, more compact, and easier to control, however, it comes at a cost, as it reduces the dexterity of the hand.

The thumb, index, and middle fingers are responsible for most of the hand grasps required for activities of daily living, including power, tripod grasps, and lateral pinch [26]. Daniel M. Wolpert et al. [56] analyzed the natural movements made by the hand during everyday life and found that the thumb has the highest level of independent movement, scoring almost two-fold higher than the index finger in overall digit independence. The index finger is still considered the most independent finger, with a twofold difference from its nearest rival among the other fingers. Therefore, many under-actuated mechanisms developed for hand exoskeletons focus on the thumb and index finger due to their high level of independence in many movements, while the middle finger is often grouped with the ring and pinky fingers due to their high level of interdependence [29].

The adaptive concept used by exoskeletons, such as Exo-glove Poly [32] and the glove proposed by Minas Liarokapis et al. [26] reduces the number of actuators needed by exoskeletons and allows the digits to adapt to objects with irregular dimensions for better grasp. These mechanisms create a differential mechanism, allowing fingers to flex even if others are blocked by the environment. In these type of mechanisms the actuated digit is considered independent if the digit could stay extended while the other digits are flexed using the mechanism. Most of the actuation modules presented in the literature that actuates the thumb, index and middle fingers while applying the adaptive concept in their design, does not provide true independence to the three digits. In these designs, at least one of the digits is still dependent on the movement of the others. That is demonstrated in the introduction section and Table 2, which present examples of modules and the degree of independence they provide for each digit.

In summary, the previous designs of under-actuated mechanisms required multiple actuators to flex the thumb, index, and middle fingers independently. Relying on a single actuator typically limited the independence of at least one of these fingers. In study II, a novel adaptive actuation mechanism was proposed, which utilized a differential mechanism and aimed to achieve the following characteristics:

- The actuation mechanism drives the thumb, index and middle fingers.
- A single actuator is used.
- The actuation mechanism is adaptive to the irregular shapes in the environment (i.e. the thumb, index and middle fingers are independent).
- The mechanism provides stable grasps with hand postures close to the natural grasps.
- The mechanism allows to block the movement of the thumb or any of the fingers actively to increase dexterity.

Study II examined the independency (i.e. adaptivity) of these fingers and the thumb during object grasping tasks using the proposed mechanism. It also tested the ability of the mechanism to provide a stable grasp with a grasping posture close to the natural grasp.

3.1 The Proposed Adaptive mechanism

The design of the proposed mechanism took into consideration the five main features mentioned in the previous section. The mechanism mainly consisted of one tendon and three pulleys that coupled the thumb and the two fingers, index and middle fingers, together. One end of the tendon was connected to the flexion mechanisms at the index finger while the other end was connected to the middle finger. The tendons were routed around the three pulleys as presented in Figure 8 (a). The two outer pulleys (i.e. A and B in Figure 8 (a)) were pulled together using a rigid link, while the pulley in the middle (i.e. C in Figure 8 (a)) was excluded from the rigid link and was pulled under the effect of the tendon, which was routed around it. The pulley in the middle was directly connected to the thumb. The described differential mechanism coupled the thumb, index, and middle fingers together. Despite this connection, each digit could still move independently when it came into contact with objects in the environment. When a particular digit touched an object, its flexion stopped, but the other exo-tendons continued to flex and move the corresponding digits, as illustrated in Figure 8.

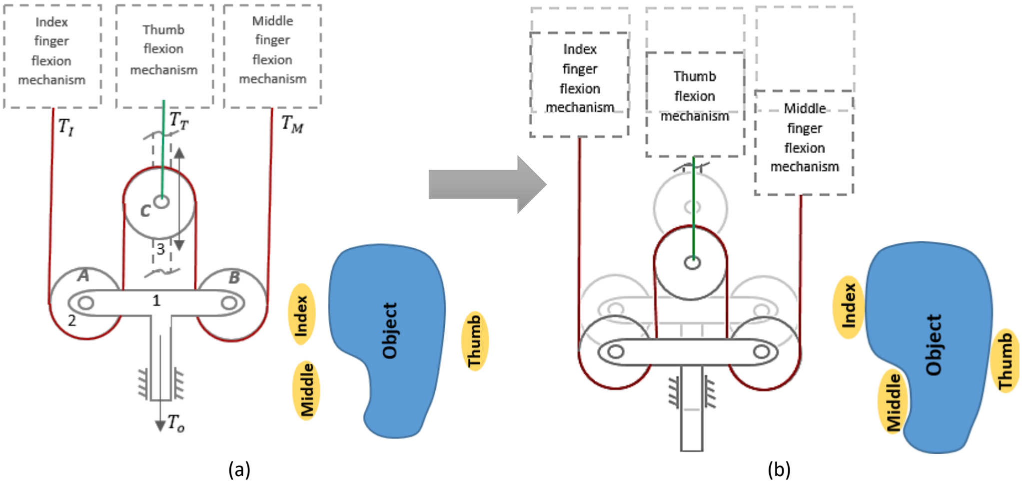
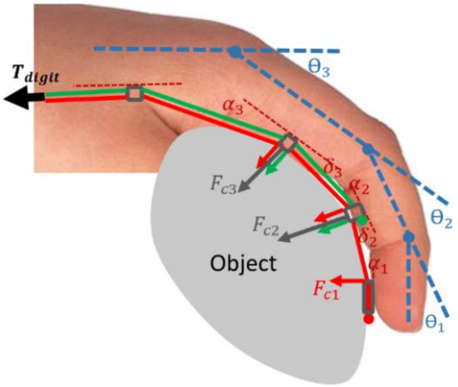


Figure 8. (a) Pulley based actuator mechanism (Schematic Diagram). This mechanism Couples the index and middle fingers with the thumb; 1- rigid link, 2- pulley, 3- linear bearing. (b) The state of the actuation mechanism after grasping



$$F_{c\ phlanx} = \begin{cases} 2\left(T_{digit}\sin\alpha_{Phalanx} + T_{digit}\sin\delta_{phalanx}\right) & ; \quad Phalanx = 3 \\ 2\left(T_{digit}\sin\alpha_{phalanx}\right) + T_{digit}\sin\delta_{phalanx} & ; \quad phalanx = 2 \\ T_{digit}\sin\alpha_{phalanx} & ; \quad Phalanx = 1 \end{cases}$$

Figure 9. Kinetic Analysis for a finger in-contact to an object using the proposed flexion tendon routing configuration proposed in study I. (The figure is modified from [57])

an irregular shaped object, demonstrating the effect of the independent movement of the digits provided by the mechanism.

When the three digits get in-contact with an object (i.e. grasp an object), the differential mechanism distributes the actuator pulling force T_0, which pulls the rigid link between the thumb's exo-tendon and the exo-tendon corresponding to the fingers, according to equation (1).

$$T_I + T_M = T_T; \qquad T_I = T_M \tag{1}$$

The differential mechanism always provide the thumb with a pulling force T_T equal to the sum of the forces provided to the index T_I and middle T_M fingers.

The tendon pulling force is transmitted to a contact force F_c applied by the corresponding finger on the grasped object. The relation between the tendon pulling force and the contact force is a function of the finger posture (i.e. joints angles), as shown in Figure 9, taking into consideration that the angles at the tendon turning points $\alpha_{Phalanx}$ and $\delta_{phalanx}$ are functions of joints angles θ_{joint}. When the finger is fully extended and the flexion angles of all phalanges are zero ($\theta_{joint} = 0$), the contact forces across the phalanges are also zero. The contact force increases by flexing the phalanges.

The exo-tendon routing configuration around the three phalanges of the digits (i.e. the thumb, index and middle fingers) were described in details in chapter II. The exo-tendons that actuated the fingers passed from the volar side of the wrist directly to the finger while the thumb's exo-tendon passed along the ulnar side of the palm. From the furthest part of the palm, the exo-tendon directed to the

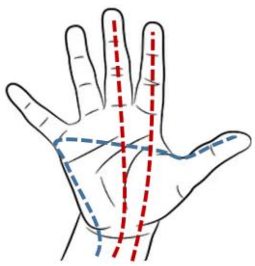


Figure 10. Exo-tendons' lines of action for the thumb, index and middle fingers. (The figure is from [57])

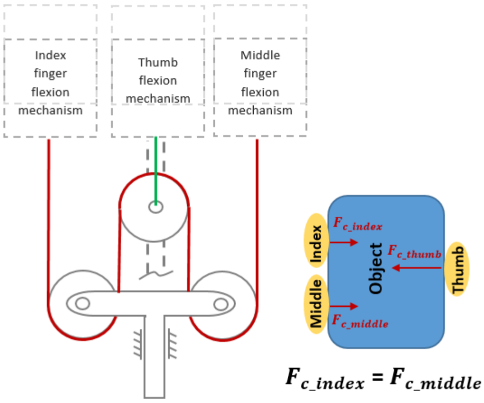


Figure 11. The actuation mechanism state while grasping regular shape object. The contact forces at the index and middle fingers are equal.

thumb, as presented in Figure 10. Therefore, it was assumed that the line of action for the thumb was against the fingers.

From the previous explanation, grasping regularly shaped objects generates equal contact forces at the index and middle fingers. Assuming that the phalanges dimensions of the thumb, index and middle fingers are similar, the contact force generated by the thumb on the object is equal to the sum of the index and middle finger's contact forces, Figure 11.

For grasping irregularly shaped objects, the index and middle fingers have different postures and generate different contact forces on the grasped object. If the sum of all contact forces from the thumb and the fingers across the object doesn't reach its equilibrium state, then the exoskeleton will keep on changing the postures of the thumb and the fingers, which consequently changes the value of their contact forces until the fingers' digits reach the equilibrium state, Figure 12.

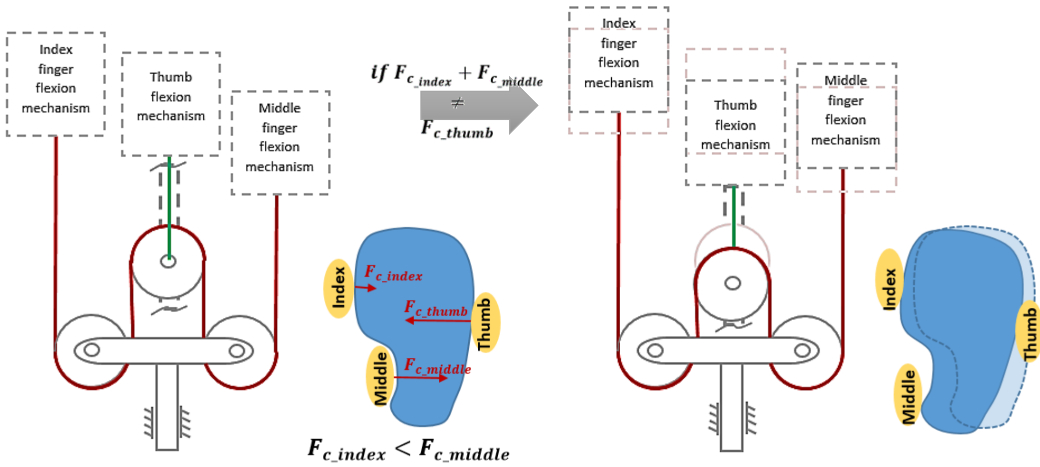


Figure 12. (a) The actuation mechanism state while grasping irregular shape object. The contact forces at the index and middle fingers are not equal. (b) The actuation mechanism adapt the fingers to have an equilibrium grasp where the contact forces are equal on both sides of the object.

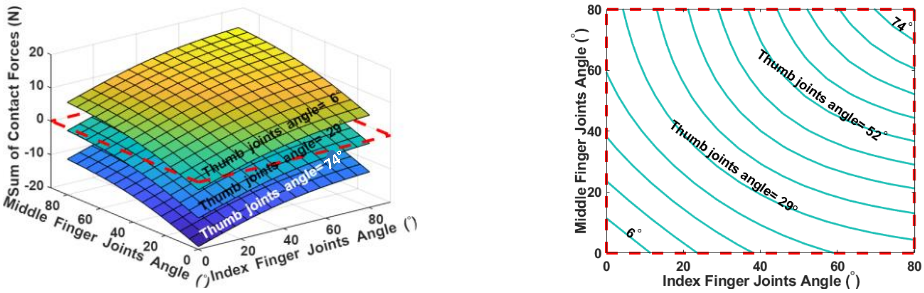


Figure 13. Hand postures for a balanced grasp. (a) The sum of contact forces across the object in-contact for different thumb, index and middle fingers angles; the thumb joints angle are constant at each layer. (b) Equilibrium plane, where the contact forces across the object are balanced for any hand posture lay in this plane. The thumb joints angle are constant along each contour. (The figure is from [57])

To understand the behavior of the hand digits to reach the equilibrium state, Figure 13, presents the relation between the postures of the three digits (i.e. the thumb and the fingers) and the sum of the contact forces they apply on the object.

Figure 13(a) shows various hand postures and their corresponding contact forces on an object in contact with a soft glove. Each layer represents the sum of contact forces for hand postures with different finger angles but the same thumb angle. Figure 13(b) is a cross-section of the same space, showing all the hand postures that generate balanced contact forces across the object. There are infinite possible postures for a balanced grasp, depending on the initial posture and the shortest path to reach equilibrium.

3.2 Evaluation

To evaluate the proposed actuation mechanism, a series of experiments were conducted using the actuation module of the exoskeleton shown in Figure 14 (Study II). The first experiment examined the mechanism's performance in grasping regular-shaped objects, while the second experiment focused on grasping irregular-shaped objects. Finally, the mechanism's performance was tested during a pinch grasp with deactivated middle fingers. The Experiments were conducted on eight healthy subjects.

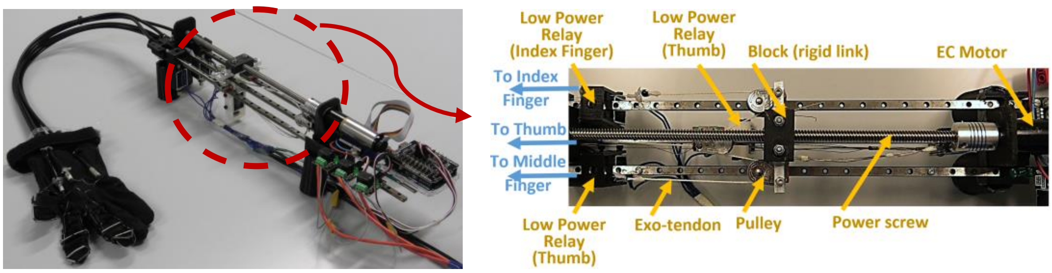


Figure 14. Soft hand exoskeleton with actuation module based on the proposed flexion actuation mechanism (i.e. Pulley differential mechanism). Power Screw serves the purpose of transferring the pulling force from the EC-motor to the differential mechanism. (The figure is modified from [57])

A costume force measurement device was implemented to measure the contact forces at the thumb, index and middle fingers, based on load cell for each digit. Each load cell was covered by a 3D-printed cap to create a symmetric cylindrical shaped device. For the second experiment, the radius of cap at the middle finger's side was increased by 15 mm.

To measure the kinematics of the phalanges in the three digits (i.e. thumb, index and middle fingers), a costume made glove was implemented using flexible bend sensors (Spectra symbol Inc., 5.5 cm length) at each phalanx of the digits.

Regarding the first experiment, the subjects used the soft exo-skeleton to grasp the force measurement device in its symmetric form (i.e. all caps have the same radius) with their thumb, index, and middle fingers. The contact forces between the device and the glove were balanced, with equal forces on the index and middle fingers compared to the force on the thumb side, as shown in Figure 15(a). The fingers had similar flexion angles at their joints, resulting in similar contact forces. The difference in finger poses between the voluntary grasp and the active grasp, using the hand exo-skeleton, was within a small percentage of the full range of motion for each joint. More details can be found in Figure 15(b), which presents joints angles and the difference in poses for the index and middle fingers.

In the second experiment, subjects grasped the force measurement device in its irregular form (i.e. the radius cap at the middle was increased by 15 cm than the other caps) using the soft exo-glove and their thumb, index, and middle fingers. The contact forces between the device and the glove were

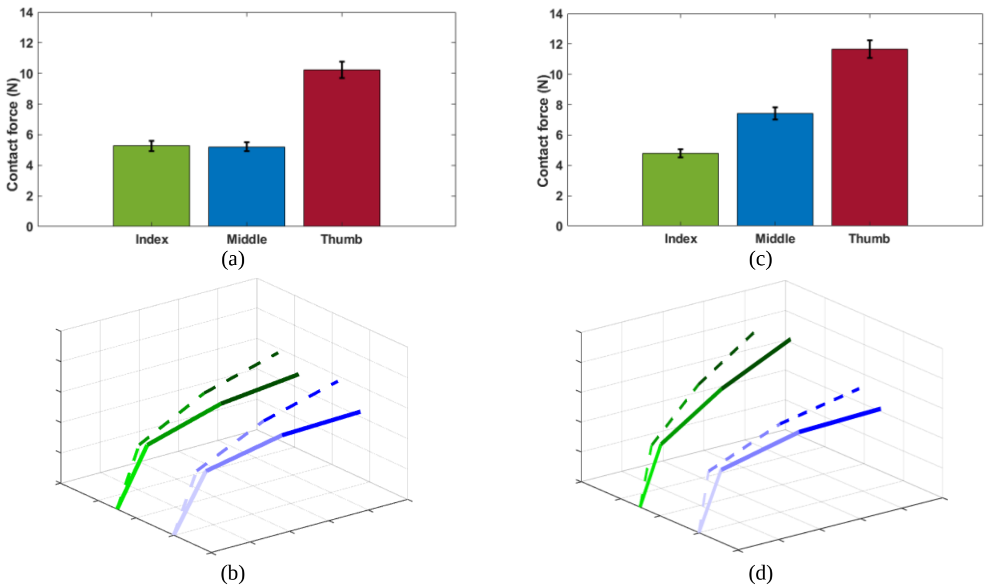


Figure 15. The kinetic and kinematic responses of the soft glove while grasping the force measurement device in its (a), (b) regular and (c), (d) irregular form. (a) Force distribution between the Thumb, Index and middle fingers in addition to (b) the flexion profile of the index (i.e. green links) and middle (i.e. blue links) fingers grasping the force measurement device with the assist of the soft glove (represented by solid links) and compared with a voluntary grasping (represented by dotted links). (c) Force distribution in addition to (d) the flexion profile of the index and middle fingers to grasp the irregular form of the force measurement device (i.e. a step of 15 mm between the index and middle finger caps) with the assist of the soft glove (solid links) and compared with a voluntary grasping (dotted links). (The figure is modified from *[57]*)

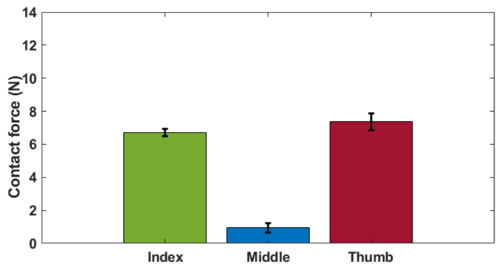


Figure 16. Contact force distribution across the thumb, index and middle fingers while performing pinch grasps. (The figure is from *[57]*)

balanced, but the force on the index finger was lower than that on the middle finger due to the device's irregular shape, Figure 15(c). The middle finger needed to flex more to adapt to the larger diameter of the device at the index finger. The difference in finger poses actuated by the exoskeleton compared to the voluntary hand pose was within a certain percentage of the full range of motion for each joint. More details can be found in Figure 15(d), which presents joints angles and the difference in poses for the index and middle fingers.

Regarding the third test, the subjects grasped the force measurement device, in its regular form, using the thumb and index finger only with the assistance of the soft exo-skeleton and deactivated the middle finger. As illustrated in Figure 16, the contact forces were distributed between the thumb and the index finger.

In conclusion, this study demonstrated the capability of the proposed actuation mechanism to perform grasps that closely resemble natural grasps, regardless of the shape of the object being grasped. This mechanism effectively distributed contact forces among the hand digits, ensuring stable grasping without the need for a dedicated controller. The exoskeleton's grasping poses closely replicated natural hand postures, enhancing the overall functionality. Additionally, the incorporation of the differential module allowed for adaptability to irregularly shaped objects, enabling a more natural and versatile grasp. Furthermore, the independent deactivation of individual fingers facilitated the execution of various gestures, such as pinch grasps, while maintaining balanced grasping for each gesture. These findings highlight the effectiveness of the proposed actuation mechanism in achieving natural and adaptable grasping capabilities for the exoskeleton.

Chapter 4

Study III

The soft hand exoskeleton comprises four main components: the glove, the actuation system, the force transmission mechanism and the human/machine interface. Regarding the glove and the actuation system, study III combines the tendon routing configuration, proposed in Study I, with the actuation system presented in Study II to develop an optimized soft hand exoskeleton that can facilitate ADLs.

To accomplish ADLs, it is required different types of postures/grasps. According to the GRASP taxonomy [58], there are 33 different types of grasp arranged according to its need to power such as power grasp, precision such as writing tripod grasp or intermediate (i.e. mixed between both types) such as lateral/tip pinch. The hand also perform non-prehensile postures, where the fingers do not oppose any of the palm, thumb or the index finger side, such as finger pointing posture. In addition, it performs the extension posture, which is necessary to approach the objects in the environment.

Therefore the following parts are optimized in the developed soft hand exoskeleton to perform ADLs:

1- The actuation mechanism is optimized to perform the adaptive grasps and the extension hand postures in a compact space using differential gears instead of pulleys.
2- The deactivation mechanism of the hand digits (i.e. thumb and fingers) is optimized for more precise control over the fingers, individually, to perform different hand gestures.
3- The developed soft hand exoskeleton includes anti-derailment mechanism to prevent any unwanted movement or disruption in the exo-tendons during hand motions.
4- A human/machine interface based on EMG signals is developed to control the integrated device, intuitively.

Finally, the study evaluates the functionality of the soft hand exoskeleton to accomplish basic daily tasks by controlling the exoskeleton intuitively and performing the following motions: Extension, Power grasp, Tripod grasp, Lateral pinch and Pointing.

4.1 The optimized soft hand exoskeleton

Study III presents a soft hand exoskeleton that is specifically designed to aid users in performing various types of grasps, including tripod, lateral pinch, and power grasps, by providing sufficient force to enhance their grasping abilities. Additionally, the exoskeleton assists in performing the pointing posture, which is essential for activities such as typing and tapping screens. The soft exoskeleton is designed to actuate only the thumb, index, and middle fingers. Figure 17 presents the actuation module, the transmission system including the anti-derailment mechanism, the glove and the EMG Myo-armband (the Myo, Thelamic lab), for the controller.

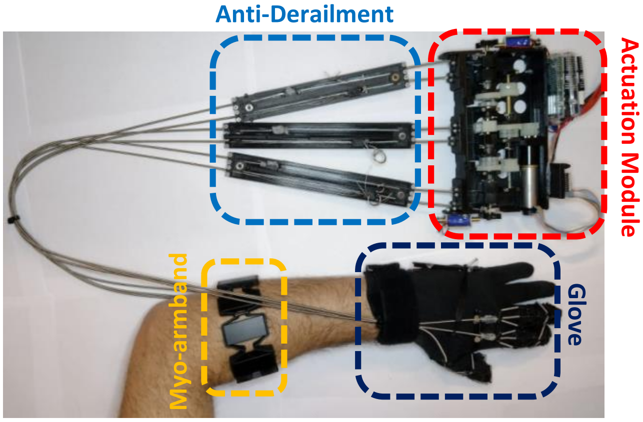


Figure 17. The Integrated soft and exoskeleton with the differential under-actuated system connected with the glove and controlled by a human/machine interface based on EMG signals collected from the myo-armband.

4.1.1 Actuation module

For the actuation module, differential gear sets were utilized instead of pulleys. The implementation of the system with pulleys, based on the flexion concept proposed in study II, was sufficient to fulfill the design requirements for the flexion side of the hand, including adaptivity. However, a differential mechanism is particularly valuable for the extension side as it allows for selective extension of individual digits while others are flexed, enabling postures such as the index-pointing posture where the index finger is extended while the thumb and middle finger are flexed. The bi-directional nature of the differential gears enables the exo-tendons to be wound in both clockwise and anti-clockwise directions, facilitating both flexion and extension movements. Consequently, the system originally designed for flexion can also be effectively utilized for extension, highlighting the advantage of the differential gear sets over pulleys.

The objective of the differential gearbox is to distribute the torque, generated from an EC motor, between the thumb and the two fingers. This is achieved by utilizing differential gears, which poses

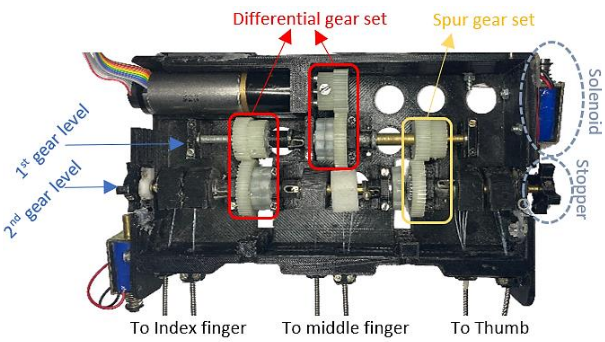


Figure 18. A differential gearbox for the soft hand exoskeleton including EC motor, two solenoids and stoppers for the rotating shafts. (The figure is modified from [59])

the capability to distribute force across two shafts and rotate them independently at different angular velocities. The proposed gearbox consists of two stages, as depicted in Figure 18. In the first stage, the motor power is transmitted through the differential gear to two shafts located on the left and right sides. In the second stage, the torque on the right side is fully transmitted by a spur gear to the thumb, while the torque on the left side is divided by a differential gear set between the index and middle fingers. Each shaft on both sides of the differential gear set in the second stage is connected to a pair of exo-tendons wound around them clockwise and anticlockwise, enabling bidirectional movement. The differential gear set offers the advantage of distributing force across two shafts and independently rotating them at different angular velocities, allowing the thumb and fingers to move independently, adapt to different shapes and perform various gestures. Bowden cables are employed to transmit power from the gearbox to the soft exo-glove, passing the exo-tendons through them.

4.1.2 Anti-derailment connector

The finger exo-tendons for both extension and flexion were attached to the same shaft in the gearbox, as previously described. When one exo-tendon was pulled towards the gearbox (the active exo-tendon), the other exo-tendon (the idle one) would derail away from the shaft. To maintain the tightness of the idle exo-tendon around the shaft and prevent derailment, an anti-derailment mechanism was introduced between the gearbox and the glove. This mechanism consisted of two slider blocks that slide along parallel paths and were connected by a cable, as shown in Figure 19. One block was positioned in the path of the extension exo-tendon, while the other was placed in the path of the flexion exo-tendon. The cable had knots that obliged the blocks to move in opposite directions. By connecting the extension exo-tendon to one block and the flexion exo-tendon to the other, the idle exo-tendon was pulled out of the gearbox and remained tightly routed around the shaft while the active exo-tendon pulled the active block. This block transmitted the pulling force to the glove via another exo-tendon attached to it, extending through a Bowden cable. Three anti-derailment connectors were used for each finger to prevent derailment and transmit the pulling force to the glove.

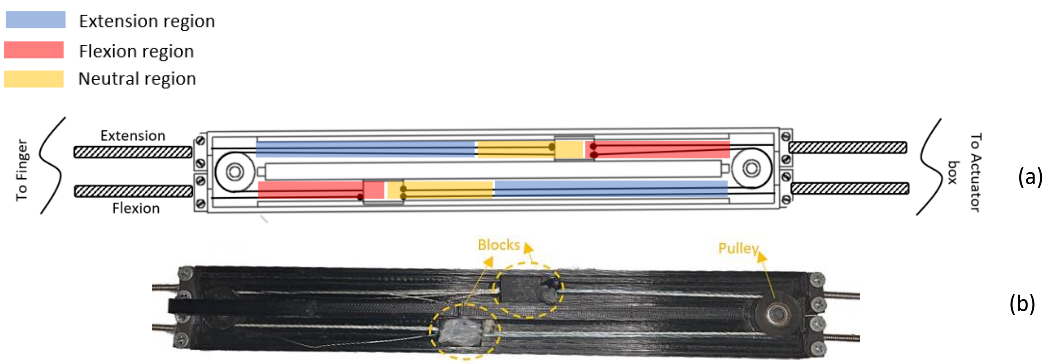


Figure 19. Anti-derailment pulley mechanism. (a) Schematic diagram for the mechanism representing the extension, flexion, and neutral region. The finger is extended when the block is at the red region. The finger is flexed at the blue region. The finger is neutral at the yellow region. (b) The implementation of the pulley mechanism. (The figure is from [59])

4.1.3 Controller

The soft exoskeleton was capable of performing four different activities. It could extend the fingers to approach the objects. It could also perform tripod and lateral pinch grasps, in addition to, pointing. The user had the ability to control the exoskeleton and select between these different activities using an intuitive controller. Myo-armband, which has eight EMG electrodes, is used to detect the electrical activity of the muscles around the forearm.

The intuitive controller consisted of two steps. In the first step, the user's intention was detected by classifying features extracted from segmented signals. Windows of 0.2 seconds with 0.1 seconds overlap were utilized for this purpose. Ten discriminative features, individually selected for each user, were input into a support vector machine (SVM) classifier for activity classification. The classifier discriminated between six classes: Extension, Tripod, Lateral pinch, Pointing, Supination and pronation. Unintentional movements were filtered out using predefined thresholds. The controller did not respond as long the highest root mean square (RMS) value of the EMG signals collected from the eight electrodes of the Myo-armband was lower than the threshold. In the second step, a finite-state machine was employed to determine the type of gesture the hand exoskeleton should perform based on the estimated user intention, Figure 20. The state machine followed a specific sequence, starting with the device responding to the extension intention. It then transitioned to states corresponding to pointing, tripod grasp, or lateral pinch. From any of these states, the device could only respond to the extension intention. The finite state machine included the pronation and supination states, as they had the potential to interfere with the other events and trigger unintentional movements. By adding them as separate events, the controller remained inactive if they are detected. This controller design allows for intuitive control of the hand exoskeleton, detecting user's intention and guiding the exoskeleton's movements accordingly.

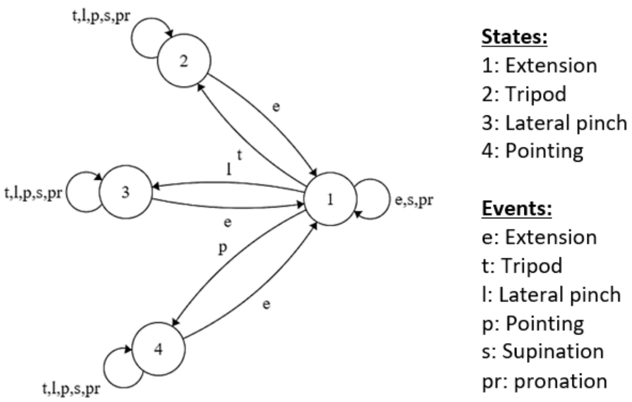


Figure 20. The finite-state machine that governs the intuitive controller decisions. (The figure is from [59])

4.2 Evaluation

Study III involved a comprehensive set of experiments aimed at assessing the functionality of the optimized soft hand exoskeleton. These experiments focused on evaluating the exoskeleton's ability to assist users in performing various types of grasps and postures, such as the tripod grasp, lateral pinch grasp, power grasp, and pointing posture. The primary objective was to examine how effectively the exoskeleton could manipulate objects to facilitate daily life activities. Additionally, the experiments sought to determine the exoskeleton's maximum capabilities in terms of grasping force and range of motion. To conduct these experiments, a total of nine healthy subjects were recruited and their participation was crucial in obtaining valuable insights and data for the evaluation process.

The first experiment compared muscle activity with and without exoskeleton assistance for different grasping types and postures. Four tasks were performed: tripod grasp (grasping a water bottle from its cap), lateral pinch (grasping a coffee cup from its handle), power grasp (grasping a 500 gram water bottle from its body), and pointing. For each task, three trials were conducted both with and without exoskeleton assistance. EMG signals were captured using eight electrodes on the myo armband during a 5-second holding period. The mean root mean square of the EMG signals was calculated for each trial. Results showed that, on average, muscle activity during active trials (without exoskeleton assistance) was 3.76 times higher for tripod grasp, 2.12 times higher for lateral pinch, 5.44 times higher for power grasp, and 4.3 times higher for pointing, compared to the assisted trials (with exoskeleton assistance), Figure 21. In summary, the muscle activity levels were significantly reduced when participants received exoskeleton assistance for all four tasks: tripod grasp, lateral pinch, power grasp, and pointing.

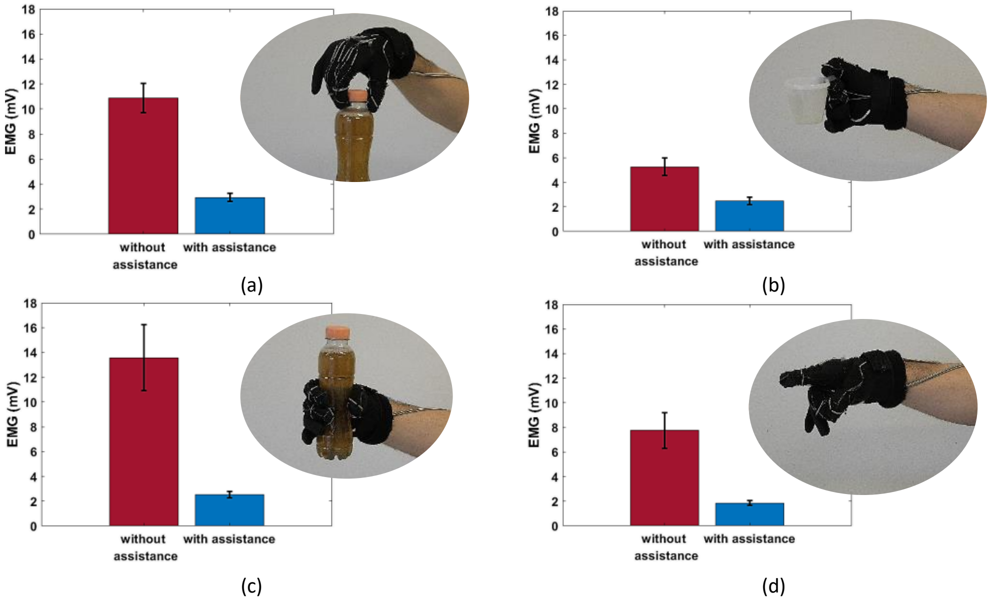


Figure 21. Mean values and standard deviations, across subjects, of the muscles activity with and without the soft hand exoskeleton assistance while performing (a) tripod, (b) lateral pinch, (c) power grasp and (d) pointing. (The figure is from [59])

The purpose of the second test was to evaluate the functionality of a soft exoskeleton for daily life activities, specifically its ability to grasp objects effectively and maintain the grasp during hand movements. To measure functionality, Grasp (GS) and Manipulation (MS) scores were used to assess the exoskeleton's proficiency in grasping objects correctly and manipulating them while holding the grasp. The test consisted of six main tasks covering four types of gestures and grasps: Index-pointing, Tripod (T), Lateral pinch (LP), and Power grasp (PG). The index-pointing task involved using a keyboard to operate a stopwatch for 5 seconds. For the other tasks, specific objects were grasped, such as a bottle for power grasp, a marker and a ball for tripod grasp, and an access card and a key for lateral pinch. The protocol for each task was defined, and a scoring system is established to measure the number of successful grasps GS and successful manipulation MS. The overall test comprised five trials, with each trial including three index-pointing tasks, three power grasp tasks, three tripod grasp tasks, and three lateral pinch grasp tasks, randomized each time. Figure 22 shows the total grasp and manipulation scores, which are the average GS and MS scores, respectively, based on nine subjects' performance in the test. The index-pointing task had the highest average grasping score at 90%. Tripod grasp tasks had the lowest average grasping score at 84.4%.

In terms of manipulation scores, subjects successfully manipulated objects in all tasks except for power grasp, where the average success rate was 92.6%. Over all, the participants succeeded in grasping the objects in almost 88% of the trials and manipulate them in 98% of the trials. Among the unsuccessful manipulation trials, it was found that 60% (6 trials) of these instances, involving all participants, resulted in the object dropping from the subject's hand. In contrast, 40% (4 trials) were attributed to the false release of the exoskeleton. In conclusion, the test results indicate that the soft exoskeleton demonstrated good functionality for daily life activities, with high grasping and manipulation scores across various tasks, except for some challenges observed in the power grasp task.

Additional experiments were carried out to assess the maximum capabilities of the developed exoskeleton in terms of grasping force and range of motion. These tests showed that the device distributed contact forces effectively, with an average contact force of 10.1 N at the thumb and 5.2 N at the index and middle fingers. The grasping force generated by the glove was sufficient for objects weighing around 500 grams. The maximum joint angles were 3.2° (DIP), 9.2° (PIP), and 12° (MCP)

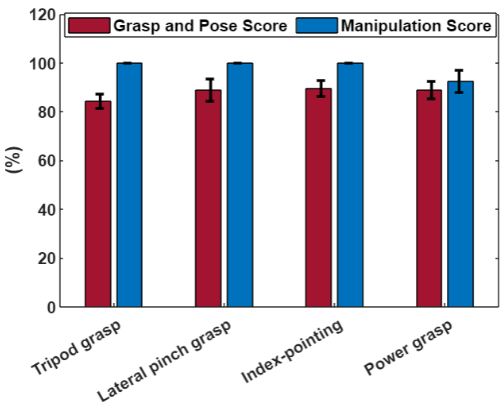


Figure 22. Exoskeleton performance results for each posture/grasp. Mean values and standard deviations, across subjects, of the grasp and pose scores, and manipulation scores for each posture/grasp type. (The figure is from [59])

for finger extension, and 33.5° (DIP), 69.8° (PIP), and 69.8° (MCP) for finger flexion. These results demonstrate the functionality and effectiveness of the soft exoskeleton in achieving natural finger movements and grasping capabilities.

As a conclusion, this study aimed to optimize the actuation module of the soft hand exoskeleton presented in chapter 3. The optimization process involved the implementation of differential gear sets, which enabled both finger flexion and extension. This advancement allowed for precise control over finger deactivation, enabling the performance of various hand gestures. Additionally, an anti-derailment mechanism was designed to prevent exo-tendon derailment from the pulling shafts, ensuring a more reliable device. To provide an intuitive user experience, an EMG-based controller was developed, allowing users to seamlessly switch between different gestures. By incorporating these enhancements, the exoskeleton provided a wider range of finger movements within a compact device. As a result, the optimized design significantly improved the functionality and versatility of the exoskeleton, empowering users to accomplish a broader range of tasks and achieve more effective grasping of objects.

Extensive testing was carried out to assess the performance and functionality of the device. The findings revealed that the device successfully achieved its objective of grasping and manipulating various objects commonly encountered in daily life activities. Users were able to intuitively select the appropriate type of grasp for different objects. Moreover, the device consistently exhibited lower overall muscle activity requirements compared to manual grasping without the device. These results highlight the device's effectiveness in enhancing grasping capabilities while reducing muscle exertion.

Chapter 5

Conclusions

The aim of this Ph.D. is to propose and implement a method based on exo-tendons to provide natural hand motion for supporting activities of daily living. For this purpose, a bio-inspired flexion/extension mechanism has been proposed to provide natural finger flexion/extension motion (Study I). An under-actuated flexion system has been proposed using pulleys to actuate the thumb, index and middle fingers, simultaneously (Study II). The proposed concepts presented in the first two studies has been implemented as prototypes and tested on healthy subjects. In study III, the flexion/extension mechanism, proposed in the first study, is integrated with an actuation system based on differential gears. A human/machine interface system based on EMG signals is used to control the integrated device intuitively. The functionality of the device and the ability of the new concepts, integrated together, in supporting the hand to perform basic daily activities has been evaluated. The overall results showed that a bio-inspired tendon based exoskeleton actuated by a differential system to flex/extend the fingers and controlled by the human using EMG signals can offer a light weight solution to provide normal hand function to accomplish ADLs.

2.1. Contributions

The main contribution of this Ph.D. is the development of a soft hand exoskeleton that could support hand movements including extension and flexion of the fingers in addition to specific fine finger movements that are useful for ADLs. As a result, bio-inspired and under-actuated mechanisms have been proposed in addition to a human/machine interface based on EMG signals for controlling the exoskeleton. In particular, the following specific contributions are made:

1- A bio-inspired flexion/extension mechanism is proposed for the fingers, based on replicating the extrinsic muscles. For finger flexion, an exo-tendon has been routed twice around the finger; at the distal phalanx and at proximal phalanx to mimic the function of the FDP and FDS tendons in the human musculoskeletal structure. For extension, two exo-tendon has been used to extend the finger simultaneously at the distal and middle phalanx as the EDC tendon in the human musculoskeletal structure. Both of the proposed mechanisms have been tested on artificial fingers and on healthy subjects. The test proved that the proposed flexion mechanism succeed to flex the finger naturally, while for extension the mechanism, it prevents the distal and proximal phalanx from being hyper extended.

2- A new method of developing an under-actuated system to flex the thumb, index and middle fingers, simultaneously, is proposed. A single motor and a differential mechanism, using a set of pulleys, pull the exo-tendons that are extended to the thumb and fingers. The explanation of the concept is presented in chapter 3. The study investigates the ability of the new concept in providing adaptive and stable grasps in addition to, the ability to block each finger individually to perform different types of grasps. The results obtained from the experiments, conducted on healthy subjects, demonstrated that the system always provide equal contact forces on both sides of the grasped object, the thumb side and the fingers side of the object, whether the object has a symmetric or non-symmetric shape and that provide an adaptive and stable grasps.

3- In Chapter 4, the adaptive actuation module, initially designed using pulleys as discussed in Chapter 3, underwent optimization and upgrades. The utilization of differential gears proved beneficial for the extension side of the hand, allowing selective extension of individual fingers while others are flexed, facilitating gestures like the index-pointing posture. The compactness of the device was improved to enhance wearability, and the bi-directional nature of the differential gears enabled finger extension and flexion. The upgraded system enabled the glove to perform various types of grasps, including power grasp, tripod grasp, lateral pinch, and pointing, with intuitive selection based on EMG signals captured from the forearm muscles. Experimental evaluations were conducted in Chapter 4, demonstrating the system's ability to support anatomical hand motions for basic daily tasks. The device exhibited a wide range of motion and grasping force, capable of handling objects weighing up to 500 grams. The pick and manipulation tasks achieved success rates of 88% and 98% respectively, validating the system's functionality.

2.2. Limitations and future work

The Ph.D. study presents new concepts, integrated design and experimental evaluation of the upper limb exoskeletons. Some limitations of this Ph.D. study require further considerations:

- The experimental studies presented in Chapters 2, 3, and 4 were conducted on healthy subjects. The muscle activity of the forearm was recorded to ensure that the hand remains at rest when the exoskeleton is active. The results of these experiments are expected to be comparable to those obtained when testing with patients who have natural passive joint stiffness values (i.e., no or low level of spasticity). However, it is necessary to conduct further testing on patients with spastic hands to evaluate the performance of the mechanisms in that specific condition.
- Abnormal sEMG signals caused by conditions like stroke or SCI, especially with spasticity, can make it challenging to distinguish voluntary and involuntary muscle activity. Further research is needed to optimize the EMG controller for spastic hands, focusing on developing algorithms to effectively differentiate between voluntary and involuntary signals. This will improve the accuracy and reliability of EMG-based control systems for devices used by individuals with spasticity.
- The same flexion/extension mechanism used for the index and middle fingers is used for the thumb ignoring the spherical motion of the Carpometacarpal joint. Consequently, the Adduction/abduction motion of the thumb is not taken into consideration while flexing the thumb. Extra DoF has to be added to control the adduction/abduction motion either passively or actively as it could improve the performance of the exoskeleton regarding the number of gestures it could provide to the hand.
- For the exoskeleton presented in chapter 4, no consideration is given to gearbox design optimization and selection of the gears and the shafts. The design of the anti-derailment

subsystem has to be further investigated to reduce its size. Its rigid structure interferes with the Bowden cables reduces the flexibility of the power transmission system between the gearbox and the soft glove.

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