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DESIGN AND BIO-MECHANICAL EVALUATION OF UPPER-BODY EXOSKELETONS FOR PHYSICAL ASSISTANCE

BY
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Design and bio-mechanical evaluation of upper-body exoskeletons for physical assistance

Ph.D. Dissertation

by

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Abstract

Exoskeleton robots are complex electro-mechanical devices designed to support humans in improving their motor abilities. The potential application of these devices can be found in motion/power amplification, rehabilitation, and therapy. Many exoskeletons have been developed and used for the aforementioned applications, while developing exoskeleton robots of high reliability, safety, and comfortability is still challenging. Therefore, new mechanisms and test methods that could simplify the exoskeleton development and evaluate the influence of these parameters are required.

The overall objective of this Ph.D. thesis focuses on developing comprehensive support for the human upper limb movements, including hand opening/closing, and investigated their implications as part of physical human-robot interaction (pHRI). Thus, three different studies were conducted, where fully powered and hybrid methods of actuation were investigated to support the human upper limb movements physically.

The first study aimed at designing a 4-DOF active/powered upper limb exoskeleton for physical assistance. The design of the exoskeleton was made safe and reliable by integrated C-ring and non-backdrivable mechanisms that help maintain the output position with low power consumption. The kinematics and dynamics of the active upper limb exoskeleton were studied, addressing the jacobian, workspace and singularity analysis, including dynamic modeling. A prototype of the active upper limb exoskeleton was developed, and a commercially available soft extra muscle (SEM) glove was integrated to supplement the users in grasping; thus, fulfilling the requirement for comprehensive motion support. In addition, a PD-based trajectory tracking control was implemented to experimentally validate the performance of the human-exoskeleton system for the two basic ADLs, i.e., drinking and picking up an object from the table. The detailed analysis demonstrated that the effectiveness of using the proposed system for physical assistance of complete disabled people.

The second study focused on investigating the physiological consequences of using the upper limb exoskeleton on the human skeletal system. A mathematical model of a human upper limb and exoskeleton was developed as

a closed-loop multibody system for further investigation of pHRI. The interaction between the human and exoskeleton was studied by simulating the dynamic response of the multibody system for two manual load lifting activities in the sagittal plane. Moreover, contact forces and torques were obtained, and the load sharing between the human and exoskeleton system was analyzed. The results obtained from the simulation and analysis demonstrated the efficacy of the upper limb exoskeleton in reducing the physical human effort during the manual load handling activities. Upon the simulations, a new method of developing a hybrid upper limb exoskeleton was proposed, which offers relatively a cost effective, lightweight, and low power solution.

Finally, the third study presented a new design method for developing a hybrid hand exoskeleton, where an additively manufactured passive hand exoskeleton was combined with a commercially available soft extra muscle (SEM) glove. The proposed hybrid hand exoskeleton design was intended to amplify the minimal residual movements or restore the lost motor function for hand opening/closing. The kinematic and static structural analyses were performed to analyze the anatomical compatibility and reliability. The prototype was developed and tested with the two healthy participants and two patients suffering from amyotrophic lateral sclerosis (ALS). Moreover, flex sensors were used to record the fingers joint angle trajectories for simple hand opening task. Three different cases were considered and compared to analyze the task kinematics, i.e., volunteer hand opening, hand opening with passive and hybrid hand exoskeletons. The statistical analysis of the recorded data from the flex sensor showed that the hybrid exoskeleton supported the patients during the hand opening and compensated for the relative hyperflexion of the fingers and wrist muscles.

The work described in this thesis contributes to the design and biomechanical evaluation of upper limb exoskeletons that can support human upper limb movements comprehensively. As a result, two novel hybrid exoskeleton designs were proposed, resulting in a low-power, cost-effective solutions. The research reported in this thesis demonstrates the efficacy of newly proposed hybrid exoskeletons as alternatives to existing fully powered and sophisticated systems. The work will thus pave the way for future study and aid in the development of more accurate knowledge of human-robot interaction.

Resumé

Exoskeletrobotter er komplekse elektromekaniske enheder, der sidder udenpå kroppen med det formål at understøtte menneskets motoriske evner. Den potentielle anvendelse af disse enheder kan findes i ensidigt gentagne arbejdsopgaver, rehabilitering og terapi. Udvikling af exoskeletrobotter med høj pålidelighed, sikkerhed og komfort er stadig udfordrende. Der er derfor behov for nye mekanismer og testmetoder, der kan forenkle udviklingen.

Det overordnede mål med denne ph.d.-afhandling er at udvikle støtte til menneskers bevægelser, herunder åbning og lukning af hånden, samt i den kontekst at undersøge betydningen af fysisk menneske-robot-interaktion (pHRI). Der er gennemført tre forskellige undersøgelser.

Den første undersøgelse havde til formål at designe et motordrevet exoskelet med fire frihedsgrader. Eksoskelettets design blev gjort sikkert og pålideligt med en integreret C-ring og en motormekanisme, der med et lavt strømforbrug opretholder en position. Kinematikken og dynamikken blev undersøgt med fokus på beregning af Jacobianten, arbejdsrum og singulariteter. En prototype af det aktive exoskelet blev udviklet og tilføjet en kommercielt tilgængelig soft extra muscle (SEM) handske for at supplere brugerne med muligheden for at gribe om genstande. Derudover blev en bane-regulering implementeret for eksperimentelt at validere ydeevnen af menneskeexoskeletsystemet ved to grundlæggende aktiviteter;at drikke og samle en genstand op fra bordet. Den detaljerede analyse viste effektiviteten af at bruge det foreslåede system til fysisk assistance til alvorligt handicappede.

Den anden undersøgelse udforskede de fysiologiske konsekvenser af at bruge exoskelettet på det menneskelige skeletsystem. En matematisk model af en menneskelig overkrop og eksoskelettet blev udviklet som et lukket sløjfe flerlegemesystem til yderligere undersøgelse af pHRI. Interaktionen mellem mennesket og eksoskeletettet blev undersøgt ved at simulere den dynamiske respons af flerlegeme-systemet for to manuelle løft. Desuden blev kontaktkræfter, drejningsmomenter, og belastningsfordelingen mellem mennesket og exoskeletsystemet analyseret. De opnåede resultater fra simuleringen og analysen demonstrerede effektiviteten af exoskelettet til at reducere den

fysiske menneskelige indsats under de manuelle håndteringer. Efter simuleringerne blev der foreslået en ny metode til at udvikle et hybridt exoskelet til overkroppen, som tilbyder en relativt omkostningseffektiv og let løsning med lavt effektforbrug.

Endelig præsenterede den tredje undersøgelse af en ny designmetode til udvikling af et hybridt hånd-exoskelet. Et additivt fremstillet, passivt håndexoskelet blev kombineret med en kommercielt tilgængelig soft extra muscle (SEM) handske. Det foreslåede hybride håndexoskeletdesign var beregnet til at forstærke eller genoprette den motoriske funktion til åbning og lukning af hånden. Kinematiske og statiske strukturelle analyser blev udført for at analysere den anatomiske kompatibilitet og pålidelighed. Prototypen blev udviklet og testet med to raske deltagere og to patienter med amyotrofisk lateral sklerose (ALS).

Ydermere blev flexsensorer brugt til at registrere fingerleddets vinkelbaner ved simpel åbning af hånden. Tre forskellige tilfælde blev betragtet og sammenlignet for at analysere opgavens kinematik. Den statistiske analyse af de registrerede data fra flexsensoren viste, at det hybride exoskelet støttede patienterne under åbning af hånden og kompenserede for den relative hyperfleksion af fingre og håndledsmuskler.

Det arbejde, der er beskrevet i denne afhandling, bidrager til design og biomekanisk evaluering af exoskeletter, der kan understøtte menneskelige bevægelser i overkroppen. Som et resultat blev der foreslået to nye hybride exoskeletdesigns, hvilket resulterede i laveffekts- og omkostningseffektive, løsninger. Den forskning, der er rapporteret i denne afhandling, viser effektiviteten af hybride exoskeletter som alternativer til eksisterende fuldt motordrevne og sofistikerede systemer. Arbejdet vil således bane vejen for fremtidige undersøgelser og hjælpe med at udvikle mere præcis viden om menneske-robotinteraktion.

Publications

Parts of the doctoral study have been published in or submitted to peer-reviewed scientific journals and international conferences. The main body of this thesis consists of the following papers.

1. Muhammad Ahsan Gull, Mikkel Thoegersen, Stefan Hein Bengtson, Mostafa Mohammadi, Lotte NS Andreasen Struijk, Thomas B Moeslund, Thomas Bak and Shaoping Bai. "A 4-DOF upper limb exoskeleton for physical assistance: Design, modeling, control and performance evaluation." *Applied Sciences*, 11(13), (2021): 1-13.
   doi: 10.3390/app11135865.

2. Muhammad Ahsan Gull, Thomas Bak and Shaoping Bai. "Dynamic modeling of an upper limb hybrid exoskeleton for simulations of load-lifting assistance." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, (2021): 1-14.
   doi: 10.1177/09544062211024687

3. Muhammad Ahsan Gull, Shaoping Bai, Jakob Udby Blicher and Tobias Glaston Staermose. "Design and performance evaluation of a hybrid hand exoskeleton for hand opening/closing." *Journal of Medical Devices*, 15(4), (2020): 041007. doi: 10.1115/1.4052448

4. Muhammad Ahsan Gull, Shaoping Bai and Thomas Bak. "A review on design of upper limb exoskeletons." *Robotics*, 9(1) (2020): 1-35.
   doi: 10.3390/robotics9010016.

In addition to the main papers, the following publications have also been made.

1. Mikkel Thøgersen, Muhammad Ahsan Gull, Frederik Victor Kobbelgaard, Mostafa Mohammadi, Stefan Hein Bengtson, and Lotte NS Andreasen Struijk."EXOTIC - A discreet user-based 5 DoF upper-limb exoskeleton for individuals with tetraplegia." In *2020 3rd International Conference on Mechatronics, Robotics and Automation (ICMRA)*, Shanghai, China, pp. 79-83, October, 2020. doi: 10.1109/ICMRA51221.2020.9398351

2. Teng Long, Muhammad Ahsan Gull, and Shaoping Bai. "PD-based fuzzy sliding mode control of a wheelchair exoskeleton robot." *Transactions on Mechatronics* , 25(5), (2020): 2546-2555. doi: 10.1109/TMECH.2020.2983520

3. Muhammad Ahsan Gull, Shaoping Bai, Natalie Mrachacz-Kersting, and Jakob Blicher."WEXO: Smart wheelchair exoskeleton for ALS patients." In *i-CREATe 2018: Proceedings of the 12th International Convention on Rehabilitation Engineering and Assistive Technology*, Shanghai, China, pp. 97-100, July, 2018. doi: 10.5555/3281667.3281686

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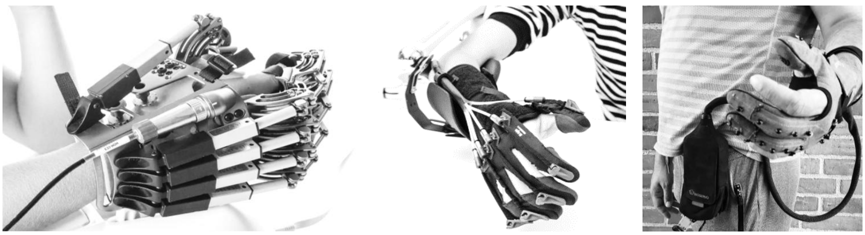
Muhammad Ahsan Gull
Aalborg University, January 20, 2022

Chapter 1

Introduction

Upper body exoskeletons are wearable robots designed to comply with the human musculoskeletal structure for the purpose of motion amplification or rehabilitation. These devices can be designed as a soft or rigid-body mechanism, having similar kinematics as the actual human limb, and their joints are expected to coincident with anatomical joints. Recent studies have highlighted the significance of using this technology in medical care and industrial applications. For example, the exoskeletons can be used to provide intensive therapy sessions for restoration of the lost motor functions or can be used to amplify the residual movements, shown in Fig. 1.1. Moreover, they can also supplement the user in everyday manual load handling activities and relive the human's musculoskeletal structure, shown in Fig. 1.2.

The development of ergonomic upper body exoskeletons is challenging in mechanism design, selection/ implementation of the control methods, and physical human-robot interaction (pHRI). Several design methods have been



(a) (b) (c)

Figure. 1.1. Examples of commercially available active hand exoskeletons, (a) Hand of Hope by rehab robotics [1, 2], (b) Gloreha Sinfonia by Gloreha [3, 4], (c) soft extra muscle glove by BioServo.

(a) (b) (c)

Figure. 1.2. Examples of commercially available upper limb exoskeletons, (a) MATE XT developed by Comau [5, 6], (b) ShivaEXO developed by Ergosante technologies [7], (c) Skelex 360 developed by SkelEX [8, 9].

adopted to develop a variety of robotic exoskeletons, including active, passive, and semi-passive mechanisms, but only a few are successfully commercialized with limited functionalities. Most commercially available solutions are either passively actuated exoskeletons designed to relieve the human musculoskeletal structure in a harsh industrial environment or actively actuated devices strictly designed for therapy in clinical settings. Ekso Vest (by Ekso Bionics, Richmond, USA), BESK G arm exoskeleton (by GOGOA, Bizkaia, Spain), Skelex (by SkelEX, Rotterdam, Netherlands), ShivaEXO (by Ergosante technologies, Anduze, France), MATE (by COMAU, Grugliasco, Italy), Soft extra muscle (SEM) glove (by Bioservo Technologies, Kista, Sweden), Hand of Hope (by Rehab-Robotics, HongKong) and Gloreha Sinfonia (by Gloreha, Lumezzane, Italy) are some notable examples of commercially available exoskeletons. On the other hand, researchers are now focusing on more complex problems that enhance the features and guarantee a safe and comfortable dynamic interplay between the human and exoskeleton system.

1.1 State-of-the-art upper body exoskeletons

Several upper body exoskeletons were developed during the past few years, for motion amplification and rehabilitation applications. Some notable commercially available upper body exoskeletons and research prototypes are shown in Figs 1.1, 1.2, and 1.3. This section outlines the state of the art of upper limb exoskeleton designs and their performance assessment methods firstly on the active and then the passive systems. In addition, an overview of hand exoskeletons for motion amplification/rehabilitation is provided. Different design approaches used to amplify/restore the anatomical hand movements by preventing the flexor hypertonia are presented along with their potential advantages and disadvantages.

1.1.1 Active upper limb exoskeletons for physical assistance

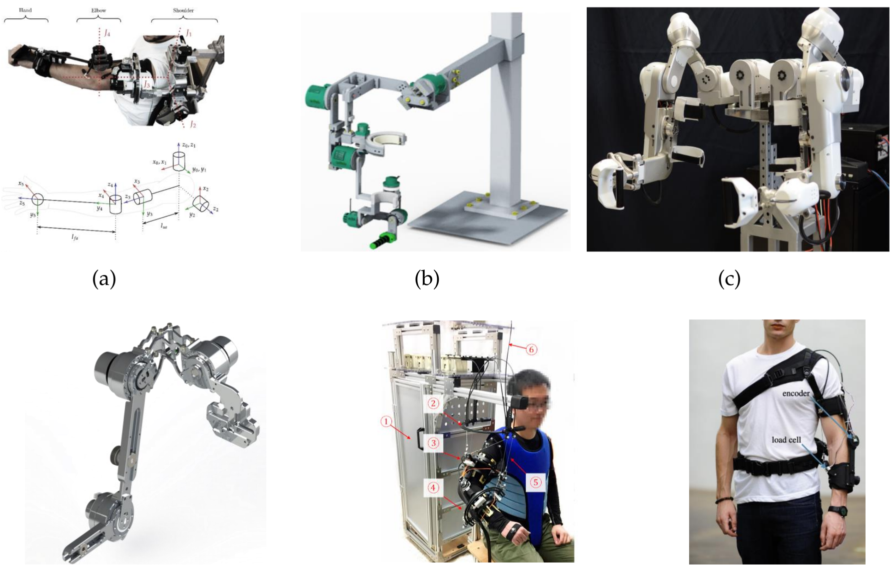
This section presents the state-of-the-art for upper body exoskeletons designed to complement the human upper limb musculoskeletal structure and support the human in different fields of applications. The main focus is the recent development in exoskeleton design along with their biomechanical implications for different types of power amplification and assistive applications.

Some upper-body exoskeletons including BRIDGE, u-Rob, Harmony, UB-EXO, cable driven arm exoskeleton and soft wearable exosuit are displayed in Fig. 1.3. Of them, Fig. 1.3(a) shows a five-DOF upper limb exoskeleton, called Bridge, developed to support the physically disabled people in their every day activities [10]. The exoskeleton was designed to support three-DOF human shoulder joint movements, elbow extension/flexion, and wrist pronation/supination. The design consists of C-ring mechanisms to control the human shoulder internal/external rotation and wrist pronation/supination. While the other three movements were controlled using a direct-drive method where the stepper motors were directly mounted over the anatomical joints. An inverse kinematic model was developed to control the position of the end-effector in task space. The kinematic model was investigated to optimize the workspace that led to reducing static torques and avoiding singularities. In addition, velocity control was implemented as a low-level control technique to actuate the motors.

Two different high-level control methods, including joystick control and gaze control, were selected to control the exoskeleton movements in task space. The system was initially evaluated with three healthy subjects, and the tracking error was close to zero. The study was later extended to evaluate the efficacy of the exoskeleton system with physically disabled people [11]. Moreover, a spring-loaded gravity compensation mechanism was introduced in the design to compensate for the gravity torque and reduce the requirement for the excessive shoulder joint torque by 46%.

Rasedul et al. [12] proposed a design of a seven-DOF upper limb exoskeleton, namely u-Rob shown in Fig. 1.3(b). The device was designed to support post-stroke survivors and simultaneously used for their rehabilitation. The exoskeleton was equipped with two different operational modes where it can be used to coordinate the human's upper limb movements in task space or can be used to perform the different types of rehabilitation exercises in joint space. Moreover, two load cells were used to analyze the interaction forces between the human upper limb and exoskeleton system. A PID-based trajectory tracking control was implemented to drive the system, and the maximum tracking errors were noted to be 1.85° for the elbow joint during a coordinated joints movement and 1.81° for diagonal reaching. Furthermore, the performance of the system was also investigated in the Cartesian space, where it has to control the human hand movements in 3D space precisely. The maximum deviation from the actual trajectory was noted to be 1 *cm*, 2.12 *cm*, and 1.5 *cm* during reaching in the traverse plane, sagittal plane, and in 3D space, respectively.

Kim et al. [13] proposed a 7-DOF upper limb exoskeleton called Harmony, shown in Fig. 1.3(c). Compared to Bridge and u-Rob exoskeletons that have only used three-DOF to coordinate with the human shoulder joint movements, Harmony introduced five active DOF to support the complex human shoulder girdle and glenohumeral (GH) movements. The design addresses a challenge associated with the shoulder complex, namely, instantaneous change in the center of rotation in the shoulder GH joint during protraction/retraction and elevation/depression of the human upper limb movements. A revolute joint with a parallelogram mechanism was developed that caters for the kinematic discrepancy due to the translation of the



(a) (b) (c)

(d) (e) (f)

Figure. 1.3. Upper limb exoskeletons designs, (a) BRIDGE prototype [10, 11], (b) seven-DOF u-Rob prototype [12], (c) Harmony prototype [13], (d) four-DOF UB-EXO prototype [14], (e) cable driven arm exoskeleton [15], (f) soft wearable exosuit [16].

GH joint. Three revolute joints were coupled perpendicular to support the human upper arm movements in 3D space. Moreover, series elastic actuators were used to drive the elbow joint and wrist compliantly.

Teng et al. [14] presented a new paradigm of integrating a 4-DOF UB-EXO with a commercially available soft extra muscle (SEM) glove. The upper limb exoskeleton was designed to actively support the human shoulder abduction/adduction, extension/flexion, and elbow joint extension/flexion. While a parallelogram mechanism was introduced to passively support the human shoulder internal/external rotation and compensate for the translational motion of the glenohumeral joint, shown in Fig. 1.3(d). The basic design was adopted from [17], and Teng et al. investigated the potential impact of using an integrated design of UB-EXO with SEM glove to support physically disabled people in activities of daily living, such as drinking. Therefore, a PD-based fuzzy sliding mode control (FSMC) was selected to track the joint angle trajectories. The results demonstrated that PD with FSMC has precisely supported the human upper limb in an ordinary drinking task and compensated for unmodeled system dynamics and uncertainties.

Chen et al. [15] proposed a new cable-driven upper limb exoskeleton design that accommodates the inaccurate estimation of anatomical parameters, shown in Fig. 1.3(e). The design consists of a vest, upper arm module, and forearm module. The vest was used to adjust the human upper limb into the system and improve motion stability. A base cuff and upper arm cuff in the upper arm module were used to attach the system to the human upper limb, which controls 3-DOF shoulder movements and provide desired force and torque during motion training. Finally, an integrated forearm cuff was used to directly interact with the human forearm to support the extension/flexion movements. All these cuffs were fabricated in aluminium, and the inner structure was developed with soft material to ensure a comfortable interaction between the human and exoskeleton system. Six Bowden cables attached to the aluminium cuffs were used to drive the exoskeleton through the brushless DC motors (Maxon RE35) mounted on the stationary platform.

Chiaradia et al. [18] proposed a multipurpose soft wearable exoskeleton, called exosuit, to support the human forearm extension/flexion movements, which not only complements people in ADLs but also intended to support physically weak individuals in clinical settings. The exoskeleton was designed with a soft wearable material consisting of fabric cloth, boa lacing and velcro straps, as shown in Fig. 1.3(f), which wraps around the human upper limb, and a cable-driven mechanism was used to transmit 8.5 Nm of continuous torque to the human upper limb musculoskeletal structure. Xiloyannis et al. [16] investigated the design of an exosuit used to support the wearer in a dynamic task and compensated for the human arm weight. An experimental study was performed to evaluate the impact of using exosuit on task kinematics, dynamic response of the human upper limb with exoskeleton assistance, and induced fatigue. All these parameters were compared with the human upper limb movements executed without the exoskeleton assistance. The results showed $64.8 \pm 7.66\%$ reduction in muscular effort and $59.20 \pm 5.58\%$ reduction in elbow joint torque.

Naaour et al. [19] proposed a 1.85 kg novel soft pneumatic elbow exoskeleton. The exoskeleton was designed with a thermoplastic polyurethane cased with twill-polyester, and two carbon plates were embedded to support the dorsal side of the upper arm and forearm. Two inflatable thermoplastic polyurethane tubes were used to control the forearm extension/flexion movement bilaterally. These tubes were folded and embedded inside the soft elbow joint exoskeleton system, which were used to redirect applied forces via pneumatic actuators and bilaterally control elbow joint flexion. The soft exoskeleton system was evaluated for the simple carrying task using 5 kg payload and reduced the physical human effort by 43% measured in terms of elbow joint flexion torque. Experimental results demonstrated that the exoskeleton supported the human upper limb and reduced the average muscle activation by 50%, which leads to reduced induced fatigue and metabolic rate up to 61%.

1.1.2 Passive upper limb exoskeletons for physical assistance

In addition to the active upper limb exoskeletons that require an external power source and complex control algorithms, passive exoskeletons are now being investigated for physical assistance, and some of them were turned into commercial products. For example, Paexo by Ottobok [20], Skelex 360 by SkelEX [21], Shoulder X by SuitX [22], BESK exoskeleton by GOGOA, Ekso Vest by EKso Bionics, Air Frame by Levitate Technologies [23], MATE XT by Comau, Shiva EXO by Ergo Sante and EXHAUSS system by EXHAUSS [24] are some commonly available exoskeletons in the market and their detail descriptions can be found in Table 1.1. These devices have proved their significance in reducing physical human effort in everyday activities, their use in clinical/rehabilitation applications is likely to appear in the near future.

Most commercially available exoskeletons are designed to support the shoulder joint during arm elevation activities and targeted the industrial use case. Besides the exoskeletons that support the human upper arm, a device that may support the human forearm is also required. EXHAUSS Stronger, FORTIS, Fawcett Exsovest, and Robomate are examples of commercially available exoskeletons that could support the human elbow joint for specific tasks. Their designs have made it difficult to use them in narrow workspaces during logistics operations and other industrial applications.

The field of passive upper limb exoskeletons has exploded in the recent year, there have been may studies preformed and many are still in progress focusing more complex issues. Zhou et al. [25] proposed a conceptual design of a passive upper limb exoskeleton that comprises of spring-loaded two parallelogram mechanisms for gravity compensation. A spring is placed in each parallelogram structure collinear with the lower bar (approximately parallel to the human arm) and the other end is connected to the vertical bar. The proposed design was biomechanically evaluated and optimized for a selected motion assistance problem in AnyBody environment where it supported the human with biracial plexus injury in a simple drinking task. Stadler et al. [26] presented an iso-elastic upper limb exoskeleton for manual load handling called Robo-Mate. Robo-Mate consists of a spring loaded parallelogram arm module designed to compensate for a maximum 4.5 kg of human arm weight and 7.5 kg of payload. Additionally, the spring allows the lift force to be adjusted from 40 N to 120 N and has an effective range of $\pm 45^{\circ}$ with reference to the horizontal position.

Castro et al. [27] presented a passive upper extremity orthosis, designed to support an individual suffering from amyoplasia, i.e., joints contractures and deformities. The device is designed to support the 3-DOF spherical shoulder joint movements through a spherical scissor mechanism and 1-DOF elbow joint extension/flexion movement. Moreover, a partial gravity mechanism was introduced that consists of a mono-articular and a bi-articular spring that amplifies the minimal residual bicep function. The flexion torque profile obtained from the virtual simulation showed a reduction of 20.566% about the shoulder joint. Further more, the design was experimentally validated with a amyoplasia patient, the results demonstrated that the user was able to attain positions in the frontal plane close to the mouth, thus enabling independent eating/drinking.

Different design methods and spring placement typologies were used to develop the upper limb exoskeletons. Several other methods, such as compensating human arm weight and gravity torque with gas springs, were also developed focusing the load carrying and rehabilitation application [28, 29]. The method of integrating the gas spring increases energy density and improves the structure by keeping the exoskeleton compact, so that it has a greater load bearing capacity.

Table 1.1. Commercially available upper limb exoskeletons with their technical specifications.

Exoskeletons	**Weight** (*kg*)	**Supported movement**	**Mechanism type**	**Support level**	**Manufacturer**
H-VEX	2.5	Upper arm elevation	Multi-linkage spring-loaded energy dissipation mechanism	Max 5.5 kg^*	Hyundai Motor Group
Skelex 360	2	Upper arm elevation	Passively actuated cable driven mechanism	1-4.9 kg^*	SkelEX, Rotterdam, Netherlands
Shoulder X V3	3.17	Upper arm elevation	Cam based cable driven passive mechanism	-	Suit X, Emeryville, CA, USA
BESK exoskeleton	3.5	Upper arm elevation	Passively actuated	5-15 kg^*	GOGOA, Bizkaia, Spain
Paexo Shoulder	1.9	Upper arm elevation	passively actuated cable pulley mechanism	58% reduction in AD for overhead lifting	Ottobock Duderstadt, Germany
Ekso Vest	6.5	Upper arm elevation	passively actuated gradually increasing torque mechanism	2.2-6.8 kg^*	Ekso Bionics, Richmond, CA, USA
Airframe	2.7	Upper arm elevation	Passive progressive support mechanism	80% reduced exertion*	Levitate Technologies, San Diego, CA, USA
MATE XT	3	Upper arm elevation	Passively actuated shoulder exoskeleton	5.5 kg^*	Comau, Turin, Italy
Shiva EXO	-	Arm elevation	Passively actuated constant force mechanism	-	Ergo Santé Technologie, Anduze, France

* Manufacturer's specification

Table 1.1. Commercially available upper limb exoskeletons with their technical specifications (Cont.).

Exoskeletons	**Weight** (kg)	**Supported movement**	**Mechanism type**	**Support level**	**Manufacturer**
X-Rise	2-3	Upper arm elevation	Passively actuated upper limb exoskeleton	0.5-6 kg^* per hand	ExoRise, St. Leningradskya, Russia
CDYS	2.4	Upper arm elevation	Passively actuated spring & cable driven mechanism	-	DL Crimson Dynamics Technology, Dalian, China
Exy ONE	3.55-4.3	Upper arm elevation	Passively actuated shoulder exoskeleton	Max 8 kg^* for each arm	Exy, Av. Comendador Franco, Curitiba, Brasil
PLUM	1.5	Upper arm elevation	Passively actuated shoulder exoskeleton	1-6 kg^*	Human Mechanical Technologies (HMT), Trabes, France
EXHAUSS system	9	Directly interact with payload	Spring-loaded mechanical arms	Max 5-9 kg^*	EXHAUSS, France

* Manufacturer's specification

1.1.3 Hand exoskeletons for motion amplification and rehabilitation

Upper limb exoskeletons are generally designed to support the human arm in manipulation, and they do not provide assistance/motion correction of anatomical hand movements. Therefore, a device that could complement human upper limb motion with anatomical hand movements is required. Given the requirement for hand support, this section focuses on the key development in hand exoskeletons mainly designed to support the human hand in restoring lost motor function, amplifying minimal residual hand opening/closing, or movement correction.

Hand exoskeletons are designed to support a range of practical activities, i.e., power grasp, lateral pinch, tripod grasp, and pointing, etc. Several rigid mechanisms and soft gloves were proposed to actively or passively support the anatomical hand movements while focusing on different research problems. Among those, some notable passive devices and commercial hand exoskeletons with their technical specifications are enlisted in Table 1.2.

Soft hand exoskeletons have been widely studied to support physically impaired people in their activities of daily living (ADLs). However, their functions in supporting different levels of spastic hand are fairly limited. For example, Abdelhafiz et al. [30] proposed a novel bio-inspired cable-driven soft glove where a nylon cable is attached to the distal part of the finger and routed along the radial side of the distal phalange, middle phalange, and proximal phalange. This cable was then connected to the Bowden cable near the proximal interphalangeal (PIP) joints to control the finger flexion movement using a brushless DC motor. The method of routing adopted in this soft exoskeleton ensures equal distribution of applied force along the radial sides of the finger. It prevents the over-tightening of the nylon cable around the distal part of the finger. A similar product called Carbonhand (a continuation of a soft extra muscle glove by Bioservo) [31] was designed to improve/amplify the human grasping capabilities. The glove is fabricated with a soft textile material and provides a different level of assistive force, which directly acts on the distal point of human fingers. Since the CarbonHand is commercially available in the market and has proved its significance for several ADLs, its use is relatively limited as it requires volunteer hand opening.

Kang et al. [32, 33] proposed a cable-driven soft hand exoskeleton to support the opening/closing of the index finger, middle finger, and thumb. The glove was fabricated in silicon, and Teflon tubes were embedded inside to guide the routing of cables. Two sets of cables/wires were used for the opening and closing of each finger, i.e., the cable connected to a U-shaped thimble and passing through the radial side of the finger was used to assist finger flexion movement. In contrast, the cable connected to the distal phalange and passing through the dorsal side was used to actuate the finger extension.

Although the glove completely supports the hand opening/closing function, its impact on physically impaired people was not investigated. In addition, a study that could evaluate its impact on anatomical hand movements should be performed.

Lee et al. [34, 35] proposed a bio-mimetic design of a cable-driven hand exoskeleton for post stroke rehabilitation. The device was designed to actively support the anatomical movements of the human hand, i.e., opening and closing. Four exo-tendons were used to drive each finger and reproduce the anatomical joint coordination pattern. Of them, two exo-tendons were used to replicate the human finger major extensor and flexor muscles. In comparison, the other two exo-tendons replicate interosseous muscles' pathways and prevent the hyperflexion of the distal or middle phalange.

Besides the soft hand exoskeletons, actively actuated rigid-body exoskeletons were developed and reviewed in [43–53]. However, the requirements for the external power source and their weight have limited their use outside clinical settings, i.e., Hand of Hope and Amendo are examples of stationary hand exoskeleton platforms used for rehabilitation. As passive hand

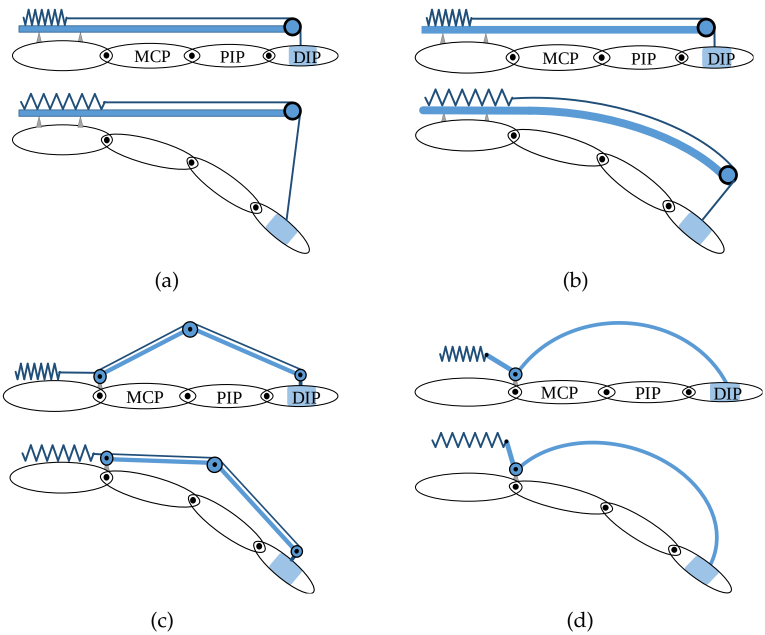


Figure. 1.4. Different types of actuation methods adopted in the development of passive hand exoskeleton, (a) cable driven finger extension mechanism with a stiff cable guide [36, 37], (b) cable driven finger extension mechanism with a compliant cable guide [38, 39], (c) self-aligning rigid-body/ parallelogram mechanism [40, 41], (d) a lever arm support mechanism [37, 42]

exoskeletons use only springs or other compliant energy storing elements, they are portable and easy to use for at-home rehabilitation or therapeutic purposes.

Some basic configurations of the actuation methods adopted for passive hand exoskeletons can be found in Fig. 1.4. Fig. 1.4(a) shows a cable-driven finger extension mechanism where a cable connects an elastic element/actuator to the fingers over a stiff cable guide [36]. This mechanism supports the finger extension movement, but the assistive force applied by the mechanism is not always perpendicular to the finger during the whole range of motion. Consequently, the lateral component of the force increases, causing excessive pressure at the fingertip/point of contact and resulting in an uncomfortable interaction. Ates et al. [38, 39] proposed a cable-driven finger extension mechanism through a compliant guide as shown in Fig. 1.4(b). A special feature of this mechanism is to always maintain the assistive force perpendicular to the finger as long as the compliant guide follows the finger extension/flexion movement. The stiff cable guide mechanism and compliant guide mechanism require an accurate placement over the dorsal side of the fingers for its proper functioning. Hence, these mechanisms may not always provide an ideal solution to various hand opening/closing activities. Self-aligning rigid body/ parallelogram mechanism, presented in Fig. 1.4(c), provides an alternate solution to support the anatomical hand opening movements by preserving the alignment between the hand exoskeleton and human fingers [39]. Parallelogram/self-aligning mechanisms have been widely used in many exoskeleton applications as they decouple the translation and rotation [54, 55]; thus do not require precise placement and accommodate the hands/limbs with different physiological parameters. However, the mechanism may not allow abduction/adduction movements of the fingers that could cause an uncomfortable interaction [42].

The passive hand exoskeletons are expected to provide an affordable, safe and reliable solution for several rehabilitation applications. A number of devices have been developed. For example, Brokaw et al. [56] proposed a passive hand exoskeleton called HandSOME that was designed for post-stroke rehabilitation and correction of human hand movement by compensating flexor hypertonia. The HandSOME design is a modified version of the lever arm support mechanism, as shown in Fig. 1.4(d), which uses a set of springs and elastic cords to coordinate fingers and thumb extension movements. The simplicity of the design allows to replace the spring, or any change in its placement helps achieve the desired assistance level. Preliminary clinical trials showed that HandSOME was able to provide optimal rehabilitation sessions for a longer period that was achieved at the cost of reduced grasping force. So far, the device was only evaluated for users with an Ashworth tone level less than 2; thus, it is not recommendable for people with weak flexor muscle.

Table 1.2. Commercially available & passive hand exoskeleton systems with their technical specifications.

Hand Exoskeletons	**Weight**	**Supported movement**	**Mechanism type**	**Output force/torque**	**Manufacturer**
HandSOME** [56]	220 g	Hand opening	elastic strings	0-4 Nm	-
CyberGrasp	450 g	Extension/flexion of fingers	Cable driven mechanism with servo motor	12 N	CyberGlove Systems LLC, San Jose, CA, USA
Hand of Hope [2]	500 g	Hand open/close	Cable driven with 5× liner DC motors	-	Rehab-Robotics, Hong Kong, China
Gloreha [57]	250 g	Grasping & pinch	Cable driven mechanism with DC motor	20 N	Sinfonia, Lumezzane, Italy
CarbonHand [31]	700 g	Grasping (M, R & T)	Cable driven motorized mechanism	20 N	Bioservo, Kista, Sweden
Daiya Power Assist Glove [58]	Glove = 120 g Controller = 680 g	Hand open/close	Inflatable soft robotic glove exoskeletons	Max. pressure 0.17 MPa	Daiya Industry Co. Ltd. Okayama, Japan
Amandeo	-	Extension/flexion of fingers	Passive mechanism for fingers rehabilitation	-	Tyromotion, Graz, AUSTRIA
Tendo	300 g	Finger closing	Cable driven active glove	-	Tendo, Lund, Sweden
SaeboFlex** [36]	-	Finger extension (R & T)	Extension springs	-	Saebo, North Carolina, USA

T : Thumb; M : Middle finger; R : Ring finger

** Passive hand exoskeletons

Ates et al. [38, 42] proposed a passive interactive hand exoskeleton, called SCRIPT passive orthosis, to support the human hand extension movements. The SCRIPT orthosis comprises three additively manufactured sub-modules; the finger module consists of a lever arm support mechanism, which can approximately provide a perpendicular force to support the finger extension movement and reduce friction. The thumb module is identical to the finger submodule. However, an additional DOF is provided to adjust the orientation of the carpometacarpal (CMC) joint. A parallelogram mechanism, a modified form of a self-aligning mechanism shown in Fig. 1.4(c), interacts with the hand plate to adjust the orientation of the human hand. The script was specifically designed to accommodate the undesired torques caused by involuntary hyperflexion of the human wrist and fingers. However, the device can be used in providing therapy, subject to the patients' ability to contract their flexor muscles voluntarily. The passive exoskeletons have proved their significance in tone management that can not be achieved with the cable-driven soft hand exoskeletons. However, the requirement for the optimal selection and placement of the elastic element is an open research question. The long-term use of hand exoskeletons might cause muscle weakness [59, 60], hence a study that could evaluate the long-term use of these devices on the human hand should be performed.

Several design methods have been adopted to develop actively actuated soft hand exoskeleton gloves, soft pneumatic gloves and passively actuated hand exoskeletons targeting different applications. Some complicated issues noted in developing hand exoskeletons are as follows:

1. A standard method is required to evaluate the impact of using soft hand exoskeletons in reproducing anatomical joint movement.

2. The kinematics of the soft hand exoskeletons should be investigated for the different levels of hand spasticity [43]. Moreover, the interaction forces between the exoskeleton and fingers should be analyzed as any uncomfortable interaction may cause hyperextension/hyperflexion of DIP or PIP joints [30].

3. The design of the soft hand glove should be investigated for safe and comfortable interaction [45]. For example, the tendons or cables passing through the dorsal side of the fingers apply excessive force on the PIP and MCP joints during the finger extension movement and cause an uncomfortable interaction.

4. In the case of soft pneumatic gloves, inflatable hyperelastic materials mounted on the dorsal side of the fingers is used to support the hand opening/closing. However, the kinematics of the inflatable actuators are not always consistent with the anatomical finger movements [37].

5. A method to evaluate the dynamic interplay between the human hand and the exoskeleton system should be developed. Moreover, the interaction forces between the human hand and exoskeleton should be analyzed because most cable-driven soft gloves cannot equally distribute the applied forces on the musculoskeletal structure.

1.1.4 Biomechanical evaluation

The challenge of developing an upper limb exoskeleton lies in analyzing its complex interaction with human upper limb movement, thus studies that could evaluate the response of the human movements to the exoskeleton assistance are needed. Different modeling methods and experimental techniques have been used to evaluate the influence of exoskeletons on the human musculoskeletal systems. However, investigating the task kinematics, interaction forces or the response of specific muscle group subject to robotic assistance are commonly used parameters to analyze the efficacy of a upper body exoskeletons.

Exoskeleton design modeling is a primary element that can be used to analyze the design parameters and biomechanical implications prior to development phase. Denavit–Hartenberg (DH) parameters characterization is among one of the profound representation in developing kinematic model of robotic exoskeletons and it can be used to obtain a simplified formulation [61]. However, it can not be directly employed to study the redundant systems or closed chain parallel mechanisms that are commonly used in exoskeleton robots. In the literature, this method was used to develop a unified model for the human upper limb and exoskeleton and considered it as an open chain serial mechanism [13, 14, 62–68]. This modeling method can also be extended to analyze the dynamic response of the unified system, such as using Lagrange formulation or Newton Euler method, but it can not be used to study the interaction between the human and exoskeleton. Other modeling methods, i.e., multibody modeling approach [69], and tools, i.e., AnyBody [70] and OpenSim [71], facilitate in developing more detailed models where the exoskeleton is working in a close collaboration with the human musculoskeletal structure. These modeling method and tools facilitate the users in determining the response of the human musculoskeletal system to the robotic assistance. Moreover, they have been extensively used in many studies to perform the biomechanical evaluation and exoskeleton design optimization by considering the complicated human factors [25, 72–74].

Simulating the human response under the influence of external forces or torques applied by the exoskeleton remains a major issue in modeling work [25]. In addition, a comprehensive musculoskeletal model is needed that certainly plays a vital role in developing a reliable exoskeletons. A comprehensive model must include all joints connected with biarticular muscles and split the larger muscles into force elements that allow the simulated muscle to control the degrees of freedom influenced by the muscle [75]. At present, only a limited number of models are available, all based on inverse dynamic based simulations, such as the Delft shoulder and elbow model (DSEM) [76], Newcastle shoulder model [77], Gerner and Pandy model (GPM) [78], Waterloo model (WSM) [79] were developed based on the definition of a comprehensive musculoskeletal model. All these models are quite similar to each other, muscles discretization, muscle wrapping technique, and detail representation of the models are key differences that impact the accuracy and sensitivity of the musculoskeletal model. Furthermore, the aforementioned models are not very detailed and lack some muscles, OpenSim [80] and AnyBody [70] tools have provided alternative platforms with more detailed musculoskeletal models that have been extensively used for biomechanical evaluation and exoskeletons design optimization.

Biomechanical evaluation of upper limb exoskeletons using analytical techniques has significantly improved the design, but these techniques are not capable enough to analyze other human factors such as metabolic cost, respiration rate, task kinematics in a real-time environment, the way an individual perceives the assistance from the exoskeleton side, and its long-term effects on the human musculoskeletal system. Several methods have been adopted to experimentally validate the biomechanical compatibility of upper limb exoskeletons with human arm movements. Analyzing the spatial configuration of any wearable robot is a primary requirement that directly effects the kinematic and dynamic properties of the human-exoskeleton system. Any variation in the system due to external disturbances, lack of kinematic stability, and modification in the task kinematics due to exoskeleton can easily be determined by using different types of position sensors, such as encoders [10, 14, 68, 81, 82], vision-based motion capture systems [6, 27, 83–85], flex sensors [37, 86–88], inertial measurement units [24, 89], etc.

In most experiments, force/torque sensors are used to detect the assistance level provided by the exoskeleton [6, 90] or interaction between the human and exoskeleton systems [91–95]. These force sensors can simultaneously be used to control the assistive force field and support the users in performing every day tasks or can be used for rehabilitation/ therapeutic purposes by exerting resistive force/torque [96]. Since the integration of force sensors between the human and exoskeleton systems are used to measure the physical interaction, the perception of comfort/discomfort and reduction in physical human effort with exoskeleton assistance cannot measured directly from these sensors. Hence, surface electromyography (EMG) methods were used as a non-invasive indicator for onset muscle activation, its relation to the muscle force production, and its use as an index of fatigue processes occurring within a muscle [20, 24, 97].

Yin et al. [59] investigated the impact of using a passive upper limb exoskeleton, namely PULE, in reducing the physical human effort during a bolt installation task at three different working heights. Fifteen healthy subjects participated in the experiments, and the bilateral recording of surface electromyography (EMG) from the anterior deltoid (AD), middle deltoid (MD), trapezius (TR), and triceps (TB) muscles were used to evaluate the effectiveness of using PULE. The statistical analysis of surface EMG data shows a total reduction in the perceived discomfort (RPD) was 52.4%. Moreover, the initial EMG muscles activation was significantly decreased and prevented the work-related musculoskeletal disorder during an overhead lifting task especially working under high height conditions. Besides the quantitative analysis, subjective feedback shows that the design restrained upper body movements and modified the task kinematics due to its structure [59]. Some subjects reported that they were not feeling comfortable while wearing it, which suggested for future design improvement.

A similar study was reported by Alabdulkarim et al. where the potential effects of three different exoskeletons, including FORTIS, Shoulder X, and Fawcett Exsovest exoskeletons, were evaluated and compared for a simulated overhead drilling task [22, 98]. Bilateral recordings of surface EMG from AD, MD, TB, and iliocostalis lumborum (ILL) muscles were used to quantify the impact of three distinct exoskeleton designs during an overhead drilling task. Hence, the maximum acceptable frequency (MAF) and muscle activation were the key parameters measuring the physical human effort. It was observed that FORTIS led to a significant reduction in MFA. Moreover, the variation in the tool mass from 2 kg to 5 kg led to reducing the maximum acceptable frequency by 25% and increasing the peak muscular activation across all four recruited muscles. An overall analysis of EMG data shows that FORTIS and Fawcett Exsovest exoskeletons elevated the loading effect on the human lower back. While Shoulder X reduced the peak muscular activation specifically about the shoulder muscles and maintained the task quality.

Paexo (a 4.3 kg upper limb exoskeleton by Ottobock) is designed to support the wearer in everyday physical demanding activities such as load lifting and transporting it to a shorter distance. Maurice et al. [20] studied the impact of using Paexo exoskeleton for an overhead pointing task and investigated its efficacy on the human musculoskeletal structure, task kinematics, and user acceptance. The experimental results show that AD muscle activation was reduced by 55%. A reduction in the heart rate and oxygen consumption was also noticed during the experimental sessions, which indicated that the task was relatively less exhausting with Paexo. Further, the exoskeleton did not have any positive or negative effects on the task kinematics and movement strategy, which shows that the device is biomechanically compatible with the given task. Apart from investigating the physiological and biomechanical effects of Paexo, some limitations of the study were noted.

For example, the EMG data recorded from the AD muscle does not provide a complete overview of the shoulder joint. Other muscle groups should be included to investigate arm elevation and stabilization. Presently, the study only considered a basic arm elevation task and ignored other complex movements which usually exist on the factory floor.

Hall et al. [97] presented a biomechanical analysis of a passive shoulder exoskeleton designed to support the anatomical shoulder elevation by compensating for gravity torque. The study further investigated its effect on human task kinematics and EMG muscle activation during a dynamic shoulder elevation task for the dominant arm. Nine EMG sensors were used to determine the muscle activation about a shoulder joint, and seven infrared motion capture cameras were used to track the human arm elevation. The exoskeleton assistance notably reduced the physical human effort, and the maximum muscular activation occurred approximately beyond 60% of the dynamic arm elevation. Further, the anti-gravity modified the task kinematics, i.e., the elevation angle of the human shoulder joint varied for the initial 59% of the shoulder abduction movement and 39% of scaption movement. It was reported that the human arm accelerated 22% faster with the anti-gravity assistance and pulled the human arm at a relatively higher elevation angle. Thus the subjects have to make an effort to decelerate their arm, which affects shoulder joint postural stability while approaching the target. The study concludes that an integration of a tunable passive assistance mechanism is required to achieve better postural stability.

Almost all passively actuated commercial upper limb exoskeletons are designed to support the human arm and allow to manually adjust the assistance level by varying the stiffness of the elastic/energy storage element. Grazi et al. [99] presented a design of a semi-passive upper limb exoskeleton, namely H-PULSE, which regulates the assistance level. This regulation in the assistance level can be achieved by a novel motorized tuning method and provides a modulating torque profile. The design was evaluated for prolonged overhead screwing/unscrewing tasks for three different levels of assistive torques. Shoulder muscles activation using surface EMG, i.e., anterior deltoid (AD), posterior deltoid (PD) and upper-trapezius (UT) muscles, heart rate, and subjective feedback were the key performance metrics that were used to study the influence of H-PULSE on the human musculoskeletal structure. The statistical analysis of EMG shows that the maximum assistance provided by the H-PULSE sufficiently reduced the muscle activation, i.e., 42% reduction in AD, 42% for PD, and 50% reduction in UT muscle activation relative to the task that was performed without the exoskeleton assistance. The reduction in the heart rate was noted to be 7% for low assistive torque, 10% for medium assistive torque, and 8% for high assistive torque. Moreover, Grazi et al. reported that the assistive torques were symmetrically supporting both arms and compensated the gravity torque about the shoulder joint, i.e., the gravitational torque compensation was 47% with low assistance, 52% with medium assistance, and 56% with the high level of assistance. Despite the study presented promising results, some limitations were also noted. For example, the study only explores the activation of shoulder muscles; the effects of H-PULSE on the other muscle group should also be investigated. Moreover, the study investigated the short-term use of this exoskeleton in the laboratory environment. However, a study that could evaluate its effects for more realistic industrial tasks/applications is required.

Theurel et al. [24] investigated the physiological impact of using a 9 *kg* upper body exoskeleton system, namely EXHAUSS Stronger, during manual load handling, i.e., load-lifting in the sagittal plane, transporting a toolbox to 30 meters, and repeated stacking and unstacking of four boxes. The surface EMG recorded from the right anterior deltoid (AD), right triceps (TB), right erector spinae (ES), and right tibialis anterior (TA) muscles were compared with and without the exoskeleton assistance for each task. The statistical analysis of EMG shows that the exoskeleton reduced the AD muscle activation for lifting and stacking/unstacking tasks. However, the activity of TB and TA muscles was significantly increased exoskeleton during the load transporting task. The study concluded that the exoskeleton relived the shoulder flexor muscles, but that was achieved at the cost of increased postural strain, cardiac activity, and modified task kinematics.

Huysamen et al. [100] evaluated the performance of an 11 *kg* Robomate for a static overhead task with a 2 *kg* payload. It was noted that the exoskeleton tended to reduce the biceps muscle activation by 49% and the medial deltoid muscle by 62%. Besides, the device did not have any negative impact on the lower back and trunk muscles; it could be due to the fact that the study did not investigate antagonistic muscular activation. Moreover, some design limitations were noted: (a) arm straps cause to induce high localized pressure, (b) bulky design and large footprints constrained some anatomical movements. Further design improvements that could improve the usability of Robomate are required.

So far, the studies have only presented the impact of using these aforementioned devices for very simple overhead lifting or static tasks in the sagittal plane. However, in an actual industrial environment, the tasks could be more complex; hence, these devices should be investigated for the long-term manual load handling activities (involving prolonged complex postures, bends, and twists).

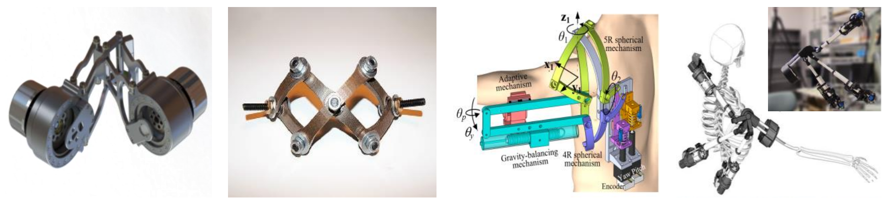
1.2 Exoskeleton design challenges

In the previous section, an overview of recent upper body designs and their performance assessment method/ biomechanical evaluation were presented.

It is noted that an ergonomic exoskeleton that could complement the human upper body without constraining the anatomical workspace by ensuring a safe and comfortable pHRI is difficult to achieve. Several factors which could be challenging the development of an ergonomic upper body exoskeletons are considered, as described presently.

1.2.1 Workspace and singularity

A large and singularity-free workspace is desirable for exoskeleton robots. This particularly applies to the interactions with complex human shoulder and wrist joints. Therefore a detailed kinematic model of a human-exoskeleton system that could evaluate the influence of these two parameters is required. Christensen et al. [17] proposed a mechanical design of a hybrid spherical mechanism for a shoulder exoskeleton to support the three degrees of freedom (DOF) human shoulder movements. The hybrid mechanism comprises two revolute joints connected using multi-linkages double parallelogram structure (DPL) and form a remote center of motion (RCM) mechanism. Castro et al. [101] used a similar approach where two revolute joints are interconnected through curved scissor linkages to form a RCM spherical mechanism for shoulder exoskeletons. Since the kinematic analysis of both RCM spherical mechanisms has shown that they can provide a relatively large and singularity-free workspace, the passive medial/lateral rotation has limited its use for many rehabilitation applications. Besides, several active and hybrid RCM mechanisms [13, 103, 104] were developed to support the complex anatomical movements of the human shoulder joint, shown in Fig. 1.5, but their size, weight, and design complexity have made it difficult to bring them out of the laboratory/clinical environment. In addition to the shoulder exoskeleton, different design methods were adopted to develop forearm and wrist exoskeletons. Among the existing approaches, the



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

Figure. 1.5. Examples of some notable RCM mechanism for upper limb exoskeletons, (a) double parallelogram mechanism [17], (b) scissor mechanism [101], (c) parallel actuated mechanism [102] (d) parallel actuation with passive slip mechanism [103] direct-drive method and the C-ring mechanism are commonly used to support extension/flexion movements of the human forearm and wrist rotation, respectively [13, 102–105]. These mechanisms are not always biomechanically compatible with the upper limb musculoskeletal structure, and a minor misalignment can modify the task kinematics that constrain the workspace.

1.2.2 Portability issue

Powered exoskeletons are designed to support the human upper limb by providing a modulating torque profile. So far, many powered exoskeletons have been developed for medical or rehabilitation applications. They can be either used to support physically impaired/disabled people in their activities of daily living or provide therapy to restore some motor functions. Though the literature has shown the significance of using powered exoskeletons in health care, they can provide a regulated and higher assistive torque. Lack of portability due to the size, weight, and requirement for an external power source has made these devices difficult to be used for other assistive applications such as industrial or military purposes [106]. On the other hand, passive exoskeletons gradually enter the commercial market as they are portable and do not require an external power source [69]. However, these devices are limited in their range of applications. Most commercially available passive exoskeletons are only designed to support the human shoulder joint while performing an overhead task. Therefore, a portable device supporting the human forearm is required.

1.2.3 Biomechanical compatibility

The upper body exoskeletons are designed to be worn by the user, and it has to be biomechanically compatible with the human musculoskeletal structure. Ideally, the kinematic joints should be well aligned with the anatomical joint of the human upper limb, thus causing to preserve the alignment throughout its range of motion (ROM). However, the anatomical joints are relatively complex and do not behave like the typical mechanical joint as the rotational joint axes change their location during manipulation. Moreover, any discrepancy between the human and exoskeleton robot can change the task kinematics and causes uncomfortable interaction. Hence, a comprehensive biomechanical model which could evaluate the impact of using an exoskeleton system and possibly helps to optimize the design is required.

The biomechanical model should also evaluate the unwanted consequences of the exoskeleton system on the human musculoskeletal structure, which have not been achieved so far. Long-term impact of using an exoskeleton is another open research question in biomechanical studies. Some notable biomechanical modeling studies that have been considered to analytically evaluate the upper limb exoskeleton designs are reviewed in [107].

1.2.4 Exoskeleton design modeling

The human and exoskeleton are two independent dynamic systems, and their integration tends to alter the dynamic properties of both systems or possibly constraints/modifies the task kinematics. Therefore, a comprehensive human upper limb model which could evaluate the influence of using an exoskeleton system on the human musculoskeletal structure is required.

Several musculoskeletal modeling and analysis tools, including OpenSim and Anybody, are being employed to investigate the aforementioned problem. These tools can be used for several purposes, such as estimating the anatomical joints' contact forces and their effects under the influence of external/applied forces and internal contact forces that include the forces due to muscle activation or ligaments. Since these platforms provide a better option to investigate the effects of using the upper limb exoskeleton in human physiology or can be used to optimize the design, it is not clear that these platforms can be used to generate the same results and clinical outcomes. Furthermore, it is not confirmed whether external joint moments are sufficient to draw the conclusion for any study. A comprehensive review of these two problems can be found in [107, 108].

1.2.5 Compliant joint and actuation

The term compliant joint or compliant actuator refers to a joint/actuator that allows deviation from its equilibrium position under the action of external force/torque [109]. Compliant actuators/joints can be categorized into two main types, i.e., series elastic actuators (SEA) and variable stiffness actuators (VSAs).

SEAs are defined as the actuators/joints with fixed compliance that can be achieved by placing an elastic element between the actuator/power train

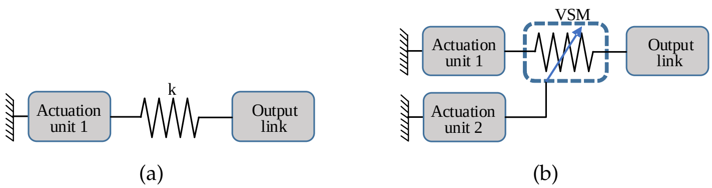


Figure. 1.6. Basic configuration of compliant joint. (a) Fixed compliance joint. (b) Variable stiffness joint.

and load shown in Fig. 1.6(a). SEAs provide a better pHRI, safety, back-drivability, shock absorption capabilities, and optimized energy expenditure. Still, the optimal selection of elastic elements for these joints/actuators is a major challenge. The choice of the elastic element severely influences the dynamic response of the system and tends to either modify its bandwidth or torque resolution [110]. Hence, the stiffness dichotomy should be considered and investigated before developing the exoskeleton system. The recent development in exoskeleton technology has accommodated this issue by introducing VSAs. A basic configuration of the VSAs can be seen in Fig. 1.6(b).

1.2.6 Performance assessment of physical human-exoskeleton interaction

Recent advancements in exoskeleton technology have proved its potential to be used in several applications, as discussed earlier. Successful commercialization of some wearable robots has developed a consensus that there should be standardized design and test procedures to validate the impact of using exoskeletons in terms of safe and comfortable human-robot interaction [111, 112]. The National Institute of Standards and Technology (NIST) developed standard testing and measurement procedures for the robotic manipulators, including stationary and mobile platforms. These testing procedures are designed to investigate the response of robotic platforms in terms of accuracy and repeatability. Moreover, ISO 13482 [113] standard safety requirements for personal care robotic devices has been developed, but it does not consider human in a loop.

From the exoskeleton's point of view, ASTM F3443 [114] propose standard guidelines to evaluate the impact of using wearable robots in a manual load handling activity. ASTM F3443 did not proposed performance metrics to access these guidelines, and these procedures can be applied to the use of inmate objects only. Besides, no standard performance metrics are developed for the medical graded exoskeletons, requiring the doctor's perception. Special procedures for design, including testing methods and performance metrics, should be developed by considering the human in the loop. Bostelman et al. [115] proposed some metrics that can be used to assess the impact of using exoskeleton robots, including navigation, perception, task management, manipulation, duration of the tasks, speed, perceived comfort, ergonomics, portability, cybersecurity, etc. However, procedures to evaluate these performance metrics should be developed to evaluate the impact of using robotic exoskeletons.

1.3 Objective and research questions

Given the utility and the challenges associated with the development of the upper limb exoskeletons, *the objective of this Ph.D. study is to investigate the methods of providing comprehensive support to human upper limb movements in activities of daily livings (ADLs) and analyze their functional reliability as a part of physical human-robot interaction.*

Upper body exoskeletons interact with the human and form a closed-loop system. A design that could safely and comfortably comply with the human musculoskeletal system by ensuring functional reliability remains a major concern for the research community. Therefore, this Ph.D. study investigates the theory and principles of physical human-robot interaction and analyzes the impact of using upper body exoskeletons for physical assistance in different aspects. With this, it is hypothesized that *"ergonomic upper limb exoskeletons can effectively and comprehensively support/correct the human upper limb and impaired hand movements by compensating for any harmful interactions or modified task kinematics".*

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

Q1: How a fully powered exoskeleton can be designed and evaluated to comprehensively support the human upper limb movements for the activities of daily livings?

Q2: Can a hybrid method of actuation be adopted to design an upper limb exoskeleton for physical assistance as an alternative to the fully powered actuation?

Q3: How a hand exoskeleton can be designed to effectively support the anatomical hand opening and closing while preventing the hyperflexion/hyperextenion of DIP or PIP joint?

1.4 Scope of work

In response to the research questions and to realize the impact of comprehensive support on the human upper limb musculoskeletal system, the following research tasks were performed during this study.

- Design and development of a 4-DOF active upper limb exoskeleton for physical assistance (**Q1**).
- Implementation of PD-based trajectory tracking control and experimentally studied the reliability of using upper limb exoskeleton for activities of daily living (**Q1**).

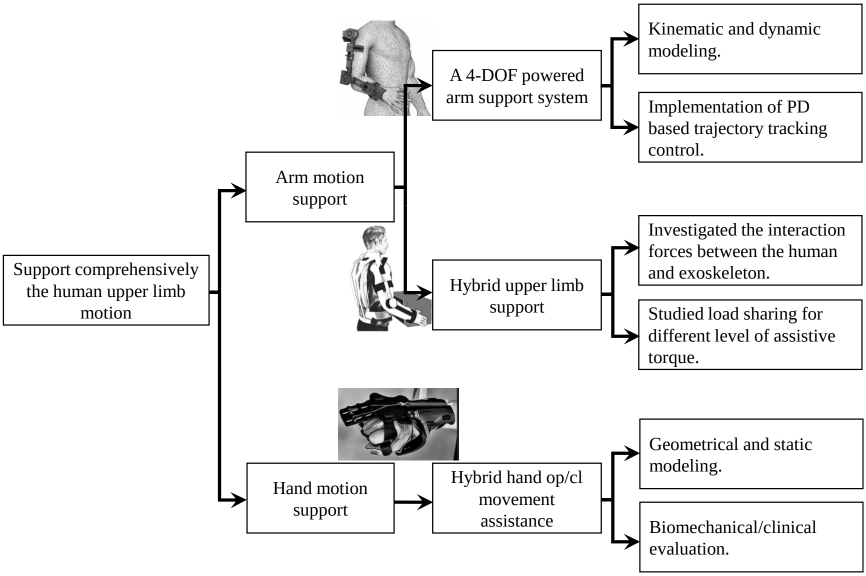


Figure. 1.7. Workscope of this Ph.D. study

- Multibody modeling of a human upper limb and hybrid exoskeleton to analyze the physical human-robot interaction and simulation of the load-lifting task in the sagittal plane (**Q2**).
- Design of a low power and light weight upper limb hybrid exoskeleton for physical assistance (**Q2**).
- Kinematic and static modeling of the passively actuated hand exoskeleton (**Q3**).
- Development of a passively actuated hand exoskeleton to support the physically impaired people in functional hand opening and compensation of flexor hypertonia (**Q3**).
- Development of a new hybrid hand exoskeleton by combining the passively actuated hand exoskeleton and soft extra muscle (SEM) glove to support the normal hand opening/closing and biomechanical evaluation(**Q3**).

Fig. 1.7, demonstrates the sub-goals, methodology, and tasks performed to achieve the objective of this Ph.D. study.

1.5 Research methodology

The research methodology adopted in this Ph.D. thesis is based on four cornerstones: idea generation through problem identification, designing, simulation, and experimental data collection and performance evaluation.

Upper limb wearable robots are among the key technologies explored during the past few years to support human arm and hand movements. To understand the requirements for human upper limb comprehensive motion support, existing upper limb exoskeletons, including the hand exoskeletons, were reviewed and identified the key technological challenges that helped build motivation for idea generation. Upon the identified research gaps and state of the art, design strategies/methods were selected for further investigation. The proposed design ideas for upper limb and hand exoskeletons were initially modeled and simulated for the different task conditions to analyze the human-exoskeleton interactions. After that, experimental studies were performed to analyze the reliability and performance of exoskeleton systems. The data collected from these studies were used to quantify the implications/effects of the proposed designs on human musculoskeletal system that were later compared with existing solutions.

1.6 Outline of thesis

The thesis consists of five chapters.

Chapter 1 introduces the upper body exoskeletons, providing a concise overview of recent technological developments, covering mechanical designs, control methods, and performance assessments for upper limb and hand exoskeletons, and highlighted the key design issues. Upon the key technological challenges and the state of the art of the upper limb and hand exoskeletons, the objectives of this Ph.D. study are presented, followed by research questions.

Chapter 2 describes the mechanical design of a 4-DOF upper limb exoskeleton to physically support people in activities of daily living. The design is analyzed from several aspects, including kinematic and dynamic analysis, workspace and singularity analysis, and implementation of PD-based trajectory tracking control that evaluates the reliability and rationality of the proposed system.

Chapter 3 presents a dynamic model of a human upper limb and exoskeleton system using a multibody modeling method. The model is used to study the physical human-robot interaction and torque sharing between the human and exoskeleton systems during manual load handling. Consequently, a new upper limb hybrid exoskeleton design is proposed that provides a portable and energy-efficient solution for physical assistance.

Chapter 4 proposes a new design and performance assessment of a hybrid hand exoskeleton for hand opening and closing.

Chapter 5 concludes the thesis, where summaries of the main articles are presented, along with their contribution and future suggestions.

Chapter 2

Paper I

A 4-DOF upper limb exoskeleton for physical assistance: Design, modeling, control and performance evaluation

Muhammad Ahsan Gull, Mikkel Thoegersen, Stefan Hein Bengtson, Mostafa Mohammadi, Lotte NS Andreasen Struijk, Thomas B Moeslund, Thomas Bak and Shaoping Bai

The paper has been published in the
Applied Sciences Vol. 11(13), pp. 1–13, 2021.

Chapter 3

Paper II

Dynamic modeling of an upper limb hybrid exoskeleton for simulations of load-lifting assistance

Muhammad Ahsan Gull, Thomas Bak and Shaoping Bai

The paper has been published in the
Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science , 2021: 09544062211024687.

Chapter 4

Paper III

Design and performance evaluation of a hybrid hand exoskeleton for hand opening/closing

Muhammad Ahsan Gull, Shaoping Bai, Jakob Blicher and Tobias Glaston Staermose

The paper has been accepted for publication in the
Journal of Medical Devices Vol. 15(4), 2021: 041007.

Chapter 5

Conclusions

The aim of this Ph.D. study is to develop and investigate methods to comprehensively support human upper limb movements, including anatomical hand opening/closing. For this purpose, a 4-DOF powered upper limb exoskeleton was designed and integrated with a SEM glove to support users in ADLs (Study I). A kinematic model of the 4-DOF powered upper limb exoskeleton was developed to analyze workspace and singularities, and PD based trajectory tracking was implemented to experimentally evaluate the tasks performance. The work was further extended to evaluate the new concept of using a hybrid exoskeleton in supporting human arm manipulation (in Study II). A new design was proposed and a multibody modeling method was adopted to analyze the dynamic interaction and the torque sharing between the human upper limb and hybrid exoskeleton for two manual load handling activities. Subsequently, Study III aimed at developing a novel hybrid hand exoskeleton to support the anatomical hand opening/closing. The proposed design was analytically evaluated by developing kinematic and static models. A prototype was developed and tested for functional hand opening and closing with two healthy subjects and two ALS patients in the clinical setting. The overall results conclude that the use of hybrid exoskeletons in supporting human upper limb movements can offer a relatively energy-efficient and lightweight solution that would be an alternative to the complex and heavy powered exoskeletons.

5.1 Summary of main articles

A summary of three research articles are presented in this section.

Article I

Article I presents a 4-DOF upper limb exoskeleton to support the physically disabled wheelchair users in their activities of daily livings (ADLs), shown in Fig. 5.1. In general, six degrees of freedom are considered to be sufficient in achieving the desired position/orientation in the 3D task space. Given the requirements for the end-user application, i.e., tetraplegia users, and safety, the DOFs were reduced to four. The exoskeleton was designed to actively support the anatomical shoulder extension/flexion, upper arm internal/external rotation, elbow joint extension/flexion, and wrist rotation. Direct drive method and a worm gear mechanism were used to flex/extend the exoskeleton's shoulder joint and elbow joint, respectively. While two C-ring mechanisms were used to control the upper arm and wrist rotation. The proposed design was investigated in various aspects such as a kinematic analysis, singularity and manipulability analysis, and dynamics. Initially, the kinematic model was developed using DH parameters to analyze the singular configuration of the robotic exoskeleton, upon which the regions of high manipulability and low manipulability were identified. This analysis helped us in the exoskeleton's path planning or possibly bypass the singular configurations in task space. In addition, a commercially available soft extra muscle (SEM) glove was also integrated to control human hand opening/closing.

A model free PD-based trajectory tracking control was implemented to drive the exoskeleton system. Two different experiments were designed and performed to evaluate the reliability and repeatability of the exoskeleton, including an object picking up task and a drinking task. Two healthy subjects participated in the experiments, and the joint angle trajectories were

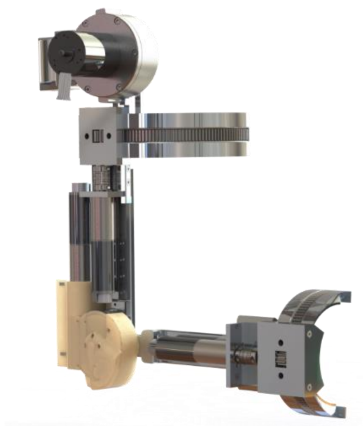


Figure. 5.1. Mechanical design of 4-DOF upper limb exoskeleton.

recorded. The efficacy of the exoskeleton was evaluated by comparing the actual trajectory with the reference trajectory for the individual joint. Root mean square error (RMSE) was used to analyze the system's performance across 16 trials recorded from the test subjects for each task. Average RMSE values were found to be 0.0184 *rad* for shoulder extension/flexion movement, 0.0027 *rad* for upper arm internal/external rotation, and 0.0071 *rad* for elbow joint movement. Similarly, the human exoskeleton system satisfactorily tracked the desired trajectory for a normal drinking task. The overall tracking performance of the exoskeleton's shoulder joint was relatively lower than the upper arm rotation and elbow joint extension/flexion. We believe that an implementation of a gravity compensation or implementation of an adaptive control method that could handle uncertainties or unmodeled dynamics can improve the performance of the shoulder joint. However, this effect was not observed in the C-ring and worm gear mechanisms because they are less likely prone to uncertainties or gravity torque.

Article II

Article II describes a new hybrid upper limb exoskeleton design where a detachable active forearm exoskeleton was developed and integrated with Skelex 360. The exoskeleton was designed to passively support the human upper arm elevation and actively support the human forearm extension/flexion movements by providing a modulating torque profile. The exoskeleton was intended to support the workers and alleviate their physical performance in a harsh industrial environment by preventing the risk of prolonged musculoskeletal fatigue. This theory of using a hybrid exoskeleton to reduce physical human effort was analytically investigated by modeling the human arm and hybrid exoskeleton as a multibody closed-loop system. The model was then extended to simulate the dynamic response of the multibody closed-loop system using the Lagrange multiplier approach. Two manual load handling tasks, i.e., overhead lifting and static load transferring tasks, with 3 *kg* payload were designed and simulated in MATLAB environment.

The simulation results reveal the interaction/contact forces between the human upper limb model and hybrid exoskeleton that help determine the critical points in task space. These sets of critical points present the information about the kinematic configuration where the exoskeleton could not sufficiently support the human upper limb model. In addition, the power-sharing between the human-exoskeleton system was also analyzed. It is noted that the hybrid exoskeleton supported the human shoulder joint and reduced maximum effort by 22.65% measured by comparing the human shoulder joint torques with and without the exoskeleton assistance. Moreover, the active forearm exoskeleton module was designed to regulate the assistive torque that was varied from 0% to 50%. Simulation shows a reduction in the physical human effort by 50.39%. All these results signify the use of a hybrid upper limb exoskeleton to relieve the human skeletal system and prevent work-related musculoskeletal disorder.

Article III

Article III presents a new design of a hybrid hand exoskeleton to support the minimal residual hand opening and closing of physically disabled people, including those suffering from spastic or clenched hands. Initially, a spring-loaded cable-driven passive hand exoskeleton was developed to support the finger/thumb extension movement and tone management. The design was analytically investigated with static and kinematic models. The kinematic model was used to study the response of the fingers' joints movements subject to passive assistance. In this work, the passive hand exoskeleton was additively manufactured with polylactic acid (PLA) plastic. Static structural analysis was performed to analyze the equivalent stresses and deformation, which were in the acceptable range.

The passive hand exoskeleton alone cannot assist people suffering from relative hyperflexion or weakness in the finger flexor muscle. Therefore, the passive hand exoskeleton design was extended to integrate with a commercially available soft extra muscle (SEM) glove to form a hybrid exoskeleton. The proposed design was developed and tested with two healthy subjects and two patients suffering from amyotrophic lateral sclerosis (ALS). Eight flex sensors were used to record the joint angle trajectories for the ring finger, middle finger, and thumb extension movements. The data recorded from the flex sensor were analyzed statistically and compared among the different conditions, i.e., with and without exoskeleton assistance. The results demonstrated the effectiveness of using a hybrid exoskeleton to support physically disabled people and compensate for volunteer hyperflexion of the wrist and fingers that severely impact human hand kinematics.

5.2 Contributions

The main contribution of this Ph.D. study is the development of upper limb exoskeletons that could comprehensively support human upper limb movements, including hand opening/closing. As a result, some novel hybrid exoskeleton designs were proposed. Test methods were developed for biomechanical investigation which demonstrated effectiveness of using hybrid exoskeletons as an alternative to the fully powered exoskeleton. In particular, the following specific contributions are made:

1. A 4-DOF active upper limb exoskeleton was proposed and integrated with a commercially available soft hand exoskeleton to comprehen-

sively support the human upper limb motion. The design was presented in Chapter 2, which was evaluated to support the human upper limb movements in basic ADLs safely and comfortably. The study demonstrated that using C-ring and worm gear mechanisms to support the anatomical shoulder rotation and elbow joint extension/flexion movements provides a reliable solution against the unmodeled dynamics or uncertainties. In addition, the non-backdrivable nature of these mechanisms supported the system in holding its output position without power consumption, thus ensuring a safe and reliable interaction.

2. A new method of developing a hybrid upper limb exoskeleton for physical assistance was proposed, where an actively actuated elbow joint module was developed and integrated with a commercially available passive shoulder exoskeleton called Skelex. The design was presented in Chapter 3 and a multibody model of a simplified human upper limb skeletal system and proposed hybrid exoskeleton was developed to analyze the dynamic interplay between the human-exoskeleton system during two manual load handling activities. The results obtained from the virtual simulations demonstrated the effectiveness of using a hybrid upper limb exoskeleton that could offer a low power and lightweight solution to support human upper limb movements.

3. A novel hybrid hand exoskeleton to support the user in hand opening/closing was proposed and developed. The proposed design has an ability to compensate for the involuntary contraction of flexor muscles caused by hypertonia. The study presented in Chapter 4 investigates the biomechanical compatibility and reliability of the proposed mechanism through kinematic and static modeling. In addition, clinical trials were performed to validate the hybrid exoskeleton for safe and comfortable interaction. The data collected from the experimental study were used to analyze the swan neck deformity and hyperflexion of the distal phalange for each finger. The results showed that the new design could support the anatomical hand opening/closing by ensuring a safe and comfortable interaction. The method of developing the hand exoskeleton can be applied to other fields of applications such as post-stroke rehabilitation or therapeutic purposes.

5.3 Limitations and future work

The Ph.D. study presents integrated design, mathematical modeling, and experimental evaluation of the upper limb exoskeletons. Some limitations of this Ph.D. study have not be noted that require further considerations:

- Currently, no consideration was given to the mechanical design optimization. In the future, a parametric investigation will be performed to optimize the structural design of upper limb exoskeletons that could possibly helps to reduce the size and weight.

- The experimental studies presented in Chapter 2 and 4 focus on the short-term use of exoskeletons to support the human upper limb and hand movements. A study focusing on the long-term use of this device and its impact on the human musculoskeletal structure is needed as some studies reported that the long-term use of upper limb exoskeletons might induce muscle weakness [59, 60].

- A PD-based trajectory tracking control was implemented to drive the 4-DOF active upper limb exoskeleton; however, the controller cannot compensate for the large variation in system dynamics or uncertainties.

- The model presented in Chapter 3 was only used to study the load sharing between the human upper limb and exoskeleton system in the sagittal plane. However, actual industrial environment manual load lifting/carrying can be more complex (involving upper limb manipulation in coronal and traverse planes) [116].

- The geometrical model for passive hand exoskeleton in Chapter 4 can only be used to analyze the extension/flexion movements of fingers and thumb and cannot be used to study the influence of abduction/adduction of the MCP joint, and spherical motion of the CMC joint with the exoskeleton assistance.

- No consideration was given to hand exoskeleton design optimization and selection of elastic elements in the case of passively actuated/ hybrid mechanisms. The design/model should be further investigated for structural optimization to improve the kinematic and dynamic response.

In order to address the above mentioned limitations, the following tasks are recommended for future study:

- A parametric investigation could be performed to minimize the power requirement, to maximize the workspace or to improve any other cost function such as torques and forces. This investigation would yield optimal design and improve the topology of actuators that would reduce the size and weight.

- An adaptive control method that could compensate for the unmodeled system's dynamic/uncertainties could be implemented and investigated to study the reliability and stability of the powered upper limb exoskeleton.

- The analytical model presented in Chapter 3 could be redefined to extend the study for 3D space, and more complex movements should be considered to evaluate the exoskeleton's design.
- The design of the hybrid hand exoskeleton could be extended to control the abduction/adduction movements of fingers and orientation of the thumb, which makes the exoskeleton be used for more complex and variety of tasks.
- Design optimization could be implemented for an appropriate selection and placement of elastic elements in case of passively actuated/ hybrid mechanisms that can improve the dynamic response of the coupled human-exoskeleton system.

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Appendix I

A review on design of upper limb exoskeletons

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