LICENTIATE THESIS NO. 15

The Robustness and Energy Evaluation of a Linear Quadratic Regulator for a Rehabilitation Hip Exoskeleton

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Gävle University Press

Dissertation for the Degree of Licentiate in Electrical Engineering to be publicly defended on Monday 28 November 2022 at 10:00 in Krusenstjernasalen, University of Gävle.

External reviewer: Research Expert Dr. Gianni Borghesan, Katholieke Universiteit Leuven

Gävle University Press
ISBN(PDF): 978-91-88145-97-0
urn:nbn:se:hig:diva-39907

Distribution:
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www.hig.se

Abstract

The implications of gait disorder, muscle weakness, and spinal cord injuries for work and age-related mobility degradation have increased the need for rehabilitation exoskeletons. Specifically, the hip rehabilitation exoskeletons due to a high percentage of the mechanical power is generated by this join during the gait cycle. Additionally, the prolonged hospitalisation after hip replacement and acetabular surgeries that affect human mobility, the social-economic impacts and the quality of life. For these reasons, a hip rehabilitation exoskeleton was our focus in this research, as it will contribute being a sustainable solution to take over the burden of physiotherapy and let patients perform their rehabilitation at home or outdoors.

This thesis details an approach of creating a hip rehabilitation exoskeleton, starting with modelling, simulating, and controlling the rehabilitation hip joint in a based-simulation environment. The mathematical model and the reason for using a series elastic actuator in the hip joint to execute the movement in a sagittal plane are more detailed. Because trajectory tracking is commonly used for controlling rehabilitation exoskeletons to ensure safe and reliable motion tracking methods; therefore, two desired torque signals were tested and analysed with the optimal linear quadratic regulator (LQR). The experiments were performed using two torque signals of a healthy hip joint—representing the sit-to-stand (STS) and the walking activity for their importance in lower limb movements. However, the mathematical model used as a basis of the optimal control strategy is usually influenced by multiple sources of uncertainties. Therefore, four case studies of various optimal control strategies were tested for a twofold reason: to choose the most optimal control strategy, and to test the energy consumption of these cases during the STS and walking movements, because the long-term goal is to produce a lightweight and reliable rehabilitation hip exoskeleton.

The research showed compelling evidence that tuning the control strategy will not influence the robustness of an optimal controller only, but affect the energy consumption during the STS and walking activity, which needs to be considered in exoskeleton control design regarding its applications.

Keywords: Hip Rehabilitation Exoskeleton, Robust Controller, Energy Consumption, Series Elastic Actuator (SEA), LQR Control, Luenberger State Observer, Torque Control.

Sammanfattning

Behovet av exoskelett för rehabilitering har ökat p.g.a. komplikationer som uppstår vid arbete och åldersrelaterad försämring. Komplikationerna består bland annat av gångstörning, muskelsvaghet och ryggmärgsskador. Speciellt höftexoskelett avsett för rehabilitering är extra intressant på grund av att rehabilitering inom detta område omfattar långvarig sjukhusvistelse efter höftprotes- och acetabulära operationer. Höftleden är en av de leder som utsätts för relativt höga mekaniska påfrestningar och minskad rörelseförmåga leder inte sällan till socioekonomiska effekter och minskad livskvalité. Av denna anledning kommer höftexoskelett för rehabilitering vara det primära området i denna avhandling då det kommer att vara en lösning för att minska belastningen inom sjukvård och låta patienter utföra sin rehabilitering hemma på egen hand.

Denna avhandling beskriver en metod för att skapa ett höftexoskelett avsett för rehabilitering med början i modellering, simulering och kontroll av en höftled av exoskelett i en simuleringsmiljö. Genom att använda ett serieelastiskt manöverdon för att utföra en höftledsrörelse i ett sagittalt så uppnås en mer detaljerad matematisk modell. Genom att använda banspårning, som vanligtvis används för att kontrollera exoskelett för rehabilitering för att säkerställa säkra och pålitliga rörelsespårningsmetoder, så analyserades två vridmomentssignaler mot en linjär kvadratisk regulator (LQR). Simuleringarna utfördes med hjälp av två vridmomentsignaler som representerar sitt-till-stå (STS) och gångaktivitet hos en frisk höftled. Den matematiska modellen som används för att hitta den optimala kontrollstrategin påverkas vanligtvis av flera osäkerhetskällor. Därför testades fyra fallstudier av olika optimala kontrollstrategier för två skäl: den ena för att välja den mest optimala kontrollstrategin emellan och den andra för att mäta energiförbrukningen för dessa STS och gångrörelse så att vi kan producera ett lätt och pålitligt höftexoskelett avsett för rehabilitering.

Forskningen visar övertygande bevis för att inställning av styrstrategin inte bara kommer att påverka robustheten hos en optimal styrenhet utan även påverkar energiförbrukningen under STS och gångaktivitet vilket måste beaktas vid design av exoskelett.

Nyckelord: Höftexoskelett för rehabilitering, Robust reglering, Energiförbrukning, serieelastiskt manöverdon (SEA), LQR reglering, Luenberger State Observer, Moment reglering.

Acknowledgements

First of all, I would like to give my warmest thanks to my supervisor Professor Niclas Björsell for his continuous support, guidance, enthusiasm and immerse knowledge throughout this research.

My thanks also to my assistant supervisor Professor Daniel Rönnow for his support and feedback. Special thanks to Dr. Mikael Cronhjort, Dr. José Chilo, Dr. Håkan Hugosson and Mr. Per Ängskog, who guided and helped me in various ways. I owe thanks to my colleagues at the university of Gävle and the PhD students for their beneficial discussions and feedback about my research.

Finally, I want to express my thanks to my beloved family, especially my wife Sarwin for her selfless love, encouragement and endless support through good and bad. Many special thanks to my first teachers in my life, my father Professor Suleiman and my mother Amel for all support and encouragement through my entire life. Love you!

Special praise and thanks to God, the Almighty for giving me the strength and patience through all years to accomplish my goals.

With you all, this work is achieved and becomes possible.

Rabé Andersson
Gävle, Nov. 2022

List of Papers

This thesis is based on the following papers, which are referred to in the text by Roman numerals.

Paper I (Accepted) to *ITIKD*
Andersson, R. & Björsell, N. (2023). The Technical Challenges in Orthotic Exoskeleton Robots with Future Directions: a Review Paper. *IT Innovations and Knowledge Discovery ITIKD*

Paper II
Andersson, R., Björsell, N. & Isaksson, M. (2021). Robots are a Promising Investment to Fight Pandemics. *8th International Conference on Signal Processing and Integrated Networks (SPIN)*: p-p 458–463.
doi: 10.1109/SPIN52536.2021.9566116

Paper III (Accepted, In press)
Andersson, R. & Björsell, N. (2022). The MATLAB Simulation and the Linear Quadratic Regulator Torque Control of a Series Elastic Actuator for a Rehabilitation Hip Exoskeleton. *5th International Conference on Intelligent Robotics and Control Engineering (IRCE 2022)*

Paper IV
Andersson, R. & Björsell, N. (2022). The Energy Consumption and the Robust Case Torque Control of a Rehabilitation Hip Exoskeleton. *Applied sciences.* 12(21):11104.
doi: https://doi.org/10.3390/app122111104

Abbreviations

SCI	Spinal Cord Injury
LQR	Linear Quadratic Regulator
SEA	Series Elastic Actuator
STS	Sit To Stand
LO	Luenberger observer
PID	Proportional Integral Derivative
DM	Disk Margin
DGM	Disk Gain Margin
DPM	Disk Phase Margin
RMSE	Root Mean Square Error
HRI	Human Robot Interaction
pHRI	Physical Human Robot Interaction
cHRI	Cognitive Human Robot Interaction
DH	Denavit Hartenberg
DoF	Degree of Freedom
RoM	Range of Motion
CGM	Classical Gain Margin
CPM	Classical Phase Margin
GM&PM-C	Gain and Phase Margin Combined
TL	Torque Level
HH	Healthy Hip
EMG	Electromyography
EEG	Electroencephalogram

Table of Contents

1. Introduction

1.1. Motivation of this Thesis

Age-related physical changes and mobility degradation affect both society as a whole and the individuals within it. According to a United Nations report, there are 810 million people aged 60 or above worldwide, with 11% and 20% living in Europe and Asia, respectively[1]. In addition, the demographical changes reported by the United Nations in 2019 showed that the number of elderly people will reach 1.5 billion by the year 2050, which makes the situation become alarming [2]. The huge numbers mean more personal care supports are needed to maintain a better quality of life and overcome the issues presented due to mobility degradation and the increasing dependency of these people on others, which influence the quality of life and sustainability in the end.

Moreover, the elderly people usually suffer from age-related pathologies such as osteoporosis, spinal cord injuries (SCI), cardiovascular, cerebrovascular, and fragility fractures, which affect their mobility, prolonged hospitalization, and their independence[3,4]. Thus, exoskeleton technology is a potential solution for mobility that makes elderly people more active in their daily lives, perform their daily tasks independently of others, and stay longer in their homes before moving to assisted care centres.

Based on all the aforementioned reasons for exoskeleton needs to support human mobility and ageing in place, we focused our research on the lower limb exoskeleton with a proposed solution for mobility rehabilitation purposes for elderly people. Moreover, motivation was owed to the hip rehabilitation exoskeleton as 45% of the mechanical movements are generated in the hip joint, as well as the increased number of incidences of pelvic and acetabular fractures in Sweden in last decades, which leads to increased needs for rehabilitation and hospitalization [5,6].

1.2. Objective of the Performed Research

The first objective of the preformed thesis is to extend the knowledge from the previous research articles regarding the technical challenges within exoskeleton technology, aiming to focus our research questions on a suggested exoskeleton that enhances one or a few of the main technical challenges. In addition, the aim is to have a guidance to the recent common knowledge of the challenges facing this technology. Moreover, expanding the view of the research gaps and trends for new and senior researchers in their future exoskeleton devices and research.

While, the second objective is formed as a result of the changes worldwide represented by the pandemic outbreak, which let scientists from multiple disciplines work together to beat the coronavirus. For this matter, we investigated the ways of using robots as a whole and exoskeletons as a part of different fields to overcome future needs and pandemics. As a result, for the aforementioned reasons in (1.1) and with the knowledge in mind about the technical challenges, we focused the research objectives on a rehabilitation hip exoskeleton. With a long-term goal of having an affordable rehabilitation hip exoskeleton using an optimal control that will contribute taking over the rehabilitation burden in hard times like pandemics and be used at home. Finally, the ambition of having mobile rehabilitation exoskeletons using an optimal control strategy and transparent behaviour in the joint space, formed the third objective of investigating how various tuning optimal strategies affecting not only the robustness of the exoskeleton regulator, but the joint energy consumption in sit-to-stand and walking movement activities. Therefore, this thesis summarises two specific research questions (RQ) as follows:

RQ1: What are the needs, the technical challenges and the suggested future directions of orthotic exoskeleton robots? (Paper I and Paper II)

RQ2: How can the design and control algorithms be developed for efficient energy consumption?

In which, the methodology of implementing the hip exoskeleton design, its model, and the control is achieved in a simulation-based environment that were illustrated in (Paper III). A series elastic actuator (SEA) was used in the joint space that was also controlled by an optimal linear quadratic regulator.

Finally, how the robust control strategy and the energy consumption be affected by tuning the optimal linear quadratic regulator is more disclosed in (Paper IV). For this end, Figure 1 shows the overview of the papers as well as the RQs respectively.

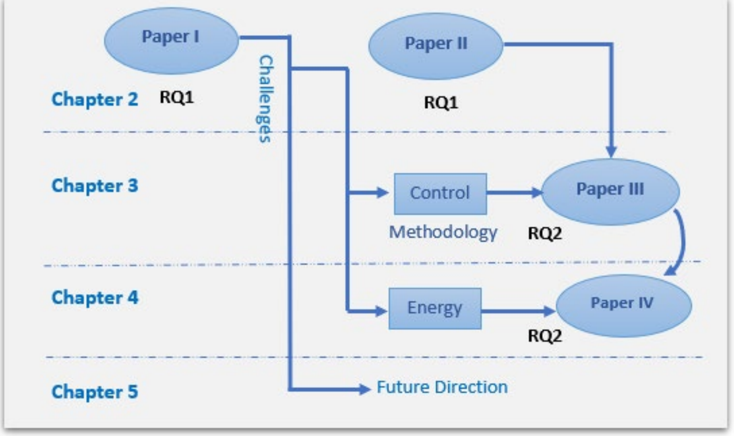


Figure 1. The Thesis Layout with Research Questions

On top of these objectives and research questions, the thesis and research work contribute to fulfill some of the United Nations sustainable development goals (SDGs), such as SDG 3-Good health and well-being as well as SDG 11-sustaiable cities and communities.

1.3. Research Methods

The method is mainly based on modelling of rehabilitation hip exoskeleton, which is also validated by a simulation-based environment. The research involves designing and simulating a prototype exoskeleton for experiments. A suggested 3D hip exoskeleton is complying with the kinematics and dynamics requirements to perform predefined trajectory motions of sit-to-stand and walking movements for the aimed rehabilitation sessions due to the importance of mobility movements for individuals' quality of life. The 3D model was controlled by utilising an optimal linear quadratic regulator, which was then optimised, analysed and compared with four different optimal strategies to validate the energy consumption of each movement step that can be utilized for various adoption scenarios of future rehabilitation sessions.

1.4. Overview of Appended Papers

Paper I: The Technical Challenges in Orthotic Exoskeleton Robots with Future Directions: a Review Paper

The aim of this paper is to shed light on the technical challenges facing exoskeleton technology. By having in mind that there are other social and ethical challenges for this infancy technology, still, we focus with the presented paper on the technical aspect for three reasons; first, we focus on contributing with research toward an exoskeleton solution for society; second, we give new researchers as well as senior scientists a compelling overview of such challenges; and third, we try to report the research gap and future directions found in published articles in the form of books, research articles, and websites to be quick guidance in this field.

Paper II: Robots Are a Promising Investment to Fight Pandemics

The paper aims to investigate which robots have been used since the COVID outbreak and concentrate on the fields in which robots can play an active role in curbing the spread of such a disease in the future. This paper sets out the different robots implemented for hospital, non-hospital use, and possible use that can be deployed amidst the pandemic. Among these robots are exoskeleton robots that can be used in rehabilitation sessions, especially since such sessions were suspended during the pandemic due to the shortage of professional staff who were already overwhelmed on the frontline, and to protect them and the patients by reducing the contact between them. The study was based on a literature search on large cross-sectional fields that recognize the relative importance of using sustainable solutions like robots as a whole and exoskeletons as a part of overcoming the current issue. This study intends to encourage societies, academia, engineers, and innovators to invest more in robots that cannot catch the virus and consequently introduce beneficial solutions to fight such pandemics. To this end, a rehabilitation exoskeleton prototype was our focused research device.

Paper III: The MATLAB Simulation and the Linear Quadratic Regulator Torque Control of a Series Elastic Actuator for a Rehabilitation Hip Exoskeleton

In this paper, we present a step-by-step method of a model-based design within a simulation environment in which a rehabilitation hip exoskeleton is addressed. The hip joint has attracted our attention because of the high percentage of lower limbs mechanical power are generated by this joint. The need for rehabilitation exoskeletons for patients who require prolonged hospitalization and rehabilitation sessions after hip replacement, pelvic or acetabular fracture surgeries was another motivation to conduct this research.

The research started first with a kinematic study of the DH parameters for the human lower limbs; secondly, designing a hip rehabilitation using Autodesk Inventor software to mimic the average length and joints' ROMs for a human weighted 73 kg and 174 cm height. Thirdly, modelling the exoskeleton prototype using the Simscape Multibody toolbox in the MATLAB simulation environment based on previous stages. The resultant model contains a SEA due to its safety, backdrivability, and transparency features. Fourthly, the model-based design is controlled by an optimal LQR to perform a predefined trajectory motion. The trajectories are extracted from the torque signals of a healthy hip joint. Finally, the admittance control strategy was implemented for STS and walking movements due to their relative importance in human mobility and quality of life.

Therefore, this research article is a methodology paper where it sets a hip rehabilitation exoskeleton in simulation-based environment for the further experiments and more analysis, optimization and assessment for the control strategy can be conducted. Moreover, using the LQR and LO in this study have showed motivated results based on root mean square errors (RMSEs) between the desired and measured torque signals of the limb motions.

Paper IV: The Energy Consumption and the Robust Case Torque Control of a Rehabilitation Hip Exoskeleton

This paper puts Paper III in context and evaluates the robustness of the optimal control strategy, as the goal is to choose the most robust case that tolerates a high margin of uncertainty before the system becomes unstable. For this reason, four optimal control cases have been studied, as the exoskeleton model usually has various sources of uncertainties. Keeping in mind that our rehabilitation hip exoskeleton is aimed to be used at home and outdoors; thus, choosing a proper energy source concerning its application is a must in this matter. Therefore, we asked whether the most robust optimal controller was consumed less energy and having better performance in tracking the desired signal. Therefore, this study has examined the impact of the robustness on the energy consumption of the rehabilitation exoskeleton performing STS and walking activities by the principle of admittance control within a simulation-based environment in which the energy consumption of a rechargeable battery was calculated. The energy consumption was defined, a number of times, and the walking distance could be reached at five different speeds using the hip rehabilitation exoskeleton with an optimal controller. The research showed that the most robust case affected the STS more than it influenced the walking movement by using the same robust case and rechargeable battery.

1.5. Co-authors' Statements

Paper I: The Technical Challenges in Orthotic Exoskeleton Robots with Future Directions: a Review Paper
The author of this thesis was the main contributor of this paper who performed the research question, conducted the literature search and wrote the manuscript. Professor Niclas supervised the work and contributed with guidance and comments on the text.

Paper II: Robots are a Promising Investment to Fight Pandemics
The research and paper were planned by the author of this thesis together with Professors Niclas Björsell and Magnus Isaksson. The author of this thesis conducted the research design, formulating the research questions, methodology, investigation, and writing of the paper. Professor Niclas supervised the work and contributed with guidance and comments on the text.

Paper III: The MATLAB Simulation and the Linear Quadratic Regulator Torque Control of a Series Elastic Actuator for a Rehabilitation Hip Exoskeleton
The research was planned by the author of this thesis together with Professor Niclas Björsell. The simulation model of the rehabilitation hip exoskeleton was created by MATLAB software with the help of the Simscape Multibody toolbox, while the hip exoskeleton was modelled by using the Autodesk Inventor software. The designing and modelling process of the hip exoskeleton and selecting the control strategy were carried out by the author of this thesis, who also performed the simulation, the analysis, conclusion, results, and writing of the paper. Professor Niclas supervised the work and contributed with guidance and comments on the text.

Paper IV: The Energy Consumption and the Robust Case Torque Control of a Rehabilitation Hip Exoskeleton
The research and the paper were planned by the author of this thesis and Professor Niclas Björsell. The author was responsible for the software investigation, simulation, visualisation, and validation of the results, while he and his supervisor collaborated on the conceptualisation, methodology, and formal analysis. The graphs and tables were created and analysed by the author of this thesis, who also wrote the original paper under the advice and guidance of his supervisor.

2. Background about Exoskeleton

2.1. The Orthotic Exoskeleton

From time immemorial, human beings have shown the need for tools to compensate or increase the human gait ability for daily tasks. For the importance of human limbs activities, different gait assistive devices such as canes, crutches or orthotic gaits were created [7]. However, these tools were first passive until the development and innovations of robotic devices introduced the powered "wearable robots" and "exoskeletons" [8].

The concept of "exoskeleton" is a popular term for the external skeleton, which provides the wearer's body with structural support. On the other hand, the exoskeleton is opposite to the internal skeleton, also called the "endoskeleton", which supports the body internally, such as the bones in the vertebrate [9]. An exoskeleton is a wearable robotic system built to have the same structure as the human structure [10]. The exoskeleton structure can be attached either parallel to the human being as 'Orthotic devices' or in a series to the human limb like 'Prosthetic devices' [11]. An exoskeleton primarily consists of external rigid links and elastic components, hence protecting the wearers from injuries and supporting them with additional armour [12].

This thesis focuses on orthotic exoskeletons and excludes prosthetic ones, as the latter are electromechanical devices used for amputated limbs [13].

2.2. The Exoskeleton's Origin

Creating assistive devices to augment and strengthen human agility was not a new idea since the first powered exoskeleton was developed in 1890 by a Russian engineer called Nicholas Yang [14]. Then it was followed by the creation of the "Pedometer" by a United States inventor in 1917 [15]. Additionally, the first whole body-powered mobile machine called "Hardiman" was developed by General Electric in the 1960s [16–18].

Later on, the exoskeleton systems were developed in many countries because of their importance in enabling or assisting the human limbs and affecting human abilities. Among these countries are the United States, Japan, Germany and other European countries. The developments in mechanics, automation, and biological science played an active role in the spread of exoskeletons [19].

The initial explorations documents showed that the first patent application for human augmentations containing the term "exoskeleton" belonged to 1966 (US#3,449,769). Three years later, an active walking exoskeleton was developed in 1969 by Mihajlo Pupin Institute, Serbia [17]. A half-century later, the miniaturisation of electronic components and lightweight materials let the word "exoskeleton" emerge extensively in many scientific papers from the early 2000s and the years after [20].

Since the early stages of exoskeleton technology, many reasons have motivated research institutions and companies to develop different exoskeletons [20]. However, new reasons will continuously appear as various human needs emerge in multiple domains. Thus, a contribution part of this chapter is to introduce quick guidance on the development motivations of different exoskeletons by reviewing their various types and applications use.

2.3. The Exoskeleton Development Motivations

Exoskeletons offer many facilities by enabling mobility to augment or compensate the remaining gait functionality for their wearers. All exoskeletons, commercial or research ones, vary in their duties. Exoskeleton's benefits are different depending on applications, designs, people's age, and people's various sensory impairments [21]. Hence exoskeletons are used in various fields such as the military, industry, medical care, and various hazardous situations and hard times like pandemics [22], though exoskeletons are built:

2.3.1. For Soldiers

In military applications, exoskeletons augment the soldiers' ambulation endurance to walk longer and faster by reducing the metabolic cost. The military exoskeletons prevent back injuries and reduce the work burden on soldiers' hip, knee and ankle joints in the case of a lower limb exoskeleton. The more support the soldiers get during their marches, the more weapons they can carry over long distances [23,24].

2.3.2. For Industrial Workers

Industrial exoskeletons prevent industrial workers in their labours. Exoskeletons are beneficial in construction, agriculture, manufacturing, and industries, requiring different monotonous tasks with bending and carrying heavy objects. Thus, more companies are adopting exoskeletons to minimise lower back pain and reduce the probability of severe injuries usually occurring from different labour-related accidents [25]. Among these industries are Audi, Ford, Honda, Hyundai and Boeing [26].

Exoskeletons aid elderly workers in performing intensive duties, letting them stay longer at work before retiring. Apart from the robotic exoskeletons at work, these devices provide physical benefits for older adults while doing different daily activities such as walking, shopping, toileting and bathing, which contribute to mobility and being independent [27].

Moreover, fewer injuries at work lead to lower healthcare costs and more profits for industries since employee turnover reduce [10]. As a result, implementing exoskeletons helps industries use the workspace environment sufficiently and avoid taking up any room for automated heavy machines [21].

2.3.3. For Elderly people

The ageing demographic changes worldwide — reported by the United Nations in 2019 — emphasise that there are 703 million people aged 65 years or over around the world. This number will be doubled to 1.5 billion by 2050 [28]. The ageing societal concerns make robotic technologies such as exoskeletons proper solutions that assist elderly people in their daily activities.

Exoskeletons support or compensate for the performances of their wearers. The wearers can be healthy elderly people whose abilities decreased, yet still let them be independent in their daily activities [29]. The activities can vary from toileting, sitting, standing, walking on a flat floor or descending and ascending in various environments that help elderly people stay longer in their accommodations and enhance the quality of life.

The exoskeleton lets elderly people remain mobile, independent and active in their life, which promote living longer in their homes than in assisted care centres or institutions. By enabling elderly people to stay active and healthier is the recommended key for sustainable future mentioned by the current healthcare and social policies as “ageing in place” that affects the quality of life and the financial benefit to all [30]. Thus, the interest in developing different exoskeletons also increases to overcome the expected rising cost of health care assistance [31,32].

Nevertheless, robotic exoskeletons support elderly people whose muscles are fatigable and affected by age changes in their daily activities [33]. Among the muscles affected by age is “Tibialis Anterior muscle”, which its weakness affects the quality of life for older people [34]. The weakness in this muscle gives older people a stumbling stance which seems that elderly people are about to fall. Thus, it increases people’s anxiety of falling or breaking their legs, leading elderly people to be more dependent on help. Besides, the weaker the muscles will become, the more sitting time will elderly people spend in their lives. This makes their bones vulnerable to fractures and getting pressure ulcers, which are also common in older people and patients with spinal cord injuries (SCIs) [35].

2.3.4. For Patients Medical Use

The medical exoskeletons can be designed for the hand, upper extremity, or lower extremity, which attracted the most attention for researchers and innovators due to the potential importance of human mobility [17,18,20]. These devices are commonly used as assistive or rehabilitation devices to improve the quality of life. They can be fixed or mobile devices [36].

The rehabilitation exoskeletons are used to restore/enhance the impaired human limb functionality by assisting/resisting the human limb’s motion, which improves human limbs performance. Some rehabilitation robotic exoskeletons are fixed devices placed on a treadmill, such as “Lokomat”, which are supported by supervision to monitor patient progress using rehabilitation exoskeletons [37,38]. Whilst others are mobile rehabilitation exoskeletons like a hybrid assistive limb (HAL), Indego and Rewalk.

2.3.5. For Spinal Cord Injured People

Some implications of immobility for people with paraplegia can cause severe problems with urinary, osteoporosis, pressure ulcers, digestive troubles, cardiovascular and blood clots. However, exoskeletons will reduce the mentioned implications enhance the functionality of bladder organ, cardiovascular, and body fat problems by providing people with SCIs the ability to walk again [39,40]. Additionally, exoskeletons reduce the time needed for rehabilitation after the trauma or stroke and, as a consequence, the heightened risk of suicide. Especially that this suicide usually happens in the first five years of impairment because people are unfamiliar with their unknown world [41]. The robotic exoskeleton has enormous potential for reducing metabolic costs, and physical and mental fatigue [42].

Psychologically, It is not the patients only who benefit from using exoskeletons, but their families and caregivers taking care of the SCI people [43]. An example of a stroke recovery exoskeleton is "EksoNR" by Ekso Bionics, which gives a patient the ability to stand upright again and a tremendous psychological impact at the end [44].

2.3.6. For Reducing Workplace burden

The robotic exoskeletons show potential incomes for reducing the workplace burden for caregivers in hospitals, who bend and execute repetitive tasks every day [10]. The "Power suit" is a robotic exoskeleton for nurses to lift patients on and off beds and prevent nurses from back pain [45]. Therefore, assistive exoskeleton technologies are vital in decreasing the level of metabolic energy, the fear of performing challenging tasks, and reducing anxiety [46].

2.3.7. For Surgeons

Surgeons can also use exoskeletons in their long-session surgical operations to reduce fatigue, minimise tremors, and perform accurate movements during long-time sessions. A good example was an exoskeleton used for surgeons in a Russian clinical hospital during a twelve-hour urological surgery. Hence, exoskeletons can encourage more doctors and hospital workers to use them in the future [47,48].

2.3.8. For Hazardous Environments

Wearable exoskeleton robots are excellent intervention solutions in hazardous environments, such as the HAL exoskeleton used after the Fukushima Daiichi nuclear disaster. The reason for using HAL exoskeleton was due to its ability to reduce the ambulation time in harsh terrain and increase the ability to carry heavy loads, which could minimise the radiation by 50%, as such device covers many parts of the wearer's body [22,47,49].

2.4. The Technical Challenges

An exoskeleton usually needs to be lightweight, reliable, robust, and easy to use as it operates in close contact with human wearers. The exoskeleton users usually need some assistance, augmentation or rehabilitation to regain or compensate for an impaired limb movement or degradation. However, this technology has challenges, represented by the mechanical part, energy sources that powering it, structural design that should be suitable for its application, and selecting the appropriate actuators [48]. Some of these issues are seen in:

2.4.1. Challenges in Human-Robot Interaction

A part of exoskeleton operation is basically based on the interaction force between the human and the exoskeleton. This interaction can be cognitive human-robot interaction (cHRI) and physical human-robot interaction (pHRI), in which the cHRI can be a bidirectional, unidirectional and in closed-loop interaction behaviour. However, because the exoskeleton control strategy collects the biosignals via sensors and reacts respectively; thus, some challenges are presented by the collected signals, which can vary with different people or impossible to be sensed for impaired patients [13].

On the other hand, the interaction points or fractures connecting the exoskeleton with the human are commonly banded tightly into a human to avoid shaking or wobbling in order to perform a good control system and pursue the stiff contact as possible [13,50,51]. However, these fractures are usually rigid structures that can be a source of pressure ulcers, generating heat and leading to discomfort [52].

2.4.2. Challenges in Sensors and Controllers

More critical challenges arise by using different sensors that measure various quantities. These quantities can be positions, forces/ torques, electromyogram (EMG) or electroencephalogram (EEG) signals that are also essential for exoskeletons control system to generate the needed power to compensate or regain human limbs' abilities [50,53]. The supported exoskeleton forces are usually measured by force sensors, which can be affected by system uncertainties or are hard to estimate, for instance, in the simulation stage of building a proper control strategy [13,54,55]. Moreover, the EMG signals rely on placing electrodes on the skin's surface, while EEG signals are collected from a noninvasive cap. Hence, more problems arise as these signals are different between people, sensitive to muscle allocations (for EMG), require calibration that is time-consuming [56], and are also weak signals that can be affected by any error in amplification/ filtering that affect the control strategy at the end [53,57].

The diversity of exoskeleton workspace or environmental conditions usually provides additional challenges for exoskeletal control systems. Many types of research exoskeletons are laboratory-based designs that operate within laboratory environments or at rehabilitation centres or hospitals. Thus, the designer has to adapt the exoskeleton to specific environments. As more difficulties of exoskeleton functions appear when using exoskeletons within different environments that are not designed for. Adding to that, the controller has to be reliable to the environment it is designed for and robust to the mathematical model uncertainties that are invertible in the modelling stages.

2.4.3. Challenges in Structural Design

The robotic and biological system designs are different; thus, they have to be considered in exoskeleton design [13]. The biomimetic should cope with human limb function, limb length and the joints' structural design. The joints and structures for both exoskeletons and their wearers have to be aligned and

"Kinematically compliant". Otherwise, it could break the limbs or harm their wearers. The kinematic compliance and the imitation of the biological system are essential for matching the exoskeleton's joint rotation and human anatomical joint axes to ensure a truly ergonomic exoskeleton [13,48,58].

Different exoskeleton joints are also other than human joints. For the mechanical representation, some human joints can be represented as hinge or spherical joints, which are not a valid assumption for biomechanical representation. For instance, the glenohumeral joint of a human shoulder —imposes not only a rotational but a translational movement, which is usually simplified into a spherical joint that causes macro-misalignments in exoskeleton design [58]. This can already add a difference in human movements and the workspace of these components especially, that the range of motions (RoMs) and the degree of freedoms (DoFs) for exoskeletons' joints have not to be smaller than the human limbs' workspace; otherwise, it restricts the motion of the exoskeleton's wearer [13].

2.4.4. Challenges in Selecting Actuators and Batteries

In exoskeleton design, selecting an actuator for a suitable application is crucial because it affects the exoskeleton's performance, mobility and efficiency. The actuator types used in exoskeletons are electrical, pneumatics, hydraulic and SEA [59]. Additionally, many actuators are limited in torque and bulky, which adds more weight to exoskeletons and makes it more challenging to control. Moreover, the heavyweight exoskeleton usually needs more power sources to drive than lightweight ones.

As exoskeleton devices deal with pHRI, thus it should be mechanically transparent and backdrivable [60]. A backdrivability feature represents system's capability of physical interaction, which is already a challenging aspect in human-based exoskeleton design. The challenge comes as healthy human joints are naturally backdrivable, whereas exoskeleton joints, in most cases, have motors with torque amplifiers (gears), which increases the joint impedance and stiffness that yields having a system to be non-backdrivable. The transparency, on the other hand, describes how a robotic exoskeleton follows human movements in a transparent way without resistive forces. The challenges in mechanical transparency are more affected by mass, inertia, structural design, actuators, electronics and various applications; thus, they need to be carefully selected [13,61].

Thus, a system with a human-centred design ought to be safe, compliant and capable of dealing with the differences between the two systems; otherwise, a system will be experienced as uncomfortable and hard to control [62]. To this end, pneumatic muscles and SEAs are among the actuators used to introduce compliance, provide low mechanical output impedance, and increase peak power output [55,63,64]. Moreover, SEAs present accurate and stable torque control over time, shock tolerance due to its elasticity, which provides high confident force control, comfortable wearability, and at the end extend the joint operation's lifetime [8,16–24].

While the challenges in batteries are emerged as they add extra weight to exoskeleton devices depending upon their energy capacity. The power sources can be rechargeable sources as Lithium-ion batteries, AC charged batteries; Ni-MH batteries, Ni-Zn batteries or direct power supplies such are those used for laboratory-based environments [65]. Thus, the power sources require to be carefully selected to have lightweight exoskeletons with functional versatility [31].

2.4.5. Challenges in Selecting Materials

Different materials are usually used in designing exoskeletons' structures, such as carbon fibre, aluminium, plastic, fibre and titanium. The exoskeleton structure has to be light; otherwise, it affects users' productivity by slowing their motion and the time of its usability [66]. The heavy exoskeleton affects human biomechanics and influences human ambulation [31], as orthotic exoskeletons are attached to the human wearer. Thus, the simple design structure with good weight distribution is the requisite of a good exoskeleton.

2.4.6. Challenges in Safety and Ergonomics

As an exoskeleton operates to be attached directly to a human; therefore, a reliable, robust and safe system should be guaranteed [19,47,67]. Safety is also a factor that restricts many exoskeleton devices from being accepted by the Food and Drug Administration (FDA) regarding usability[68], as well as covering those devices by insurance companies can be an issue to accept as many exoskeletons are not even approved yet by the FDA[69].

Another considerable matter is how ergonomic an exoskeleton is to fit an application as well as the wearer; otherwise, the exoskeleton can harm or break a limb (see 2.4.3). Additionally, it can take (10-30) minutes for donning and doffing an exoskeleton as well as more time is required for safely checking before using the device [50,70,71]. Some exoskeleton users usually need to get help in donning or doffing such devices, for instance, the medical or rehabilitation exoskeletons [72]. Therefore, the time of don and doff any exoskeleton can be an aspect that falls under the ergonomic feature, which is also a challenging issue that should be reduced to as little as feasible.

Lastly, the hygiene of keeping exoskeleton devices sanitised and clean for sharing use in hospitals and workplaces can be a challenging aspect. Therefore, having an exoskeleton for each user will spend time adjusting and fitting the exoskeleton to the user's limbs, and it will solve the hygiene concern [73].

For this knowledge of these technical challenges, the motivations and needs, as well as more investment toward rehabilitation exoskeletons in hard times like pandemics—disclosed in Papers I and II, we proposed a rehabilitation exoskeleton prototype with a concentration of operating in indoor and outdoor environments. Therefore, the exoskeleton prototype is provided with rechargeable batteries. The suggested control strategy is chosen to be an optimal controller to overcome some issues than other conventional controllers do. The reasons of choosing the optimal controller are more illustrated in Chapter 3 as well Paper III and Paper IV.

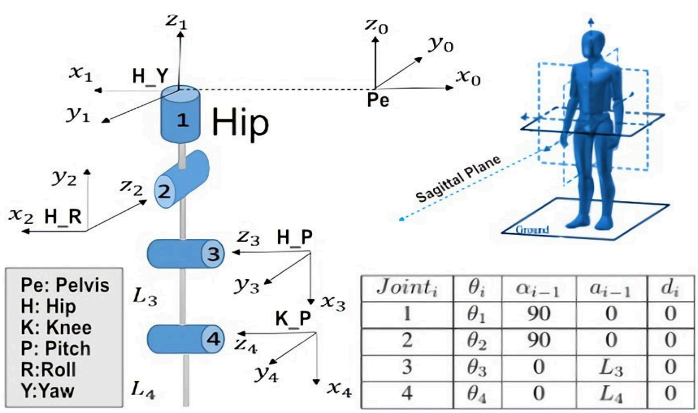
In the sense of the RoMs, our exoskeleton fits the RoMs and the legs length of the average human biological properties represented by [74,75]. For the movement trajectory, we targeted the rehabilitation movements in a sagittal plane, which also are aligned with the human joint rotation axes. The actuator used then is a SEA for its safety, transparency, backdrivability and other criteria that are more presented in the following chapters. At the same time, the selected material is chosen to be aluminium for the proposed prototype.

3. The Modelling and Control

The exoskeleton performance is influenced by many factors like actuator selection, sensors, controllers and structural design that utilized several parameters, which could be tweaked many times before giving good results. Additionally, such devices operate in close contact with a dynamical system represented with a human body where the safety is a critical factor. For this reason, exoskeleton system needs to be studied and analysed before it manufactured and attached with a human. Therefore, a simulation software plays pivotal role in determining the effects of the various parameters and structural mechanism as well as assessing scenarios that could be expensive and/or time consuming with a real prototype. But, before testing an exoskeleton prototype in simulation-based environment, a modelling stage is inevitably for this matter. Thus, the modelling of a rehabilitation hip exoskeleton is more described in the following section.

3.1. The Modelling

To model a rehabilitation hip exoskeleton, an anatomical study of human system has been executed where a hip joint is usually represented as spherical joint (3-DoF) and the knee joint as a revolute joint (1-DoF) with an assumption that a human body consists of rigid segments connected together via joints. For simplification purposes, the joints perform rotational movements without any displacement. Therefore, a kinematic study of a human lower limb consisting of a hip and knee joints are presented, which highlights the biomimetism between the human biological lower limb and the robotic ones. To overcome the challenges of misalignment (see 2.4.3), the position and orientation of the hip and knee joints were described by using the Denavit Hartenberg (DH) parameters. The DH parameters were also the basis for constructing the model in a simulation environment later. Figure 2 shows the DH parameters for our hip rehabilitation exoskeleton designed to perform the movements in a sagittal plane.



$Joint_i$	θ_i	α_{i-1}	a_{i-1}	d_i
1	θ_1	90	0	0
2	θ_2	90	0	0
3	θ_3	0	L_3	0
4	θ_4	0	L_4	0

Figure 2. The DH Representation of the Hip Rehabilitation Exoskeleton

The next stage is to design the hip rehabilitation exoskeleton using the Autodesk Inventor, which is integrated with the kinematic analysis mentioned previously into a MATLAB simulation environment using the Simscape multibody toolbox. A SEA was selected for the hip joint due to its safety and enhanced torque/mass ration comparing with other actuators like electrical and hydraulic ones (see 2.4.4). While the detailed transfer function and the construction of the SEA are disclosed in the articles [76,77], whereas the rehabilitation hip exoskeleton model in a simulation based environment is revealed in Figure 3.

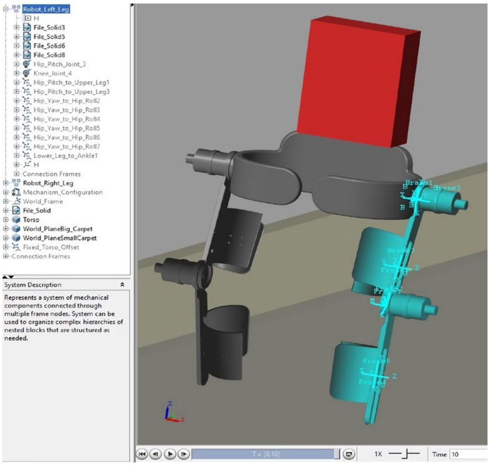


Figure 3. The Simulated Rehabilitation Hip Exoskeleton

The mathematical representation of right leg of the exoskeleton system with its SEAs at the hip joint was also found as it is the basis of control stage later for tracking trajectory movements. Especially, one common task for rehabilitation exoskeleton is to train a human limb passively to follow a predefined trajectory motion, which can be used in correcting a gait locomotion or training weak muscles. For this end, controlling the gait movements with respect to desired trajectories is vital and more described in as following.

3.2. The Control Strategy

The control strategy is a way to manage a system (plan) for certain behavior using some rules or algorithms. The proportional integral derivative (PID) is among these strategies that have been used widely in exoskeleton. As we use a SEA in the hip joint that has also been tested with a PID by other researchers, which showed its inadequate solution due to the feedforward term was required for neglecting the unmodeled dynamic term of the system [78,79]. For this reason, we use a controller called LQR to control the SEA in the joint space. We aim to test and analyse the exoskeleton behaviour and control it to track two hip torque signals during STS and walking movements in a sagittal plane [80].

The desired hip torque signals can be any torque signal suited for the patient needs, but for the simulation purposes, we used torque signals for a healthy hip joint. As the torque signals used for the input to the control strategy, thus we used an admittance control strategy, in which the control strategy scheme of a hip rehabilitation exoskeleton is illustrated in Figure 4.

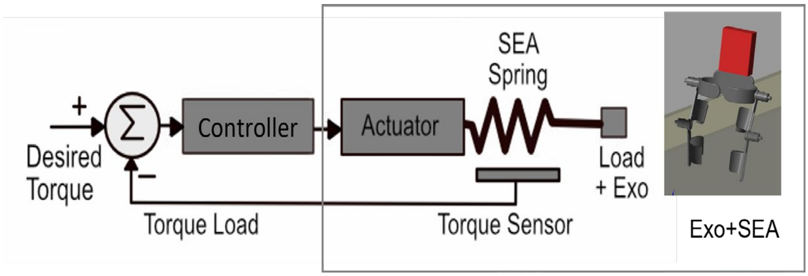


Figure 4. The Control Strategy Scheme

Due to the fact that the feedback control strategy needs always to sense the current state of the system, a solution used was a full state observer called a Luenberger observer (estimator), that could also be used when it is a challenging to measure the state of a system or expensive to measure certain quantities. Thus, a Luenberger observer was used with a combination of an LQR.

The LQR controller is used to find the optimal pole placement based on the wight of Q and R matrices to find the minimum cost function J, as the following.

$$u = -Kx, \tag{3.1}$$

$$J = E\left[\lim_{T\to\infty} \frac{1}{T}\int_0^T [x^T Qx + u^T Ru]dt\right], \tag{3.2}$$

where u is the system input, while K is the feedback gain and x are the system states. The Q and R are the design matrices, which can also be viewed as controller's tuning knobs. The value of K depends on the weight matrices of Q and R, respectively. The larger the wight value in R sets more penalty on the input signal u and the same is valid for the larger value of Q matrix with respect to the state of the system x. The value of K will also influence the system response at the end. While the desired control signals to be tracked are torque signals of a healthy hip joint for STS and walk movements as illustrated in Figure 5 and Figure 6.

Finally, the best controller was chosen with respect to the minimum root mean square errors (RMSEs) between the measured torque signal and the desired one at the input stage [81]. The results of LQR in tracking the desired signals are shown in Figure 7 and Figure 8, respectively.

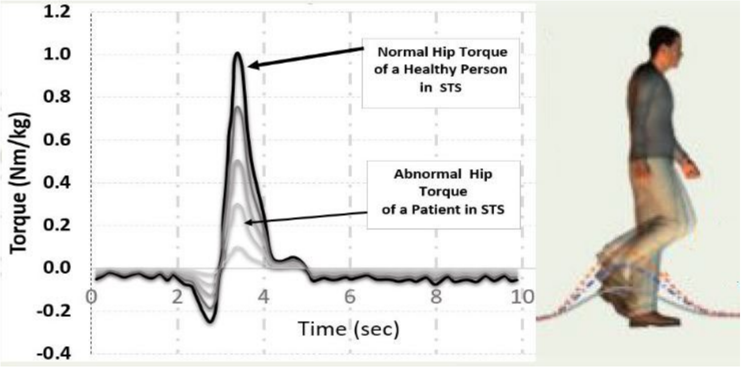


Figure 5. The Hip Torque Signal for a Healthy Hip Joint During STS

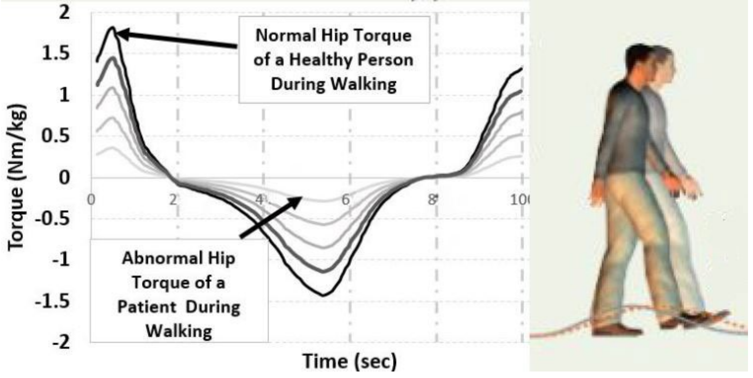


Figure 6 The Hip Torque Signal for a Healthy Hip Joint During Walk

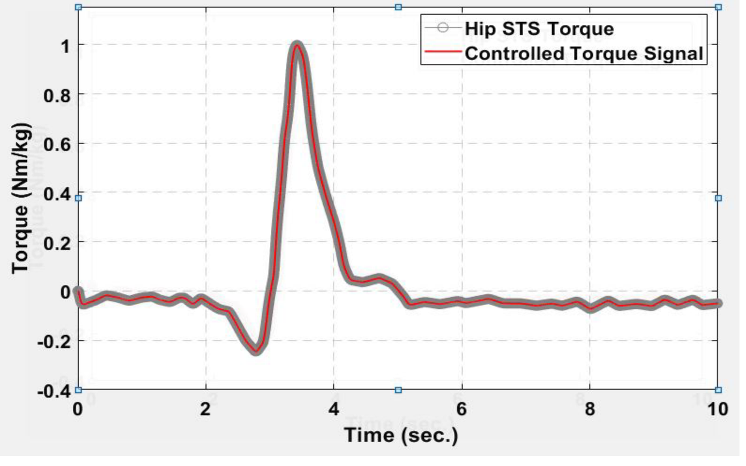


Figure 7. The LQR Hip Torque Controlled Signal During STS

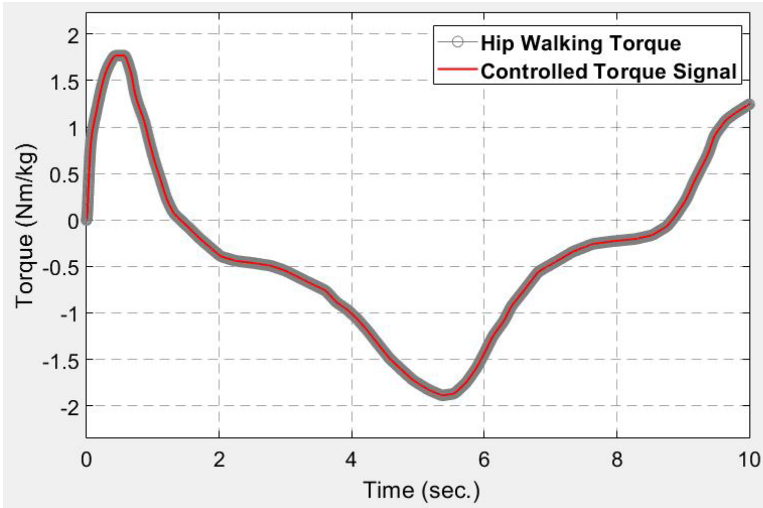


Figure 8. The LQR Hip Torque Controlled Signal During Walk

4. The Optimal Case Studies and Their Energy Consumption

For the control optimization in our exoskeleton technology that works on the challenge discussed in (2.4.2) that a controller has to be reliable and robust to mathematical uncertainties. We studied the robustness of our optimal controllers in this chapter. Basically, any system contains components that are simplified in the mathematical representation regarding to the physics laws [81,82]. Thus, a mathematical model will never represent the exact real system's behaviour. Furthermore, systems may also have disturbance sources or other stochastic noise, i.e. (ageing or noises) or even other dynamical behaviours that are hard to be represented mathematically. This raise a question on what will happen to our controller if there is uncertainty in the mathematical representation or any other disturbances in the system?

The importance of a mathematical model representation appears when controlling systems that implement some roles and algorithms for certain behaviour. However, the controller may not be reliable for the real hardware as the mathematical representation is only an approximation for real system. Thus, checking the robustness of a control system is another way to guarantee that the proposed controller design is valid and reliable even when there are uncertainties or disturbances in the system that lie within a design margin.

For these reasons, we chose four optimal control cases (Case 1-4) for few reasons: The first reason is to examine the robustness of the proposed controller cases by checking the tolerance margin for the mathematical model uncertainties. Secondly is to validate the performance of these controllers in tracking the desired input torque signals to these controllers. Thirdly, to investigate the energy consumption of our rehabilitation hip exoskeleton that works out another challenge disclosed in (2.4.4), which emphasis choosing a suitable energy battery to avoid extra weight. Thus, we examine the effects of robustness on the energy consumption of a battery connected to our rehabilitation hip exoskeleton in a virtual based environment. Mainly, choosing an appropriate energy source will not only be sustainable, but it guarantees using a suitable battery source and avoiding extra weight that may be added to the prototype by extra batteries than needed for specific applications.

Therefore, we show four optimal controller cases and the energy consumption concerning each case that prove the effects of Q and R matrices on the LQR stability and its robustness. This method could be used when a prototype is restricted with some physical design and actuators, impossible to change some physical properties or to reduce the energy consumption. Therefore, the robustness may contribute for energy consumption by tweaking the Q and R matrices to change the energy consumption. To this end, the following sections are describing the optimal controller cases and the energy consumptions related to each case.

4.1. The Optimal Case Studies

The robustness for four controller cases (Case 1-4) of LQR has been investigated, in which *Q* and *R* matrices are chosen empirically. We mainly studied the gain margin (GM), phase margin (PM) for each case study, and the disk margin (DM) as the DM is crucial when there is a combination of uncertainties in the gain and phase together. We noticed that the fourth case controller had the highest disk margin (DM=1.4) than other cases, which means that the controller strategy, is more reliable to uncertainties and the changes between the mathematical model representation and the real system. Moreover, the Nyquist curve, another method of checking the robustness of the closed loop system, has also been studied and showed the same results.

The performance of tracking the desired torque signals at each controller case was also examined with a combination of five levels of torque signals of a healthy hip joint during STS and walking movement, as rehabilitation sessions are intended to be performed for these movements. The desired torque signals represent various angular velocities of the joint's movements at five levels of hip torque (TL1 to TL5), as shown in Figure 10 for STS and Figure 11 for walking movements, respectively.

Then the performance of tracking the desired torque signals (predefined trajectory) at all levels was measured by the RMSEs between the desired input torque control (TL1-TL5) and the measured torque signals. Next, comparisons between the controller cases and their RMSEs at each torque level are summerised for both STS and walking movements. While the final section reviews how the energy consumption was calculated in the simulation environment at each controller case for STS and walking motions of a hip joint with various torque levels — representing different angular velocities of the hip joint.

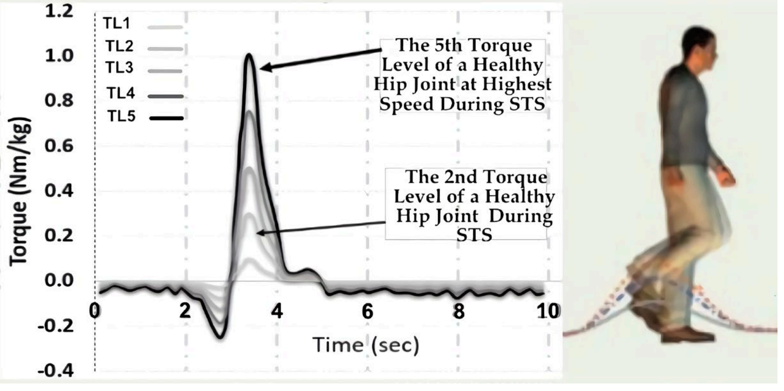


Figure 9. The Hip Torque During STS Activity

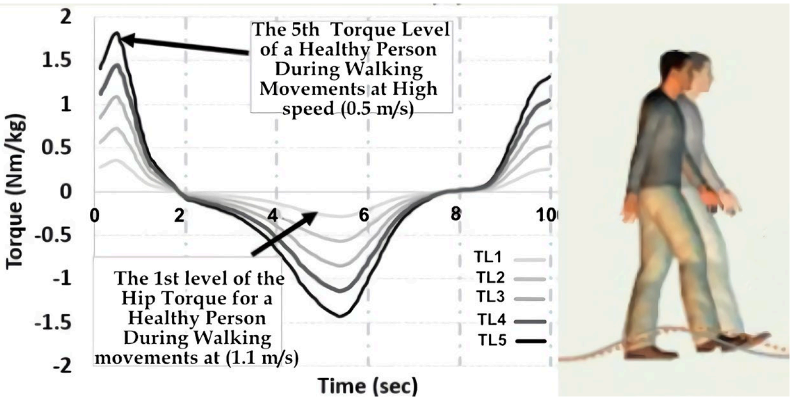


Figure 10. The Hip Torque During Walking Activity

4.2. The Energy Consumption

The simulation of the energy exerted from a battery connected to a hip joint was calculated with five torque levels (angular velocities) and controller cases. The calculation was executed to ensure the number of times STS can be performed using a battery in a simulation-based environment before it runs out of charge. Similarly, a simulation of how long distance can be reached in walking movements at various speeds was also accomplished. For this purpose, more energy sources could be added or eliminated according to the application or the patient's needs during the rehabilitation session, especially the lightest feasible weight possible is what attracted the users and innovators in the end.

The simulation of the energy consumption is based on applying the following equation (4.1), where θ is the angular position at each torque input for the hip; thus, the derivative quantity represents the angular velocity $\dot{\theta}$ is also attainable. Finally, the power needed to rotate the motor *P* at each torque can be calculated by the toque τ multiplied by its respective angular velocity $\dot{\theta}$, as follows.

$$P = \tau \cdot \dot{\theta}, \quad (4.1)$$

Therefore, the energy *E* needed for each movement step, whether at STS or walking activity, can be calculated by the following equation.

$$E = E_{Th} + |E_{Da}| = \int P_{Th}(t)dt + \int P_{Da}(t)dt, \quad (4.2)$$

where E_{Th} and E_{Da} are thrusting and damping energies, which are assumed to be equal. Consequently, the energy consumed for STS and walking activities at various torque levels and optimal controller cases (Case 1-4) are concluded. As we assumed using a rechargeable battery (Lithium-iron 48V,150 watts) in our simulation environment, we calculated the energy needed for each step by dividing 150 watts / energy exerted at each step (calculated previously) = number of times to perform the STS.

The same procedure was calculated to find the number of steps in walking movements. But, dividing the (nr. of steps) / (nr. of steps per km ≈ 1312.3) calculates the distance in km that can be reached using that battery with respect to the torque level and the control case selected.

5. Results and Discussion

This chapter contains two subsections: one that describes an overview of the results concluded from RQ1, and those are summerised from RQ2. While the second subsection is dedicated to our future research.

5.1 Results Connected to Research Questions

The detailed results are illustrated in the original papers, and therefore the results are briefly summarized here.

5.1.1 Results Linked to RQ1

The results are based on literature reviews that show some technical challenges within exoskeletons' various structural designs to fit versatile applications, and the sensors to measure multiple quantities used with various controller strategies. The HRI and the mechanical transparency between exoskeletons and their users are also vital as they influence exoskeleton controllers. The actuator selection and energy sources have to be carefully selected to fulfill the intended applications. The materials selected for exoskeleton structures affect exoskeletons' weight, applications, and productivity of their wearers. But the safety and ergonomic concerns overlap, as exoskeletons have to be ergonomic and safe to be considered wearable devices.

The study presented future research gaps found in literature articles within various fields, such as safety analysis related to physical and psychological aspects and the risk related to using exoskeletons both in public and at home. Another research gap mentioned focuses on exoskeleton user's satisfaction, which targets users of different backgrounds. Moreover, testing new materials to manufacture exoskeleton structures, microcontrollers, and miniaturised sensors will reduce exoskeleton weight, which other researchers are also highlighted. However, more safety tools such as airbags or sensors that measure heat between the fixtures and wearers' skins are interesting research.

Lastly, the need for exoskeletons in society is reported in different domains, especially rehabilitation exoskeletons during the hard times the world has experienced since the COVID-19 outbreak. In particular, such devices can reduce the burden of overwhelmed caregivers and doctors, facilitate using rehabilitation sessions at home and consequently minimise spreading the virus and save lives.

5.1.2. Results Linked to RQ2

An implementation of a rehabilitation hip exoskeleton design and model in a simulation-based environment where a SEA is mounted in a joint space to track the trajectory motions of a healthy hip joint during STS and walking movements. The LQR controller with a LO was used for active hip joints, in which four case controllers with their robustness were proposed and examined.

The controller cases were examined during STS and walking movements with respect to three criteria: robustness, performance in tracking the trajectory motions, and energy consumption. The robustness was studied in a combination of GM & PM as well as the Nyquist plot, which shows that a more tolerant controller to system uncertainties with higher DM was Case 4.

While the controllers' performance was based upon RMSEs, which were tested with all controller cases at five torque levels, which were the controller's inputs. The results showed that the RMSEs of controller Case 4, which was concluded as the most robust case controller, rejected the hypothesis that Case 4 would have the minimum RMSEs and best control performance. This was true with STS and walking movements at all torque levels. In contrast, controller Case 1 showed better controller performance with respect to the minimum RMSEs of the simulation tests. The explanation of such results connected to controller Case 1 had a faster response with its dominant pole at (P3 = −47.8) compared with Case 4 with the dominant pole at (P3 = −19.4).

For the energy consumption, the results showed that controller Case 4 exerted the minimum energy at all torque levels during STS, which consequently gave the highest number of times achieving STS. However, controller Case 1 showed sufficient energy consumption with a minimum exerted energy at (TL1 and TL5), whereas controller Case 2 exerted less energy at (TL2, TL3, and TL4). The energy consumption, control performance, and robustness can be switched into various modes to fit various applications and patients' needs, which need to be considered in exoskeleton designs.

6. Conclusions

Throughout the years, different exoskeletons have been developed within various domains. This thesis provides qualitative and quantitative research within exoskeleton technology, which are formulated in two research questions.

The first RQ was: *What are the needs, the technical challenges and the suggested future directions of orthotic exoskeleton robots?*

The answered was concluded by qualitative research represented with a literature review presenting a summary of exoskeletons needs and revealing their technical challenges facing orthotic exoskeleton robots.

Many technical challenges appear due to the human limb complexity and the differences between the biomechanical and anatomical systems. Different control systems, actuators, fixtures, materials, and energy storage systems like batteries have to be selected carefully to minimise the technical challenges. At the same time, safety concerns are fundamental to getting any exoskeleton approved by the FDA. The safety issue has been a major obstacle for insurance companies to cover such expensive devices, which also affects the exoskeleton accessibility among people.

The future research gaps and needs for exoskeleton technology have been mentioned to include more research related to end-user satisfaction, the energy sources where powerful batteries are needed. The smart materials will play a pivotal role in exoskeleton design and weight as well as more research, which contain safety tools with emerging technologies in wearable exoskeleton, is needed. The qualitive research showed the societies increasing needs of a rehabilitation exoskeleton with the emerging of the COVID-19, which also motivates focusing on rehabilitation hip exoskeleton in this study.

The second RQ was: *How can the design and control algorithms be developed for efficient energy consumption?*

A (4-DOF) rehabilitation hip exoskeleton is designed step by step in a simulation-based environment, which uses a SEA at the hip joint and is controlled by the LQR and LO in an admittance control strategy. The torque signals are based on sit-to-stand (STS) and walking motion activity. The RMSEs are used to validate the control performance while the energy consumption is conducted in a simulation environment with four proposed controller cases during STS and walking at five various speeds. Moreover, the robustness of the four cases are tested in this study. The results support that LQR ensures finding the optimal controller with a minimum cost function, which will not affecting the pole placement of the system, but energy consumption and the control performance. This enlarges the insight on new possibilities to affect the energy consumption with good control performance when the exosekeleton is restricted by certain design aspects such as mass, actuator selection and materials.

By evaluating the controller with STS and walking activities showed that what is valid for STS could not be suitable for walking movement for the same controller case or speed. The differences in applications or movements provide ample evidence that evaluating energy consumption and control performance have to take into account the application aimed to perform with the assessment.

Future Work

This dissertation is the halfway part of a study focusing on a rehabilitation hip exoskeleton with the long-term goal of producing a lightweight and reliable rehabilitation hip exoskeleton that can be used in public and at home.

The controller-related energy consumption comparison with various torque levels during STS and walking movements will have differences compared to real-world scenarios, as well as walking on a treadmill or overground. Thus, the following article will examine the robustness, controller performance, and energy consumption of the physical rehabilitation hip exoskeleton prototype, compared to the simulation results. Furthermore, the simulation process was performed under some assumptions, such as the linear time-invariant system being the basis of the LQR controller strategy; therefore, using a combination of a sliding mode observer with a disturbance observer prototype, where the non-linear components, parametric uncertainties of the model, and external disturbances are the main focus of the next study. The controller will be examined by people of various ages and backgrounds with multiple torque levels suited to their needs, ages, and abilities. The assessment of the hip exoskeleton will consider the controller performance and energy consumption of various movement trajectories for multiple applications and taking into account users' satisfaction and suggestions. Not only will the controller be examined, but various materials will be examined in the hip rehabilitation prototype in terms of ergonomics, control, and energy consumption.

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Papers
Associated papers have been removed in the electronic version of this thesis.
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